

Pertanika Journal of SCIENCE & TECHNOLOGY

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PERTANIKA JOURNAL OF SCIENCE & TECHNOLOGY

About the Journal

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Foreword

Welcome to the first issue of 2025 for the Pertanika Journal of Science and Technology (PJST)!

PJST is an open-access journal for studies in Science and Technology published by Universiti Putra Malaysia Press. It is independently owned and managed by the university for the benefit of the world-wide science community.

This issue contains 25 articles: six review articles; two short communications; and the rest are regular articles. The authors of these articles come from different countries namely Australia, China, India, Indonesia, Iraq, Malaysia and Nigeria.

One of the articles in this issue explored the acoustic emission (AE) partial discharge (PD) localization in oil based on an artificial bee colony (ABC). Data from a previous AE PD experimental study, which includes the coordinates of three AE sensors and the time difference of arrival (TDOA), were used to construct the nonlinear localization equations. It is known that localization algorithms are among the factors that can affect PD localization accuracy, and the ongoing research in this area underscores the need for further advancements in this topic. Therefore, the ABC proposed to estimate the PD location through a colony of 120 bees, evenly divided into 60 employed and 60 onlooker bees. After 500 iterations, the optimal solution was the estimated PD location produced by ABC. Comparisons with the genetic algorithm (GA), particle swarm optimization (PSO) and bat algorithm (BA) revealed that the distance error, maximum deviation and computation time for AE PD localization based on ABC are the lowest. Details of this study are available on page 241.

The next article reviewed the precision of mangosteen maturity using conventional machine learning methods, namely Random Forest, Decision Tree, Support Vector Machine and K-Nearest Neighbor. Image samples of 253 mangosteens across six maturity stages were used, with 20 regions of interest each. 112 Gray-level Co-Occurrence Matrix and color features were extracted to train models using texture, color, and combined features. The evaluation metrics used for assessing the validity of predictions included precision, recall, F1-score, accuracy, and Cohen's Kappa. The Random Forest classifier achieved high validation scores, with an accuracy of 0.76 and Cohen's Kappa of 0.70 for combined features, 0.75 and 0.69 for colored features, and 0.46 and 0.33 for texture features. Details of this study are available on page 283.

The article by Zaahidah A Mohiju et al. from Malaysia studied the effects of electron, gamma and neutron irradiation on the superconducting properties of $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$

bulk samples. Their study revealed that electrons, gamma, and neutron irradiations reduced the critical temperature (T_c) and peak temperature (T_p) of Bi-2223 superconductors. Among these, neutron irradiation caused the most significant T_p decrease by 22.9%, highlighting its effectiveness in introducing microstructural defects. These defects serve as pinning centers, disrupting superconducting capabilities more than other irradiation types. Consequently, neutron irradiation is identified as the most impactful method for modifying Bi-2223's superconducting properties. The detailed information of this study is available on page 423.

We anticipate that you will find the evidence presented in this issue to be intriguing, thought-provoking and useful in reaching new milestones in your own research. Please recommend the journal to your colleagues and students to make this endeavour meaningful.

All the papers published in this edition underwent Pertanika's stringent peer-review process involving a minimum of two reviewers comprising internal as well as external referees. This was to ensure that the quality of the papers justified the high ranking of the journal, which is renowned as a heavily-cited journal not only by authors and researchers in Malaysia but by those in other countries around the world as well.

We would also like to express our gratitude to all the contributors, namely the authors, reviewers and Editorial Board Members of PJST, who have made this issue possible.

PJST is currently accepting manuscripts for upcoming issues based on original qualitative or quantitative research that opens new areas of inquiry and investigation.

Editor-in-Chief Luqman Chuah Abdullah



SCIENCE & TECHNOLOGY

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Primary Recovery of Carboxymethyl Cellulase from Thermophilic *Bacillus licheniformis* 2D55 Using an Aqueous Two-phase System

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ABSTRACT

This study uses an aqueous two-phase system developed from a polymer and salt to purify a thermostable carboxymethyl cellulase (CMCase) produced by thermophilic *Bacillus licheniformis* 2D55. The effects of system parameters, such as polyethene glycol (PEG) molar mass, salt concentration, crude load, NaCl concentration and pH on partitioning and recovery efficiency, are evaluated. Sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE) is used to determine the purity of the CMCase. The enzyme is successfully purified, achieving a 10.9-fold purification and 86.62% yield. The maximum purification condition is achieved in ATPS comprising 20.5% PEG 8000/15% sodium citrate, with a crude load of 17% (w/w), NaCl of 1.0%

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E-mail addresses: kazeem.mo@unilorin.edu.ng (Muinat Olanike Kazeem) upmsahar@yahoo.com (Sahar Abbasiliasi) jooshun@gmail.com (Tan Joo Shun) azaris@upm.edu.my(Azhari Samsu Baharuddin) nor'aini@upm.edu.my (Nor' Aini Abdul Rahman) * Corresponding author (w/w) and pH at 7.0. Under these conditions, a partition co-efficient of 0.21 is observed, indicating that CMCase preferentially partitions to the bottom phase. These results demonstrate the potential of ATPS for the purification of thermostable CMCase from the fermentation broth of thermophilic *Bacillus licheniformis* 2D55.

Keywords: Aqueous two-phase system, *Bacillus licheniformis* 2D55, carboxymethyl cellulase, enzyme, partial purification, polyethene glycol

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INTRODUCTION

Cellulases are enzymes involved in the bioconversion of cellulose, which accounts for 40%–50 % of the weight of agro-waste biomass. It catalyses the cleavage of the β -1,4-glycosidic bonds linking the glucose molecule polymer of cellulose into cellodextrins, cellobiose and glucose (Co & Hug, 2020). Among cellulases, carboxymethyl cellulases (CMCase) are of special attention due to their role in initiating the process of cellulose hydrolysis. The global enzyme market receives a significant share of CMCase due to its high demand in industrial processes such as food, feed and beverage (Kumar et al., 2019), waste management (Pham et al., 2022), detergent (Abedi et al., 2022), textile (Vajpayee et al., 2022) and biofuel (Hoffman et al., 2021) industries. They have also found special usefulness in aiding the decomposition of straws to improve soil fertility (Shi et al., 2019) as well as improving animal feed digestibility (Selzer et al., 2021).

A plethora of microorganisms, bacteria and fungi (mesophilic or thermophilic) produce CMCase under induction when grown on agro-waste biomass (Kazeem et al., 2021; Sadida & Manchur, 2021). Interestingly, much attention is now drawn to enzymes from thermophilic bacteria for industrial uses due to their high stability, increased substrate solubility, reduced contamination risk and reduced cooling cost. CMCase from thermophilic bacteria has been reported in some species of Bacillus and (Ulucay et al., 2022) Thermoanaerobacterium (Harnvoravongchai et al., 2020). However, the purification of this enzyme usually involves multiple laborious chromatographic steps in which high purity and large-scale production are not economically available. Such multiple steps reported for CMCase include ammonium sulphate precipitation and anion exchange diethylaminoethanol (DEAE)-Sepharose (Banerjee et al., 2020), ultrafiltration and column Q Sepharose (Bettache et al., 2021), ammonium sulphate, DEAE-cellulose, Sephadex G-100 (Shankar et al., 2021), ammonium sulphate precipitation, DEAE- Sephadex A-50, ultrafiltration, gel filtration (Sephadex G-100) (Olukunle et al., 2021). Nevertheless, each technique faces limitations, which may include high cost, low purity and low yield. Thus, improvement in downstream processing is necessary since downstream processing accounts for 80 % of the total production cost (Júnior et al., 2020).

The ATPS is widely applied to separate and purify microscopic and macroscopic biological molecules, including enzymes (González-González et al., 2022). This technique is commonly known to yield high-purity products in a single step (Singla & Sit, 2023). The ATPS, which consists of polyethene glycol (PEG) and salt, is widely accepted owing to the varied differences in hydrophobicity between the two phases and its low cost of salt (Saddique et al., 2020). ATPS are formed by mixing polymer, salt and water at appropriate concentrations, forming two immiscible liquids where proteins are separated (Moteshafi et al., 2022). It allows simultaneous extraction, purification and concentration of the target proteins. The polymer-salt system is advantageous over the polymer/polymer system due

to the low viscosity salt phase, low interfacial tension between the phases, higher density and considerable selectivity (Hamta & Dehghani, 2017).

Hence, the present study employed ATPS based on a polymer/salt system, favouring the one-sided partition of compounds due to larger differences in the physico-chemical properties between the two phases. It is valuable during the first purification step when most contaminants must be separated. The most common inorganic salt employed was potassium phosphate. However, using high salt concentrations poses a waste disposal and an environmental problem. This problem could be surmounted by recycling the polymers and salts or by choosing other salts, such as sodium citrate, which is biodegradable and non-toxic. For similar reasons, sodium citrate was selected in this study in the construction of the ATPS as it has a lower eutrophic potential and is more biodegradable compared with other salts (Wang et al., 2022).

Until now, very few studies have reported CMCase purification via ATPS (Ho et al., 2017; Liu et al., 2019). Reports on the purification of CMCase from *Bacillus licheniformis* using ATPS are lacking in the literature so far. The present study, therefore, evaluated the partitioning competence of CMCase from thermophilic *B. licheniformis* 2D55. The appropriate ATPS composition suitable for the separation of CMCase was determined using varying PEGs and salts. Furthermore, factors such as the pH of ATPS, crude enzyme load, and sodium chloride concentration (NaCl) that affect the efficiency of ATPS for the recovery of CMCase were investigated to maximise CMCase purification.

MATERIALS AND METHODS

Supplies

PEGs of different molar mass (MM) ranging from 4000 g/mol to 10,000 g/mol were supplied by Sigma-Aldrich (St. Lious, USA). Potassium dihydrogen phosphate (KH₂PO₄), di-potassium hydrogen phosphate (K₂HPO₄), ammonium sulphate (NH₄)₂SO₄, magnesium sulphate (MgSO₄), sodium citrate (NaH₂C₆H₅O₇), citric acid (C₆H₈O₇), sodium acetate (CH₃COONa), hydrochloric acid (HCL), acetic acid (CH₃COOH) and sodium hydroxide (NaOH) were sourced from Merck (Darmstadt, Germany). The bovine serum albumin and the bicinchronic acid (PierceTM) kit for protein assay were supplied by ThermoScientific (Rockford, USA).

Bacterial Strain and Carboxymethyl Cellulase Production

A thermostable CMCase-producing *Bacillus licheniformis* 2D55 isolated from hot compost was used (Kazeem et al., 2017). The CMCase production medium contains the following in submerged fermentation (g/L): urea, 1.0; peptone, 11.0; MgSO₄.7H₂O, 0.40; and CaCl₂.2H₂O, 0.03; Tween 80, 0.2% (w/v). The carbon source was prepared from a mixture of rice husk and sugarcane bagasse, 7% (w/v), with the final pH adjusted to 3.5

while agitation was set at 180 rpm (Kazeem et al., 2016). The bacterial cells were set at $OD_{600} = 1.0$, and 3% (v/v) bacteria cells were transferred into the 100 mL production medium and used as an inoculum. After 18 h of shaking at 50°C, the fermentation broth was centrifuged at 2,860 × g, 4°C for 10 min. A clear top layer (Crude enzyme) was gently withdrawn for storage at 4°C.

Assay for Carboxymethyl Cellulase

CMCase activity was carried out as Wood and Bhat (1988) described with minor variation. Briefly, 0.5 mL of the crude enzyme was mixed with 0.5 mL of 1% (w/v) carboxymethyl cellulose (CMC) in 0.5 mM sodium phosphate buffer (pH 7.5). The concoction was allowed to stay in a water bath (30 min; 50°C). Reducing sugar liberated was analysed following the dinitro salicylic acid method (Miller, 1959). A unit of CMCase enzyme activity was defined as the amount of enzyme that reacted with the substrate to release μ 1 mol of glucose/ min at the stated condition of the assay

Bicinchronic Acid Assay (BCA Assay)

The BCA kit with the bovine serum albumin (BSA) standard was employed to analyse protein concentration. A 0.1 mL enzyme was added to a 2 mL BCA reagent. The mixture was then incubated in a 37°C water bath for 30 min. The intensity of the resulting colour was determined by a spectrophotometer (SECOMAN, 30100 Ales, France) at 562 nm wavelength. The protein concentration of the samples was obtained from the BSA standard curve.

Salt Selection for ATPS

The stability of CMCase with five different salts: magnesium sulphate (MgSO4), di-potassium phosphate (K_2HPO_4), ammonium sulphate (NH_4)₂SO₄, sodium citrate ($Na_3C_6H_5O_7$), sodium acetate (CH₃COONa) was examined. The system pH was maintained at 7.0. The pH of the phosphate salt was adjusted with potassium di-hydrogen phosphate. Magnesium sulphate and ammonium sulphate were adjusted with sodium hydroxide and hydrochloric acid. In contrast, acetic acid and citric acid were used to adjust the pH of sodium acetate and sodium citrate, respectively. Different salt concentrations were mixed with the crude enzyme for 1 h, after which residual CMCase activities were determined to select the salt preferable for ATPS.

ATPS Studies

The ATPS were studied from 50% (w/w) stock of PEG solution of different molar mass (MM) (4000 g/mol, 6000 g/mol, 8000 g/mol and 10,000 g/mol) and sodium citrate stock solution [40% (w/w)]. The ATPS was prepared in a 15 ml centrifuge tube. The amount of the PEG solution, sodium citrate solution and distilled water was weighed and mixed with

crude enzyme at 14% (w/w) to form a 10 g system of pH 7. The solution was mixed using a vortex for 10 min and centrifuged at $2860 \times g$ for 10 min to achieve a phase separation. The phase separation of PEG at the top phase and sodium citrate at the bottom phase was completed by allowing the tubes to stand for 10 min. Finally, samples from both phases were collected for analysis of CMCase activity as well as the overall protein concentration.

Determination of Partition Coefficient (K), Purification Factor (P_F) and Yield (Y %)

The CMCase coefficient of partition (K) was calculated using Equation 1 to extract the proportion of CMCase activities from the two phases.

$$\mathbf{K} = \frac{A_T}{A_B} \tag{1}$$

Where, A_T and A_B are the equilibrium of the CMCase activities (U/mL) at the top and bottom phases.

Specific activity (SA) of CMCase is the ratio between CMCase activities (U/ml) in the phase sample to the total protein concentration (mg) following Equation 2.

$$SA\left(\frac{U}{mg}\right) = \frac{cellulase\ activity\ \left(\frac{U}{mL}\right)}{Protein\left(\frac{mg}{mL}\right)}$$
[2]

Purification factor (P_F) is the ratio of the specific CMCase activity (U/mg) of the recovered CMCase activity at the bottom phase to the original specific CMCase activity in the crude feedstock, calculated according to Equation 3

$$P_{F} = \frac{SA \text{ of phase sample}}{SA \text{ of crude feed stock}}$$
[3]

The CMCase activity yield from the bottom phase in the bottom phase was determined as illustrated in Equation 4

$$Yield (\%) = \frac{Enzyme \ activity \ in \ bottom \ phase \ \times \ volume \ of \ the \ bottom \ phase}{Enzyme \ activity \ in \ x \ supernatant \ \times \ volume \ of \ supernatant} \times 100$$
[4]

Sodium Dodecyl Sulphate -Polyacrylamide Gel Electrophoresis (SDS-PAGE)

The electrophoresis chamber (Bio Rad, USA) was used for this analysis. The SDS-PAGE investigation was executed using an electrophoresis unit, according to Abbasiliasi et al. (2014). The bottom phase sample was precipitated with trichloroacetic acid at 10 % (w/v).

A desalting column was used to remove the salt, while a protein concentrator with a 10 kilo Dalton (kDa) cut-off (Thermo Scientific, Massachusetts, US) was used to concentrate the protein. The concentrated samples were obtained after centrifugation ($12,100 \times g, 4^{\circ}C$, 20 min). Thereafter, 20 µl precipitate was suspended in 5 µl denaturing buffer (100mM Tris-HCL pH 6.8, 4% (w/v) SDS, 20% (v/v) glycerol, 10% (v/v) β-mercaptoethanol and bromophenol blue). The mixture was loaded onto the gel after boiling for 10 min. The SDS-PAGE was carried out according to Laemmli (1970) by loading protein samples onto solidified gel containing 12% resolving gel [2.5mL 1.5 M Tris HCL (pH 8.8), 100 µL 10% SDS, 3.0 mL 40% (w/v) Bis-acrylamide solution, 100 µL ammonium per sulphate (APS) and 5 µL tetramethylethylenediamine (TEMED), 4.3 mL dH₂O] and 5% stacking gel [0.5 mL of 1M Tris-HCL, 0.5 mL 40% Bis-acrylamide, 40 µL 10% SDS, 40 µL APS, 2.920 dH₂O, 5 µL TEMED]. The gel was run at 180 V for 40 min. Staining commenced with the Coomassie Brilliant Blue, followed by distaining, and the resulting band was viewed.

RESULTS AND DISCUSSION

The Effect of the ATPS Salt on Carboxymethyl Cellulase Activity

Results from the influence of salt concentrations (5%–20 %) on the CMCase activity were as shown in Table 1. Increasing the concentration of the salt resulted in a decreased enzyme activity among all the salts tested.

Table 1

cellulase activity

However, sodium citrate at 5% and 10% concentrations yielded 28.59 U/mL and 26.28 U/mL of CMCase activity, respectively. It was followed by 5% sodium phosphate (26.55 U/mL). The CMCase activity was strongly inhibited by magnesium sulphate. This may be due to protein denaturation by aggregation (Torosyan & Shoichet, 2019). When sodium acetate was used as a separating salt, the activity of CMCase decreased. The use of high concentrations of salt in ATPS poses a disposal problem. Hence, the problem can be addressed by either recycling salt or choosing non-toxic and biodegradable salt. The stability of CMCase in sodium citrate is advantageous to this study (Ma et al., 2018; Ng et al., 2011). Hence, sodium citrate was selected as the salt of choice for subsequent studies.

Salt	Concentration (%, w/w)	CMCase activity (U/mL)
Sodium	5	26.55 ± 0.62
phosphate	10	25.38 ± 0.56
Magnesium sulphate	20	22.93 ± 0.21
	5	21.53 ± 0.09
	10	19.15 ± 0.31
	20	$15.45{\pm}~0.18$
Ammonium sulphate	5	26.41 ± 0.43
	10	25.06 ± 0.46
	20	21.51 ± 0.28
Sodium	5	28.59 ± 0.21
citrate	10	26.28 ± 0.43
	20	21.49 ± 0.53
Sodium acetate	5	25.55 ± 0.51
	10	23.98 ± 0.31
	20	20.71 ± 0.21

Selection of ATPS bottom salt for carboxymethyl

Influence of PEG Molar Mass, Curde Load, pH, and NaCl on Carboxymethyl Cellulase Partitioning Behaviour

The current work did not use the design of experiments to maximise CMCase purification in the partitioning experiment. Variables affect the ATPS, and interactions between the combinations of variables impact the response either positively or adversely (for example, yield, PF, and K). Significant variables that are screened have a big impact on the outcome. The ATPS partitioning of CMCase employing a factorial design will provide more accurate results and potential interdependencies between the variables.

The selection of a suitable PEG molar mass is usually the first step required in ATPS for protein recovery. The PEG molar mass decides the extent of the partitioning of the target protein and impurities in the extract. It has been previously demonstrated that the effectiveness of the extraction is largely influenced by the phase-forming molecules and the number of polymer-protein interactions, which is governed by the degree of polymerisation of the polymer (Iqbal et al., 2016). The influence of the PEGs on the partitioning behaviour of the phase system was observed in Table 2. Table 2 shows that the partition coefficient (K) was less than 1 (i.e. K < 1) in all the PEG /citrate examined, ranging from 0.32 to 0.63, indicating that the CMCase was preferably segregated into the bottom salt-enriched phase. In a similar result, CMCase from *B. subtilis* occupied the bottom salt-enriched phase of the PEG 6000 and sodium citrate aqueous biphasic system (Ho et al., 2017). Our findings are also in accordance with Albuquerque et al. (2020), who claimed that increasing the PEG molar mass from 1000-6000 (g/mol) resulted in K reduction (all the K values were smaller than 1) for purified tannase-acryl hydrolase from Aspergillus sydowii using ATPS (PEG/ citrate). Variation in partitioning is usually attributed to the hydrophobic and hydrophilic interface between the phase-forming PEG/salt and the external part of the protein of interest (Liu et al., 2019). It was reported that an increased hydrophilic region on the molecular surface of CMCase increased the CMCase separation into the hydrophilic bottom phase of sodium citrate (Ilari et al., 2009). Enzymes with highly hydrophilic proteins have greater protein affinity toward the salt-rich phase (González-Valdez et al., 2011; Sofijan et al., 2017). In this study, the PEG 8000/citrate ATPS resulted in a substantial maximum CMCase with a K of 0.32 and P_F of 6.18.

Additionally, the PEG yield obtained in the PEG 8000 g/mol showed the highest compared to PEG 2000 g/mol and PEG 4000 g/mol. The PEG 2000 g/mol and 4000 g/mol results in P_F at 1.63 and 3.23, respectively. Lower PEG molar mass limits the segregation of CMCase to the PEG phase, which is favourable for purifying CMCase. It was also observed that the K decreased with an increase in PEG molar mass. The system comprising PEG 4000 g/mol and PEG 6000 g/mol achieved a reduction of K from 0.63 to 0.52. This result shows that apart from hydrophobicity, the efficiency of partitioning is also affected by the phase component's molecular conformation and molar mass. A hydrophobic PEG further increases

Table 2

Molar mass PEG ^a (g/mol)	Partition coefficient (K)	Purification factor (P_F)	Yield (%)
4000	0.63	1.63	47.11
6000	0.52	3.32	58.89
8000	0.32	6.18	68.72
10,000	0.58	1.96	50.34

Influence of polyethyleneglycol molar mass on the partitioning behaviour of carboxymethyl cellulase in aqueous two-phase system

Note. ^a 20.5 % (w/w) PEG + and 15 % (w/w) sodium citrate. Results are means of triplicate readings \pm SD

the hydrophobicity of the ATPS due to an increasing PEG molar mass (Ng et al., 2011). Hence, there is a space shortage for the enzyme at the PEG phase, resulting from the volume elimination effect (Nagaraja & Iyyaswami, 2015). It is favourable to CMCase partitioning due to volume elimination resulting from space insufficiency experienced at the PEG-rich phase.

This allows efficient extraction of the CMCase to the bottom citrate phase, thereby decreasing the partition coefficient (K). In addition, increasing the molar mass of PEG up to 10,000 g/mol decreased the P_F to 1.96 while K increased to 0.58. Similarly to this study, a high PEG molar mass of up to 10,000 g/mol resulted in a concomitance decrease in P_F for the purification of polygalacturonase (Remli et al., 2018). This occurrence could be elucidated through exclusion impact, whereby long chain PEG 10,000 g/mol limits free volume in the PEG phase, thereby leading to the segregation to the bottom phase, the undesirable proteins (Nagaraja & Iyyaswami, 2015). Consequently, this allows space for competition between unwanted proteins and enzymes. This phenomenon could lead to excluded volume (Nagaraja & Iyyaswami, 2015) or a repulsion effect (Ho et al., 2017). Proteins are precipitated between phases as a result of the volume exclusion, whereas the enzyme is drawn back to the top PEG phase as a result of the repulsive volume effect. This phenomenon can be explained by declining free volume or saturation of the polymer phase, which causes protein entrapment at the interphase in systems with high molecular weight polymers (Torres-Bautista et al., 2022). Nagaraja and Iyyaswami (2015) have additionally reported a comparable outcome for the recovery of fish protein from fish processing industrial effluent in a PEG-sodium sulphate system.

Additionally, the use of larger molecular weight PEG could have an impact on the phase characteristics due to increased viscosity and compact polymeric network development (Karkaş & Önal, 2012). The ATPS is also influenced by factors that interact to enhance or decrease the purification efficiency. Several studies have shown the interaction between the PEG molar mass and the citrate concentration in ATPS. Amaral et al. (2020) demonstrated that partition coefficient (K) was influenced by PEG molar mass and citrate concentration for extraction and partitioning of protease of *Aspergillus tamarii* Kita UCP1279 using factorial design. PEG molar mass and citrate concentration exert an antagonistic effect,

increasing the K value when both variables were increased to the maximum. A similar phenomenon was observed with the purification of lectin, where PEG molar mass and citrate concentration exert the most significant effect on the K value (Porto et al., 2011). In their study, synergistic interaction between the two variables was observed. Thus, a simultaneous increase in both variables will increase the yield. Based on the previous study by Aziz et al. (2017), PEG concentration and citrate concentration showed a significant interaction effect on the partition coefficient (p<0.0004) and purification fold (p< 0.0001). However, the molar mass of PEG and citrate did not (p>0.05).

Hence, the interaction effects in PEG and citrate have to be considered during the experiment's design. In another study, Herculano et al. (2012) explored the purification of cellulolytic complex from *Aspergillus japonicus* using PEG/citrate aqueous two-phase systems. They reported that pH and citrate concentration demonstrated a negative correlation with the response K. They observed that a low value of PEG concentration and molar mass with high citrate concentration favoured the transfer of CMCase to the top phase, which increased K to 3.30. Therefore, the most appropriate molar mass chosen for subsequent studies was PEG 8000 g/mol.

The role played by the crude load in changing the phase behaviour in ATPS of the target protein cannot be overemphasised. The crude load feedstock may change the ATPS volume ratio (Vr), affecting the desired protein's partitioning behaviour. Enzyme loading volume in ATPS is also important to enable the processing and recovery of larger feedstock, which is advantageous to industrial downstream processing (Sofijan et al., 2017). Crude loads were applied in the range of 2% to 20% (w/w), as illustrated in Figure 1. The CMCase was

greatly improved when the crude load was increased to 17%, resulting in a maximum yield of 78.13%. The increase in crude load separated the target CMCase to the bottom phase, as reflected by the lowest K value at 0.24. This concentration achieves a balance of attractive and repulsive forces between the target enzyme and phase-forming component, ensuring their interactions are highly favourable.

However, a further increase in the crude enzyme load beyond 17% (w/w) resulted in the declination of the ATPS partitioning. Higher crude load at 20% (w/v) negatively impacted the ATPS partitioning behaviour due to a reduction in the phase volume ratio, thereby leading to a change in the



Figure 1. Influence of crude load on carboxymethyl cellulase partitioning in PEG 8000/citrate, ATPS. The crude load added to the aqueous two-phase system composition was varied from 2.5% to 20% (w/w). Results are means of 3 readings \pm SD. K = Partition coefficient

composition of the phases. This result is in accordance with previous literature (Abbasiliasi et al., 2014; Sukohidayat et al., 2018). Alteration of the system composition resulting from increasing ATPS crude load could diminish the Vr in the system (Ng et al., 2011). An increase in crude loads up to 20% resulted in a decline in yield to 70%, leading to an increase in K value to 0.28. It could be that the frontier of concentration at 17% (w/w) was exceeded by a higher crude load at 20% (w/w), therefore altering the partitioning behaviour of the target CMCase. Thus, the CMCase occupies the interface rather than being extracted from the bottom phase. In agreement with Sukohidayat et al. (2018), the precipitation of target protein at the interface resulted from a lack of space at either of the two phases. Furthermore, the precipitation of proteins at the inter-phase of ATPS resulted in the loss of enzyme activity (Chow et al., 2015). Therefore, crude enzyme at 17% (w/w) was designated the best concentration and used in further studies.

The pH affects the electrochemical characteristics of protein and ATPS. The electrochemical interaction plays a vital role in protein purification via ATPS (Iqbal et al., 2016). Thus, it will significantly affect CMCase partitioning. Hence, the pH of the system varied between the range of 5.0 to 8.5 (Figure 2). From this study, an increase in pH to 7.0 enhances the distribution of impurities at the top phase, thereby decreasing the value of K and enhancing the yield at the bottom phase. However, pH beyond 7.0 moved the contaminant into the salt-dominated phase and shifted the CMCase into the PEG-dominated phase, thereby increasing the K and leading to a decline in the yield. This phenomenon is supported by the earlier literature (Ho et al., 2017; Sofijan et al., 2017). It can be visualised that the values of K diminished (0.32 to 0.24) with pH increase (5.0 to 7.0).



Figure 2. Influence of pH on carboxymethyl cellulase partitioning in PEG 8000/citrate ATPS. The results are means of 3 readings \pm SD. K = Partition coefficient

However, pH beyond 7.0 increases the K values to 0.37 (at pH 8.0), resulting in a concomitant decrease in yield to 71%. The highest yield of 78.13% was obtained when the pH was maintained at 7.0. The pH affects the target protein net charges, altering the attractive and repulsive forces of the protein of interest and the phase composition (Amid et al., 2014). Increasing the system pH at a higher value than the pI value of the CMCase creates an enzyme with a negative charge, which develops an attraction for the PEG phase (+ charge), thereby decreasing the CMCase yield at the salt-enriched phase (Ratanapongleka, 2010). The isoelectric point (pI) value of CMCase from *Bacillus* sp ranges between 5.0 and 7.0 (Yin et al., 2010). When the pH approaches the pI value of CMCase, the net charge of the enzyme becomes constant and the total charges near zero, where the enzyme is of neutral pH; the change in yield and K was not noticeable in ATPS with pH 5.5 to 7.0 (Ho et al., 2017). Purification of CMCase from Bacillus valezensis A4 with ATPS composed of PEG 4000/phosphate requires a pH of 8.5 for maximum recovery (Liu et al., 2019). According to Soares et al. (2011), using a factorial design, the volume exclusion impact of PEG 8000 was stronger than the pH electrostatic effect and, combined with a low citrate concentration, favoured the partitioning of Con A protein to the bottom phase.

In another study by Herculano et al. (2016), a negative interaction effect of PEG concentration and pH was experienced. In this case, an increase in PEG concentration with a simultaneous decrease in pH increased the PF of xylanase. In this study, the PEG 8000/citrate at pH 7 with the lowest K (0.24) was selected for further studies because it was inferred that the CMCase was more stable at neutral pH.

The NaCl concentration will affect the hydrophilic proteins, which will, therefore, influence the enzyme separation in the ATPS. The NaCl concentration will affect the variation in the hydrophilic proteins, which will, therefore, influence the enzyme separation in the ATPS. The Variation in the ATPS NaCl concentration will affect the hydrophilic nature of the proteins, thereby influencing the separation of the enzyme. The NaCl concentration will affect the hydrophilic proteins, which will influence the enzyme separation. The effect of NaCl concentration on [0 to 1.25%, (w/w)] CMCase partitioning is illustrated in Figure 3. From the results, an increased NaCl to 0.75% (w/w) separated the enzyme to the bottom salt-enriched phase with a higher P_F of 9.68 compared to the ATPS without the addition of NaCl (8.94). The yield of CMCase increased from 78.12% to 83.12% with increasing NaCl concentration from 0 to 0.75%. The addition of NaCl at 1% (w/w) in PEG 8000/ citrate ATPS achieved the maximum yield at 86.62%. The P_F of 10.6 was recorded as the maximum at this concentration. It shows that the bottom phase harbours more enzymes.

The above results indicated that the NaCl concentrations influenced the enzyme partitioning. The electrical potential difference produced by adding NaCl may affect the ATPS protein partitioning. The unequal distribution of additional salt at different concentrations between the two-phase samples could improve the separation of the target



Figure 3. Influence of additional NaCl concentration on carboxymethyl cellulase partitioning in aqueous two-phase system. NaCl at concentrations between 0%–1.25% (w/w) was maximised in the ATPS. Results are means of three experiments \pm SD. PF = Purification fold

and enhance the biomolecules (Anvari, 2015). A better interaction between CMCase and the NaCl could be due to the higher generated electrical potential, separating additional CMCase from the bottom phase (Ramesh & Murty, 2015). Adding sodium chloride might create a disorder in the water structure due to the higher electrical potential created amid the two phases, consequently improving the contact of the phase composition with the CMCase (Settu et al., 2015). When NaCl at 1.25% (w/w) was added to the ATPS, Y and PF decreased to 84.06 and 8.19, respectively. Excessive addition of NaCl could partition CMCase and unwanted protein to the same phase, consequently reducing the Y and the P_F.

In addition, NaCl at higher concentrations could decrease enzyme activity and modify target proteins' structural properties, thus leading to protein denaturation (Ketnawa et al., 2010). Similar to this study, Ho et al. (2017) reported that a 1% NaCl concentration was required for the purification of *B. subtilis* CMCase in ATPS consisting of PEG 6000 and sodium citrate. However, a higher NaCl concentration of up to 4% (w/w) was reported with PEG 8000/citrate ATPS partitioning of cyclodextrin glycosyltransferase (CGTase) (Ng et al., 2011). Increasing the NaCl concentration to 5% (w/w) leads to a decrease in P_F beyond the non-addition of NaCl, pulling non-target protein to the bottom phase (Ho et al., 2017). Therefore, 1% NaCl was sufficient for PEG 8000/citrate ATPS partitioning of CMCase.

The Molecular Weight of CMCase

Figure 4 shows the purified partitioned CMCase from PEG8000/citrate in ATPS. The result's evaluation shows multiple bands in Lane 2, signifying the presence of both the impurities and the target protein. However, a sample from the salt-rich citrate bottom phase (Lane 3)

shows a distinct band corresponding to 56 kDa. The result is in accordance with the CMCase produced from *Bacillus cereus* FOA-2, which was reported to have a molecular weight of 56 kDa (Olukunle et al., 2021).

Comparison of Purification Enhancement and Partitioning Behaviour of Cellulases from Different Microorganisms

The purification and partitioning behaviour of cellulases has been studied for bacteria and fungi isolated from various environments (Table 3). Different two-phase systems have been used to achieve purification enzymes. Notably, ATPS, which consists of PEG/citrate or PEG/phosphate, has been reported for cellulase purification. According to Liu et al. (2019), Cellulase from Bacillus Valezensis A4 was recovered at a yield of 67.8% in ATPS consisting of PEG 4000/ K_2 HPO₄ at pH 8.5 and 5% (w/w) NaCl concentration. Results from the current study are comparable to the previous study, as indicated in Table 3. Despite 100% purification not being achieved, partial purification of CMCase from Bacillus licheniformis 2D55 using ATPS has been successfully demonstrated in PEG 8000/citrate.



Figure 4. Sodium dodecyl sulphatepolyacrylamide gel electrophoresis (SDS-PAGE) analysis for purification of carboxymethyl cellulase in polyethene glycol 8000/citrate aqueous two-phase system. The purity of the carboxymethyl cellulase was assessed with 12 % SDS-PAGE analysis. The protein maker's molecular weight ranged from 11 to 100 kDa. SDS-PAGE- Lane 1: Protein molecular marker; Lane 2: crude sample; Lane 3: purified carboxymethyl cellulase from ATPS bottom phase

Table 3

Isolate	Phase composition	Condition		Reference
Bacillus subtilis	PEG 6000/citrate	Vr 0.29, NaCl 1% (w/w), pH 7, crude load 20 % (w/w)	Y _B 88%, P _F 4.8, K 0.44, MW 32-46 kDa	Ho et al., 2017
Bacillus Valezensis A4	PEG 4000/K ₂ HPO ₄	NaCl 5% (w/w), pH 8.5, crude load 2g (w/w)	Y _B 67.8%, P _F 1.14, MW 35 kDa	Liu et al., 2019
Bacillus licheniformis 2D55	PEG 8000/citrate	NaCl 1% (w/w), pH 7, crude load 17% (w/w)	Y _B 86.62%, P _F 10.9, K 0.21, MW 56 kDa	This study

Partitioning behaviour of cellulases from Bacillus species at different conditions

Note. Vr = volume ratio

CONCLUSION

The aqueous two-phase system was a prospective method for purifying CMCase of thermophilic Bacillus lichiniformis 2D55. ATPS has been recognised as a potential and powerful primary separation and purification step in the overall product recovery train. This system is a viable alternative for CMCase purification because of the phase-forming polymers' low cost, making it suitable for large-scale applications. Based on the results of this study, the maximum yield (88.62%) and $P_{\rm F}$ (10.98) were successfully recovered from the salt-rich bottom phase upon incubation of the system at PEG 8000 /citrate (20.5/15%, w/w) 1%, (w/w) NaCl, at pH 7.0 and crude enzyme load at 17%, (w/w). The hydrophilic nature of the enzyme assists in separating the CMCase into the salt-rich phase obtained at the bottom layer. Hence, the ATPS provides a good degree of enzymes since it reduces the loss of enzymes and eventually improves enzyme recovery. The result shows that this technique could be advantageous to the enzyme industries since a cheaper and relatively straightforward separation and purification strategy could be achieved in a single step. It is obvious that the ATPS is an efficient recovery technique for CMCase, addressing the need for scalability and effective bioprocess technology with a high purification factor. Further investigations will be conducted using factorial design to build upon our findings and provide a complete understanding of the system.

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Review Article

A Comprehensive Review Based on Analysis Modeling, Mechanical Vibration Control Strategies, and Optimization Methods of Robotics Flexible Manipulator Structures

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ABSTRACT

Flexible Manipulators (FMs) provide a number of benefits, containing reduced weight due to the thinness of the robot's linkages. Although the initial plan was to use actual robots' flexibility or slenderness to their advantage, the complex dynamics of the systems piqued interest in using an experimental flexible manipulator as a testing ground for various modeling or control strategies. A review is essential for researchers who want to align their study objectives with those of the field because the literature is extensive and diverse. Due to the widespread usage of flexible manipulators in different mechatronic and robotic applications over the past few decades, many academics worldwide are now interested in researching this topic. Studies are categorized here according to the control and modeling technologies of flexible manipulators and methodologies. Review of recent works on analysis, modeling, mechanical vibration, control algorithms, gyroscope

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E-mail addresses: a.moloody@yahoo.com (Abbas Moloody) zizan@upm.edu.my (Azizan As'arry) saihong@upm.edu.my (Tang Saihong) kamil@upm.edu.my (Tang Saihong) zuhri@upm.edu.my (Raja Kamil) zuhri@upm.edu.my (Zuhri Yusoff) * Corresponding author technology and applications, difficulties in managing flexible manipulators and their anticipated future, and the majority of the notable evolutionary and optimization algorithms, including Genetic Algorithm (GA), Differential Evolution (DE), and Fuzzy Logic (FL), as well as modification approaches and techniques, are discussed and underlined. This study examines many publications, thoroughly reviewing the analytical, mathematical, dynamical modeling, mechanical vibration control techniques and most of the notable evolutionary and optimization algorithmic approaches of Robotic Flexible Manipulator (RFM) structures.

Keywords: Differential evolution, double links, mechanical vibrations, multi-links, optimization, robotics flexible manipulator, single link

INTRODUCTION

Mechatronics and robotics areas and systems have garnered increasing interest from researchers in recent years because of their widespread usage in engineering science and scientific research applications, such as space exploration, undersea surveys, industrial and military sectors, welding, painting, assembling, and medical applications. Robotic and mechatronic manipulators are multi-segment devices that are electronically controlled and interact with their surroundings to carry out tasks. As shown in Figure 1, every component of mechatronic systems requires research and development (R&D) work. These manipulators are widely used in industrial production and have many other specialized applications. Generally, these manipulators are divided into Rigid Manipulators (RM) and Flexible Manipulators (FM). Much research has been done to design methods for modeling and controlling flexible robotic control systems. Therefore, various experimental investigations were performed to verify the proposed modeling and control methods. Dynamic and mathematical modeling, analysis, and control of dynamic mechanisms began in earnest in the 1970s. Pole Position (PP) (Paul et al., 1988), Lyapunov-Based Control (LBC) (Ge et al., 1996), and Integrated Resonance Control (IRC) (Pereira et al., 2011) are just some of the feedback control methods that have been studied for precise positioning and vibration control of single-link robotic flexible manipulators. This discussion presents an overview of the foundation, control and modeling of robot flexible manipulators and the popular theory of evolutionary algorithms that have been extensively studied to address the areas of optimization and applications and different techniques since its introduction by Storn and Price (1997).



Figure 1. Typical of a mechatronic system block diagram
MATERIALS AND METHODS

Robotics Flexible Manipulator (RFM) Structures

Robotic Flexible Manipulators (RFM) are typically employed to pick up loads and transport them to a predetermined place. It has a number of benefits over Rigid Robotic Manipulators (RRM), including quick reaction, reduced power consumption, less weight, a smaller actuator required, a cheaper total cost, more maneuverability, and ease of transport. An example of a typical RFM for a single connection is shown in Figure 2. However, because of the complexity of multi-link systems, experimental development is restricted to single-link manipulators. Flexible manipulators are an essential advancement in robotic systems, aiming to increase productivity. They are suitable for a wide variety of jobs and environments. They are in high demand to replace humans in difficult jobs, routine tasks, and dangerous situations to perform operations faster, more profitably, and more precisely. Therefore, RFM dynamic analysis and controller design are more difficult to solve. Despite its advantages, the main disadvantage of RFM is vibration failure due to its low stiffness (Chen et al., 2019).



Figure 2. Configurations of a typical RFM : (a) Theoretical model; and (b) Experimental model (Chen et al., 2019)

Mechanical Vibration of (RFM) Structures and Suppression

For many years, attempts have been made to preserve mechanical vibration factors and regulate mechanical vibration. Vibration reduction methods are divided into passive and active approaches (Figure 3) (Vishal & Aradhye, 2016). Vibration causes are protected by eliminating extra energy sources, reducing input forces, and isolating them from external disturbances. The parametric adjustments mostly affect the mass and stiffness of parts. Vibrations are an unwelcome occurrence in construction. Structures may be damaged, or system performance may be harmed as a result of the unwanted vibration. Vibration reduction is a serious concern when using flexible structures, especially in the aircraft and



Figure 3. Flow chart for types of vibration damping (Vishal & Aradhye, 2016)

robotics sectors. However, controlling, reducing, and suppressing RFM vibrations are still regarded as major and critical issues.

Modeling Strategies of RFM Structures

The dynamic model is the foundation for dynamic analysis, dynamic performance evaluation, and manipulator optimization design when modeling and analyzing flexible manipulators. In investigating such systems' dynamic behavior and control, the many applications of flexible manipulators draw much interest. However, because of the lengthy and connected set of dynamic equations and the system's flexibility, this is recognized to be a challenging task (Rahimi & Nazemizadeh, 2014). Figure 4 shows that such systems have no exact solutions. Figure 4(b) depicts the design of a robot single-link flexible manipulator with a clamp. By analyzing integrated mode (Tang et al., 2021), three types of single-link RFMs have been studied: single-link flexible manipulators, single-link rigid-joint manipulators.



Figure 4. (a) Configurations of Flexible Manipulator (FM) and Rigid Manipulator (RM) (Rahimi & Nazemizadeh, 2014); and (b) Configurations of Flexible Manipulator (FM) (Tang et al., 2021)

Modeling of Single-link RFMs

The discussion is on the flexible single-link manipulator modeling literature and groups contributions into categories, models, and additional investigations. However, the robot model must include the system's non-linear dynamics and dynamic parameters for flexible robotics analysis. The four basic finite-dimensional models, such as the Lumped Parameter (LP) (Huston, 1980), Assumed Modes (AM) (Alandoli et al., 2016), Finite Elements (FE) (Lochan et al., 2016), and Concentrated Mass (CM) models (Pereira et al., 2014), are generally used to represent the dynamic equations of these systems.

Modeling of Double Links RFMs

Robotic manipulators with a few flexible links are desirable because they do not suffer from the significant control issues brought on by the heavy inertia forces produced when the rigid, heavy links in traditional robots move at high speeds. In reality, only two of the average six-link industrial robot's links frequently experience large inertial forces, so these two links should be flexible. Planar dynamic model developed by Vakil adaptable link by integrating the Assumed Mode Method (AMM) with Lagrange's Equation and taking into consideration the tip mass and mass moment of inertia, flexible joint Manipulators of two links, or double manipulators, were created (Vakil et al., 2012).

Modeling of Multi-RFMs

Jian and Wen (2017) demonstrate the bias of an n-linked robot's flexible manipulators using finite terms of series and the Euler-Bernoulli beam model. The Lagrangian method is applied to the dynamics system to obtain the dynamics equation of the general soft manipulators of the n-linked robot. Contrary to single-link manipulators, multi-link RFMs cannot be calculated using a linearized model, as realized by Cannon and Schmitz (1984).

Classical Control Strategies of RFM Structures

There are two basic types of control techniques for RFM systems: feedforward (Open Loop) (OL) and feed-back (Closed Loop) (CL). While feedback control techniques employ estimation and measurement of the system states for controlling the rigid body motion and vibration suppression, feedforward approaches are mostly designed for vibration suppression and include changing the input command or reference to minimize system vibrations. The control of RFMs is covered in this part, along with evaluations of feedforward and feedback control methods (Cannon & Schmitz, 1984) (Figure 5).



Figure 5. (a) Open loop and; (b) Closed loop control system (Cannon & Schmitz, 1984)

PID Control Techniques of RFMs

Proportional, Integral, and Derivative (PID) control is a relatively simple closed-loop system. The signal driving the plant consists of a proportional gain (K_P), an integral gain (K_I), and a derivative gain (K_D). Thus, PID was coined in Equation 1 and Figure 6. On the error signal, the proportional gain is a pure gain adjustment.

$$u(t) = [K_{P} e(t) + K_{I} \int_{0}^{\tau} e(t) dt + K_{D} \frac{de(t)}{dt} = K_{p} + \frac{1}{s} K_{I} + K_{D} S]$$
[1]

The error signal is the discrepancy between the plant's location and the targeted position. The derivative gain modifies the plant's damping, whereas the integral gain modifies the plant's accuracy (Bansal et al., 2017).



Figure 6. PID control scheme (Bansal et al., 2017)

Intelligent Control Strategies of RFM Structures

Intelligent control based on Fuzzy Logic (FL) (Mbede et al., 2003), Figure 7 Neural Networks (NN), (Rahimi & Nazemizadeh, 2014), Figure 8 and Genetic Algorithms (GA) is a method that appears promising for the control of RFM systems. Intelligent control systems have been designed in great detail for many control applications. Previous studies have demonstrated that intelligent control methods perform better than alternative control strategies for some systems. For flexible manipulators, NN-based controllers have been developed and put into use after much work. Learning control, as it was first termed, was first investigated in the 1960s (Tsypkin, 1968). Since then, its popularity and range of applications have steadily risen, and it is being used in practically all fields of science and technology.



Figure 7. Block diagram of fuzzy logic control system (Mbede et al., 2003)



Figure 8. Structure of artificial neural network system (Rahimi & Nazemizadeh, 2014)

Combined Control Strategies of RFM Structures

Active Force Control of RFMs

Robots often interact with objects found in the workplace as part of various manipulation tasks. Controlling the forces the manipulator produces in its surroundings is preferable rather than only the end effector's position. Small changes in the end effector's trajectory for a rigid manipulator can produce extremely high contact pressures that might be detrimental to the objects, the robot and the people it interacts with (Spong & Vidyasagar, 1989). AFC, in general, is a mathematical framework for identifying torque or force disturbances in a system and makes calculations easier by anticipating compensating torque. Active Force Control (AFC) and intelligent calculations have long been coupled for superior results. This combination has been applied in a variety of circumstances. Fuzzy logic, Genetic Algorithms (GA), Neural Networks, and iterative learning are used for effective integration. The purposeful application of force to offset external vibration effects is known as Active Vibration Control (AVC). Active vibration control systems have become a feasible option for bridging the low-frequency gap, as shown in Figure 9.



Figure 9. AF controls the flexible manipulator block diagram (Abdul et al., 2014)

Active Vibration Control of RFMs

According to recent papers, active Vibration Control (AVC) is increasingly used with new hardware technologies. Piezoelectric actuators and sensors are among the new available sensors and actuators. AVC reduces the amplitude of vibration in dynamic systems. It works by synthesizing the cancellation signal and absorbing unwanted disturbance forces to artificially reduce the impact of vibration on the system. For managing and reducing FLM vibration, (Kiang et al., 2015) outlined the benefits and drawbacks of various control strategies used for AVC in FLMs, which are depicted diametrically opposite in Figure 10. The installation of piezoelectric material along the link improves the detection and control

capacities of the vibration-suppression system by serving as both an actuator and sensor (Figure 11) (Bailey et al., 1985).



Figure 10. Control schemes (Kiang et al., 2015)



Figure 11. (a) The general idea of the AVC damping system; and (b) modeling and AVC of a flexible beam (Ros et al., 2015)

Semi-active and Passive Vibration Control of RFMs

Depending on the dynamic reaction, the semi-active system uses a variable stiffness or variable damping mechanism to change the structural properties of structures. In a semi-active system, control devices and indirectly acting forces that affect objects are powered by limited power sources. Semi-active control systems can dynamically change their attributes without adding energy to the building. Magnetorheological (MR) dampers, variable orifice dampers, and tunable liquid dampers are examples of semi-active devices. They use a variety of passive damping strategies, including viscoelastic materials, friction devices, tuned dampers, isolators, and impact dampers.

Velocity Feed-back Repetitive Control of RFMs

Green and Sasiadek (2002) employ repeated control and fuzzy logic, with the primary objectives being to reject periodic disturbances (including in the steady state) and follow periodic references with zero steady-state error. Until the effects of flexibility are removed, the controller iteratively repeats the recurrent trajectory control to control a two-link RFM. Feliu et al. (2005) developed a repetitive control-based control scheme for single-link RFMs. However, it suppresses vibrations upon execution of each motion to avoid the need for recursively repeated trajectories.

End-point Acceleration Feedback Control of RFMs

Although it is no longer as tempting for research involving robots, this control approach has been the focus of various study inquiries during the past 20 years (Paul et al., 1988). Based on end-point acceleration sensors, they developed a proportional feedback control system for a cantilever beam with a bonded piezoelectric patch actuator. An acceleration feedback controller was created using the forced vibration of an intelligent cantilever beam. The design accounts for external harmonic disruption (An et al., 2013).

Control Issues and Difficulties of RFM Structures

The elastic deformation and associated oscillation at the tip cause FLMs to lose stability. Flexural vibrations at the ends of the links are undesirable during movement since the flexible link itself may have several degrees of freedom (Pradhan & Subudhi, 2012). These challenges are exacerbated when traveling at high speeds because these FLMs display non-minimum phase (i.e., unstable zero dynamics) (Rokui & Khorasani, 2000) characteristics and have exceedingly intricate and non-linear dynamics. These systems introduce undershoots, a time-delay phenomenon (Yurkevich, 2011). The FLM's highly non-linear governing equations may have unlimited freedom depending on the manipulator geometry.

Future Vision of RFM Structures

Flexible robotics is an area of autonomous systems that has received much research due to the vast quantity of material written on the subject over the past thirty years. Even entire books have previously been written on it (Tokhi & Azad, 2008). The physical platform's simplicity allows for the study of novel control strategies. However, as Benosman and Vey (2004) stated, most modeling and controllability-related subjects have already been properly covered in earlier work. Some issues, however, remain unresolved and provide room for significant advancement. Certain manipulators with a tiny stiff arm joined to a big flexible base have been created for precise jobs. However, the problem of creating flexible robots with features resembling real industrial robots has not yet been fully resolved. Applications for robots doing grabbing, polishing, surface identification, and shape identification, among other activities, can be created (Somolinos et al., 2002).

Sensors and Actuators of RFM Structures

Open-loop (feedback control) or closed-loop (feedback control) strategies can modify the FLM tip's trajectory. The two types of feedback controllers are collocated control and non-collocated control. These include robust control (based on linear state feedback), adaptive control, robust control (based on robust control), and robust control (based on robust control). Intelligent control is based on neural networks or fuzzy logic. The tip displacement, via the strain or acceleration of the manipulator, accounts for most feedback signals for FLMs (Feliu et al., 2005) (Figure 12).



Figure 12. Smart structure, (Dubravko, 2009)

Accelerometer

Accelerometers employed an accelerometer to confirm that the combined strain gauge and camera outputs were accurate. A piezoelectric acceleration sensor was fastened to a link at a certain location (Paul et al., 1988) and utilized as feedback for the positive position feedback control technique. According to Li et al. (2013), an accelerometer measured the end-point position and transmitted it to the motor controller for a flexible manipulator system's combined feedforward and feedback control.

Ultrasonic Sensor

A single-link RFM uses an ultrasonic sensor positioned at the tip and a receiver fastened at the hub to detect the link's deflection (Ho & Tu, 2006).

Position Sensitive Devices

A Position Sensitive Device (PSD) was attached to the tip of a single-link RFM to measure tip deflection, and the PSD and an accelerometer were attached to the tip of a single-link RFM to estimate tip deflection and tip velocity. This technique was used in Mahmood et al. (2007).

Piezoelectric Materials

As the use of lead zirconate titanate (PZT), Piezoelectric materials are frequently employed as sensors and actuators in smart constructions because of this coupling property. Piezoelectric patches were used to measure vibration in a flexible link composite manipulator. PZT was employed as an actuator to regulate the vibration of the cantilever beam (Dong et al., 2006).

Gyroscope Technology and Applications

Gyroscopes (G) challenge underactuated systems, often employed as actuators in various plants, such as unground haptic devices, satellites, and undersea vehicles. Gyroscope control design has been the subject of several publications (Rodr'1guez et al., 2017). The external torques that affect those systems are unknown disturbances. The gyroscope's Rigidity (R) and Precession (P) qualities have been used in engineering design for a long time. Gyroscopes must be rigid to keep their orientation in space while spinning. When a frame is spinning, a gyroscope installed on the frame can be used to measure or maintain orientation and angular velocity. It is a wheel supported by two or three gimbals, which are pivoting supports that enable the wheel to rotate around a single axis. John Serson invented the first thing that resembled a gyroscope in 1743 (Braghin et al., 2007).

Optimization Methods of RFM Structures

Flexible structures have been utilized with effective vibration control methods and approaches, such as Differential Evolution Optimization (DEO), to achieve the required vibration suppression for precise accuracy. Different controller settings can be tuned to improve different control system characteristics depending on the system's kind and performance. The error signal, its derivatives, and occasionally its integral, as well as other state variables and auxiliary variables employed as input signals, are all given to the controller in such a system (Jung et al., 2015).

Evolutionary Algorithm Modification Method

Metaheuristic Search Algorithms (MSAs) are envisioned as suitable options to meet complex modern optimization difficulties by employing their search procedures influenced by numerous natural phenomena. Differential Evolution (DE), an MSA created by Storn and Price (1997), is regarded as one of the most widely used optimizers to address challenging optimization issues. DE, a population-based approach from the Evolution Algorithms (EA) family, is frequently used for diverse optimization issues. It produces new offspring under certain conditions by recombining solutions, in contrast to other Evolution Algorithms (EAs), employing scaled difference vectors to disturb the solutions and create offspring. If the new child solution outperforms the old individual solution, the old individual solution will be removed. Many academics focus on improving the efficiency of the DE algorithms, with each group of researchers focusing on one of the DE stages or components. Xiang et al. (2015) presented a novel DE mutation method that combines the DE/current/1/bin and DE/pbest/1/bin mutation techniques.

Genetic Algorithm Method

Genetic algorithm control (GA) is a technique for intelligent control that is not modelbased. It uses a search technique based on how natural selection functions. A stochastic search algorithm belongs to the class of heuristic approaches. GA mimics the genetic processes of natural evolution to resolve optimization problems. Online and offline applications of GA methods are possible. GA is paired with other traditional and

reliable controls for several TLFM control characteristics. Research methods based on natural selection and genetics are known as genetic algorithms (Goldberg, 1989). Genetic algorithms use the ideas of natural selection and genetics to optimize non-linear functions. Genetic algorithms' performance is frequently better than conventional methods since they are population-based and use global search strategies (Fogel, 1994). Figure 13 depicts the basic phase cycle employed by genetic algorithms.

Differential Evolution Algorithm Method

To solve a certain class of issues, such as Linear Programming Problems (LPP), Integer Programming Problems (IPP), Quadratic Programming Problems (QPP), Non-convex Optimization, and many more, optimization is a decision-making process (Pant et al., 2020). Differential Evolution (DE), an optimization technique used to improve the fuzzy-PID controller, is also discussed. The Evolutionary Algorithms



Figure 13. Steps in genetic algorithm (Rahimi & Nazemizadeh, 2014)

(EAs), a large family of stochastic optimization algorithms motivated by biology, are connected to DE (Sloss & Gustafson, 2020). The first chromosome serves as the basis value for the mutant chromosome, and the scaler (F) is created by multiplying the difference between the second and third chromosomes. The DE mutation method commonly has the following format: "DE/*/n," where "*" denotes the target vector taken into account throughout the mutation process and "n" denotes the number of different vectors involved. During the crossover step, the target and mutant vectors cross probabilistically to produce an offspring or trial vector. Through this crossover process, the target solution may acquire the features of the donor solution or mutant. The uniform crossover technique is controlled by a Crossover Rate (CR) with a value between [0,1]. Local and global selections are two distinct selection types (Figure 14).



Figure 14. DE consecutive phases

RESULTS AND DISCUSSION

The Single, Double, and Multi-Link Flexible Manipulators, especially in the SLFM, were the subject of this paper's assessment of various approaches for analysis, mathematical and dynamical modeling, mechanical vibration control strategies, and optimization methods of Robotics Flexible Manipulator (RFM) structures. A published paper may simply address the implementation of a controller and optimizations on the FLM as a sophisticated test bed. Figures 15 and 16 and Tables 1, 2, 3, 4, 5, 6 and 7 provide general findings and signals.



Figure 15. (a) Typical signals of vibration control result in 1; and (b) vibration control results in 2 (Hirano et al., 2010)

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Figure 16. Mechanical vibration control of typical RFM structures in step response (Zebin & Alam, 2010): (a) Result 1; (b) Result 2; and (c) Result 3

Table 1

Parameters for link 1 of a typical RFM structures

No	Parameters for link 1	Values
1.	No of element, N _i	1
2.	Length, L _i	0.9 m
3.	Mass density per unit volume, P _i	2710 kg/m ³
4.	Cross sectional area, A _i	$6.0833 \times 10^{-5} m^2$
5.	Youngs modules, E _i	$7.11 \times 10^{10} \text{N/m}^2$
6.	Second moment of area, I _i	$5.2530 \times 10^{\text{-11}}m^4$

Table 2

Parameters for link 2 of a typical RFM structures

No	Parameters for link 2	Values
1.	No of element, N _i	1
2.	Length, L _i	1.1 m
3.	Mass density per unit volume, Pi	2710 kg/m ³
4.	Cross sectional area, A _i	$6.0833 \times 10^{-5} m^2$
5.	Youngs modules, E _i	$7.11 \times 10^{10} \text{N/m}^2$
6.	Second moment of area, I _i	$5.2530 \times 10^{\text{-11}}\text{m}^{\text{4}}$

Table 3		
Results for link 1	of a typical	RFM structures

	Control	Over Shoot	Rise Time	Settling Time	Steady State Error
No	Strategy	(%)	(s)	(s)	
1.	Case 1	9.11	0.62	1.2392	0
2.	Case 2	13.45	0.46	0.9866	0
3.	Case 3	0	0.5	0.5496	0

	Control	Over Shoot	Rise Time	Settling Time	Steady State Error
No	Strategy	(%)	(s)	(s)	
1.	Case 1	8.22	0.56	1.4432	0
2.	Case 2	15.5	0.31	0.9466	0
3.	Case 3	0	0.37	0.5192	0

Table 4Results for link 2 of a typical RFM structures

Table 5

Dynamic analyses and dynamical problem and complexities involved in a two-link flexible manipulator

No	Dynamic Analyses	Related Papers
1	Dynamic strength and reliability analyses	Castri and Messina (2010)
2	Energy scavenger	Dogan (2012)
3	Symmetric dichotomy-based model	Li and Wang (2000)
4	Vibration suppression	Karagulle et al. (2015)
5	Approximate dynamic model	Tomei and Tornambe (1988)
6	Eigenvalue problem analyses	Castri and Messina (2010)
7	Flexible space manipulator	Chu and Cui (2012)
8	Wheel suspended flexible manipulator	Yuwei et al. (2011)
	Dynamical problems and Complexities	
9	Control Complexities a. non-minimum phase	Chen and Paden (1996)
10	Control Complexities b. Underactuation	Bergeman (1996)
11	Control Complexities Non-collocation	Karkoub et al. (1995)
12	MIMO system	Wang and Gao (2003)
13	Uncertainties a. Truncation of flexible modes	Zhang et al. (2004)
14	Uncertainties b. Control spillover	Khorrami and Jain (1992)
15	Uncertainties Eigenvalues problem	Book et al. (1975)
16	Uncertainties c. Observation spillover	Khorrami and Jain (1992)

Table 6

Applications of the DE algorithm and methods with other artificial intelligent algorithms

No	DE Applications	Years	Related Papers
1	Prediction	2018	(Peng et al., 2018)
2	Feature selection	2018	(Yao & Ge, 2018)
3	Image processing	2020	(Sui et al., 2020)
4	Clustering	2019	(Ahmad et al., 2022)
5	Health care	2019	(Wang et al., 2019)
6	Path planning	2020	(Chellaswamy et al., 2019)
	DE Methods		
7	with ANN	2018	(Mason et al., 2018)
8	with CS	2019	(Zhang et al., 2019)
9	with PSO	2019	(Wang et al., 2019)
10	with WOA	2018	(Xiong et al., 2018)

No	Modeling method	Problems	Schemes	Related Papers
1	Lumped parameter	Position control	Classical control	Khorrami and Sandeep (1994)
		Vibration suppression		
2	Lumped parameter	Tip position control	Robust control	Lochan and Roy (2015)
		Vibration suppression		
3	Lumped parameter	Trajectory	Robust control	Bossert et al. (1995)
4	Lumped parameter	Position control	Robust control	Theodore and Ghosal (2003)
		Tip trajectory tracking		
5	Assumed modes	Trajectory tracking	Classical control	Mahamood and Pedro (2011)
		Vibration suppression		
6	Assumed modes	Position control	Classical control	Chen et al. (2011)
7	Assumed modes	Position control	Classical control	Fukuda and Arakawa (1987)
		Vibration suppression		
8	Assumed modes	Tip position control	Robust control	Bai et al. (1998)
		Trajectory tracking		
9	Finite element	Tip position control	Classical control	Zhang et al. (2004)
		Trajectory tracking	Robust control	
			Intelligent control	
10	Finite element	Tip position control	Classical control	Zebin and Alam (2010)
		Vibration suppression	Robust control	
			Intelligent control	
11	Finite element	Trajectory tracking	Robust control	Schoenwald et al. (1991)
12	Finite element	Position control	Robust control	Liu and Zhang (2013)
		Vibration suppression		
13	Non-parametric	Position control	Classical control	Vandini et al. (2014)
14	Non-parametric	Position control	Hybrid control	Maouche and Meddahi (2016)
		Vibration suppression		
15	Non-parametric	Trajectory tracking	Robust control	Yazdizadeh et al. (2000)
			Intelligent control	
16	Non-parametric	Position control	Classical control	Chu and Cui (2015)
		Vibration suppression		

Table 7Available techniques and modeling methods

CONCLUSION

This survey of the literature on state-of-the-art flexible manipulators demonstrates that dynamic analysis and control of Flexible Link Manipulators (FLM) is a developing field of study in manufacturing, automation, and robotics. Applications span simple pick-and-place operations of an industrial robot to microsurgery, maintenance of nuclear reactors, and space robotics. In fact, there is no assurance that a published article presents a way superior to alternative theories of manipulator control. Figure 17 provides general findings, charts, signals, and summaries, as shown below. In fact, there is no assurance that a published



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article presents a way superior to alternative theories of manipulator control. The specific results registered in the world and Europe are classified in journals and publications as research papers such as modeling and controlling flexible manipulators (Alandoli et al., 2016; Fukuda & Arakawa, 1987; Pereira et al., 2014), optimal control strategies for flexible manipulators (Ge et al., 1996), vibration suppression of flexible manipulators (Karagulle et al., 2015), optimal trajectory planning for flexible manipulators (Atef et al., 2012; Liu & Zhang, 2013) in conferences as International Conference on Robotics and Automation (ICRA) and International Symposium on Flexible Automation (ISFA). Results of publications of researchers and experts working in modern methods in the field of machine modeling and simulation as a research and practical issue related to Industry 4.0 registered in the world are classified in journals and conferences as research papers such as Cyber-Physical Systems architecture (Lee et al., 2015), Enterprise systems with State-of-the-art and future trends (Li et al., 2018), Undesirable Emergent Behavior in Complex Systems (Grieves & Vickers, 2017).

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Review Article

A Review of Distribution Network Expansion Planning

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ABSTRACT

Distribution Networks Expansion Planning (DNEP) is very complex and involves improving the system to meet the increasing demand using the most cost-effective strategy. Among the planned choices are the extension of substations, upgrade of distribution feeders, installation of additional Distributed Energy Resources (DERs), installation of Capacitor Banks (CBs) and many other methods. Distribution planners in contemporary networks must have faith in the reversibility of investments where Renewable Energy Resources (RERs) inject clean and cost-effective for DNEP to meet growing demand and environmental requirements. The comprehensive review of DNEP carried out in this paper covers all possible objective functions and problem constraints. With the rise of electric vehicles (EVs), there is a growing need to assess the impact of EV charging on distribution networks. Understanding how EV loads affect the network helps plan future expansions to efficiently accommodate the charging infrastructure. Integrating DERs, such as solar panels, wind turbines, and energy storage systems, is changing how electricity is generated, distributed, and consumed. Assessing the integration of DERs into distribution networks is crucial for optimal network planning and operation. In addition, CBs are essential for power factor correction and voltage regulation in distribution networks. Including CBs in expansion planning helps improve network efficiency, reliability, and overall power quality.

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Keywords: Capacitor banks, distributed energy resources, distribution networks, electric vehicles load, expansion planning

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INTRODUCTION

According to the World Energy Transitions Outlook published by the International Renewable Energy Agency (IRENA) in 2021, significant cuts in greenhouse gas emissions are required to achieve the Paris Agreement's aim of keeping the rise in global temperature well below 2°C. Reducing emissions over the coming decades will need more energy transition expenditures, such as expanding renewable energy sources and enhancing the energy infrastructure. Plans for the national and regional energy transformation are provided, together with projections for 2030 and 2050, by the IRENA program Renewable Energy Map (REmap), which creates roadmaps for renewable energy. Developing regional studies aims to comprehend how a region can support an energy transition pathway that respects countries' unique energy resources, socioeconomic status, and institutional and regulatory endowments. It also contributes to the global emission reduction goal and leverages opportunities to meet regional energy and investment goals. A roadmap for the REmap has been developed for the Association of Southeast Asian Nations (ASEAN) to meet its target of 23% renewable energy in the energy mix by 2025 (IRENA, 2023).

Over the past few decades, carbon dioxide (CO₂) emissions have gradually increased. In 2018, the transportation industry contributed more than one-fourth of all Global Greenhouse Gas (GHG) emissions (Francisco et al., 2020). As a signatory to the Paris Agreement, Malaysia is dedicated to establishing a low-carbon society. The Malaysian government wants to cut greenhouse gas emissions by 45% by 2030 compared to GDP (gross domestic product) in 2005 (UNFCC, 2015). The most recent National Transport Policy (NTP 2019–2030), with the goal of "Advance Toward Green Transport Ecosystem," reflects this aim (MOT, 2019). As a result, the Malaysian government is encouraging the use of Energy Efficient Vehicles (EEV), which includes Electric Vehicles (EVs), with the goal of having all EEVs on the road by 2030 (KeTTHA, 2017). In order to solve this problem, it has been shown that EVs are a cleaner, quieter and more energy-efficient alternative to Internal Combustion Engine Vehicle (ICEV). The benefits of EVs to the environment and economy are particularly strong (Francisco et al., 2020).

Protecting the reliability of the power distribution network is an ongoing problem. Higher expectations for supply stability and resilience, increasing energy prices, supporting demand growth, ensuring environmental sustainability and keeping up with new distributed generating technologies are all obstacles (Pinto et al., 2019). Also, the reform of the energy supply business and the increase in market competitiveness need greater efficiency and the introduction of new, cutting-edge consumer goods and services. Utilities may change the conventional network distribution system as a result of the increased user engagement made possible by the development of smart and digital technologies. However, this necessitates a new set of network design requirements and disturbs established methods of grid management. Smart developing technologies like renewable energy resources, battery energy system storage, and Volt-VAR optimization are gaining traction as potential alternatives to expanding existing networks to improve system dependability. Using nonnetwork solutions to lower network demand and postpone network investment may be the most cost-effective option when the price of conventional network solutions is prohibitive (Liu et al., 2017).

One of the topics that must be investigated is the expansion planning of the Active Distribution Network (ADN). The planning studies for this expansion model consider the consequences of ideal operating circumstances. Through active management of these resources, the network's Distributed Energy Resources (DERs) are utilized in accordance with each operational situation. Investment in distribution network assets, such as feeders, substations, and DERs systems combining traditional gas turbines and renewable wind generators, is jointly considered at the planning level (Kabirifar et al., 2019). In Figure 1, the numbers of published relevant and significant literature from 2014 to 2022 emphasize the significance of research in this area. Research regarding expansion planning of distribution networks considering electric vehicle loads has been increasing, and the trend shows it will keep increasing due to market sentiments. Figure 2 shows the number of published relevant and significant literature in different countries to infer the global application of this study.



Figure 1. Number of relevant research published by years



Figure 2. Number of relevant research published by country

DISTRIBUTION NETWORK EXPANSION PLANNING OVERVIEW

The primary objective of distribution planning is to provide a steady supply of energy to meet customer demand at the lowest cost feasible considering the load, in accordance with asset management best practices and in an ecologically conscious way. The main planning difficulties are determining the most economical expenditure in proportion to the expected risk of supply dependability or the frequency and impact of breakdowns. Planning methodology is evolving to align with the growth of active control in smart-grid applications. Through multi-objective, probabilistic and risk-oriented planning, the innovative approach to distribution network planning that integrates active distribution network capabilities offers more affordable solutions (Aghaei et al., 2014; Esmaeili et al., 2016; Hemmati et al., 2015).

Distribution Network Expansion Planning Objectives

An objective function is a mathematical expression that describes the current state of a multivariate system. Depending on the problem or intended value, changing these variables will result in the biggest or smallest optimal value. The goal functions can be maximized or minimized to get that value (Verma et al., 2019). Many objectives and functions need to be considered during the execution of the distribution network expansion planning, which can be categorized into financial, income-related, technical, optimal size and location, as well as social and economic. The objectives functions of design and planning criteria of DNEP shall take into consideration the following:

- (i) Minimization of total emissions (Esmaeili et al., 2016; Ehsan & Yang, 2019a, 2019b).
- (ii) Feeder, substation and Distributed Energy Resources investment cost (Esmaeili et al., 2016; Aghaei et al., 2014; Hemmati et al., 2015).
- (iii) Volt-VAR optimization by Capacitor Banks (Ameli et al., 2017; Ayoubi et al., 2017).
- (iv) Battery Energy Storage System (BESS) investment and operation cost (Masoumi-Amiri et al., 2021; Cossi et al., 2012; Ehsan & Yang, 2019a, 2019b).
- (v) Energy loss minimization (Aghaei et al., 2014; Dumbrava et al., 2011).
- (vi) Voltage Stability & Voltage Profile Improvement (Esmaeili et al., 2016; Lin et al., 2019; Poornazaryan et al., 2016).
- (vii) Reliability Improvement (Aghaei et al., 2014; Dumbrara et al., 2011).
- (viii) Minimize Line Loading (Gallano & Nerves 2014).
- (ix) Optimal Power Flow (OPF) solution (Hemmati et al., 2015).
- (x) Load variations and purchased energy (Bagheri et al., 2015).
- (xi) Asset investment cost (Mazhari et al., 2015).

Thirty-five (35) relevant and significant review papers have been summarized to map out the current trends of the research and important criteria of Distribution Network

Expansion Planning, Distributed Energy Resources (DERs), Capacitor Banks, and Electric Vehicle Loads worldwide. Table 1 shows a comparison of the review papers based on the potential areas by types of network systems that previous research has covered in each paper. Table 2 shows a summary of research areas related to electric vehicles. Table 3 summarizes research areas related to integration with distribution systems. Meanwhile, Table 4 shows a summary of research areas related to objective functions and constraints that have been taken into consideration related to DNEP research. Objective function selection clearly shows increasing penetration of DERs, adoption of capacitor banks and expansion cost optimization. However, the research regarding the adoption of the integration of EVs load as the objective is still limited. Hence, this creates the motivation to execute research toward integrating EV load into DNEP. Furthermore, Table 5 summarizes the optimization methods researchers in previous research have adopted. Several scholars suggested using heuristics to directly optimize complicated optimization problems. It is difficult to ensure that the solution is globally optimum despite its simplicity of implementation. Many heuristic evolutionary algorithms, such as Tabu Search, Ant Colony, Particle Swarm Optimization, Genetic Algorithm, and Monte Carlo, have been introduced.

Distribution Network Expansion Planning Constraints

Any technological problem's effectiveness and applicability rely on the precise definition of an objective function, and the selection of constraints constricts the available options. DNEP challenges have a similar characteristic. To find the best solution for every site, the proper technological, social and economic factors must constrain the objective functions of DNEP issues. Constraints are the requirements on various objective functions in DNEP to arrive at the most optimal, consistent, and economical solution. Therefore, efficiently solving DNEP issues depends greatly on the selection of suitable constraints. The current study tries to compile the restrictions considered in more than eighty original publications published throughout ten years. The limitations taken into consideration by several distinguished scholars have been explored by grouping them into technical, non-technical, time and financial and other limitations. Concerning the assimilation of DERs and BESS, special considerations necessary for choosing limitations for DNEP have also been highlighted.

According to Figure 3, most researchers consider uncertainties, reliability, load growth, and asset investment minimization their objective functions and constraints.

The EV load is yet to be considered in most research regarding DNEP. Hence, this situation leads to the motivation to further study the impact of the EV load on the existing distribution networks. Many constraints need to be considered during the execution of the distribution network expansion plan. The constraints of design and planning criteria of the distribution network shall take into consideration the following:

Arasteh et al., 2016	7 7	\geq		Arasteh et al., 2016)			
Muñoz-Delgado et al., 2015	222	~		Muñoz-Delgado et al.,			
Cossi et al., 2012	~ ~	\geq		2015			
Ramirez & Bernal, 2001	7 7			Cossi et al., 2012			
Dumbrava et al., 2011	~ ~	~		Ramirez & Bernal, 2001			
Neiadfard-Jahromi et al.				Dumbrava et al., 2011			
2015	2 2			Nejadfard-Jahromi et al.,			
Mazhari et al 2015	7 7	~		2015			
Georgilakis &				Mazhari et al., 2015			
Hatziargyriou., 2015	2 2			Georgilakis &			
Ieddi et al 2019				Hatziargyriou., 2015			
Moradijoz et al 2017	~	~		Jeddi et al., 2019			
Ehsan & Yang 2019h	~	~		Moradijoz et al., 2017	>		
Ehsan & Yang 2019a	~	~		Ehsan & Yang, 2019b	>		
Melgar-Dominguez et al				Ehsan & Yang, 2019a	>		
2021	2	>		Melgar-Dominguez et al.,			
El-Ela et al., 2019		\geq		2021			
Lopez et al., 2021		\geq		El-Ela et al., 2019			
KC & Regmi, 2019		\geq		Lopez et al., 2021			
Sirjani, 2017		\geq		Siriani 2017			
Eid et al., 2022		\geq		Fid et al. 2017			
Rangarajan et al., 2017		>		Rangarajan et al 2017			
Ayalew et al., 2022	7	7		Avalew et al., 2022			
Moazzami et al., 2019	~	~		Moazzami et al., 2019			
Amjady et al., 201 /	-	-		Amjady et al., 2017			
Srinivasan & Visalakshi,		\geq		Srinivasan & Visalakshi,			
2017 Uses at al. 2015		~		2017			
Hoog et al., 2015	_	-		Hoog et al., 2015	>		\geq
Bagheri et al., 2015		_		Bagheri et al., 2015			
Lin et al., 2019	-	_		Lin et al., 2019			
Poornazaryan et al., 2016		~		Poornazaryan et al., 2016			
Masoumi-Amiri et al.,	~	\geq		Masoumi-Amiri et al.,			
2021)				2021			
Ayoubi et al., 2017		~		Ayoubi et al., 2017			
Hemmati et al., 2015	2	~	es	Hemmati et al., 2015			
Aghaei et al., 2014	2	~	hicl	Aghaei et al., 2014			
Esmaeili et al., 2016		~	ve	Esmaeili et al., 2016			
Kabirifar et al., 2019		-	tric	Kabirifar et al., 2019			
Manriquez et al., 2020		_	slec	Manríquez et al., 2020	>	\geq	
Pinto et al., 2021	-	-	to é	Pinto et al., 2021			
L	a E	ork	ted			50	ing
ape	tem yste	etw	rela	thei	s	ginį	arg
e b	lan Sys n S	ž	as 1	e e e	icle	har	CP
enc	on F ssio	ion	are	enc	Veh	U t	mal
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Table 1 Research areas by types of network system

Reference paper	Arasteh et al., 2016 Muñoz-Delgado et al., 2015 Cossi et al., 2012 Ramirez & Bernal, 2001 Dumbrava et al., 2011 Nejadfard-Jahromi et al., 2015 Mazhari et al., 2015 Georgilakis & Hatziargyriou., 2015 Jeddi et al., 2019 Moradijoz et al., 2017 Ehsan & Yang, 2019b Ehsan & Yang, 2019b Ehsan & Yang, 2019a Melgar-Dominguez et al., 2021 El-Ela et al., 2019 Lopez et al., 2021 KC & Regmi, 2019 Sirjani, 2017 Eid et al., 2022 Rangarajan et al., 2017 Ayalew et al., 2017 Srinivasan & Visalakshi, 2017 Hoog et al., 2015 Bagheri et al., 2015 Din et al., 2017 Hoornazaryan et al., 2016 Masoumi-Amiri et al., 2015 Aghaei et al., 2017 Manríquez et al., 2020 Pinto et al., 2021
Distributed Energy Resources (DER) / DG Capacitor Banks Micro Grid	
Table 4 Potential research areas	elated to objective functions and constraints
Reference paper	Arasteh et al., 2016 Muñoz-Delgado et al., 2015 Cossi et al., 2012 Ramirez & Bernal, 2001 Dumbrava et al., 2011 Nejadfard-Jahromi et al., 2015 Mazhari et al., 2015 Georgilakis & Hatziargyriou., 2015 Jeddi et al., 2019 Moradijoz et al., 2017 Ehsan & Yang, 2019b Ehsan & Yang, 2019a Melgar-Dominguez et al., 2021 El-Ela et al., 2019 Lopez et al., 2021 KC & Regmi, 2019 Sirjani, 2017 Eid et al., 2022 Rangarajan et al., 2017 Ayalew et al., 2017 Srinivasan & Visalakshi, 2017 Hoog et al., 2015 Bagheri et al., 2015 Lin et al., 2017 Hemmati et al., 2017 Aghaei et al., 2017 Hemmati et al., 2015 Aghaei et al., 2015 Aghaei et al., 2015 Aghaei et al., 2015 Masoumi-Amiri et al., 2016 Masoumi-Amiri et al., 2016 Masinifar et al., 2019 Manríquez et al., 2020 Pinto et al., 2020 Pinto et al., 2021
Multi- Period Multi-Objective	
Reliability AC power flow Uncertainties	<u> </u>

Arasteh et al., 2016 Muñoz-Delgado et al., 2015 Cossi et al., 2012 Ramirez & Bernal, 2001 Dumbrava et al., 2011 Nejadfard-Jahromi et al., 2015 Mazhari et al., 2015 Georgilakis & Hatziargyriou., 2015 Jeddi et al., 2019 Moradijoz et al., 2017 Ehsan & Yang, 2019b Ehsan & Yang, 2019a Melgar-Dominguez et al., 2021 El-Ela et al., 2019 Lopez et al., 2021 KC & Regmi, 2019 Sirjani, 2017 Eid et al., 2022 Rangarajan et al., 2017 Ayalew et al., 2022 Moazzami et al., 2019 Amjady et al., 2017 Srinivasan & Visalakshi, 2017 Hoog et al., 2015 Bagheri et al., 2015 Lin et al., 2019 Poornazaryan et al., 2016 Masoumi-Amiri et al., 2021 Ayoubi et al., 2017 Hemmati et al., 2015 Aghaei et al., 2014 Esmaeili et al., 2016 Kabirifar et al., 2019 Manríquez et al., 2020 Pinto et al., 2021

Reference paper



Table 4 (continue)

Arasteh et al., 2016					Arasteh et al., 2016	\geq	7	
Muñoz-Delgado et al.,					Muñoz-Delgado et al., 2015	>	\geq	
2015					Cossi et al., 2012	\geq		
Cossi et al., 2012					Ramirez & Bernal, 2001	>	\geq	
Ramirez & Bernal, 2001					Dumbrava et al., 2011		\geq	
Dumbrava et al., 2011					Nejadfard-Jahromi et al.,	>	\geq	
Nejadfard-Jahromi et al.,					2015 Mazhari et el. 2015			
2015					Conveilation &	1		
Mazhari et al., 2015					Georgilakis &	\geq	\geq	
Georgilakis &					Iaddi at al. 2010			
Hatziargyriou., 2015					Moradijoz et al. 2017		~	
Jeddi et al., 2019		_	_		Fhean & Vang 2019h		ť	
Moradijoz et al., $201/$		~	~		Elisan & Tang, 20190			
Ensan & Yang, $2019b$					Melgar-Dominguez et al			
Ehsan & Yang, 2019a					2021			
Melgar-Dominguez et	~				$E_{1}E_{1}e_{1}e_{1}=2010$	>		
al., 2021					Li-Lia et al., 201°	Ś		
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Lopez et al., 2021					Siriani 2017	>		
KC & Regmi, 2019					Eid et al., 2022			
Sirjani, 2017					Rangarajan et al., 2017			
Eid et al., 2022					Avalew et al., 2022			
Rangarajan et al., 2017					Moazzami et al., 2019	>		
Ayalew et al., 2022					Amjady et al., 2017			\geq
Moazzami et al., 2019					Srinivasan & Visalakshi,			
Amjady et al., 2017					2017			
Srinivasan & Visalakshi,					Hoog et al., 2015	>		
2017					Bagheri et al., 2015	>		
Hoog et al., 2015					Lin et al., 2019			
Bagheri et al., 2015					Poornazaryan et al., 2016	>		
Lin et al., 2019					Masoumi-Amiri et al., 2021			
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Table 4 (continue)





Figure 3. A Summary of objective functions and constraints in DNEP

- 1. Voltage drops (Bagheri et al., 2015; Hoog et al., 2015).
- 2. Substation loading and branch current limit (Bagheri et al., 2015; Liu et al., 2017; Ehsan & Yang, 2019a, 2019b).
- 3. Network radiality constraint (Ameli et al., 2017; Pathak & Prakash, 2018).
- 4. Demand response (Pinto et al., 2021; Muñoz-Delgado et al., 2015).
- 5. Microgrid (Masoumi-Amiri et al., 2021; Pinto et al., 2019; Twaisan & Barisci, 2022).
- DGs reactive power capacity, DGs active power capacity and DGs penetration (Arasteh et al., 2016; Esmaeili et., 2016; Kumar & Kumar, 2020; Pinto et al., 2019; Srinivasan & Visalakshi, 2017).
- 7. Network loss (Srinivasan & Visalakshi, 2017).
- 8. Nominal power rating of transformers (Hoog et al., 2015).
- 9. Nominal current ratings of lines (Pinto et al., 2019).
- 10. Phase unbalance (Hoog et al., 2015).

Distribution Network Expansion Planning Integration with Electric Vehicle Loads, Distributed Energy Resources and Capacitor Banks

Due to several key factors, research related to Distribution Network Expansion Planning and integration with EV load, DERs, and CBs is gaining more prominence than previous research. With the increasing adoption of electric vehicles, there is a rising demand for efficient integration of these loads into the existing distribution network. This necessitates the need for advanced planning strategies to accommodate the charging infrastructure and Table 6

Summary of research related to Distribution Network Expansion Planning and integration with EVs load, DERs and CBs

References	Year	Contribution	EVs Load	DERs	CBs
Aghaei et al., 2014	2014	The objective functions of Multi-Stage Distribution Expansion Planning include cost reduction, voltage stability index, active power losses, and Energy Not Distributed.	No	Yes	No
Hemmati et al., 2015	2015	The results revealed that using DG increased system performance, improved the voltage profile, decreased planning expenses, and reduced losses.	No	Yes	No
Bagheri et al., 2015	2015	DERs have been considered as the expansion planning options that verified the efficiency of the proposed method in decreasing the total cost of environmental pollution	No	Yes	No
Esmaeili et al.2016	2016	A multi-objective framework is suggested for simultaneous network reconfiguration and DER power allocation in distribution networks.	No	Yes	No
Poornazaryan et al., 2016	2016	A new index has been developed to evaluate the ideal size and position of DG units, taking into consideration load fluctuation, to reduce active power losses and improve the voltage stability margin.	No	Yes	No
Rangarajan, et al., 2017	2017	The proposal of a unique notion of leveraging smart PV inverters as virtual detuners for removing network resonances sets the basis for further study.	No	Yes	No
Ameli et al., 2017	2017	This framework may accept various cooperative behaviors among decision-makers. The stochastic behavior of a gridable parking lot is being examined as an alternative supply resource to improve the dependability of the distribution network.	Yes	No	No
Srinivasan & Visalakshi, 2017	2017	An application to reduce power loss in distribution networks by allocating and sizing DGs units and capacitors as efficiently as possible, both with and without reconfiguring the network	No	Yes	Yes
Sirjani, 2017	2017	The best position and size of capacitors were chosen based on system equivalent circuits, predicted wind speed, and harmonics to minimize energy losses, optimize reactive power, and lower management costs.	No	No	Yes
Ameli et al. 2017	2017	A unique technique for concurrent dynamic scheduling of feeder reconfiguration and CB switching is presented in DG units with unknown and variable generations over time.	No	Yes	Yes
Ayoubi, et al. 2017	2017	A novel method for placing capacitors in the presence of harmonic distortion is described, along with a suggested resonance index.	No	No	Yes
References	Year	Contribution	EVs Load	DERs	CBs
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Quevedo et al., 2017	2017	BESS can contribute to the coordinated DNEP by integrating renewable energy and EV charging demand, minimizing investment and operating expenses, and eliminating the need to extend existing substations.	Yes	Yes	No
Kabirifar et al., 2019	2019	The investment, maintenance, operation, and unsupplied energy expenses' net present value (NPV) is reduced.	No	Yes	No
Moazzami et al. 2019	2019	Deploy DERs as candidate equipment for distribution system growth to meet operational and economic needs while avoiding feeder extension and substation concerns.	No	Yes	No
Jeddi et al., 2019	2019	The suggested optimization model calculates the size, placement, and power factor of DERs. Other selection criteria include the transformer or line improvements requirement and the ideal year for DER installation.	No	Yes	No
Yu et al., 2019	2019	In conjunction with the various incremental distribution service pricing supervision mechanisms, incremental power distribution planning models that suit the appropriate demands are proposed.	No	No	No
KC & Regmi, 2019	2019	This study employs an analytical technique. The distribution system's load flow is performed using a backward/forward sweep algorithm.	No	No	Yes
El-Ela et al., 2019	2019	Various goal functions are used in the allocation issue under consideration to optimize the voltage profile, maximize operational loss savings, reduce overall investment costs, and increase loading capacity.	No	Yes	Yes
Pinto et al., 2019	2019	Coordinated operation and expansion planning reduce the problem's total cost, and demand response and DERs coordination results are more consistent.	No	Yes	Yes
Kumar & Kumar, 2020	2020	A novel multi-objective function model is devised to tackle the Multistage Distribution System Planning problem with planning and operational limitations.	No	No	No
He et al., 2022	2021	The expansion site selection and capacity plan of EVCSs are obtained to lower the total yearly societal cost of charging stations.	Yes	No	No
Lopez et al., 2021	2021	The goal function uses three-phase capacitor banks dispersed across the distribution network and sized to produce minimum power loss values.	No	No	Yes
Pinto et al., 2021	2021	The suggested computational model is described as a mixed integer nonlinear optimization problem, which is addressed using a combination of Monte-Carlo simulation and optimum power flow.	No	Yes	No

Table 6 (continue)

References	Year	Contribution	EVs Load	DERs	CBs
Masoumi- Amiri et al., 2021	2021	The inclusion of a microgrid structure in distribution network development plans improves operational conditions and encourages investor engagement in the electricity system.	No	Yes	No
Zhang et al., 2021	2021	A multi-objective planning model for the sizing and placement of EVSEs and the extension of a power distribution network with significant wind power penetration.	Yes	No	No
Melgar- Dominguez et al., 2021	2021	The goal function of this optimization model is to reduce the predicted cost of energy acquired from the market, as well as charges related to carbon emission levies while maximizing energy purchased from DG developers.	No	Yes	Yes
Ayalew et al., 2022	2022	The performance of the existing and improved networks is evaluated using current and expected load demand for the year 2030.	No	Yes	No
Borozan et al., 2022	2022	For large-scale and long-term, DNEP suggests Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Building (V2B) investment and operation models under multi-dimensional uncertainty.	Yes	No	No
Gholami et al., 2022	2022	This article aims to arrange EV charging stations and smart PV inverters in distribution networks simultaneously to minimize power loss, voltage deviation, and voltage imbalance.	Yes	Yes	No

Table 6 (continue)

manage the additional load effectively. The proliferation of DERs, such as solar PV systems and energy storage, adds complexity to the distribution network. Research focusing on the optimal integration of DERs along with EV loads can help enhance system reliability, flexibility, and efficiency. Meanwhile, CBs are crucial in improving power factors, reducing losses, and enhancing voltage stability in distribution networks. By incorporating CBs into expansion planning alongside EVs and DERs, researchers can explore holistic approaches to enhance grid resilience and stability. The focus on integrating EVs load, DERs, and CBs into DNEP research reflects a shift towards addressing the evolving challenges and opportunities in modern power systems, aiming to facilitate a more sustainable, efficient, and reliable energy infrastructure. Table 6 summarizes relevant research articles on Distribution Network Expansion Planning and integration with EV load, DERs and CBs. According to Table 6, the comparison of reviewed research has been focused on EV load, DERs and CBs and shows that no previous research considered EV load, DERs and CBs in the DNEP research.

The primary issue with DNEP is the intricacy of the distribution networks. Power balance, voltage profiles, branch capacity, DG restrictions, radiality constraints, network loss and pollutant emissions are just a few requirements that must be met. As a result, the

researchers broke the DNEP challenges into smaller components and offered a range of methods to address different issues. In any event, to arrive at a workable solution, we need sufficient information on the DNEP models. As the trend indicates, future optimization challenges should consider power supply. Volt-VAR optimization by CBs, the integration of RERs, and the load of EVs can all lead to more optimum solutions.

IMPACT OF ELECTRIC VEHICLES (EVS) LOAD TOWARD DISTRIBUTION NETWORK

It is widely acknowledged that the most effective way to address pollution, global warming and energy sustainability issues is to electrify the transportation industry. The EV adoption and distribution level is expected to see a range of growth rates worldwide, depending on the accessibility of charging infrastructure, user desire, and income. With a low number of EVs and charging stations, the distribution network is not expected to encounter any technological problems. However, as the penetration of EVs increases, several technological problems surface. Violations of voltage limits, harmonic distortion, and higher losses might result from these problems. To enable demand response and provide different operating reserves using the energy stored in EVs, vehicle-to-grid operation (V2G) may also be taken into consideration.

As one of the possible energy solutions to lower system peak demand, the V2G operates on Smart Grid infrastructures that provide effective network and EV communication. EVs require a connection to the electrical grid to obtain charging for propulsion. EVs are dynamic loads that might disperse throughout the power grid. The reliability and quality of the power supply will be put at risk by the connectivity of a sizable fleet of EVs to the power grid. As a result, the technical effects of EV charging will be discussed and considered when all Electric Vehicles Supply Equipment is planned, installed and operated (Fan et al., 2021; Francisco et al., 2020; Zhou et al., 2014). Some of the impacts of electric vehicles (EVs) load on distribution network systems are as follows:

- 1. Increase in peak demand (Gallo, 2016).
- 2. Increase in power losses (Veldman & Verzijlbergh, 2014).
- 3. Voltage drop/Voltage profiles (Energy Commission, 2017).
- 4. Overloading of system components (Francisco et al., 2020).
- 5. Phase unbalanced (Veldman & Verzijlbergh, 2014).
- 6. Harmonics (Lucas et al., 2015).
- 7. Electric Vehicles (EVs) load massive penetration (Francisco et al., 2020; Taljegard et al., 2019).

When modeling a DNEP problem, the interaction between transportation and distribution networks, as well as various charging facilities like parking spaces, private charging locations at houses and quick charging stations, may be considered. If the Distribution Network Operator is authorized to invest in RERs, the illiquidity of these resources must be considered. Because Grid Parking Lot storage capacity is an excellent tool for encouraging RER integration, the cooperative interaction between Distribution Network Operator and Grid Parking Lot Operator should be reflected in the operational phase as well as the planning level (Moradijoz et al., 2017). Researchers can also incorporate further, more thorough modeling of the interactions between park visitors and the effect of renewable energy on incremental planning (Yu et al., 2019). The operational problem's accuracy might be improved by modeling short-term uncertainty in EV availability and the effects of smart charging on battery deterioration but at the price of the problem's scale and tractability.

Future research will examine the effects of including smart charging investment options in distribution expansion planning under uncertainty, as well as the influence of various EV fleets on their option values (Borozan et al., 2022). Real-world transportation and distribution network data might be included in the optimization to produce more practical planning outcomes. One may also examine EVCS real-time functioning concerns, such as missing data, data delay, and sensor failure. In certain circumstances, data processing techniques such as deep learning may be able to ease these concerns (Zhang et al., 2021).

For distribution systems with realistic load models, the following are possible combinations of variables for DGs with EV planning: (a) Size, location, and types of DGs with EVs and (b) The types, placement, and synchronization of DGs and EVs. The location, size, and management of various types of DGs with EVs in distribution networks with varied load situations may be improved using realistic approaches. Future distribution systems with diverse, dynamic loads may utilize hybrid optimization methods to improve placement, scalability, and coordinated control over different types of DGs with EVs (Singh & Dubey, 2022). There are several unresolved concerns, such as how to mitigate power quality problems caused by electric vehicles and imbalanced networks, simultaneously reconfiguring the network and allocating renewable energy to increase the capacity of EVCSs (Gholami et al., 2022). The EV charging station extension planning study can take into account the foreign mature ancillary services market, traffic light location, quantity, and the real driving patterns of electric car users influence on forecasting charging demand, and the EV charging and discharging power adjustable to its participation in the influence of peak regulation, among other factors (He et al., 2022).

Researchers can consider the potential that when EVs are not in use, they may pump power into the network. Additionally, the model will incorporate additional generational technology (Quevedo et al., 2017). The analysis of electric vehicle charging and discharging methods should pay attention to the percentage of various electric vehicle users (operating and non-operating cars) willing to engage in aggregation regulation under various compensation price incentives (Zou et al., 2022). In addition to enhancing network stability, BESS may be utilized to mitigate the stochastic nature of renewable generating and EV charging demand. The optimization model could consider BESS's position and size in later rounds. To provide planning outcomes that are more realistically applicable, the optimization process might make use of data from actual distribution and transportation networks. Charging station real-time operating problems, including missing data, delays, and sensor failure, could also be taken into account. Sometimes, data processing methods like deep learning can help to solve these problems (Zhang et al., 2021). Figure 4 shows a tree diagram for DNEP, together with the impact of EV load penetration and integration with DERs and CBs.



Figure 4. Tree diagram for DNEP

INTEGRATED DISTRIBUTION NETWORK EXPANSION PLANNING WITH DERS

The planning problem for the ADN differs from standard DNEP problems in how DERs are integrated. The distribution system known as the ADN can manage a variety of DERs, including loads, storage, and generators. It is important to note that ADN enhances network performance at the planning and operation levels by reducing the influence of renewable resources' unpredictability. A paradigm for ADN planning that considers active

resource management was put out. Reference (Al-Kaabi et al., 2013) put out a multiconfiguration, multi-period optimum power flow approach to assess the effect of various DG configurations. A long-term dynamic planning of DGs taking active management into account has been given (Abapour et al., 2015). These studies have produced separate DNEPs. To manage the output power of DGs, Karagiannopoulos et al. (2017) initially increased the network's assets before introducing a real-time tractable iterative AC OPF.

The utility planning approach for the DNEP was proposed (Mansor & Levi, 2017). The two-step strategy that has been presented extends network assets in the first stage and takes network operation into account in the second. These two articles examine planning and operation levels separately, but an integrated framework is necessary. ADN planning models for multiple-stage, multiple-load scenarios have been proposed (Shen et al., 2016). While network reconfiguration and DGs dispatch are dealt with in the operating problem, the network assets are enlarged in planning. The ambiguity of resources is not addressed, however. The planning of a cooperative multistage distribution network that takes into account active resource management is presented (Kabirifar et al., 2019). The distribution system operator (DSO) seeks to reduce investment and operational expenses related to the proposed planning and operation levels.

When electricity is produced from sources, frequently renewable energy sources, close to the point of consumption rather than centralized generating sources from power plants, the process is referred to as distributed generation (Ayalew et al., 2022). Several types of DGs can be integrated into distribution network expansion planning as follows:

- 1. Solar (Rangarajan et al., 2017)
- 2. Biogas (Freitas et al., 2019)
- 3. Biomass (Ferreira et al., 2018)
- 4. Hydro Power (Raza et al., 2013)
- 5. Fuel Cells (Pinto et al., 2021; Veldman & Verzijlbergh, 2014)
- 6. Wind (Amjady et al., 2017)
- 7. Cogeneration (Cogeneration Technologies, 2022)
- 8. Energy storage (Comodi et al., 2017)
- 9. Flywheel Energy Storage Systems (Technologies of Energy Storage, 2022)
- 10. Batteries (Technologies of Energy Storage, 2022)
- 11. Superconducting Magnetic Storage Systems (SMES) (Carnegie et al., 2013).

Many benefits of distributed energy resources, such as installing DER units, may enable them to lower their power costs or achieve higher levels of dependability. Additionally, DERs may lower the price of enhancing the power system, lowering the overall cost of supply that customers must pay. By replacing other, more emissions-intensive generations, increased DER penetration may also aid in lowering the total emissions intensity (Twaisan & Barisci, 2022). Over the last ten years, the liberalization of energy markets, rising fuel prices, environmental concerns, and the high cost of constructing a new big power plant have all contributed to the drive for small-scale distributed generation (DG) units to be installed in the distribution network (DN) to fulfill the increasing demand for electricity. However, the network becomes active and bi-directional when DG units are connected to the DN. The role of DGs in modern DN is progressively growing. Predictions state that about 20% of the next generations will be implanted. It is widely established from earlier research that distributing DG units inside the DN optimally leads to a decrease in power loss, an increase in voltage and dependability, an improvement in power quality, and the postponement of network upgrades (Amjady et al., 2017; Energy Commission, 2017; Moazzami et al., 2019; Srinivasan & Visalakshi, 2017).

Rapid load growth rates cause the distribution equipment to become overloaded, and because replacing overloaded power system components is expensive, it is not a simple task. To lower peak demand, novel incentive schemes, including permanent demand reduction, load curtailment/shifting, distributed generation (DGs), and others, have been created in response to growing economic pressure to fully utilize the capacity of present power equipment. The electrical utilities must plan appropriately if they want to see an improvement in consumer satisfaction with electric energy. This development has been noticed by utilities, who have taken DGs into account while building and running distribution networks. When placed in the best possible position, distributed generation (DG) may reduce power losses, improve supply quality and reliability, and save construction costs associated with transmission and distribution (Ahmed et al., 2022; Ayalew et al., 2022). DG units have been distributed into distribution networks using hybrid Harmony Search and Particle Artificial Bee Colony methods to lower power loss and improve the voltage profile (Muthukumar & Jayalalitha, 2016; Jeddi et al., 2019).

INTEGRATED DISTRIBUTION NETWORK EXPANSION PLANNING WITH CAPACITOR BANKS

To provide reactive power compensation, maintain security and reliability, and raise bus voltage, capacitors are positioned along the Radial Distribution Network (RDN). To improve voltage control and boost power factors at the sub-station bus, capacitors of the proper size should be installed along the feeders. A review of the literature revealed many artificial intelligence strategies that may be used to address the problem of the ideal placement of capacitors. A differential search method Eid et al. (2022) has been used to optimize the DGs unit in the presence of the static VARs compensator to minimize power loss in distribution systems.

Capacitors are positioned along the RDN to provide reactive power compensation, preserve security and dependability, and increase bus voltage. However, installing capacitors of the right size along the feeders will enhance voltage control and increase

power factors at the substation bus. According to a literature survey, several artificial intelligence approaches might be used to tackle the optimum capacitor placement problem. Reactive power assistance is necessary for distribution networks. Shunt capacitor banks that are able to provide power factor correction and voltage control can offer this support or appropriate compensation. The inductive characteristics of distribution lines, including line charging capacitances and other inductive elements, like transformer impedances and loads, cause network resonances (Rangarajan et al., 2017).

Capacitors are frequently placed in distribution systems for reactive power compensation to reduce power and energy loss. Size and placement are important considerations when using a capacitor to minimize loss. Additionally, the proper positioning of capacitors is crucial to minimizing system power losses and overall capacitor costs. This paper compared the voltage dips and power losses before and after the capacitor installation. The results indicated that the suggested solution may enhance the distribution system's voltage performance and power losses, which would be advantageous for the distribution networks (KC & Regmi, 2019). A heuristic-based optimization technique is investigated Lopez et al. (2021) to improve the voltage profile and reduce power loss in a medium voltage distribution network. The goal function uses three-phase capacitor banks dispersed across the distribution network and sized to produce minimum values for the losses. Ant colony and genetic optimization algorithms were used as two heuristic techniques for this localization and dimensioning. An Improved Grey Wolf Optimizer has been put out in this study to address the coordinated allocation of DGs and CBs in distribution systems.

CONCLUSION

DNEP is very complex and involves improving the system to meet the increasing demand using the most cost-effective strategy. Among the planned choices are the extension of substations, upgrade of distribution feeders, the installation of additional DERs facilities, installation of CBs and many other methods. Distribution planners in contemporary networks must have faith in the reversibility of investments where Renewable Energy Resources (RERs) inject clean and cost-effective for DNEP to meet growing demand and environmental requirements. In addition, the increasing adoption of EVs poses challenges for DNEP. EV loads have the potential to strain existing infrastructure due to increased demand for electricity, especially during peak charging times. It could require utilities to invest in upgrading and expanding distribution networks to accommodate the additional load from EV charging. Hence, careful planning and integration of EVs into distribution network expansion plans are essential to ensure grid reliability and cost-effectiveness. A comprehensive review of DNEP has been carried out in this paper, which covered all possible objective functions, problem constraints, various horizon times as well as problem variables, the optimization model (single/multi-objective), utilization of DERs, utilization of CBs, and problem uncertainties. The examined literature demonstrates that several notable researchers have taken distinct objective functions into consideration to accomplish comparable DNEP goals.

In summary, a holistic approach to DNEP that considers EV loads, DERs integration, and Capacitor Banks installation is essential for designing sustainable power systems that are resilient, efficient, and capable of supporting the transition to a cleaner energy future. When it comes to EV loads, a holistic approach would involve forecasting future demand from EV charging stations and strategically planning network upgrades to accommodate this load without compromising grid stability. Combining this with integrating DERs can help balance supply and demand, maximize renewable energy utilization, and enhance grid resilience. Moreover, installing Capacitor Banks strategically along the distribution network can help improve power factor correction, reduce losses, and enhance voltage regulation. By considering all these components together, utilities can optimize their investments, minimize system inefficiencies, and create a more sustainable power system capable of effectively meeting future needs.

There are several key areas for further research in DNEP to address emerging challenges and optimize the integration of renewable resources. First, advanced modeling and simulation can accurately capture the dynamic behavior of distribution networks with high penetrations of renewable energy sources, energy storage systems, and electric vehicles. Second, researching and developing optimization algorithms that effectively manage distributed energy resources, demand response programs, and other grid-edge technologies to improve grid reliability, efficiency, and cost-effectiveness. Next, investigate strategies to enhance grid resilience and flexibility by integrating microgrids, smart grid technologies, and automated control systems. By focusing on these research areas, stakeholders can improve DNEP practices, accelerate the transition to sustainable energy systems, and contribute to a more resilient and efficient grid infrastructure for the future.

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Spatial Dynamics of Macrobenthos Assemblages in Different Breakwater Systems in Kuala Nerus, Terengganu, Malaysia

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ABSTRACT

The Sultan Mahmud Airport runway extension in 2008 resulted in coastal erosion along the Kuala Nerus shorelines. In response, different breakwater systems were constructed to mitigate erosion. Despite previous reports highlighting the effects of breakwaters on marine organisms, the local impact remains uncertain. Therefore, this study investigates the spatial impact of different breakwater systems on macrobenthos composition in the Kuala Nerus coastal area. Samplings were conducted at 12 substations across five main stations, covering sheltered and exposed areas. Results revealed 27,137 macrobenthos individuals, with groyne exhibiting the highest macrobenthos composition (8448.79 \pm 2813.73 ind./m²). Gastropoda dominated (4971.01–41608.70 ind./m²), followed by Bivalvia (2927.54–12391.20 ind./m²) and Polychaeta (1000.00–4956.52 ind./m²). Macrobenthos compositions in the sheltered and exposed stations differed significantly (p < 0.05). The coastal

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Keywords: Bathymetry, breakwater system, groyne, Kuala Nerus, macrobenthos

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INTRODUCTION

Macrobenthos composed of macroinvertebrates with sizes of 500 µm and above, including annelids, molluscs, crustaceans, and echinoderms, inhabit the soft-bottom substrates of marine and estuarine environments (Amfa et al., 2020). These communities play significant and diverse ecological roles, such as maintaining the sediment and water quality of the areas, serving as important food sources for fishes, larger invertebrates, and birds, and functioning as great bioindicator species (Araujo-Leyva et al., 2020; Ehrnsten et al., 2022). Benthic organisms with a significant relationship with sediments are highly susceptible to contaminants due to prolonged exposure and limited movement (Desrosiers et al., 2019). Therefore, changes in their composition could indicate an area's health status, including in modified coastal regions with breakwater systems (Costas, 2016).

Kuala Nerus district, encompassing an area of 40,000 hectares, has experienced rapid urbanisation driven by business activity, eco-tourism gateway, sports and recreational events, and educational hub, supporting its dense population of approximately 158,000 people in 2002 (Ahmad et al., 2014; Wahid, 2022). Naturally, the fishing and local villages along the Kuala Nerus northern coast have been highly vulnerable to intense wave action and erosion, particularly during the annual northeast monsoon season. The erosion worsened following the completion of the Sultan Mahmud Airport runway extension in 2010 (Zulfakar et al., 2020). In response to this erosion, different breakwater systems, including groyne, semi-enclosed jetty-type and parallel breakwaters, and revetments, were installed along the Kuala Nerus coastline to mitigate erosion.

The groyne in Teluk Ketapang was initially built for airport runway extension, marking the inception of coastal structures in the Kuala Nerus district (Ariffin et al., 2020). Following that, the semi-enclosed jetty-type breakwater in Tok Jembal, originally parallel, was later repurposed to sustain the local fishing community, providing a safer and calmer harbour and maintaining the navigation channel's depth (Ariffin et al., 2018). Additional groynes, revetments, and parallel breakwaters were constructed between December 2016 and December 2020 to enhance coastal protection further. They were strategically placed along the northern Kuala Nerus coast to defend against wave action and currents, ultimately reducing erosion in the affected areas.

Breakwater systems are coastal engineering structures designated to defend and protect shore areas, harbours, marinas and navigation channels from the effects of waves, currents and tides (Schoonees et al., 2019). Nonetheless, they pose significant negative impacts, such as affecting the coastal ecosystems' function, reducing shoreline resilience, influencing sediment transport, fragmenting the coastal space and disturbing macrobenthos habitat (Fitri et al., 2019; Jahangirzadeh et al., 2012). The sediment compositions (organic matter and contaminants) determine the macrobenthos habitats, food sources, health and reproductive success (Matthiessen & Law, 2002). The hydrodynamic condition influences

sediment transport, resulted in burying and exposing benthic organisms, affecting their survival and distribution (Wiesebron et al., 2021).

In Malaysia, breakwater systems are expected to increase due to the growing coastal populations, expanding coastal cities, and climate change threats (Siegel, 2020). However, despite its increasing prevalence, limited studies examine its environmental impacts, particularly concerning coastal ecosystems' ecological perspective, biodiversity, and productivity. In addition, the breakwater systems' research is often overlooked and given less priority by the scientific community, funding agencies, and policymakers, likely due to its multidisciplinary nature. This lack of focus hinders a comprehensive understanding of the ecological consequences of coastal armouring, impeding effective coastal management strategies.

Furthermore, the ecological importance of macrobenthos is significant, especially in light of coastal development's impact on the coastal ecosystem (Chowdhury et al., 2024). However, there is a paucity of research investigating the impacts of breakwater installation on the benthic community. Hence, this study provides valuable insights into the repercussions of different breakwater systems on local marine ecosystems, highlighting the complex interactions between soft-bottom characteristics, food availability, and hydrodynamic stress. While previous global reports highlighted the potential impact of such structures on marine organisms, this research adds novelty by providing empirical data on the actual effects.

This study hypothesised that various coastal structures in Kuala Nerus may have distinct effects on sediment characteristics, seabed condition and hydrodynamics, which may, in turn, modify the food sources' distribution and composition, ultimately impacting the macrobenthos composition, abundance and trophic structure (Holzhauer et al., 2020). The primary objective of this study is to investigate the spatial impact of different breakwater systems in Kuala Nerus on the benthic community over one monsoonal cycle, supported by comprehensive environmental data of sediment (grain size, organic matter and heavy metals) and water physical parameters acquired through multiple field surveys.

MATERIALS AND METHODS

Samplings have been conducted at five main stations with 12 substations (average depth 7 m) in the Kuala Nerus coastal area, specifically from the Sultan Mahmud Airport runway (5°23′25.7″ N, 103°06′59.9″ E) to Batu Rakit (as a reference station) (5°27′09.0″ N, 103°02′58.4″ E), covering different breakwater systems such as groyne (St. 1), semienclosed jetty-type breakwater (St. 2), and parallel breakwaters—without (St. 3) and with tombolo (St. 4), in the first four stations (Table 1; Figure 1). Sampling over one monsoonal cycle was conducted as follows: in March 2021 and 2022, representing the post-northeast monsoon (NEM) season; in July 2021, denoted the southwest monsoon (SWM) season; Nur Fazne Ibrahim, Muzzalifah Abd Hamid, Mohd Fadzil Mohd Akhir, Wan Izatul Asma Wan Talaat, Ong Meng Chuan and Izwandy Idris



Figure 1. Map of the study sites along the Kuala Nerus coastal area. Map of Peninsular Malaysia showing the location of Kuala Nerus, Terengganu (left), and five main stations near the different breakwater systems along the Kuala Nerus coastal area (right). Station 1: groyne; Station 2: semi-enclosed jetty-type breakwater; Station 3: parallel breakwater without tombolo; Station 4: parallel breakwater with tombolo; and Station 5: Reference station in Batu Rakit (free from breakwater). \blacktriangle : exposed substations. Δ : sheltered substations

Table 1

Geographical location and category of 12 substations from five main stations of different breakwater systems in Kuala Nerus, Terengganu

	Stations (St.)	Locations	Substations	Latitude (N)	Longitude (N)	Category
1	Groyne	Teluk	1.1	5°23'25.7"	103°06'59.9"	Exposed
		Ketapang	1.2	5°23'47.5"	103°07'04.3"	Exposed
			1.3	5°23'58.0"	103°06'26.6"	Sheltered
2	Semi-enclosed		Outside lagoon	5°24'08.2"	103°06'06.6"	Exposed
jetty-type breakwat	jetty-type breakwater	Tok Jembal	Inside lagoon	5°24'12.6"	103°06'15.5"	Sheltered
3 Paralle breaky withou	Parallel	Tok Jembal	3.1	5°24'21.6"	103°05'56.7"	Sheltered
	breakwater		3.2	5°24'32.4"	103°05'54.2"	Exposed
	without tombolo		3.3	5°24'32.0"	103°05'45.7"	Sheltered
4	Parallel	Tok Jembal	4.1	5°24'38.2"	103°05'39.4"	Sheltered
brea tom	breakwater with		4.2	5°24'45.9"	103°05'40.3"	Exposed
	tombolo		4.3	5°24'42.9"	103°05'33.4"	Sheltered
5	Reference station	Batu Rakit	5	5°27'09.0"	103°02'58.4"	Exposed

in October 2021, representing the post-SWM season; and in December 2021 indicating the NEM, subjected to suitable tides, sea conditions, and weather. Sampling locations were based on the water current flow and longshore drift, likely influencing the sediment types and macrobenthos distribution. The substations were categorised as either sheltered (the inner, left, and right sides of breakwater systems) or exposed (directly facing the sea). Coordinates of all sampling locations were marked using the Global Positioning System (GPS).

Macrobenthos Collection

A total of 36 sediment samples were collected (triplicates at each substation) using a Ponar grab with a 0.023 m² surface area operated from a boat (Discovery IV of Universiti Malaysia Terengganu). Samples were prepared for environmental and biological analyses. Approximately 150 g of sediment samples were allocated for grain size determination, total organic matter (TOM) measurement, and heavy metal analysis. Simultaneously, biological analyses comprising macrobenthos from the remaining samples were retrieved via the decantation method using a 0.5 mm mesh size sieve, preserved in 80% ethanol, and stored in labelled containers for further identification (Ibrahim et al., 2023).

The ethanol-preserved sediment samples containing macrobenthos were roughly sorted under a stereoscopic microscope to remove shell fragments, grain particles, and macro-marine debris. Subsequently, the clean macrobenthos samples were finely sorted for species classification, identification, and quantification using references such as Abele and Kim (1986), Day (1967), Gibson and Knight-Jones (2017), and Valentich-Scott (2003).

Grain Size, TOM, and Heavy Metals

In grain size analysis, approximately 100 g of sediments were oven-dried at 70°C for 72 hours and then dry-sieved using an Octagon mechanical shaker with 4, 2, 1, 0.5, 0.25, 0.15, and 0.63-mm layer sizes. The sediments retained on each layer were weighed, and the data were computed in Microsoft Excel for further analysis (Bachok et al., 2009).

The TOM content in sediments was determined using a loss-on-ignition method, ashed at 550°C for eight hours in a muffle furnace (Carbolite Gero, UK) (Bensharada et al., 2022). Heavy metal detection encompassing lithium (Li), chromium (Cr), lead (Pb), copper (Cu), zinc (Zn), iron (Fe), and cadmium (Cd) was performed using the Teflon bomb digestion method (Ong et al., 2016), and measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS Perkin Elmer ELAN 6100) (Method EPA 6020A; EPA, 2007).

Water Physical and Hydrodynamic Parameters

Triplicates water physical parameters' readings (salinity, pH, dissolved oxygen [DO], and temperature) were recorded using a Quanta Multiparameter Probe (OTT Messtechnik

GmbH & Co. KG) at seawater surface (~ 1 m depth). Bathymetry data from the Kuala Terengganu River mouth estuary until Batu Rakit was obtained from a study by Ariffin et al. (2020). The estimation of the wave and current patterns of Kuala Nerus was performed using MIKE 21 Spectral Wave and Flow Model FM. Wave and current data validation was conducted by field sampling using an Acoustic Doppler Current Profiler (ADCP) in July 2021. Tidal readings were computed using harmonic constants at the Kuala Terengganu tidal station, provided by the Royal Malaysian Navy. The model used secondary wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) as a time series input.

Data Analysis

Macrobenthos density (ind./m²), relative abundance (%), Margalef species richness (d), Shannon diversity index (H'), and Pielou's evenness index (J') were determined at each substation using Paleontological Statistics Software Package (PAST). Mann-Whitney and Kruskal–Wallis tests were used for non-normally distributed data (p < 0.05). Subsequently, species composition and abundance were grouped using the Bray-Curtis similarity coefficient (Bray & Curtis, 1957) displayed in the dendrogram plot. The relationship between the biological indices and environmental factors of the sediment characteristics (organic matter, heavy metal, gravel, sand, silt, and clay) and physical parameters (current speed, significant wave height, depth, wind speed, temperature, DO, salinity, and pH), were analysed using Spearmen's correlation and Multiple Linear Regression (MLR) analysis by utilising Statistical Package for the Social Sciences (IBM SPSS Statistics version 21). The MLR models were constructed using a stepwise approach, where variables were added or removed based on their significance levels (p < 0.05). Model fit was assessed using the coefficient of determination (R²) and Kruskal–Wallis. Assumptions of MLR, including linearity, independence of residuals, homoscedasticity, and normality of residuals, were checked and met. The relationship between macroinvertebrate assemblages and environmental variables was further analysed using principal component analysis (PCA), computed in statistical software, PAST version 2.14.

RESULTS

Species Composition and Abundance of Macrobenthos

A total of 27,137 macrobenthos individuals belonging to 7 phyla, 16 classes, 92 families, 124 genera, and approximately 144 species were recorded in the present study. The commonly shared phyla among all stations were Mollusca, Annelida, Arthropoda, and Echinodermata. The commonly shared classes at the lower taxonomic level included Gastropoda, Bivalvia, Scaphopoda, Polychaeta, Ostracoda, Malacostraca, and Echinoidea. Phylum Mollusca recorded the highest composition (90.68%), followed by Annelida (6.19%) and Arthropoda (2.26%). In detail, Gastropoda had the highest abundance (4971.01–41608.70 ind./m²),



Figure 2. Average density (ind./m²) of macrobenthos (class taxa) throughout the sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu

followed by Bivalvia (2927.54–12391.20 ind./m²) and Polychaeta (1000.00–4956.52 ind./m²) (Figure 2).

The highest average macrobenthos density was documented in station 1 of the groyne structure (8448.79 ± 2813.733 ind./m²), whereas the lowest was in station 3 of parallel breakwater without tombolo (3213.53 ± 1276.324 ind./m²) (Figure 3). The macrobenthos density in the reference station (St. 5) documented half of the first station (groyne) (4872.46 ind./m²). The macrobenthos density in the sheltered stations is higher (201956.52 ± 12982.672



Figure 3. Average density (ind./m²) of macrobenthos in five main stations of coastal man-made structure areas in Kuala Nerus, Terengganu

ind./m²) than in the exposed stations (177340.58 \pm 20267.560 ind./m²). A significant macrobenthos density was detected among the five main stations of different breakwater systems and between sheltered and exposed sites (p < 0.05).

Species diversity (H') ranged from 2.014 to 2.878, with the sheltered stations recording a lower species diversity (H'= 2.014-2.622) (Figure 4). Macrobenthos in both sheltered and exposed stations were interpreted as having low to moderate species diversity (H'= 2.014-2.878). The evenness index (J') ranged from 0.410 to 0.802, with the sheltered stations recording lower values (0.410-0.729). The Margalef richness index varied from 4.185 to 6.028, showing relatively stable values across the sheltered stations, in contrast

to the more variable values observed at the exposed stations. No significant differences in macrobenthos diversity, evenness, and richness were detected between the sheltered and exposed stations (p > 0.05).

Spatially, two prominent groups were recorded at a 48% similarity level, separating exposed station 3.2 from the others (Figure 5). At approximately 63%, another two main groups were documented, splitting Clusters A and B. In Cluster A, the exposed and sheltered sides of station 1 of the large groyne (substations 1.1 and 1.3) were grouped. The cluster was further divided into two main groups: 1) station 3.3 (80% similarity level) and 2) stations 4.2 and 5 (96% similarity level), and the stations of the inside lagoon and station 3.1 (93% similarity level). In Cluster B, at an 81% similarity level, two main branches formed, with sheltered station 4.3 standing alone and separated from another branch.



Figure 4. Species diversity (H'), richness (d), and evenness (J') of macrobenthos across sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu



Figure 5. Bray-Curtis similarity based on hierarchical clustering of substations shown using a dendrogram plot showing the macrobenthos assemblage pattern in different breakwater systems in Kuala Nerus

Environmental Aspects of Different Breakwater Systems

Various sand sizes have mostly made up the soft bottom of the Kuala Nerus coastal area (Figure 6). In detail, the sheltered stations are dominated by very fine sand (30.680%–77.322%) and the exposed stations are governed by coarse sand (up to 44.34%). Overall, TOM content ranges from 0.88% to 2.97% (Figure 7), with the sheltered stations being relatively stable compared to the exposed stations. No significant difference exists in TOM percentages between the sheltered and exposed stations (p > 0.05). The heavy metal concentrations of lithium (Li), chromium (Cr), iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) in the surface sediments of the Kuala Nerus coastal area are within the allowed value for the Upper Continental Crust (UCC) (Table 2). Hence, the area is considered uncontaminated and unpolluted.



Figure 6. Sediment characteristics at sheltered and exposed stations in coastal man-made structure areas in Kuala Nerus, Terengganu



Figure 7. Percentage value of total organic matter content (%) across sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu

The current speed showed a decreasing pattern across the sheltered stations and an increasing trend across the exposed stations, ranging from 0.0292 to 0.0421 m/s and 0.0507 to 0.0812 m/s, respectively (Figure 8). A consistently low significant wave height

Table 2

Heavy metal concentrations in the sheltered and exposed sites of the different breakwater systems in Kuala Nerus. UCC = upper continental crust

Average of heavy metals (ppm)													
	Sheltered							Exposed					
	1.3	Inside lagoon	3.1	3.3	4.1	4.3	1.1	1.2	Outside lagoon	3.2	4.2	5	UCC
Li	3.82	3.11	4.18	4.18	4.18	6.09	4.77	3.68	2.85	2.75	4.16	4.45	22
Cr	4.97	3.51	1.29	11.11	6.11	8.38	3.15	2.16	8.41	6.79	3.76	8.05	35
Fe (%)	4.86	3.67	3.60	6.44	10.87	13.55	8.47	4.51	3.95	4.69	6.39	12.62	308.9
Cu	0.67	0.30	0.82	2.14	0.18	0.26	0.98	0.17	0.40	0.89	1.12	0.29	14.3
Zn	4.12	4.09	6.02	6.66	6.25	6.63	6.96	5.01	3.17	2.80	5.97	6.01	52
Cd	0.02	0.02	0.05	0.06	0.04	0.02	0.03	0.03	0.01	0.00	0.03	0.02	0.1
Pb	0.96	0.85	1.05	1.27	1.29	1.94	1.41	0.91	0.59	0.43	1.17	1.34	16
As	0.61	0.80	0.82	0.90	0.90	1.32	1.21	0.89	0.57	0.55	0.90	0.83	2
Hg	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.06



Figure 8. Temporal current speed (m/s) in the Kuala Nerus coastal area throughout the Asian monsoon system

(H_s) was recorded in the sheltered station (Figure 9). The bathymetry of the Kuala Nerus coastal area varied from 2.5 ± 0.5 to 8 ± 0.5 m, with a control station of 10 ± 1 m in depth (Figure 10). The deepest station was located at the front side of the large groyne (station 1.2), whereas the shallowest station was on the left side of the parallel breakwater without tombolo (station 3.3).

The average water parameters showed consistent readings (Figure 11). The temperature and salinity range from 29.23 °C to 29.73 °C and 31.44 to 32.02 ppt, respectively (Figure 11A), while the DO and pH range from 2.22 to 2.61 mg/L and 8.26 to 8.42, respectively (Figure 11B). Overall, no significant difference was detected in water physical parameters across the sheltered and exposed stations (p > 0.05).



Figure 9. Seasonal significant wave height (Hs) at sheltered and exposed substations in different breakwater systems in Kuala Nerus, Terengganu



Figure 10. Bathymetry of the Kuala Nerus coastal area in sheltered and exposed substations in different breakwater systems



Figure 11. Average water physical parameters throughout sheltered and exposed stations in different breakwater systems in Kuala Nerus: (A) Temperature (°C) and salinity (ppt); and (B) Dissolved oxygen (DO) (mg/L) and pH

Relationship between Macrobenthos Assemblages and Environmental Parameters

PCA accounted for 43.75% of the sample variation in the first two axes (Figure 12). PC1 showed TOM, silt + clay, all heavy metal types, temperature, salinity and pH as the most significant factors with a positive correlation. In contrast, gravel, DO, current speed, and wave height revealed a negative correlation on factorial axis 1 (35.86% of the total variance). In PC2, current speed, wave height, depth, TOM, silt + clay, AS, Li, Fe, Pb and Zn were the most significant factors and positively correlated. In contrast, Cd, Cr, temperature, salinity, sand, pH, Cu, gravel, and DO negatively correlate on factorial axis 2 (7.85% of the sample's variation). The macrobenthos density strongly correlated positively with wave height, depth, TOM, and silt + clay, revealing a negative correlation with DO, gravel, Cu, pH, sand, salinity, and temperature. The macrobenthos diversity has a strong positive correlation with current speed, DO, gravel, wave height and depth and negatively correlates with pH, sand, salinity, temperature and heavy metals of Cr and Cd. The macrobenthos evenness has a strong positive correlation with gravel and DO and a strong negative correlation with TOM, silt and heavy metals of As, Li, Fe, Pb and Zn. The macrobenthos richness has a strong positive correlation with current speed, wave height, and depth, and it revealed a strong negative correlation with the pH, sand, salinity, temperature, and heavy metals of Cr and Cd.

Table 3 shows the spatial correlation between the environmental parameters and macrobenthos assemblages. Macrobenthos density had a significant positive correlation



Figure 12. Principal component analysis (PCA) ordination showing sampled stations clustering based on a Euclidean distance matrix considering environmental parameters and four biotic assemblages (diversity, evenness, density, and richness)

Table 3

Spearmen's correlation (r) between each environmental parameter and macrobenthos assemblages in different breakwater systems in Kuala Nerus, Terengganu

Parameters	Density (ind./m ²)	Diversity (H')	Evenness (J')	Richness (S)
TOM (%)	.417**	0.072	467**	.315*
Sand (%)	0.211	0.242	-0.030	0.204
Gravel (%)	0.185	0.192	0.088	0.205
Silt + clay (%)	-0.052	-0.126	-0.208	-0.094
Li (ppm)	0.090	-0.026	380**	0.148
Cr (ppm)	0.180	0.030	-0.203	0.134
Pb (ppm)	0.159	0.007	384**	0.207
Cu (ppm)	-0.085	0.070	0.033	0.096
Zn (ppm)	0.044	0.062	255*	0.186
Fe (%)	0.107	-0.196	270*	-0.032
Cd (ppm)	0.022	0.026	-0.230	0.198
As (ppm)	0.201	0.024	467**	.257*
Current speed (m/s)	0.039	0.170	0.213	-0.014
Wave height (m)	-0.199	-0.179	0.158	298*
Depth (m)	.262*	0.132	-0.059	0.079
Wind speed (m/s)	388**	319*	.299*	502**
Temperature (°C)	.286*	0.140	-0.232	.275*
DO (mg/L)	-0.250	-0.028	.278*	-0.173
Salinity (ppt)	0.028	.307*	0.003	.342**
рН	0.021	-0.238	-0.062	-0.245

Note. **Correlation is significant at the 0.01 level (two-tailed); *Correlation is significant at the 0.05 level (two-tailed)

with TOM (%), depth (m), temperature (°C), and wind speed (m/s) (p < 0.05). Macrobenthos diversity had a significant positive correlation with salinity (ppt) and a negative correlation with wind speed. Macrobenthos evenness showed significant positive correlations with the wind speed (m/s) and dissolved oxygen (DO) and a significant negative correlation with TOM (%) and heavy metals of Li, Pb, Zn, Fe, and As. Macrobenthos richness had a significant positive correlation with TOM (%), salinity, As, and temperature and a significant negative correlation with wind speed (m/s) and wave height (m).

Multiple Linear Regression (MLR) analysis revealed TOM (%) as the most significant predictor for macrobenthos density (Figure 13). Salinity, wind speed, and current speed were the significant predictors of macrobenthos diversity. TOM (%) and arsenic (As) were significant predictors for macrobenthos evenness, with As being the most important



Figure 13. Multiple Linear Regression (MLR) analysis between macrobenthos assemblages (density (ind./ m^2), diversity (H'), evenness (J') and richness (s)) and environmental parameters (sediments, heavy metals and water physical parameters) with significant correlations (p < 0.05)

contributor influencing evenness. Wind speed, salinity, TOM, wave height, and silt + clay were selected as significant predictors for macrobenthos richness, with wind speed as the most influential factor. In summary, the MLR analysis revealed specific environmental parameters that significantly influenced each type of macrobenthos assemblage.

DISCUSSION

Breakwater systems have been widely acknowledged as artificial reefs, influencing macrobenthos assemblages by changing the hydrodynamics, sediment characteristics, food sources, and food web interactions (Holzhauer et al., 2020). In this study, station 1 of the groyne structure harbours the highest macrobenthos population, consistent with studies by Walker et al. (2008) in Southern Queensland (Australia) and Keller and Pomory (2008) in Santa Rosa Island Beach (USA). The groyne exhibited great macrofaunal abundance and biodiversity by restricting water circulation, producing lower energy conditions, creating a muddy pool and facilitating the thriving of a diverse macrobenthic community in the region (Becchi et al., 2014).

The macrobenthos composition in the sheltered stations in the present study can be related to findings in Bertasi et al. (2007) and Munari et al. (2011) in the Lido di Dante (Northern Adriatic Sea) and Punta Marina (Italy), respectively. The low-crested breakwaters from both studies have created sheltered areas for establishing brackish-water species and served as lagoonal species' channels along the coast. In addition, the species diversity and density in the sheltered beaches are typically higher than the exposed beaches (Kaullysing et al., 2017), with the macroinvertebrates' distribution in sandy beaches generally patchy due to the biological aggregations, localised food concentrations and tidal as well as seasonal migrations (Ellers, 2021).

In relation to Mollusca as the dominant taxa found in the present study, the different breakwater systems prove to be able to host diverse assemblages of molluscs, with the structure, slope and age of breakwaters possibly affecting the mollusc species (Orand & Fisher, 2021). Molluscs, considered early colonisers of substrates, have become the most abundant organisms in the coastal zone. They are attributed to their strong adaptation and survival skills, making them more tolerant to biological and chemical changes (Underwood & Chapman, 2013). In addition, their resilience to physical stressors in wave-exposed areas is potentially attributed to their intrinsic characteristics, such as reproduction and stress resistance, as well as extrinsic factors, like habitat availability and species interactions (Airoldi & Bulleri, 2011; Fortunato, 2015).

In contrast to the present study, Moreira et al. (2006, 2007) and Rivera-Ingraham et al. (2011) reported the unsustainable of molluscs (limpet and chiton) on artificial substrates due to the substrate complexity, which lack of microhabitats (crevices and rock pools). The microhabitats created by the coastal structures possibly contribute to a higher number of

taxa (Kefi et al., 2015; Strain et al., 2018), leading to enhanced recruitment and survival of sessile and mobile macrofauna (Atilla et al., 2005).

In the Kuala Nerus coastal area, the complex and uneven bathymetry notably impacts the area's dynamic processes, particularly water flow, exchange, and particle transport pathways across passages, as Daryabor et al. (2016) highlighted. The deepest locations at the front and right sides of Station 1 are attributed to the strong hydrodynamic effect of waves and currents from the southward areas, which cause continuous scouring, leading to active sediment transport and erosion (Ariffin et al., 2020). The presence of shallow sheltered and deeper exposed areas in station 2 of the semi-enclosed jetty-type breakwater is attributed to the slow current speed inside the lagoon compared to the exceptionally high current speed outside the lagoon, which then flows northward and parallel to the shorelines (Ariffin et al., 2020). The strong current that washed away the sediments has led to the unsuccessful creation of a sand tombolo at the original location but successfully forming it at the next parallel breakwater station (e.g., station 4) with a weaker current speed.

The low significant wave height (H_s) across the sheltered stations of Kuala Nerus might be attributed to the dissipation, reflection, transmission, and diffraction of wave energy through wave breaking induced by the structures (Galani et al., 2019; Sierra & Casas-Prat, 2014). The presence of different breakwater systems in the Kuala Nerus coastal area has resulted in changes in current speeds and the creation of both sheltered and exposed areas, potentially leading to shifting in community equilibrium and affecting the macrobenthos assemblages and distributions (Stender et al., 2021). The interaction between ocean waves and current strength in the area, creating favourable environmental conditions and promoting species survival (Munari et al., 2011). Similarly, Zanuttigh et al. (2005) reported that breakwaters and groynes increased water residence time during extreme events and caused current flow reduction in sheltered stations. Conversely, in the absence of breakwater structures, currents are stronger in shallow water, leading to severe serial erosion, hence washing away the organisms from the area (Jeans et al., 2012).

The domination of coarser and medium sands in exposed stations (excluding the reference station) might be attributed to several combined factors of stronger wave propagation, fast water current flow and low water level, which hinder the deposition of fine particles and allow settlement of coarser and medium-sized particles (Bertasi et al., 2009). Conceptually, the heaviest particles settle first along the coast, whereas the finest ones are carried further, thus contributing to muddy bottoms (López, 2017). In exposed stations, strong currents have transported the sediments by picking up and moving fine particles to other stable hydrodynamic areas (e.g., sheltered areas) while leaving coarser grains suspended in the stronger current area. The fine sands in the sheltered areas are presumed to create frictional surfaces that demand significant energy for macrobenthos penetration and movement. The substantial energy has caused the organisms to stay below

the interface, potentially contributing to higher macrobenthos density in sheltered stations (Wiesebron et al., 2021).

In the reference station in Batu Rakit (St. 5), the macrobenthos composition is potentially shaped by organic matter content and sediment grain size. The sufficient organic matter not only supports the food web diversity of macrobenthic organisms (Sczcepanek et al., 2021) but also helps in creating microhabitats for various macrobenthic organisms (e.g., some polychaetes species construct tubes using organic matter, providing shelter and protection from predators) (Merz, 2015; Vinn, 2021). The stable organic matter content, particularly in the sheltered stations of Kuala Nerus, is presumed to be contributed by the rigid sediment structures, which effectively entrapped the drifting organic materials. This finding is supported by Carugati et al. (2018), who reported the highest TOM at sheltered stations due to a reduced hydrodynamic export to the open sea. The exposed stations dominated by coarser and medium sands recorded lower TOM, likely due to the high sands' porosity and permeability, which slightly inhibit the passage of high organic matter in the area.

The lower heavy metal concentrations in the surface sediments in the Kuala Nerus breakwater area were deemed to have a minimal impact on the coastal ecosystem. The movement of pollutants in this area is affected by the combination of currents and waves near the coastal structures, as supported by Tao and Han (2002). Prevailing currents potentially transport heavy metals and originate from various sources, such as sewage and industrial effluents, brine discharge, agricultural activities, and coastal development (Yunus et al., 2020). In this study, the heavy metals in the sediments might derived from natural processes as no significant enrichment sources (e.g., anthropogenic activities) were found. As a result, all sampling stations in the Kuala Nerus coastal areas were classified as having a good ecological status, indicating an unpolluted environment with uncontaminated sediments.

In addition, as the Kuala Nerus coastal area is mainly composed of sandy substrates, heavy metals did not absorb well onto the sandy particles, as compared to clay, fine, and very fine silt particles, with a larger surface area-to-volume ratio, which provided broader and more active sites for heavy metal absorption (Yao et al., 2015; Yunus et al., 2020). These smaller particles can better form large aggregates of metals bound together by electrochemical forces and organic matter (Raji et al., 2023). As a result, the breakwater areas in Kuala Nerus, dominated by sandy substrates, showed lower concentrations of heavy metals, in line with the findings by Yunus et al. (2020).

The present study found a positive correlation between macrobenthos density and sediment characteristics, indicating that sediment characteristics influence the community and distribution of macrobenthos, as Qiu et al. (2018) suggested. Specifically, sheltered stations, dominated by very fine sand and a higher TOM content, exhibited a higher macrobenthos density. The fine sand macrobenthos communities are suggested to receive sufficient nutrients from microphytobenthos' primary production, leading to enhanced growth and blooming, contributing to the higher density of organisms, as Hope et al. (2020) supported.

This study documented a higher macrobenthos density with the increase in depth and salinity, consistent with Costas (2016) and Huang et al. (2021), who highlighted salinity as one of the most influential factors in shaping benthic communities. The macrobenthos density is higher in marine environments due to higher salinity than in brackish and freshwater areas (Alipoor et al., 2011). The optimal salinity positively affects the benthic organisms' reproductive system (Vizakat et al., 1991). The broad temporal salinity variation can increase taxa numbers and lower species abundance (Alongi, 1989; Dittmann, 2002). Less-tolerated marine organisms may encounter challenges with their osmotic regulation, leading to reduced species richness and diversity (Stender et al., 2021).

The present study revealed a significant positive correlation between macrobenthos density and depth, in concordance with Kim et al. (2023). Water temperature and salinity, influenced by water depth, also play a crucial role in shaping the macrobenthos community. Shallow areas near breakwater systems may experience disturbance from waves and currents, altering sediment distribution and composition, thereby impacting organism assemblages (Munari et al., 2011). Masucci et al. (2020) highlighted that a control station with irregular depth profiles provides more microhabitats, supporting a diverse array of micro and macro-marine organisms. By contrast, sheltered stations with consistent depth profiles may experience higher levels of ultraviolet (UV) radiation, thus inhibiting the macrobenthos recruits' settlement (Masucci et al., 2020; Turner et al., 2018).

The strong relationship between water physical parameters and macrobenthos assemblages suggests that hydrodynamic activities influence distributional patterns and functional structure of macrobenthos, leading to a shift in community equilibrium, favouring opportunistic species and reducing overall diversity (Foulquier et al., 2020; Stender et al., 2021). The hydrodynamic conditions, particularly wave action, affect the soft bottom communities by smothering immobile organisms and inducing migration in mobile organisms (Foulquier et al., 2020).

In the present study, the macrobenthos assemblages were influenced by softbottom characteristics and food availability, both of which were governed by the area's hydrodynamic condition. The different breakwater systems, including groyne, semienclosed jetty-type breakwater and parallel breakwaters without and with tombolo, effectively governed the hydrodynamic condition in the study area.

CONCLUSION

This study emphasised the effect of different breakwater systems on the distribution and composition of macrobenthos in the Kuala Nerus coastal area. Station 1 of groyne structures harboured the highest macrobenthos population, with the sheltered stations exhibiting higher macrobenthos composition than the exposed stations.

The study revealed the morphological dynamism of the investigated stations, with bottom sediment and nearshore hydrodynamic circulation being major driving factors. The hydrodynamic condition significantly influenced the sediment characteristics, particularly the various sand sizes, leading to changes in organic matter and heavy metal contents. Coarser and medium sands dominate the exposed stations, while the sheltered stations are dominated by very fine sand. Low heavy metal concentrations in the surface sediments indicate an unpolluted environment of the Kuala Nerus coastal areas.

The relationship between macrobenthos and environmental factors demonstrated the importance of sediment characteristics and food availability (organic matter content) in the soft-bottom habitat governed by the hydrodynamic factors. The different breakwater systems in Kuala Nerus have altered sediment dynamics and nearshore hydrodynamics, affecting wave energy, water currents, and sediment transport, ultimately impacting the macrobenthic population and assemblages.

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Effect of Core Type on Zoned Earth Dams on Total Water Head and Flux

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ABSTRACT

Most dams constructed worldwide are zoned earth dams with cores of different materials. However, selecting the proper core material in an earth dam will reduce seepage and increase safety. Most of the available information on dam cores was extracted from laboratory experiments. In this study, cores of different materials used in three selected zoned dams of almost the same height were assessed based on acquired field data and numerical simulation. The selected dams are in Iraq and named Haditha Dam (designed with a compound core of compacted dolomite and asphaltic diaphragm), Hemrin Dams (designed with a hard clay core) and Khasa Chai Dam (designed with a silty clay core). The total water head and water flux through the core of each dam were simulated using a two-dimensional SEEP/W model. For high and low water depths in the reservoir of Hemrin Dam, the water flux ratios were found to be 140 and 50 times greater than that of Haditha Dam. For low water depth in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17. Compared with the core of the Hadith Dam, the flux through the core of the Khasa Chai Dam was found to be triple. For studied core samples, the variation in fluxes can be related to the effect of both hydraulic conductivity and geometry of the dam core. The hydraulic conductivity is affected by the core material, while the hydraulic gradient is affected by both the core material and geometry.

Keywords: Acquired data, cores, earth dams, flux, SEEP/W model, total head

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INTRODUCTION

Earth dams are storage structures constructed from highly compacted, low-permeability earth material. Typically, the components of an earth dam are shells (upstream and downstream), a core, a filter and a drain. Compared with concrete gravity dams, earth dams are economical and can be constructed at sites with diverse geological and geographical conditions (Hasan, 2019). Usually, the earth materials used in the construction of earth dams are borrowed from nearby areas. The borrowed soil used for the dam core is categorized as having very low permeability, compressibility, liquid limit, and organic contents. Earth dams have always been associated with seepage through their foundations and embankments. The seepage from earth dams resulted from the high difference in water levels between upstream and downstream and removed soil particles from the embankment. Poor design, construction, and operation may lead to the failure of earth dams due to seepage. Seepage is categorized as the main cause of failure, and it constitutes about 30%–50% of earth dam failures (Salari et al., 2021).

Therefore, the seepage rate should not exceed the acceptable limits. The core is an impermeable barrier within the embankment of a zoned earth dam to reduce seepage to an acceptable limit. The substantial reduction in seepage rate by the core is attributed to the fact that core material has permeability a hundred times lower than that of the shell material. Therefore, most drop-in seepage flow lines occur within the impervious core, and the upstream shell has a negligible effect on seepage. Moreover, the small amount of water that seeps through the central core will flow in the lower layer in the downstream shell and emerge at the dam toe. It justifies why researchers were focused on the performance of various core types. Adnan et al. (2022) analyzed the seepage in Shirin Dam, Iraq, and found that core can reduce seepage by 99%. However, Fikri et al. (2023) concluded that the failure of the Senggarang Coastal Embankment (SCE), Johor, Malaysia, by seepage is imminent if the existing very low cohesion soil of the SCE is not replaced with cohesive soil type. Mohammed et al. (2022) found that the usage of geosynthetic clay liner in a dam embankment can reduce the seepage by 22%.

The seepage rate was reduced by 35.6% when a ratio of 50% of the tire rubber powder was used in a dam core (Shuhaib & Khassaf, 2023). Alternative cores from silty and sandy soils with different additive materials were tested theoretically and experimentally in the laboratory of Alzamily and Abed (2022a, 2022b). The permeability of the alternative cores was found to be smaller than the permeability of the hard clay core used in zoned earth dams. Adamo et al. (2018) focused on the successful use of dolomite in the core of Haditha Dam. The dolomite is available in large quantities in areas surrounding Haditha Dam. Ali et al. (2020) developed a novel method for quantifying the efficiency of seepage control measures in earthfill dams. They found that the overall efficiency of different seepage control measures ranges between 51 and 70%. The effect of core permeability, core width, core base thickness, and core penetration on seepage has been studied experimentally and numerically by Salem et al. (2019) and Mostafa and Zhenzhong (2023).

However, the hydraulic performance of different control methods, such as flat slopes, toe drainage systems, and a catch drain in the tailwater, was evaluated analytically by Magdy

(2016). Harr (1962) classified the methods used to solve seepage problems as analytical, experimental and approximate. A three-dimensional finite element model was developed by Chen et al. (2022) to simulate a typical earth dam with an anti-seepage polymer cutoff wall. Moreover, Amin and Ali (2013) developed and validated new equations for the estimation of seepage rate from earth dams with high precision. The SEEP/W model was used to simulate seepage through small and large earth dams in Iraq (Ali & Odaa, 2014; Maysam & Al-Nadawi, 2020). Seepage below the foundation of Hilla main regulator, Iraq, was studied by Mahdi and Al-Hadidi (2023), while the seepage through Iraq soils (homogeneous and non-homogeneous saturated-unsaturated) was studied by Jassam and Abdulrazzaq (2019). Harpy et al. (2022) used environmental isotopes and hydrochemicals to evaluate the impact of seepage from the reservoir of Dwarege Dam, Iraq, on groundwater.

The stability of the slopes of Hemrin and Haditha Dams under different reservoir water levels was analyzed by using Geo-Studio Software (Al-Nedawi & Al-Hadidi, 2020; Malik & Karim, 2021). However, the Plaxis 3D model was used by Bredy and Jandora (2020) to analyze the slope stability of the Karolinka Dam embankment in the Czech Republic. The height of the dam embankment before and after treatment was considered in the analysis. Flow data and conditions of foundation materials of Haditha and Mosul Dams were analyzed by Ali and Odaa (2014) and Adamo et al. (2018).

This study investigated the impact of core material and geometry on seepage through three selected earth dams in Iraq based on acquired field data and simulation results from the SEEP/W model.

METHODOLOGY

Three-zone dams were selected to compare the effectiveness of their different cores in seepage control. The selected dams were Haditha Dam, Hemrin Dam and Khasa Chai Dam; the first is located west of Iraq in the Al Anbar Governorate, while the second is located east of Iraq in the Diyala Governorate. The third dam is located northeast of Iraq at Kirkuk Governorate. Figure 1 shows the locations of the dams. Field data and simulation results from the two-dimensional (2D) SEEP/W model were used in the comparison. The data on the selected dams (Haditha, Hemrin and Khas Chai) was acquired from the State Commission of Dam and Reservoir, Ministry of Water Resource. The acquired data includes reservoir water levels, seepage rates, pore water pressure, properties of dam materials and filters and other dam details.

Description and Purpose of Haditha Dam

Haditha dam was constructed on the Euphrates River, Iraq, about 7 km upstream of Haditha city, Al Anbar Governorate, as shown in Figure 1. The multipurpose dam mainly serves irrigation, power generation and flood control. It is an earthen zone dam with a length of



Figure 1. General views for the locations of the studied dams (SCODR, 2020)

8.7 km, a height of 57 m and a trapezoidal cross-section. The maximum operating discharge from the spillway is 7900 m³/s, which results in a reservoir water level of 147 m and a storage capacity of 8.2×10^9 m³. The emergency discharge is 11000 m³/s, which resulted in a reservoir water level of 150.21 m.

Materials and Geology of Haditha Dam

The core of Haditha Dam includes an asphaltic concrete cutoff, detrital dolomites and sand and gravel combination. These materials were chosen for the dam construction since they were available close to the dam site. Core from suitable traditional materials was not found in adequate quantities during the earliest stage of investigations, and this led to searching for an alternative core material. However, the existence of vast quantities of dolomite near the dam site drew the attention of the designers to use this material in the dam core. Dam authorities claim that dolomite has never been used as a core material in big dams. In addition, an asphaltic concrete diaphragm is used in the center of the dolomite core. A reinforced concrete slab revetment protects the upstream Haditha Dam face, while a rockmass revetment protects the downstream face. The total volume of materials used in the dam construction is estimated at 30×10^6 m³. The properties of the materials used in dam construction are shown in Table 1. The information collected from the State Commission of Dam and Reservoir, Ministry of Water Resource on Haditha Dam was used in the SEEP/W model to draw the dam cross-section shown in Figure 2.

Description and Purpose of Hemrin Dam

Hemrin Dam is 120 km northeast of Baghdad, Iraq, and it was constructed on the Diyala River (one of the tributaries of the Tigris River), as shown in Figure 1. The main purposes of the dam are to control floods, irrigate agricultural lands and generate power. The dam is a rockfill dam with a length of 3.5 km and a height of 53 m. Figure 2 shows the dam cross-section.

The maximum operational water level in the dam reservoir is 104 m, while the level of the spillway crest is 92 m. The maximum operating discharge is 4000 m³/s, while the actual measurements in 2022 revealed that the discharge does not exceed 1000 m³/s. The dam reservoir has a maximum storage capacity of 3.9×10^9 m³. In addition, the dam has four irrigation outlets, and each outlet was designed to discharge up to 250 m³/s. When the design discharge is 200 m³/s, the powerhouse can generate 50 MW.

Table 1	
Properties of the materials used in the construction of Haditha Dam (SCODR	, <i>2020)</i>

Material	Bulk density(γ) (KN/m³)	Cohesion (c) (KPa)	The angle of internal friction (ذ)	Coefficient of Permeability (K _h) (m/s)	Saturated water content %
Dolomite	22	30	26	1.15×10^{-7}	0.29
Clay	18.7	40	15	2.31×10^{-8}	0.47
Dolomite-limestone	22	150	32.5	1.15×10^{-8}	0.29
Compacted dolomite	20.3	0	31.5	1.15×10^{-8}	0.35
Rock muck sandy gravel	17	0	28.5	2.31×10^{-6}	0.39
Asphaltic concrete diaphragm	17.7	0	30.97	1 × 10 ⁻⁹	0.16



Figure 2. Cross section of Haditha Dam

Materials and Geology of Hemrin Dam

Besides the upstream and downstream shells, the dam has a clay core clad with coarse and fine filters. Data on dam geometry and material were used in the SEEP/W model to draw the dam cross-section, as shown in Figure 3. Table 2 shows the properties of materials used to construct the Hemrin Dam.



Figure 3. Cross section of Hemrin Dam

Table 2	
Properties of the materials used in the construction of Hemrin Dam (SCODR, 20	20)

Material	Bulk density (γ) (KN/m³)	Cohesion (c') (KPa)	The angle of internal friction (ذ)	Hydraulic Conductivity K _h (m/s)	Saturated water content %
Foundation	22	40	15	1×10^{-5}	
Shell	19	-	37	1.69×10^{-5}	0.1275
Clay core	18	30	23	2.31×10^{-9}	0.094
Fine filter	16	-	35	1.2×10^{-5}	0.1275
Coarse filter	16	-	35	0.0001	0.1275

Description and Purpose of Khasa Chai Dam

Khasa Chai Dam is a zoned multipurpose dam located 10 km northeast of Kirkuk City, Iraq. It was constructed on the Khasa Chai River, a seasonal tributary of the Zaghaitun River. The maximum storage and water levels in the dam reservoir are 101.3×10^6 m³ and 496 m, respectively. The maximum discharge from the spillway is 1686 m³/s, while the water storage is used mainly for water supply, recharging groundwater and recreation. The dam is 2.36 km long, 58 m high and has a top width of 13 m.

Materials and Geology of Khasa Chai Dam

The earth material used in the dam core is silty clay borrowed from an area near the dam site. The core extended from the dam foundation to a level of 430 to a level of 496.1 m. The

top width of the core is 4 m with side slopes of 0.75:1 (H:V) upstream and 1:0.75 (H:V) downstream. On the upstream side of the core, there is a fine filter, while on the downstream side, there is a coarse filter. Both shells upstream and downstream were constructed from sand and gravel and protected by rip rap. Figure 4 shows the dam section. The chimney, blanket and toe drain the seepage water. The geological investigations showed that the dam site is located within a clastic sequence of the Mukdadiya formation that is widely distributed in the foothill and the Mesopotamian plain zones. The formation consists of sand, silt, clay, sandstone, and gravel, with an upwardly increasing diameter, forming a conglomerate with a maximum thickness of 2050 m (Abbas, 2021). The properties of the dam materials are shown in Table 3.



Figure 4. Section of Khasa Chai Dam

Table 3

Properties of the materials used in the construction of Khasa Chai Dam (SCODR, 2020)

Material	Bulk density (γ) (KN/m³)	Cohesion (c) (KPa)	The angle of internal friction (ذ)	Coefficient of Permeability (K _h) (m/s)	Saturated water content %
Shell (Sand and Gravel)	21.58	0	38	1.25×10^{-5}	0.06
Core (Silty Clay)	17.65	98	30	5.3×10^{-9}	0.19
Fine Filter (Sand)	17	0	37	5.60×10^{-3}	0.06
Coarse Filter (Gravel)	17.7	0	38	1×10^{-2}	0.05

SEEP/W Model: Mathematical Background, Boundary Conditions and Application

The SEEP/W model is formulated to simulate water flow through both saturated and unsaturated soil (Richards, 1931; Childs & Collis-George, 1950). In addition, the model includes several "typical" water content functions that can be used to determine the

saturated hydraulic conductivity of different soil types (Geo-Slope, 2012; Genuchten, 1980) as described by Equation 1.

$$k_{w} = ks \frac{\left[1 - \left(a\varphi^{(n-1)}\right)\left(1 + \left(a\varphi^{n}\right)^{-m}\right)\right]^{2}}{\left[\left((1 + a\varphi^{n})^{n}\right)^{\frac{m}{2}}\right]}$$
[1]

where k_s is saturated hydraulic conductivity (L/T), a, n, and m are curve fitting parameters, φ the required suction range while n is determined by the following Equation 2:

$$n = \frac{1}{1-m}$$
[2]

Seepage flow through a homogeneous isotropic medium under steady-state conditions is described by the 3D Laplacian Equation 3 (Geo-Slope, 2012).

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0$$
[3]

The general governing differential equation for two-dimensional seepage can be expressed as Equation 4 (Geo-Slope, 2012).

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right) + Q = \frac{\partial\theta}{\partial t}$$
[4]

where H is the total head, k_x is the hydraulic conductivity in the x-direction(L/T), k_y is the hydraulic conductivity in the y-direction (L/T), Q is the applied boundary flux, θ is the volumetric water content, and t is time (T).

Boundary conditions are required to establish a phreatic line and pore water pressure, which are applied along the dam section. Upstream water level, downstream water level, and zero pressure represented boundary conditions. A potential seepage face boundary (an edge) will also be applied to the downstream face. A potential seepage face is a special boundary condition used when the solver locates a position where a seepage face might develop. The flow chart in Figure 5 shows the steps this study followed to run the SEEP/W model to simulate the seepage from the studied dams.



Figure 5. Flow chart for the main steps required to apply the SEEP/W model

RESULTS AND DISCUSSION

Three zoned earth dams with different core types were selected to assess the performance of cores used in zoned earth dams. The dams in Iraq are named Haditha Dam, Hemrin Dam, and Khasa Chai Dam. In the constructions of these dams, compacted dolomite with an asphaltic diaphragm in the center was used as a core in Haditha Dam, while hard clay core and silty clay core were used in Hemrin Dam and Khasa Chai Dam, respectively. The dolomite was used since vast quantities were found near the dam site. The dam authority claimed that the dolomite has never been used as a core in large dams previously. The permeability of the compacted dolomite was 1.15×10^{-8} m/s, while it was 1×10^{-9} m/s for the asphaltic diaphragm.

Moreover, the permeability of the hard clay core used in the Hemrin Dam was 2.31×10^{-9} m/s, while the permeability of the silty clay core used in the Khasa Chai Dam was 5.3×10^{-9} m/s (SCODR, 2020). To give credibility to the method used for core samples assessment, the acquired data on seepage rates and reservoir water levels for the selected dams should be checked for their quality and consistency. The data was plotted first and compared with standard field data and modelling results shown in Figure 6. The relationship between the seepage rates and the reservoir water level of an earth dam in Korea was found to be nonlinear (Lee et al. 2018). However, a linear relationship between seepage rate is directly proportional to the reservoir water level. The data on seepage rates and water levels in the reservoir of Haditha Dam was plotted and compared with the relationship presented in Figure 6. Figure 7 shows that the seepage data for the Haditha dam was scattered and inconsistent. The strength of the association between the seepage rates and reservoir water level can be found by calculating the coefficient of determination (R²).





Figure 6. The correlated relationship between reservoir water level and seepage for an earth dam in Korea (Lee et al., 2018)

Figure 7. A sample of inconsistent field data for Haditha Dam at station 26+80

However, the association does not imply a correlation, although the terms correlation and association are often used interchangeably in most statistics texts.

However, in a stricter sense, correlation refers to linear correlation, while association refers to any relationship between two variables. Equation 5 is used to determine R^2 .

$$R^{2} = \left[\frac{N\sum XY - \sum X\sum Y}{\sqrt{\{N\sum X^{2} - (\sum X)^{2}\}\{N\sum Y^{2} - (\sum Y)^{2}\}}}\right]^{2}$$
[5]

where X represents the seepage rate while Y represents the reservoir water level.

The value of R^2 for data on seepage rates and water levels in the reservoir of Haditha Dam, shown in Figure 7, was found to be 0.19, which confirmed the weak association between the variables. However, an association's strength depends on the data's characteristics for each variable. However, Ali et al. (2020) considered human error in the measurement to be one of the uncertainties in the seepage data of earthfill dams. For Hemrin Dam, a sample of the available data on seepage rates and the reservoir water level is shown in Figure 8. Although the data was found scattered with gaps, the value of R^2 was 0.84, which confirmed that the degree of association between the variables was high.

To overcome the problem of inconsistency and availability of seepage data, predicted seepage rates obtained from running a two-dimensional SEEP/W model were used to assess the performances of the three selected core types under almost the same operation conditions. The model was calibrated and validated before it was used to simulate the water flux from the core samples. The data of water levels in the reservoir of Haditha Dam that was used to plot Figure 7 were also used in the SEEP/W model to predict the seepage rates, as shown in Figure 9. The value of the R^2 for the simulation was found to be 0.86, which is much higher than the value of R^2 for the acquired data. In addition, Figure 10 shows the



Figure 8. A sample of acquired data for the Hemin Dam



Figure 9. Simulated seepage rates for various water levels in the reservoir of Haditha Dam

simulation results of the seepage rates for Hemrin Dam. The value of R^2 for the simulation results was found to be 0.94, which is higher than that for the acquired data. The data on seepage and water levels in the reservoir of Khasa Chai Dam was found to have a high association. Figure 11 shows the measured data and simulation results for Khasa Chai Dam. The value of R^2 between the observed and predicted seepage rates was found to be 0.97, which confirmed the accuracy of the model predictions (Figure 12).

Compared with the SEEP/3D model, the prediction of seepage (water flux) and total water head by using the SEEP/W (2D) model was found to be more relevant because the prediction of seepage by the SEEP/3D model is costly and requires more running time.

Moreover, Fardin et al. (2009) justified that the 3D seepage behavior in an earth dam diminishes when the overall permeability pattern of the abutments and the dam body are compatible. In addition, Niloufar and Saeed (2014) commented on the accuracy of predicted seepage rates obtained from the two-dimensional SEEP/W model and SEEP/3D model compared with measured seepage data collected from two zoned earth dams in Iran. The average calculated error between the output obtained from SEEP/W and SEEP/3D models and measured dam seepage rates were 13.67% and 8.4%,



Figure 11. Predicted and measured seepage rates for various water levels in the reservoir of Khasa Chai Dam



Figure 10. Simulated seepage rates for various water levels in the reservoir of Hemrin Dam



Figure 12. Predicted and measured seepage rates for Khasa Chai Dam

respectively. The simulated seepage rates obtained from SEEP/W and SEEP/3D models showed an insignificant difference.

Eshagh et al. (2016) and Tabari and Mari (2016) confirmed the accuracy of the SEEP/W model compared with the application of other seepage simulation methods, while Adnan et al. (2022) demonstrated the capability of the model to simulate the seepage through the Shirin earth dam under various operational and climatic conditions. Therefore, applying the SEEP/W model to predict the seepage rates through the selected cores is relevant and can be used to study conditions not covered by the acquired data. The SEEP/W model was calibrated for each core sample before application.

For Haditha and Hemrin Dams, water flux (seepage) predictions were conducted for two different water levels (high and low) in their reservoirs. But for Khasa Chai Dam, water flux was only predicted for low reservoir water levels. The high-water level in the reservoir of Haditha Dam was selected as 131.50 m, while that in the reservoir of Hemrin Dam was selected as 107.50 m. However, the low water levels in the Haditha, Hemrin and Khasa Chai Dams reservoirs were selected as 120.00 m, 96.00 m and 460.00 m, respectively. The water levels in the reservoirs of selected dams are different since their geographical locations are different, too. It makes the ground levels at the selected dams' locations different. At any dam, the water level at a point in the reservoir represents the ground level plus the water depth at that point. Therefore, the water levels in the reservoirs of Haditha, Hemrin and Khasa Chai Dams were carefully selected to result in the same water depth. For example, although the values of the selected high-water levels in the Haditha and Hemrin Dams reservoirs differed and were equal to 131.50 m and 107.00 m above mean sea level, respectively, the water depth in their reservoirs was 31.50 m.

In addition, the values of selected low water levels in the reservoirs of the above dams were 120.00 m, 96.00 m and 460.00 m above mean sea level, respectively. However, these water levels resulted in a 20 m water depth in their reservoirs. This selection is essential to demonstrate the performance of different core samples under the same reservoir water depth by taking the hydraulic gradient and water flux (seepage) as indicators. The predicted total heads using the SEEP/W model are shown in Figures 13 to 17 for the high and low water levels in the reservoirs of the selected dams. Table 4 shows the water levels and depths in the reservoirs of the selected dams, the water flux, and the calculated hydraulic gradient. The hydraulic gradients shown in Table 4 were calculated based on the drop in the total heads across the studied core types.

The kinetic head is the kinetic energy per unit weight of seepage water moving through the dam, and it is usually measured using a piezometer. The water fluxes (seepage rates) for high and low water levels in the reservoirs of Haditha Dam were predicted and found to be 5×10^{-7} m³/s/m² and 1×10^{-7} m³/s/m² respectively (Figures 18 and 19). At the same time, the predicted water fluxes for the high and low water levels in the reservoir of Hemrin

Dam were found to be 7×10^{-5} m³/s/m² and 5×10^{-6} m³/s/m² respectively (Figures 20 and 21). The predicted water flux for the low water level in the Khasa Chai Dam reservoir was 3×10^{-7} m³/s/m². Figure 22 shows the predicted flux through the core of Khasa Chai Dam. For high water levels in the reservoirs of Hemrin and Haditha Dams, the ratios of predicted fluxes through their cores were found to be 140 and 50, respectively. For low water levels in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17.

Compared with the core of the Hadith Dam, the flux through the core of the Khasa Chai Dam was found to be triple. For different core samples, the flux variation can be related to the effect of hydraulic conductivity and core geometry. The hydraulic conductivity of the dam core describes the ease with which the water seeps through it. Therefore, a core with



Figure 13. Total head through Haditha dam for the reservoir water level of 131.5 m



Figure 14. Total head through Hemrin Dam for the reservoir water level of 107.5 m



Figure 15. Total head through Haditha Dam for reservoir water level of 120 m



Figure 16. Total head through Hemrin Dam for reservoir water level of 96 m



Figure 17. Total head through Hemrin Dam for reservoir water level of 460 m

Dam name	Core type	Reservoir water level (m)	Water depth (m)	Hydraulic water gradient (m/m)	Water flux (m ³ /s/m)
Haditha	Compacted dolomite	131.5	31.50	0.350	5×10^{-7}
	with asphaltic diapgram	120.0	20	0.164	1 × 10 ⁻⁷
Hemrin	Hard clay	107.50	31.50	2.010	7×10^{-5}
		96.00	20	0.910	5×10^{-6}
Khasa Chai	Silty clay	107.50	31.5	0.290	3×10^{-7}

Table 4			
Water fluxes a	and hydraulic gradients for	the study core	types



Figure 18. Water flux through Haditha Dam for a reservoir level of 131.5 m



Figure 19. Water flux through Haditha Dam for reservoir level of 120 m



Figure 20. Water flux through Hemrin Dam for reservoir level of 107.5 m



Figure 21. Water flux through Hemrin Dam for reservoir level of 96 m



Figure 22. Flux through Khasa Chai Dam for reservoir level of 460 m

lower hydraulic conductivity gives lower flux. In addition, the core geometry affects the hydraulic gradient (the drop in total head through the dam core). In Darcy's law, the water flux is a function of both hydraulic conductivity and the hydraulic gradient. It justifies why the current study used these two variables to assess core samples. Table 4 shows that the lowest flux was found with the dolomite core with the asphaltic diaphragm. Also, the lowest hydraulic gradients occurred through the above core with values of 0.164 and 0.34. The hydraulic conductivities of compacted dolomite and asphaltic diaphragm are 1.15×10^{-8} m/s and 1×10^{-9} m/s, respectively.

The Federal Emergency Management Agency, (2014) considered that using the core made from asphalt in earthfill dams may make it more watertight. Dams with this type of core are called concrete-asphalt core embankment dams. Most concrete asphalt dams use rock and/or gravel as the main filling material. These types of dams are considered especially appropriate for areas susceptible to earthquakes due to the flexible nature of the asphalt core. Although the hydraulic conductivity of the clay core of Hemrin Dam is 2.31 × 10⁻⁹ m/s, which is lower than the hydraulic conductivity of the silty clay core (5.3×10^{-9} m/s) used in the Khasa Chai Dam, the flux from the Khasa Chai dam was lower than that of Hemrin Dam. This can be attributed to the geometries of the cores, which resulted in a higher hydraulic gradient in the Khasa Chai dam.

For the studied core samples, the variation of water flux with the hydraulic gradient is shown in Figure 23. Salem et al. (2019) analyzed the seepage flow through laboratoryscale embankment dams with an internal core. They concluded that decreasing the core permeability reduced seepage rate, gradient, and pore water pressure. However, they used the ratio between the hydraulic conductivity of the dam core and the dam shell (Kcore/ Kshell) to demonstrate the impact of changing the hydraulic conductivity of the dam core on the seepage rate. However, the present study demonstrated the performance of different



Figure 23. Variation of the water flux with the hydraulic gradient of the studied core samples

core types with their impact on the drop in total head and seepage rate (water flux). The present study is essential for dam engineers since it gives an idea about how selecting core material and geometry can improve the safety of the zone earth dams.

CONCLUSION

In this study, field data on reservoir water level, piezometric head and seepage (water flux) were acquired and used with the simulated results obtained from the two-dimensional SEEP/W model to assess the performance of three different core samples used in selected zoned earth dams in Iraq. The selected dams almost have the same height (H). The names of the dams are Haditha (H=57 m), Hemrin (H=53 m) and Khasa Chai Dams (H=58 m). The core used in the Hadith Dam was compacted dolomite (K= 1.15×10^{-8} m/s) with asphaltic diaphragm (K=1 \times 10⁻⁹ m/s) in the center while a hard clay core (K=2.231 \times 10⁻⁸ m/s) was used in the Hemrin Dam. Silty clay core was used in Khasa Chai Dam (K=5.3 \times 10⁻⁹ m/s). The acquired data for the Haditha and Hemrin Dams were checked and found either inconsistent or with gaps, while the data for the Khasa Chai Dam was consistent. After model calibration and validation, predictions from the running SEEP/W model for high and low water reservoir levels were used to assess the studied core samples. For high and low reservoir water depths, the ratio of water flux through the core of Hemrin Dam was 140 and 50 degrees greater than that of Haditha Dam. For low water depth in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17. The flux through the core of the Khasa Chai Dam tripled the flux flow through the core of the Hadith Dam. The variation in fluxes is mainly attributed to the core material's hydraulic conductivity and the effect of core geometry. The core geometry affects the value of the hydraulic gradient. For Hemrin Dam, the effect of core geometry on the hydraulic gradient and then on the flux is very obvious.

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Review Article

A Focused Review on Upper and Lower Limb Joint Torque Estimation via Neural Networks

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ABSTRACT

Joint torque estimation is an essential aspect of the control architecture in assistive devices for rehabilitation and aiding movement impairments. Healthy adult torque trajectories serve as a baseline for controllers to determine the level of assistance required by patients, evaluate impaired motion, understand biomechanics, and design treatment plans. Currently, methods of torque estimation include inverse dynamics using gold standard motion capture systems, generic mathematical models based on joint torque-angle relationships, neuromusculoskeletal modelling using surface electromyography, and neural networks. As such, this review provides a focused overview of the recent and existing neural networks tailored for upper and lower limb joint torque estimation. Dataset preparation, data preprocessing, and evaluation metrics are presented along with a detailed description of the developed networks, which are classified by model architecture. It includes artificial neural networks (ANNs), convolution neural networks (CNNs), long short-term memory (LSTM) networks, and hybrid and alternate architectures such as wavelet or explainable convolution (XCM). The performance, benefits, and limitations of the models are discussed, highlighting CNNs and LSTMs as the current optimal models for time series prediction of joint torque. This is due

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Keywords: ANN, artificial intelligence, CNN, control architecture, joint moments, LSTM, torque estimation

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INTRODUCTION

Addressing the challenges of ageing and movement impairment is necessary for individuals to maintain a good quality of life (Kruk et al., 2022). To support this, wearable assistive devices (such as exoskeletons or soft exosuits) are gaining significance for assisting impaired motion during rehabilitation or daily tasks (Liu et al., 2019; Schmidt et al., 2017). A key aspect of these devices is their controllers, which utilise joint torque estimation models to obtain a benchmark that sets and tracks the level of assistance for a patient (Moreira et al., 2021). Reference torque trajectories ensure adequate assistance is supplied to the user to complete a motion and are also important in understanding biomechanics and impaired movement and when evaluating the effectiveness of treatments (Perera et al., 2023). Hence, the progression of torque estimation methods would further assistive devices' design and control architectures. Yet, deriving torque trajectories can be complex, requiring extensive processing techniques with calculations using mathematical or human biomechanical models (Siu et al., 2021; Wang & Buchanan, 2002).

Currently, four main approaches exist for torque estimation: (1) inverse dynamics (ID), (2) mathematical modelling, (3) neuromusculoskeletal (NMS) modelling and (4) neural networks (Dinovitzer et al., 2023; Liu et al., 2019; Zhang, Soselia et al., 2023). ID involves tracking motion kinematics and external ground reaction forces (GRFs) using optical motion capture (Mocap) systems and force plates or inertial measurement units (IMUs). The Mocap data combines approximations for body segment inertia or point mass utilising kinematic link segment models. Newton-Euler or Lagrange equations of motion are used to derive joint torques with tools such as OpenSim (Delp et al., 2007; Seth et al., 2018) or Visual 3D (C-Motion Inc.). Despite ID being the gold standard for calculating joint torques, they require expensive and bulky laboratory setups, which are not ideal for integrating wearable devices (Dinovitzer et al., 2023; Siu et al., 2021). Further, mathematical models based on a linear approximation of the joint torque-angle relationship can be applied for selected movements, as proposed in the exoskeleton and exosuit by Liu et al. (2019) and Schmidt et al. (2017), respectively. While these models are easily integrated into controllers, they are generic and do not account for variations in subject characteristics such as age, anthropometry, or movement strategies (Moreira et al., 2021; Perera et al., 2023). Alternatively, NMS modelling (Figure 1) utilises surface electromyography (SEMG) signals, which measure the electric current field caused by the depolarisation of muscle fibres due to an action potential (Farina & Enoka, 2023). It calculates muscle activation via neural excitation with reference to a Hill-type muscle model (activation dynamics). Through contraction dynamics, muscle activation is used to determine muscle force (accounting for force-length/velocity relationships) and then, in conjunction with joint moment-arms, produces torque (Wang & Buchanan, 2002). Modelling tools like OpenSim with toolboxes like CEINMS (Pizzolato et al., 2015) are commonly employed for this

analysis. However, NMS modelling requires tedious calibration and processing techniques for each subject individually, while SEMG signals are inherently noisy and affected by muscle crosstalk, sweat, and displacement during motion. Hence, they are difficult to use in wearable devices for prolonged periods (Farina & Enoka, 2023; Moreira et al., 2021; Zhang, Soselia et al., 2023).

Thus, neural networks have gained prominence in torque estimation to overcome the limitations of the previous methods (Figure 1). These networks do not require a human body model; they map directly from sensor input to output torque and are good at predicting non-linear behaviour while capturing spatial and temporal information (Li et al., 2020). The benefit is that neural networks can estimate each user's dynamically varying torque



(a)



Figure 1. (a) An overview of neuromusculoskeletal (NMS) modelling for estimating joint torques using electromyography (EMG) signals, a Hill-type muscle model, and OpenSim. (b) Outline of a neural network architecture for joint torque estimation consisting of pooled, individual, and clustered network models. Reprinted and modified with permission from (Zhang et al., 2023) and published under the Creative Commons Attribution License (CC BY 4.0)

requirements while providing personalised trajectories based on subject characteristics such as age or anthropometry for more effective and natural assistance (Moreira et al., 2021). Deep learning models also eliminate the need for repetitive subject data collection and calibration or processing once trained (Mundt et al., 2021; Zhang, Soselia et al., 2022). However, the limitation is the black-box nature of these models, which masks the reasoning behind their prediction, and the relationships between input data and torque cannot be easily investigated. Additionally, the effectiveness of the network is highly dependent on the quality, quantity, and variety of training data which is necessary to ensure model generalisability (Siu et al., 2021; Wang & Buchanan, 2002; Zhang, Soselia et al., 2022).

This study aims to review existing neural network approaches for estimating upper and lower limb joint torques. The literature referenced in this study comprises different neural network architectures, input parameters, preprocessing techniques, evaluation metrics, and joint motions. The following sections present these findings and recommendations on the optimal model architectures and input parameters for joint torque estimation. Future perspectives targeted towards wearable assistive technology are also discussed.

METHODS

PubMed and Scopus databases were searched for scientific articles involving neural networks that estimate upper and lower limb joint torques based on their title, abstract, keywords, and relevance (Figure 2). The search keywords were joint torques, joint moments, neural networks, deep learning, torque estimation, and torque prediction. The exclusion



Figure 2. Number of articles identified for review on upper and lower limb joint torque estimation via neural networks

criteria were publications containing robotic joint torques, non-neural network approaches, articles older than the year 2000 and similar articles with repeating model architectures, input parameters and targeted lower or upper limb joints.

MAJOR FINDINGS

Numerous neural networks have been proposed for torque estimation utilising a range of input parameters and are categorised based on their model type, as presented in Table 1. Artificial neural networks (ANNs) consist of fully connected layers, which form the basis for more complex architectures. In these dense or multi-layer perceptron networks, each neuron per layer is connected to every neuron in the next layer, with adjustable weights and multiple hidden layers (Chandrapal et al., 2011). Similarly, time delay neural networks (TDNNs) build on ANNs by introducing delays or convolutions to extract temporal features in sequential data (Peng et al., 2015).

Convolution neural networks (CNNs) process images or grid-structured data using convolution and pooling operators coupled with non-linear activation functions to recognise spatial information effectively (Taye, 2023). Alternatively, long short-term memory (LSTM) neural networks are a recurrent neural network (RNN) type that can identify temporal features using memory cells and a gated structure comprising forget, input, and output gates to update cell and hidden states. LSTMs are particularly effective in capturing long-term dependencies and analysing time series data (Cho et al., 2014; Zhang, Soselia et al., 2022). Additionally, hybrid networks use a sequential combination of deep learning with mathematical or NMS models. Instead of directly estimating torque, the hybrid networks predict alternate parameters like GRFs or muscle activations, which are then used as inputs into mathematical (for example, ID and gravity compensation equations) or computational NMS models to derive torque (Lam & Vujaklija, 2021; Wang & Buchanan, 2002).

Dataset Preparation and Preprocessing

Neural networks for joint torque estimation use a variety of data types and sources for model training and testing. Kinematic and kinetic data are obtained either through optical Mocap systems and force plates or through wearable sensors like IMUs, encoders, or electrogoniometers (Altai et al., 2023; Dinovitzer et al., 2023; Liu et al., 2009). SEMG data provides muscle activity linked to joint torque, typically collected from the muscles involved in a joint motion (Chandrapal et al., 2011). Subject anthropometry like age, weight, or height are also considered when creating personalised torque estimation models (Moreira et al., 2021). From this, diverse and large-scale datasets should be considered for training to account for variability in human movement, subject characteristics, and generalizability of the models to a subject population.

1	I				
Model Type	Reference	Motion	Output Joint Torques	Input Parameters	Sample Size
Artificial neural networks	McCabe et al., 2023	Stair ascent	Hip flexion, extension, adduction, and abduction.	GRFs with shank and thigh IMU data.	17 healthy adults.
	Mundt et al., 2020	Gait	Hip, knee, and ankle in sagittal, coronal, and transverse planes.	Hip, knee, and ankle joint accelerations and angular velocities.	30 healthy adults.
	Molinaro et al., 2020	Gait and ramp ascent/ descent.	Hip flexion and extension.	Hip joint angle and thigh IMU.	5 healthy adults.
	Lim et al., 2019	Gait at varying speeds.	Hip, knee, and ankle in sagittal plane.	COM kinematics.	7 healthy adults.
	Chandrapal et al., 2011	Isometric and isokinetic knee movements.	Knee flexion and extension.	SEMG from 5 knee extensor and flexor muscles.	Single subject over 10 days.
	Liu et al., 2009	Squat and counter- movement jump.	Hip, knee, and ankle in sagittal plane.	GRFs.	10 healthy adults.
Time delay neural networks	Su et al., 2020	Ankle movement using a Biodex rehabilitation machine.	Ankle inversion and eversion.	SEMG from 5 lower body muscles with ankle angular velocity.	5 healthy adults and 3 rehabilitation patients.
	Peng et al., 2015	Elbow movement with arms vertical and parallel to the ground.	Elbow flexion and extension.	SEMG of two upper body muscles with joint angles and angular velocity.	4 healthy adults.
Convolution neural networks	Ozates et al., 2023	Gait	Hip, knee, and ankle in sagittal plane, with hip adduction and abduction.	Trunk, pelvis, hip, knee, and ankle joint angles in sagittal, coronal, and transverse planes.	132 healthy adults and 622 patients with cerebral palsy.
	Zhang, Fragnito et al., 2022	Gait at varying walking speeds.	Ankle plantar flexion.	Brightness mode ultrasound images of skeletal muscles.	8 healthy adults.
	Yu et al., 2022	Isometric wrist movements.	Wrist flexion, extension, pronation, and supination.	SEMG arrays for muscles around the forearm.	8 healthy adults.

 Table 1

 Overview of the existing neural networks for upper and lower limb joint torque estimation

Table 1 <i>(continue)</i>					
Model Type	Reference	Motion	Output Joint Torques	Input Parameters	Sample Size
	Moreira et al., 2021	Gait at varying walking speeds.	Ankle dorsiflexion and plantar flexion.	Ankle joint angles, angular velocity, and angular acceleration with walking speed, height, mass, foot length, sex, and age.	13 healthy adults.
	Hajian et al., 2021	Isotonic, isokinetic, and dynamic elbow movements from a Biodex rehabilitation machine.	Elbow flexion and extension.	SEMG from 4 upper body muscles with position and velocity.	5 healthy adults.
Long short-term memory neural networks	Zhang et al., 2023	Fast, normal, and slow walking with sit-to-stand, stand-to- sit, squat, jump, land, jump-up-to-stair, and jump-down-from stair.	Hip, knee, and ankle in sagittal plane, with hip adduction and abduction.	SEMG from 13 lower body muscles with hip, knee, and ankle joint angles.	8 healthy adults.
	Wang et al., 2023	Gait	Hip, knee, and ankle in sagittal plane.	SEMG from 5 lower body muscles with hip, knee, and ankle joint angles.	4 healthy adults.
	Truong et al., 2023	Squat, sit-to-stand, and object pick-up.	Knee and ankle in sagittal plane.	SEMG from 14 lower body muscles.	6 healthy adults.
	Zhang, Soselia et al., 2022	Fast, normal, and slow walking with sit-to-stand, stand-to- sit, squat, jump, land, jump-up-to-stair, and jump-down-from stair.	Hip, knee, and ankle in sagittal plane, with hip adduction and abduction.	SEMG from 13 lower body muscles with hip, knee, and ankle joint angles.	8 healthy adults.
	Siu et al., 2021	Standing, walking, running, and sprinting.	Ankle dorsifiexion and plantar flexion.	SEMG from 4 lower body muscles.	4 healthy adults.
Hybrid neural networks	Dinovitzer et al., 2023	Gait with starting, stopping, sudden speed changes and asymmetrical motion.	Hip, knee, and ankle in sagittal plane.	Joint kinematics with angles, velocity, accelerations, and segment positions.	11 healthy adults.

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Model Type	Reference	Motion	Output Joint Torques	Input Parameters	Sample Size
	Schulte et al., 2022	Gait, stair ascent/ descent, ramp ascent/ descent, sit-to-stand, and non-weight- bearing activities.	Knee flexion and extension.	SEMG from 4 lower body muscles with knee joint angle and IMU data from 8 locations.	10 healthy adults.
	Lam & Vujaklija, 2021	Gait	Hip, knee, and ankle in sagittal planes.	SEMG from 8 lower body muscles with linear and angular kinematics.	5 healthy adults.
	Wang & Buchanan, 2002	Isometric elbow movement in the sagittal plane.	Elbow flexion and extension.	SEMG from 10 upper body muscles.	1 healthy adult.
InceptionTimePlus, XCM, XCMplus, RNNplus, and Time-series transformer.	Altai et al., 2023	Gait, stair ascent/ descent and ramp ascent/descent.	Hip, knee, and ankle in sagittal planes.	IMU data from trunk, thigh, shank, and foot.	22 healthy adults.
Non-linear autoregressive with exogenous inputs (NARX)	Li et al., 2020	Isometric elbow movement in the sagittal plane.	Elbow flexion and extension.	SEMG from 2 upper body muscles.	8 healthy adults.
Autoencoder with a back propagation neural network	Huang et al., 2020	Push and pull motion.	Shoulder and elbow flexion and extension.	SEMG from 6 upper body muscles with shoulder and elbow joint angles.	3 healthy adults.
Wavelet neural network	Ardestani et al., 2014	Gait	Hip, knee, and ankle in sagittal planes with hip adduction, abduction, rotation, and subtalar eversion.	SEMG from 14 lower body muscles with GRFs.	4 patients with knee prostheses.

Table 1 (continue)

Preprocessing of these input parameters is a vital step before model training. SEMG, for instance, is filtered to remove noise and rectify it, and low pass is filtered to create an envelope. It can be normalised using the maximum voluntary contraction (MVC). Features include the mean absolute value, root mean square (RMS), zero crossings, slope sign change, simple square integral, waveform length, myopulse percentage rate, and the mean or median frequencies (Chandrapal et al., 2011; Truong et al., 2023; Wang et al., 2023). SEMG can also be interpreted as a collection of RMS windows for real-time applications (Su et al., 2020) or a collection of 2D images/arrays at every sampling instant (Yu et al., 2022). Zhang, Fragnito et al. (2022) extended this by performing a continuous wavelet transform and organising SEMG into matrices with scale components of frequency-domain information for the time sequence of the signal. It was then compared against the brightness mode of ultrasound images from skeletal muscles for specific regions of interest.

Moreover, Mocap data, GRFs, IMU readings, and joint kinematics are also subject to appropriate filtering techniques. Lowpass and bandpass filters are used to remove noise and motion artifacts and for smoothing where filter cut-off frequencies can be selected by performing a Fast Fourier Transform and observing the signal bandwidth (Crenna et al., 2021; Winter, 2009). GRFs provide vertical, anteroposterior, and mediolateral force components along with the centre of pressure (COP) or zero-moment point (ZMP) (Dinovitzer et al., 2023). From IMUs, body segment accelerations, angular velocities, positions, and sensor orientations are collected, while joint angles can also be derived (Altai et al., 2023; Dinovitzer et al., 2023; Molinaro et al., 2020; Mundt et al., 2020). Additionally, centre of mass (COM) kinematics are also considered as they are a dynamic determinant for segment kinetics during gait. Features such as COM apex (maximum point in sagittal plane), position, and velocity were utilised (Lim et al., 2019).

All data types of the input parameters are formatted into training and testing datasets based on the model architecture and nature of the study. The dataset can be randomly split for training, validation, and testing or based on the number of subjects and trials. According to the study, splitting ratios can be chosen heuristically, with common ratios being 70–20–10 or 80–10–10 for training, validation, and testing, respectively (Mundt et al., 2020; Xia et al., 2020). Considering CNNs, data is presented as a collection of images/ matrices based on batch size and time structure (Hajian et al., 2021; Yu et al., 2022; Zhang, Fragnito et al., 2022). For other architectures, dataset rows represent time-series entries, and columns represent features (Su et al., 2020; Wang et al., 2023). Overall, the quantity, quality, and variety of training data play a significant role in model performance and the generalizability of the developed networks to a population outside the training sample. Test datasets also need to be representative of a subject population to effectively evaluate a neural network's performance.

Data may also be segmented into time-slices through windowing, which allows for a memory component (LSTMs) and a continuous future torque trajectory estimation by sliding across the windows (Liu et al., 2009; Su et al., 2020; Wang et al., 2023; Zhang, Soselia et al., 2022). Studies with a variety of features also employed data augmentation techniques such as feature scaling or normalisation (Lim et al., 2019), which is on par with dimensionality reduction. High dimensional datasets may incur the curse of dimensionality, leading to increased computational load, overfitting, and difficulties in interpretation and visualisation. Accordingly, techniques such as principal component analysis (PCA) reduce the number of features while retaining relevant information in the dataset, which enhances computational efficiency (Yu et al., 2022).

Evaluation Metrics

In literature, the actual upper and lower limb torques are derived using sensors (load cells) or an ID approach via Mocap data (Figure 3). The Newton-Euler Equation 1 of motion for joint torque is used and commonly computed through biomechanical analysis software such as OpenSim. An unseen portion of data is used for testing with error and correlation evaluation metrics to determine the performance of a model. It includes root mean square error (RMSE), normalised RMSE (NRMSE), and relative RMSE (RRMSE), which quantify the error between the actual and predicted joint torques (Siu et al., 2021). Correlation coefficients (R) such as Spearman's or Pearson's are derived and highlight the similarity in fit or trend between the actual and predicted torques. Pearson's is commonly seen in literature, while Spearman's is also applicable considering the monotonic relationship between predicted and actual torques (Liu et al., 2019; Moreira et al., 2021). Additionally, the coefficient of determination (R^2) measures how well the neural network replicated the actual torques (Truong et al., 2023). Yet, it is challenging to directly compare neural network performance across studies. It is due to varying experimental setups, test datasets, validation methods, model architectures (including hyperparameters) and, in some instances, the lack of standardised evaluation metrics (Naidu et al., 2023). Hence, establishing common benchmarks for joint torque prediction (such as using gold standard Mocap with an RMSE metric) is necessary to allow comparability of results.

$$M(q) \cdot \ddot{q} + C(q, \dot{q}) \cdot \dot{q} + G(q) + F = \tau$$
^[1]

Where $\tau \in R$ is the vector of generalised torques, M(q) is the system mass matrix, $C(q, \dot{q})$ is the vector of Coriolis and centrifugal forces, G(q) is the vector of gravitational forces, and F is the vector of external forces. The generalised vectors of position, velocity and acceleration are represented by q, \dot{q} , and \ddot{q} , respectively (Truong et al., 2023).


Figure 3. Training of a neural network where ground truth values are calculated using an inverse dynamics approach, with data from an optical motion capture system and force plates. Reprinted and modified with permission from (Mundt et al., 2020) and published under the Creative Commons Attribution License (CC BY 4.0)

Neural Network Architectures

Artificial Neural Networks

Molinaro et al. (2020) developed a feedforward neural network to estimate hip torque using hip joint angles, thigh acceleration, and angular velocity as inputs from a single thigh IMU. The dataset contained five extracted features (minimum, maximum, mean, standard deviation and latest values) and was segmented into temporal windows of 350 ms. The trained network consisted of three hidden layers with 30 neurons and an exponential linear unit activation function. The model was trained under two conditions where the ambulation mode (gait or ramp ascent/descent) was known or unknown. At the same time, an early stop based on validation loss was implemented to prevent overfitting or underfitting. On average, the ANN produced an RMSE of 0.116 Nm/kg, with a 59.3% reduction compared to

a mathematical model using a mean torque profile. The study showed that ANNs produced better estimates of joint torque compared to mathematical approximations and highlighted the need for a classifier to distinguish between the different movements. Similarly, Mundt et al. (2020) used IMU accelerations and angular velocities of the lower limbs (five sensors) to predict hip, knee, and ankle torque in all motion planes. Synthetic IMU data was created using optical Mocap. At the same time, their ANN had a higher complexity with two hidden layers consisting of 6000 and 4000 neurons, respectively, followed by a 40% dropout rate and 15,000 training steps. The final network had an R of 0.95 and an NRMSE of less than 13%.

Lim et al. (2019) used COM kinematics to predict lower body joint torques, joint angles, and GRF (Figure 4). A single Sacrum IMU obtained COM data, and the study investigated which kinematic features amongst acceleration, velocity, displacement, and time contributed the most to performance. Hence, models were trained using combinations of these inputs where the ANN had a single hidden layer with 20 neurons and a sigmoid activation function. COM displacement was found to be the most significant contributor, where omission of this input increased error by up to 3%. The hip, knee, and ankle had NRMSE percentages of 10.74, 9.63 and 9.24, respectively, with R greater than 0.90. Chandrapal et al. (2011) used SEMG from five knee flexor/extensor muscles to create a direct mapping to knee joint torque. The ANN consisted of a single hidden layer with five neurons, and the lowest average error was 10.46%. However, this network is only considered a single subject and may not be generalisable to other individuals.



Figure 4. An artificial neural network (ANN) architecture for predicting hip, knee, and ankle joint torques using the centre of mass kinematics obtained from a single Sacrum inertial measurement unit (IMU) sensor. Reprinted with permission from (Lim et al., 2019) and published under the Creative Commons Attribution License (CC BY 4.0)

Moreover, Liu et al. (2009) proposed using GRFs to predict hip, knee, and ankle torques during jumping and squatting. Their ANN consisted of a single hidden layer with 10 neurons and a sigmoid activation function, and the input features were time histories of vertical GRF, vertical displacement, COM velocity, jump power, and support time. The model produced an R greater than 0.95 and relative percentage errors of 4.73, 2.13 and 6.33 for the hip, knee, and

ankle, respectively. This study showed the applicability of ANNs in predicting the nonlinear relationship between GRF and torque. Likewise, McCabe et al. (2023) extended this research by including IMU data with GRF from insoles (wearable sensors) for estimating hip torque during stair ascent. Their model had two hidden layers, each with 10 neurons and a hyperbolic tangent (Tanh) activation function sensitive to high variability inputs. The trained network had an RRMSE of 17.8% with an R² of 0.77.

Time Delay Neural Networks

As Su et al. (2020) presented, TDNNs typically consist of a fully connected ANN structure with a time delay (Figure 5). SEMG inputs are utilised as they generate 30 to 150 ms before muscle movement or motion onset. This study predicted ankle inversion/eversion torque with input features being ankle angular velocity and a 100-point RMS moving window with a 30-sample overlap of the SEMG signal of five lower body muscles. The TDNN consisted of a single hidden layer with 10 neurons and a sigmoid activation function, resulting in an NRMSE of 7.9% and an R of 0.97. This model outperformed an ANN and a support vector regression (SVR) model (NRMSE of 9.8% and 9.07%, respectively), showcasing its applicability to time series prediction. Similarly, Peng et al. (2015) developed a





Figure 5. (a) The procedure for ankle joint torque prediction, and (b) the network structure for a time delay neural network (TDNN). Reprinted with permission from (Su et al., 2020) and published under the Creative Commons Attribution License (CC BY 4.0)

TDNN for estimating elbow torque using joint angles, angular velocity, and a 200 ms moving average window of the SEMG signals from two arm muscles. The model had a single hidden layer with 25 neurons, producing an RMSE of 0.60. Additionally, this study conducted a zero-EMG test, where the SEMG signals were omitted as inputs during training. In this instance, torque prediction was almost zero, showing the importance of SEMG to this neural network architecture with a lower dependence on kinematic parameters.

Convolution Neural Networks

Moreira et al. (2021) compared the performance of a CNN and LSTM when predicting ankle torque during gait, tailored to the subject's walking speed and anthropometry. The authors also tested non-SEMG dependent torque estimation accuracy, as SEMG sensors are affected by noise from muscle crosstalk, skin-electrode displacement, sweat or temperature and, therefore, are not ideal for long-term operation in wearable devices. Two types of models were trained where the first model had inputs of ankle angle, angular velocity, acceleration, walking speed, height, mass, foot and shank length, gender, and age. The second model had SEMG signals added for two shank muscles. The CNN architecture had two convolution layers with 8–16 filters, a 2x2 kernel size and a 25% dropout, while the LSTM had a single layer with 100 neurons and a 50% dropout. Overall, the CNN outperformed the LSTM, where NRMSE, Spearman's R and R² were 0.7% against 0.58%, 0.89 against 0.84 and 0.91 against 0.79 for the CNN and LSTM, respectively. Moreover, the CNN had a faster prediction time of 0.51 ms/sample compared to 3.7 ms/sample for the LSTM.

Thus, the study highlighted the importance of torque prediction, oriented towards the user's anthropometry and speed, for personalised and more effective applications. The results showed no significant differences between CNN and LSTM models with and without SEMG signals as inputs. It justifies that SEMG is unnecessary for torque prediction in these architectures, and joint kinematics are sufficient. It is further supported by Hajian et al. (2021), where elbow torque was predicted using only SEMG and then SEMG with position and velocity from a Biodex machine. Their CNN had two convolution layers with 16 and 64 filters, a 3x3 kernel size, followed by normalisation, rectified linear unit (ReLU) activation, pooling, and dense layers. Results showed improved R² by percentages of 2.35, 37.50 and 16.67 when SEMG and position were used, compared to only SEMG for isotonic, isokinetic, and dynamic movement conditions, respectively. R² then increased by further percentages of 2.29, 12.2 and 20.50 when velocity was added for the same isotonic, isokinetic, and dynamic cases, respectively.

Further, Zhang, Fragnito et al. (2022) evaluated the CNN performance of two models for ankle torque estimation, with the first using brightness mode ultrasound images of muscles and the second using SEMG from the shank muscles as inputs (Figure 6). It was performed using ultrasound transducers with similar regions of interest for both types of inputs during

gait. Unlike SEMG, ultrasound imaging produces a direct muscle visualisation, a high signal-to-noise ratio, and no explicit feature extraction is needed. Instead, a direct mapping to ankle torque is produced. A seven-layer convolution architecture containing conv2D and pooling layers with batch normalisation and ReLU activation was used. A 3x3 kernel size was used, with the first and second convolution layers having eight and 16 filters, followed by 32 filters for the rest. This study showed that CNNs utilising ultrasound imaging had improved performance to SEMG inputs, with a reduction in NRMSE by 37.55% and an increase in R² by 20.13%. Likewise, Yu et al. (2022) also used SEMG signals as images for



(a)



Figure 6. (a) An overview of the data collection, preprocessing, and training steps for a convolution neural network (CNN) using ultrasound images of muscles as inputs. (b) The developed CNN architecture with individual layers, where the layer output size depends on the region of interest (300×300 pixels) from the ultrasound images. Reprinted with permission from (Zhang, Fragnito et al., 2022) and published under the Creative Commons Attribution License (CC BY 4.0)

predicting wrist torques. These signals were converted into 2D arrays based on electrode positioning to form a collection of input images at every sampling instant, while PCA was used for dimensionality reduction. The CNN architecture had six convolution layers (filter sizes were 16, 64, 64, 64, 64, 64 and 16) with batch normalisation, ReLU and pooling layers, a 3×3 kernel size, and a 10% dropout. Relatively good performance was seen in comparison to three regressive models and a short-time Fourier transform CNN, where R was 0.95 and 0.96, and NRMSE was 7.9% and 6.8% for pronation/supination and flexion/ extension wrist torques, respectively.

Alternatively, for time series analysis, 1D CNNs can be used, as presented by Ozates et al. (2023), for hip, knee, and ankle torque prediction. Inputs were lower body and trunk joint angles in sagittal, coronal, and transverse planes, which can be easily measured using wearable sensors and remove the need for costly Mocap equipment. This model was trained for typically developed individuals and patients with Cerebral Palsy. The 1D-CNN had five convolution layers (filter sizes of 128, 128, 512, 1024 and 2048) with five kernel sizes (30, 15, 10, 5, 3) along with flattening and 10 densely connected layers, with neurons ranging from 10000 to 100. Results showed NRMSE between 18.02%–13.58% and 12.55%–8.5%, while R was between 0.85–0.93 and 0.94–0.98 for Cerebral Palsy and typically developed subjects, respectively. Model performance was greater for typically developed subjects with lower NRMSE and higher correlation. Cerebral Palsy patients had larger gait deviations, which produced a more complex mapping from joint angle to torque, resulting in reduced performance.

Long Short-term Memory Neural Networks

Zhang et al. (2023) presented an LSTM neural network (Figure 7) for predicting hip, knee, and ankle torques and compared its performance with an NMS model. Inputs were SEMG and joint angles taken as time slice data with a t-distributed stochastic neighbour embedding algorithm for dimensionality reduction. Alternatively, the NMS model was created using the CEINMS toolbox, which derives joint torque from SEMG. Both models were trained under three conditions: (1) pooled, (2) individual, and (3) clustered. Pooled data from 10 movements was used to train a single NMS and LSTM model, while individuals used each subject's data per model, and clustered training grouped similar movements together. Clustering was performed using K-means, and a single group included movements like slow, normal, and fast walking. The LSTM consisted of 50 neurons, a Tanh activation function, and a dense layer of 64 neurons. Overall, the LSTM showcased better performance than the NMS model, where NRMSE for LSTM and NMS were less than 6.7% and less than 19.3%, respectively. The study also found that clustering did not improve LSTM accuracy but did so for NMS modelling, which shows that clustered motions have similar coordination patterns. On par with clustering, Zhang, Soselia et al. (2022) also proposed



(b)

Figure 7. (a) Overview of a long short-term memory (LSTM) neural network architecture for estimating hip, knee, and ankle joint torque. Two models were developed where (1) a uniform LSTM was trained with data from multiple tasks and (2) 10 separate LSTM models were trained for each task. Reprinted with permission from (Zhang, Soselia et al., 2022) and published under the Creative Commons Attribution License (CC BY 4.0). (b) The gated structure of an LSTM network, with forget, input, and output gates, followed by memory and hidden cell states. Reprinted with permission from (Wang et al., 2023) and published under the Creative Commons Attribution License (CC BY 4.0).

a transfer learning method where a similar LSTM was pre-trained on multiple subjects/ movements (generalised model) and then transferred its knowledge to a target subject or motion. The model can learn new tasks faster if it has learnt similar knowledge, notably with limited data. Hence, a collection of LSTMs was developed for inter- and intra-subject tasks, with some models trained on all 10 tasks or 10 separate LSTMs for each motion. Overall, RMSE was less than 0.14 Nm/kg, with significant improvements in performance once transfer learning was implemented.

Siu et al. (2021) designed an LSTM for mapping both instantaneous and sequences of ankle torque from SEMG and IMU data, with comparison to an ANN, CNN, and neural ordinary differential equation. The input data was split into historical windows of 0.5 s with a 0.49 s overlap. The LSTM had a single hidden layer with 64 neurons, two dense layers with 16 neurons each and a leaky ReLU activation function. RMSE and R for all activities were 0.08 Nm/kg and 0.88 for the LSTM, in comparison to 0.10 Nm/kg and 0.80 for the CNN. This study highlighted the superior performance of the LSTM for time series estimation. Similarly, Wang et al. (2023) developed a three-layer LSTM network (32, 16 and 8 neurons) with time-sliced input data forming a 150 ms window for time domain features and a 128 ms window for frequency domain features. The inputs themselves were five SEMG signals and three joint angles (lower body) for predicting hip, knee, and ankle torques. The model performance was compared against a Gaussian process regression model, which showed NRMSE to be less than 15% and R to be greater than 0.85. Truong et al. (2023) also produced a two-layer stacked LSTM using a collection of input features extracted from SEMG to predict knee and ankle torques. Mean R² for the knee and ankle torques were 94.9% and 85.44%, respectively. At the same time, the study further supported that LSTMs are currently the optimal architecture for time series torque prediction as they remember and employ temporal dependencies.

Hybrid Neural Networks

Considering joint torque estimation, hybrid networks predict alternate biomechanical parameters, which are then used in computational NMS or mathematical models to calculate torque (Figure 8). For instance, Dinovitzer et al. (2023) used joint angles, body segment positions, velocities, and accelerations through an ANN to generate GRF and ZMP output trajectories. These were then combined with joint kinematics into a dynamical mathematical model to derive hip, knee, and ankle torques. Parallelly, an end-to-end ANN was trained for comparison, with direct torque mapping from the joint kinematic inputs. The hybrid ANN had two hidden layers of 20 and 10 neurons and used a Tanh activation function.

Significant differences in performance were observed for the hip and knee, but not the ankle, with better accuracy from the hybrid model than the end-to-end ANN, noting that only a small sample size (n=11) was used. The hybrid model has superior generalizability to varying conditions from the training data, such as when using an assistive device which changes subject mass distribution. As such, this model was further tested on a single subject wearing an exoskeleton (Indego, Parker Hannifin, USA), where R was greater than 0.84 and 0.59 for the hybrid and end-to-end ANN, respectively. Comparably, Lam and Vujaklija (2021) developed a similar model where an ANN predicted GRF and COP and then derived



Figure 8. Overview of a hybrid neural network consisting of data collection, preprocessing and an ANN to estimate ground reaction force (GRF) and centre of pressure (COP) features. It also contains a hybrid neuromusculoskeletal (NMS) model, which uses the predicted kinetics as inputs to computationally derive joint torque. Reprinted with permission from (Lam & Vujaklija, 2021) and published under the Creative Commons Attribution License (CC BY 4.0)

joint torque through NMS modelling. Results showed RMSE less than 0.15 Nm/kg and R greater than 0.70. The reasoning behind these models is to remove the need for bulky and costly Mocap lab equipment like force plates when performing NMS analysis.

Schulte et al. (2022) presented a hybrid CNN-NMS model for multi-day estimation of knee torque. Three models were trained: (1) CNN for direct SEMG to torque mapping, (2) NMS modelling using SEMG (OpenSim via Gait2392 and Hill-type musculoskeletal models) and (3) a hybrid model where a CNN maps SEMG to muscle activation, which a NMS model uses to derive knee torque. The CNN architecture consisted of three 1D convolution layers (32 filters), batch normalisation and ReLU activation, followed by a single LSTM layer (64 neurons), a dense layer and dropout. Overall, the CNN model produced the best performance with NRMSE of 9.2%, followed by the hybrid and NMS models with NRMSE of 12.4% and 14.3%, respectively. Likewise, Wang and Buchanan (2002) also developed a hybrid ANN that maps SEMG to muscle activation, followed by an NMS model to estimate elbow joint torque. Their ANN contained two hidden layers (10 and 15 neurons) and used normalised SEMG of 10 upper body muscles. At the same time, average relative errors for isometric flexion were 4.9% for ramping up/down to relaxation and 34.2% for cycles (larger error as motion differed from training data).

Alternate Network Architectures

Apart from ANNs, CNNs, and LSTMs, alternate architectures were proposed for joint torque estimation that utilised combinations of these networks (Figure 9). Ardestani et

al. (2014) used a wavelet neural network, an ANN where the hidden layer has wavelet activation functions (Tansig and Purlin), to consider inputs in time and frequency domains. These functions use a Morlet mother wavelet, and inputs were eight SEMG and two GRF signals. Hip, knee, and ankle torque estimation were compared between a traditional ANN and the wavelet network, which produced better results with NRMSE less than 10% and R greater than 0.94. Huang et al. (2020) employed autoencoders from SEMG for feature







Figure 9. (a) Overview of the data collection, preprocessing and network architecture for a convolution neural network, InceptionTimePlus, explainable convolution (XCM), XCMplus, RNNplus and Time series transformer (TSTplus). Reprinted with permission from (Altai et al., 2023) and published under the Creative Commons Attribution License (CC BY 4.0). (b) A closed-loop controller using two non-linear autoregressive with exogenous input (NARX) neural networks for joint torque and angle estimation. Reprinted with permission from (Li et al., 2020) and published under the Creative Commons Attribution License (CC BY 4.0).

selection and shoulder and elbow torque trajectory generation. The autoencoders had three hidden layers with a Tanh activation function, while this result was fed into an ANN, producing an RMSE of 1.38 Nm/kg and an R of 0.94.

Altai et al. (2023) further trained multiple models using IMU data to predict hip, knee, and ankle torques (Figure 9). The models were (1) InceptionTimePlus, (2) explainable convolution (XCM), (3) XCMplus, (4) RNNplus and (5) Time series transformer (TSTplus). InceptionTimePlus is made of 1D CNN layers, while XCM uses 2D convolutions for feature extraction and 1D convolutions for extracting temporal information in time series interactions. XCMplus builds on XCM by keeping the 2D and 1D convolutions in sequence, while RNNplus contains a conv1D layer with a stacked LSTM architecture. Finally, TSTplus uses an encoder-decoder transformer for probabilistic forecasting. The results showed that XCM was the optimal model with an average RMSE of 0.046 compared to 0.064 from the other models. Moreover, Li et al. (2020) discussed using a non-linear autoregressive with exogenous inputs (NARX) neural network for real-time elbow torque estimation within a closed-loop controller. Muscle activation was derived from SEMG data and inputted into the network to produce joint torque. NARX consisted of a multi-layer feedforward network with a single hidden layer (5 neurons) and a Tansig activation function, which allows for highly non-linear mapping with noisy data. For the controller, two NARX models were implemented, where the first estimates joint torque, and the second uses this successively to estimate joint angle trajectories. It is run through a Kalman filter to create a closed-loop model, where joint angles are reused as inputs in the first NARX network.

DISCUSSION

This review focuses on neural networks that estimate upper and lower body joint torques for use with wearable technology. Torque trajectory generation is a necessary step in designing the control systems for assistive devices, in rehabilitation or to support impairment (Dinovitzer et al., 2023; Li et al., 2020; Siu et al., 2021; Wang et al., 2023). Healthy adult torque trajectories are a baseline for assessing impaired motion and ensuring sufficient assistive torque is supplied based on a patient's requirements. This produces a natural and effective application of aid from assistive devices (Moreira et al., 2021; Perera et al., 2023).

Compared to conventional methods of torque estimation (ID, mathematical and NMS models), neural networks offer distinct advantages which are valuable for integration with wearable technology. Once trained, they streamline the estimation process by directly mapping sensor input (for example, SEMG, GRF or IMU) to output torque while reducing the need for tedious modelling, calibration, and processing of data from individual subjects (Lim et al., 2019; Schulte et al., 2022; Wang & Buchanan, 2002). Neural networks can also provide personalised torque trajectories for each user based on age, anthropometry,

biological sex, or movement speeds. It allows for user-oriented assistive torque compared to generic levels of assistance from traditional methods like mathematical modelling (Moreira et al., 2021). Future research could expand on this by generating personalised torque trajectories based on movement execution strategies or styles for a more natural application of assistance (Perera et al., 2023). However, it is imperative to acknowledge the limitations of neural networks. The black box nature of these models limits the understanding of the relationships and estimation methods behind their torque prediction, while model performance is highly dependent on the quality and quantity of the training data (Liu et al., 2009; Siu et al., 2021). Models would also need to be re-trained when used for specific movement impairments or if user characteristics greatly differ from the trained subject data (Molinaro et al., 2020).

Existing literature, as reviewed, predicted torques with low errors - RMSE and NRMSE less than 1.4 Nm/kg and 15%, respectively, and strong correlation coefficients greater than 0.84. LSTMs produced strong instantaneous sequential torque estimates (Siu et al., 2021) for multiple movements through pretraining on a range of tasks and transferring this knowledge to a target subject (Zhang, Soselia et al., 2022). Other networks produce tailored torque trajectories by accounting for subject characteristics (Moreira et al., 2021) or through NMS modelling (Dinovitzer et al., 2023). However, most studies had small sample sizes (n < 10, Table 1), which is statistically acceptable (Lim et al., 2019; Molinaro et al., 2020; Peng et al., 2015; Zhang et al., 2023) but pose a challenge in generalising neural networks to a population. Future studies should incorporate larger datasets (n>30, considering the central limit theorem) encompassing wide age groups, subject anthropometries, characteristics, and movement strategies to account for population variance (Moreira et al., 2021; Perera et al., 2023). Moreover, models trained to estimate torque for multiple movements suffered a drop in performance. Therefore, future research should investigate the applicability and real-time capability of training multiple models for individual motions or a single model for multiple motions. Training techniques incorporating clustering (grouping similar movements) or transfer learning (leveraging pre-trained models to expedite training for new movements) can be explored as possible solutions (Zhang, Soselia et al., 2022; Zhang et al., 2023). Neural networks for torque estimation form the mid-level control component in assistive devices (Liu et al., 2019). They need to work hand-in-hand with high-level controllers for motion classification and intention detection, which would trigger the assistive device. Future work should combine these systems in real-time to improve applications for multiple movements and form an overall control architecture (Molinaro et al., 2020).

In the context of wearable devices, kinematic, kinetic or SEMG signals (from appropriate muscles) are required as inputs into the neural networks for estimating the targeted joint torques. Selections on model architecture (ANN, CNN, LSTM, or hybrid) and data preprocessing techniques such as filtering, scaling, or normalisation also need to be made. With this, the dataset needs to be split for training, testing, and validation (for example, a 70%–20%–10% split) with appropriate test methods based on the type of prediction (Mundt et al., 2021). Joint torque estimation commonly follows time series data, where walk-forward or cross-validation methods can be used depending on sequence, instantaneous, or windowed outputs (Siu et al., 2021; Yu et al., 2022). Furthermore, hyperparameter tuning is specific to each network and dataset. While there is potential for reusing training parameters from a holistic perspective, their adaptability depends on the model architecture, inputs, outputs and data characteristics. Accordingly, larger networks with more hidden layers and neurons tend to produce closer torque estimations with lower error but also require longer computation time and resources and result in slower real-time operation (Ozates et al., 2023; Truong et al., 2023).

Consideration for the optimal input parameters for joint torque estimation involves evaluating the biomechanical quantities used. While ID methods using Mocap and GRFs present the gold standard approach to torque estimation, their reliance on expensive and bulky laboratory equipment reduces portability and is not easily adopted by wearable technology (McCabe et al., 2023; Siu et al., 2021). SEMG is advantageous as it precedes muscle movement but faces issues due to noise, muscle crosstalk, sensor placement, electrode-skin displacement, sweat and temperature, making prolonged wear difficult (Su et al., 2020). Additionally, ultrasound muscle imaging captures detailed information for personalised torque estimation but produces noisy data, requires tedious preprocessing and is highly dependent on sensor placement (Zhang, Fragnito et al., 2022). Thus, the ideal inputs are kinematic parameters such as joint angles, angular velocities, and accelerations. These can be efficiently acquired from wearable sensors like IMUs or encoders, ensuring easy integration with wearable technology. Moreover, across the literature, the number of IMUs (wearable sensors) utilised varied, with certain studies using just a single IMU to accurately estimate joint torque (Lim et al., 2019; Molinaro et al., 2020). The performance of all networks was comparable (R>0.85 and error<20%), highlighting that the location of placement is a significant contributor to torque estimation compared to the number of sensors used (Höglund et al., 2021).

In comparison with the reviewed network architectures, CNNs and LSTMs produced the best overall performance for joint torque estimation. Moreira et al. (2021) stated that CNNs had a smaller computation time and better performance than LSTMs. However, Siu et al. (2021) argued that LSTMs outperform CNNs, with both studies considering SEMG inputs. Therefore, both architectures are deemed optimal as they capture the spatial and temporal dependencies when mapping inputs to output torque. They are well suited for time-series forecasting, incorporating time slices (sliding windows) for real-time operation (Wang et al., 2023; Zhang et al., 2023). Hence, an example of an architecture that could

be further investigated is the CNN-LSTM, which combines both models to capture spatial and temporal characteristics. Further research is also needed on optimal window sizes for real-time applications and techniques to minimise the burn-in time of LSTMs, as the first few values are considered for memory (Siu et al., 2021).

CONCLUSION

The study reviewed existing literature on neural networks for upper and lower limb joint torque estimation, covering diverse architectures such as ANNs, TDNNs, CNNs, LSTMs, hybrid, wavelet, NARX, and autoencoders. From this, joint kinematics were identified as optimal inputs for torque estimation in wearable devices. CNNs and LSTMs are the current optimal models for time series estimation due to their proficiency in learning spatiotemporal dependencies. Future work should prioritise larger sample sizes, more inclusive datasets, and the development of models for real-time applications. Torque estimation neural networks should also work on par with motion classifiers for intention detection and prediction of joint torque for multiple movements.

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Review Article

Concept Drift Early Fault Detection in Wind Turbine Based on Distance Metric: A Systematic Literature Review

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ABSTRACT

The Supervisory Control and Data Acquisition (SCADA) system in wind turbines generates substantial data that remains underutilized in terms of wind farm operation and maintenance (O&M). Numerous fault detection methods leveraging SCADA data are being extensively researched to reduce O&M costs. The detection methods are revolutionizing wind farm O&M strategies, shifting from scheduled passive detection to predictive active detection, with the potential to significantly reduce spare parts and labor costs. This paper presents a systematic review of wind turbine fault detection methods based on concept drift and distance metrics, employing the PRISMA methodology. The selected literature is analyzed from three perspectives: fault components, modeling methods, and data sources. Additionally, this review addresses research questions related to current trends, concept drift applications, and distance metric utilization in wind turbine fault detection. Lastly, it provides valuable insights for researchers and industry practitioners in wind energy engineering to explore future research and development in fault detection techniques for enhancing the reliability and efficiency of wind turbine operations.

Keywords: Concept drift, distance metric, fault detection, wind turbines

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INTRODUCTION

In 2022, China's grid-connected wind power cumulative installed capacity surpassed 300 million kilowatts, with over 155,000 operational wind turbines. As these turbines age, a significant proportion will exceed the manufacturer's warranty period. Wind

ISSN: 0128-7680 e-ISSN: 2231-8526 turbines beyond the typical 5-year warranty often cannot receive maintenance from the original manufacturer, necessitating third-party companies' procurement of inspection and maintenance services. The five components with the highest fault rates in wind turbines are the pitch system, inverter, generator, control system, and electrical system. The main shaft, generator, gearbox, pitch, and hydraulic systems are responsible for the most extended downtimes. These downtimes render wind turbines inoperative and incur high maintenance costs, highlighting the urgent need for intelligent maintenance transformation in wind farms.

Wind farms are typically equipped with Supervisory Control and Data Acquisition (SCADA) systems, which monitor 30 to 150 parameters. This data is stored in the SCADA database in real-time. However, a substantial amount of valuable data remains underutilized due to the lack of effective analysis methods and tools for time series data in wind farms. Therefore, analyzing these data effectively for early fault detection in wind turbines is crucial. It is worth noting that while SCADA data encompasses both time-series data and status codes, this study focuses exclusively on the analysis of time-series data. Vibration data (Feng, Ji, Ni, et al., 2023; Ni et al., 2023), although crucial for monitoring wind turbine health, is not included in the scope of this research.

Normal data can be utilized to establish the basic performance of machines, where it serves as a benchmark or threshold, indicating the machine's normal operational parameters. The monitoring process typically involves comparing newly acquired data against this established threshold. The primary objective is to detect any abnormal state of the machine, the phenomenon often referred to as concept drift. Concept drift occurs when the machine's performance deviates significantly from the threshold, exceeding or falling below it. Such deviations are frequently indicative of system faults and warrant detection and investigation. In essence, wind turbine SCADA data is typical time series data in complex industrial systems. This data is characterized by its detailed, multi-dimensional nature, encompassing information from multiple devices and components. Through the application of concept drift and related algorithms, it is possible to monitor the operational state of wind turbine equipment. Consequently, this enables a shift in the assessment of wind turbine working conditions, transitioning from periodic passive inspections to condition-based active maintenance.

This study employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method to identify and analyze 65 papers pertinent to wind turbine fault detection. The analysis begins with examining the basic characteristics of these publications, including literature type, publication date, and the first author's country affiliation. Subsequently, a comprehensive investigation focuses on three key aspects: fault types, modeling methods, and data sources. Furthermore, the study addresses three critical questions: the state-of-the-art fault detection methods for wind turbines, the current status of concept drift application in wind turbine fault detection, and the advantages of distance-based concept drift approaches. The paper concludes with a synthesis of current research findings and an outlook on future research directions.

RESEARCH QUESTIONS

This review aims to concisely overview the current wind turbine fault detection research. Recent literature has examined fault detection from various perspectives, including nondestructive detection (Márquez & Chacón, 2020), tribology (Dhanola & Garg, 2020), machine learning (Fernandes et al., 2022), and condition monitoring (Badihi et al., 2022). However, a notable gap remains in synthesizing recent wind turbine fault detection methodologies advancements. This paper intends to address this gap and focus on three core research questions, summarized in Table 1.

Table 1	
Description of research question	

No.	Description	Why this is important
Research question 1	What is the current trend in advanced fault detection methods for wind turbines?	In recent years, algorithmic research has experienced exponential growth, yielding diverse methodologies, including classification, prediction, regression, and supervised and unsupervised learning approaches. The central focus of this review is to examine how these burgeoning algorithmic advancements can be effectively synthesized and applied to shape the emerging research trends in wind turbine fault detection.
Research question 2	What is the current research status of concept drift methods in wind turbine fault detection?	The fundamental principle of concept drift algorithms lies in their ability to detect changes in data distribution. Despite this potential, there is a notable absence of comprehensive literature reviews examining the application of concept drift algorithms in wind turbine fault detection. This paper will address this gap by concentrating on concept drift-based wind turbine fault detection developments over the past years.
Research question 3	What are the advantages of distance metrics for wind turbine fault detection and concept drift?	Distance metrics are essential in wind turbine fault detection and concept drift algorithms. These metrics find diverse applications across various aspects of the analytical process, including data similarity measurement, fundamental distance functions within models, and evaluation indices. This paper will specifically examine the application of distance metric algorithms in concept drift-based wind turbine fault detection research, analyzing their advantages and contributions to this field.

METHOD

PRISMA Methodology

This systematic literature review follows the PRISMA methodology. PRISMA is a widely recognized approach to improving systematic reviews and meta-analyses' transparency, completeness, and reliability. The method provides a structured framework for conducting and reporting literature reviews.

Search Strategy

This study employs a systematic approach to conduct a comprehensive literature review on fault detection in wind turbines, specifically concept drift algorithms. The literature search is based on three primary keywords: "wind turbine," "fault detection," and "concept drift." The search process is structured in three phases:

Initial Phase: Extensive search is conducted using the Web of Science database, provides broad, multidisciplinary coverage of scientific literature.

Secondary Phase: The search is expanded to include IEEE Xplore, a database specializing in information technology and engineering literature.

Final Phase: The literature search is investigated using ScienceDirect, which offers access to a wide range of scientific and technical publications to ensure comprehensive coverage.

Data Extraction and Analysis Plan

It is planned to extract the data and analysis methods of each literature, including the following aspects: research questions, research objectives, research methods, results, data sources, relevance to wind turbine fault detection, relevance to concept drift, and use of distance metrics. A keyword pairwise query method is employed to ensure a comprehensive literature analysis. This approach facilitates the examination of intersections between fault detection, concept drift, and distance metric applications in the context of wind turbine research.

Literature Screening

The literature search process involves a comprehensive keyword search across multiple databases, as illustrated in Figure 1. The search yielded the following results: 140 relevant publications were retrieved from the Web of Science, while IEEE Xplore and ScienceDirect yielded 1,383 and 2,404 relevant publications, respectively. After the initial search, a two-step refinement process was applied, identifying and removing 556 duplicate entries across the databases. Additionally, 1,894 publications published before 2018 were excluded to focus on recent research.

Upon further scrutiny of the 1,477 publications, it was revealed that 835 publications primarily focused on vibration-related topics and their various aspects, including vibration analysis, data, experiments, datasets, monitoring, signals, signal analysis, noise, and spectrum and frequency band identification. While these topics are generally relevant to wind turbine research, they do not align directly with the specific focus of this study. Consequently, these 835 publications were excluded from further analysis. After this screening process, 642 publications remained for potential inclusion in the review.



Figure 1. Identification of studies via databases and register

The final screening process of the 642 potentially relevant publications involves several steps. First, 525 publications were deemed inaccessible. After their removal, 117 publications remained. Subsequently, 40 publications categorized as specialized science were found irrelevant to this review, along with 12 publications focused on diagnostic topics. These 52 publications were excluded. Ultimately, 65 publications were deemed relevant for this review, comprising five review papers and 60 research papers.

Analysis of Basic Literature Information

After the screening process, a comprehensive analysis of the 65 selected publications related to wind turbine fault detection will be conducted. This analysis will focus on literature type, publication year, and the first author's country, providing a clear overview of the research status in the field.

Analysis of Literature Types

A total of 65 literature items were selected and divided into conference papers and journal papers. According to the statistics, there are 11 conference papers and 54 journal papers.

Analysis of Publication Dates

Figure 2 illustrates the annual distribution of conference and journal papers from 2018 to the present. This visualization reveals several important trends and insights. The red bar chart representing conference papers exhibits an irregular pattern across the years, with no discernible trend. This irregularity can be attributed to conference papers, which are more sensitive to shortterm factors or specific events in the field. The right blue bars are the statistical results



Figure 2. Statistics of different literature types

of journal papers. The statistical number of journal papers shows an increasing trend, indicating that the scientific research resources invested in this field are increasing yearly.

Analysis of the First Author Country

Figure 3 illustrates first-author countries' distribution for conference and journal papers. This visualization reveals several important trends and insights. China (CN) leads in both journal and conference papers. This aligns with China's recent aggressive push for new



Figure 3. Statistical number for country analysis of the first author

energy policies and investments in renewable energy research. It also reflects China's growing wind energy sector and the need for advanced fault detection technologies. The United Kingdom (UK) and Spain (ES) show significant research activities. It can be attributed to their geographical conditions favorable for wind energy, long-standing traditions in wind power utilization and strong governmental support for renewable energy research. The United States (USA), India (IN), and France (FR) each contribute two journal articles. It indicates a broader global interest in wind turbine fault detection, albeit at a lower intensity compared to the leading countries.

RESULTS

Fault Analysis of Wind Turbine Components

Based on the analysis of the selected publications, it is evident that in post-2014, virtually all newly installed large wind turbines globally have adopted variable pitch, variable speed and constant frequency technology. These modern wind turbines can be broadly categorized into doubly fed asynchronous wind turbines and direct drive permanent magnet wind turbines. The primary distinction between these types is the presence or absence of a substantial transmission device—the gearbox. The research on wind turbine component fault detection primarily focuses on several key components: generators, transmission chains (including gearboxes and spindles), yaw systems, variable pitch systems, blades, and electronic components, by systematically classifying and screening the collected literature, resulting in the comprehensive overview presented in Table 2.

An analysis of Table 2 reveals significant research on faults related to generators, gearboxes, and blades within wind turbine systems. Further examination of these three critical components indicates a prevalent focus on utilizing SCADA attributes to detect and analyze abnormal temperature conditions in generators and gearboxes. This trend is evidenced by numerous studies (Jia et al., 2021; Liu et al., 2020; Qu et al., 2021; Velandia-Cardenas et al., 2021; Wang et al., 2022; Wang, Zhao et al., 2021; Xu et al., 2019). The following conclusions can be drawn from the literature in Table 2.

- (a) Faults in wind turbine components such as generators and gearboxes have significant impacts, incurring high costs in terms of time, spare parts, and repairs for replacement and maintenance. Focusing on abnormal temperature faults in gearboxes and generators can effectively contribute to reducing operational expenses. This approach enables early detection of potential issues, allowing for timely interventions and preventive maintenance, thereby minimizing the risk of catastrophic faults and optimizing the overall maintenance strategy.
- (b) Gearboxes and generators, as typical rotating equipment in wind turbines, predominantly exhibit gradual faults. The characteristic of these faults is a slow temperature drift in the rotating components, eventually leading to malfunctions.

Components	Fault type	Reference
Generator	Fault of bearing inner raceway, outer raceway, and rolling element for generator bearing	Tang et al., 2022; (Yang, Liu et al., 2022
	Generator bearing temperature Generator front bearing temperature overrun fault Generator rear bearing temperature overrun fault Generator damages the front and rear bearings et al.	Wang et al., 2022 Jia et al., 2021
		W 71 (1 0001
		Wang, Zhao et al., 2021
Caarbay	Coorthau nume damaged	Latiffanti et al. 2022
Geardox	Gearbox pump damaged Gearbox bearings damaged Gearbox noise	Latimanti et al., 2022
	Abnormal gearbox temperature rise	Liu et al., 2020; Velandia-Cardenas et al., 2021; Qu et al., 2021; Xu et al., 2019
	Gearbox pitting, broken tooth	Du et al., 2022
	Gearbox oil pressure difference anomaly	Bo et al., 2019
	Gearbox lubricant pressure anomaly	Wang et al., 2017; Yang & Zhang, 2021b
	The low temperature of the gearbox oil Gearbox frequency converter no feedback Gearbox oil flow no feedback Gearbox bearing 1 PT100 error	Chacon et al., 2020
	Gearbox high-speed stage bearing fault.	McKinnon et al., 2020
Main bearing	Bearing over temperature warning	Herp et al., 2020; Wang, Zhao et al., 2021; Xiao et al., 2022
Pitch system	Encoder Failure Slip Ring Failure Electric Motor Failure	Wei et al., 2020
	Hydraulic hoses and oil replacement Hub oil leakage Block replacement at blade B Block leakage in blade B Replacement of blade valve Nitrogen accumulator (No 4) replacement of Blade Blade tracking error during stop/operation of Blade Replacement of hyd. Cylinder	Korkos et al., 2022
	High air content in oil Pump wear Hydraulic leakage	Tutiven et al., 2018
	The pitch gear fault of blade 1	Tao et al., 2019
Blade	Blade icing fault	Tong et al., 2022; Yi et al., 2021; Velasquez et al., 2021; Aziz et al., 2022; Aziz et al., 2021

Table 2Components fault of wind turbine

Table 2 (continue)

Components	Fault type	Reference
	Blade breakages or blade rupture	Zhao et al., 2021; Yang & Zhang, 2021a
		Wang, Zhang et al., 2018
	Blade contamination	Velasquez et al., 2021
Yaw system	Yaw misalignment	Pandit & Infield, 2018; Aziz et al., 2021)
Electronic	Short-circuits of generator	Sousa et al., 2018
component		Wang, Ma et al., 2018
Sensor	Sensor faults	Kavaz & Barutcu, 2018

This gradual temperature change presents potential features that can be modeled to predict faults in advance (Wang et al., 2017; Yang & Zhang, 2021b). Consequently, early fault detection studies focusing on abnormal temperature attributes are common in this field.

- (c) Ice faults are the most extensively studied issues affecting wind turbine blades (Aziz et al., 2021, 2022; Tong et al., 2022; Velasquez et al., 2021; Yi et al., 2021). The primary reason for this focus is that ice accumulation directly reduces the active power output of wind turbines under identical wind speed conditions. This phenomenon significantly affects the power generation capacity of wind farms, resulting in decreased overall efficiency and productivity.
- (d) The primary focus is on gradual deterioration in the literature concerning the main bearing faults. Researchers typically utilize the main bearing temperature signal as the main data source for analysis to assess the potential presence of faults. This approach enables the detection of subtle changes in bearing performance over time, facilitating the early identification of developing issues (Herp et al., 2020; Wang, Zhao et al., 2021; Xiao et al., 2022).
- (e) Pitch system faults are relatively complex, encompassing multiple components and signal attributes. These faults are generally associated with hydraulic devices and motors within the pitch control mechanism.
- (f) Yaw system fault studies primarily focus on yaw misalignment issues. The main objectives of these investigations are to optimize wind energy capture and reduce the stress impact on wind turbines.

Analysis of Modeling Types for Fault Detection

A comprehensive review of the literature on early fault detection in wind turbines has been conducted, utilizing the methodologies employed in research as a basis for classification. The literature search focused on four primary categories: machine learning models, deep

learning models, statistical probability models, and other models. Table 3 presents a systematic compilation of the fault detection modeling methods utilized in the reviewed literature, offering a structured overview of the current state of research in this field.

The following conclusions can be drawn based on the analysis presented in Table 3.

(a) From the perspective of literature statistics, machine learning approaches are more prevalent than other types. The predominantly applied models include Support

Table 3

Modeling type	Algorithm	Reference
Machine learning	SVM	Velandia-Cardenas et al., 2021; Qu et al., 2021; Mammadov et al., 2021
	Support vector regression	Díaz et al., 2020; Tao et al., 2019
	One-Class Support Vector Machine (OCSVM), Isolation Forest (IF), Elliptical Envelope (EE).	McKinnon et al., 2020
	XGboost, AdaBoost	Liu et al., 2020; Mammadov et al., 2021; Velandia-Cardenas et al., 2021; Zhang et al., 2018; Trizoglou et al., 2021
	Random forest regressive	Turnbull et al., 2022; Zenisek et al., 2019; Zhang et al., 2018
	Sparse isolation encoding forest	Du et al., 2022
	Sparse Bayesian Learning (SBL) algorithm	Bo et al., 2019
	Optimized relevance vector machine (RVM) regression	Wei et al., 2020
	Adaptive neuro-fuzzy inference system (ANFIS) technique	Korkos et al., 2022
	Gaussian Process (GP) models	Pandit & Infield, 2018; Pandit & Infield, 2019
	Semisupervised extreme learning machine (SS-ELM) algorithm	Tong et al., 2022
	Minority clustering Synthetic minority oversampling technique	Yi et al., 2021
	Higher Order Statistics-Bayes classifiers	Sousa et al., 2018
	Quantile regression neural networks	Xu et al., 2019
	Improved principal component analysis	Zhang et al., 2021; Wang, Ma et al., 2018; Pozo et al., 2018
Deep learning	Dual-stage attention-based recurrent neural network	Yang, Liu et al., 2022
	Cascade SAE & LightGBM	Wang et al., 2022
	Secondary decomposition, reinforcement learning and SRU network	Liu et al., 2021

Analysis of modelling types for fault detection

Table 3	(continue)
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Modeling type	Algorithm	Reference
	Stacked long-short-term memory with multi-layer perceptron (SLSTM-MLP)	Xiao et al., 2022
	RUL Recurrent Neural Network	Herp et al., 2020
	Conditional convolutional autoencoder	Yang & Zhang, 2021a
	LSTM-SAE, CNN-SAE	Fotiadou et al., 2020
	DAE, CNN, residual attention module (RAM)	Jia et al., 2021
	Deep Neural Networks	Wang et al., 2017
	Deep Autoencoder	Wang, Zhang et al., 2018
	Joint variational autoencoder (JVAE)	Yang & Zhang, 2021b
	Multi-Channel CNN	Mohammadi et al., 2020
Probabilistic	Optimized relevance vector machine	Wei et al., 2020
statistical	Sparse heteroscedastic Gaussian Process regression	Rogers et al., 2020
model	Discrete digital model	Tang et al., 2022
	Base pattern Probability Mass Function (PMF)	Peña et al., 2021
Other methods	Failure Modes, Effects, and Criticality Analysis	Catelani et al., 2020
	Ensemble Fuzzy Classifier	Pratama et al., 2018
	Symbolic Regression (SR)	Zenisek et al., 2019

Vector Machines (SVM) (Mammadov et al., 2021; Qu et al., 2021; Velandia-Cardenas et al., 2021), Boost algorithm (Liu et al., 2020; Mammadov et al., 2021; Trizoglou et al., 2021; Velandia-Cardenas et al., 2021; Zhang et al., 2018) and decision tree (Turnbull et al., 2022; Zenisek et al., 2019; Zhang et al., 2018). These studies investigate early fault detection using machine learning from various application aspects. However, there has been a notable decrease in publications utilizing these methods over the past two years.

(b) Research on wind turbine fault detection utilizing deep learning algorithms has gained momentum, which aligns with the broader surge in deep learning research. The proportion of literature focusing on early fault detection in wind turbines based on deep learning approaches is steadily increasing. Various deep learning architectures have been employed, including Deep Neural Networks (DNN), Long Short-Term Memory (LSTM), Gated Recurrent Units (GRU), Recurrent Neural Networks (RNN), Stacked Autoencoders (SAE), Convolutional Neural Networks (CNN), and Variational Autoencoders (VAE), among others (Yang, Liu et al., 2022; Wang et al., 2022; Xiao et al., 2022; Liu et al., 2021; Yang & Zhang, 2021b; Wang et al., 2017; Yang & Zhang, 2021b). Their multilayered and complex designs characterize the structure and mechanism of deep learning algorithms. Furthermore, there is a growing demand for computing resources due to increasing computational requirements.

(c) The method based on statistical probability continues to play a significant role in early fault detection in wind turbines, primarily due to the stochastic nature of wind energy resources (Peña et al., 2021; Rogers et al., 2020; Tang et al., 2022; Wei et al., 2020). These approaches leverage statistical tools such as confidence intervals (Wei et al., 2020) and probability density functions (Peña et al., 2021) to assess the operational status of wind turbines and determine whether they are in an abnormal state.

Analysis of Data Source

Through analysis of selected literature, wind turbine fault data sources can be categorized into four distinct types: open datasets, real SCADA data, simulation data, and experimental platform data. Open datasets are primarily accessible and downloadable from online sources. Real SCADA data consists of actual operational data obtained through project collaborations or direct involvement in wind turbine maintenance activities. Simulation data is generated using software-based simulations on hardware platforms, allowing for the introduction of manual fault simulations and the collection of diverse fault data. Experimental platform data is derived from custom-built hardware simulation platforms, where researchers simulate wind turbine faults and collect fault signals using tailored data acquisition systems to create fault data samples. Table 4 presents a comprehensive analysis of these data source categories.

Through the screening and classification of data sources in Table 4, the following conclusions can be drawn:

Table 4	
Data source	information

Dataset type	Numbers of unit	Description	Location	Reference
Open datasets	en 5 WTs EDP open data, 2-year time span, asets 10-min time resolution,			Latiffianti et al., 2022
	5 WTs	EDP open data, 2-year time span, 10-min time resolution		Jia et al., 2021
	2 WTs	From the China Industrial Big Data Competition	Beijing, China	Tong et al., 2022
	3 WTs	European project OPTIMUS, 40 variables every 10 min with 101,752 samples		Chacon et al., 2020
Real SCADA	30 WTs, 22 healthy WTs	A sampling interval of 5min	mid-eastern China.	Yang, Liu et al., 2022
data	4 WTs	10-min granularity and 101 features	Prince Edward Island (PEI), Canada	Mammadov et al., 2021

Dataset	Numbers of	Description	Location	Deference
type	unit	Description	Location	Kelefence
	2 WTs	The 30s per data instance	Inner Mongolia, China	Liu et al., 2020
	3 WTs	Case 1: data per 1s Case 2: data per 1s Case 3: a section of data every 10min		Wang et al., 2022
	3 WTs	Every 10 min, 40 attributes	Spain	Zhang & Lang, 2020
	3 WTs	2 MW WTs		Liu et al., 2021
		Sampling interval 1 min		Bo et al., 2019
	21 WTs	10-min averaged SCADA data, 2 separate months of data	Europe	McKinnon et al., 2020
	132 WTs	Sampled each 10 min as averages of the past 10 min interval		Herp et al., 2020
	24 WTs	10-min interval-sampling SCADA data	Southern China	Wei et al., 2020
	5 WTs	2.3MW WTs, 10 years data, 10- min sampling interval	North-western Finland	Korkos et al., 2022
	1 WT	2.3 MW Siemens turbine, SCADA data with 10-min sampling interval		Pandit & Infield, 2018; Pandit & Infield, 2019
	117 WTs	The Ningxia dataset was sampled in 30-s intervals, and the dataset of Shandong and Anhui was sampled in 10 min intervals	Ningxia; Shandong; Anhui, China	Yang & Zhang, 2021a
	13 WTs	10 min sampling intervals, 2019 - 2020	North of Perú	Velasquez et al., 2021
	1 WTs	Onshore 2MW	Aragon, Spain	Catelani et al., 2020
	5 WTs	2.3 MW Enercon E-70 WTs, 10 min sampling intervals	El Hierro-Canary Islands- Spain	Díaz et al., 2020
		3 MW direct-drive turbine, 10 min intervals	South coast of Ireland	Fotiadou et al., 2020
	1 WT	a 2 MW direct-driven WT with cut-in, rated, and cut-out wind speeds of 3, 11, and 25 m/s, SCADA data sampling interval 10min	Lu Hejin wind farm in Chenzhou, southern China	Xiao et al., 2022
		10-min interval SCADA data, 4 wind farms	Hebei; Liaoning; Shanxi, China	Yang & Zhang, 2021b
		10-min interval, 3 SCADA datasets	Mainland China	Yang, Wang et al., 2022
	92 WTs	10-min interval SCADA data, 6 wind farms	Hebei; Liaoning; Shanxi; Shanxi; Shandong, China	Wang et al., 2017

Table 4 (continue)

Dataset type	Numbers of unit	Description	Location	Reference
	60 WTs	4wind farms, with 10-min SCADA data.	Shandong, Anhui, Ningxia, Tianjin, China	Wang, Zhang et al., 2018
	3 WTs	1.5MW, sampling rate of 1Hz	East China	Quanlin et al., 2020
Simulation data		1 kHz current signal, sampling time 5.5 s		Tang et al., 2022
	1 WT	FAST models, a barge-offshore version	NREL	Tutiven et al., 2018; Pozo et al., 2018
		Damaged gear, Cracked gear	MATLAB platform	Agasthian et al., 2019
Experiment platform data	wind turbine platform	Sampling frequency rate of 100 kHz and a sampling duration of 20 s.		Du et al., 2022
		Data was sampled at 5 kHz, with a 14-bit resolution		Sousa et al., 2018

Table 4 (continue)

- (a) The analysis of data sources reveals that faults in critical wind turbine components, particularly generators and gearboxes, substantially impact operational efficiency and costs. When replacement or maintenance is required, these components are associated with high time, spare parts, and repair costs.
- (b) The analysis of data sources reveals a relatively small number of studies based on open datasets (Chacon et al., 2020; Jia et al., 2021; Latiffianti et al., 2022; Tong et al., 2022), with the primary open databases including EDP (Jia et al., 2021; Latiffianti et al., 2022) and OPTIMUS1 (Chacon et al., 2020). Notably, there is a significant lack of comparative analysis between different research methods across these studies, which limits the ability to assess the relative effectiveness of various fault detection approaches when applied to common datasets.
- (c) The literature review reveals that studies based on real SCADA data constitute the largest proportion of research, with contributions from diverse geographical regions, including Asia (Yang, Liu et al., 2022), Europe (McKinnon et al., 2020), South America (Velasquez et al., 2021), and North America (Mammadov et al., 2021). However, the significant data variability between studies and the inherent privacy constraints of SCADA datasets limit the generalizability of research findings, confining their applicability primarily to case-specific contexts. Notably, within the geographical distribution of SCADA data sources, China emerges as the predominant contributor, as evidenced by multiple studies (Liu et al., 2020; Quanlin et al., 2020; Wei et al., 2020; Xiao et al., 2022; Yang, Liu et al., 2022; Yang & Zhang, 2021a).

- (d) Simulation data predominantly relies on NREL's FAST software (Pozo et al., 2018; Tutiven et al., 2018), with various fault types generated through parameter adjustments in the model. MATLAB/Simulink software is also employed for simulation purposes (Agasthian et al., 2019). However, the effectiveness of this method is directly related to the accuracy of the model and the similarity of wind farms.
- (e) Experimental platforms utilizing self-designed research setups have collected fault data with remarkably high sampling frequencies, typically exceeding 1000 Hz (Du et al., 2022; Sousa et al., 2018). This high-frequency data acquisition necessitates subsequent sampling or preprocessing of the original data.

Research Question Analysis

This review has significantly enhanced the understanding of early fault detection in wind turbines through a comprehensive analysis of the literature from the perspectives of fault types, modeling methods, and data sources. However, a more focused examination of the literature is necessary to directly address the three research questions posed in this paper. This discussion aims to provide explicit answers to these questions through a targeted analysis of the relevant studies, synthesizing the insights gained from the diverse approaches and methodologies employed in wind turbine fault detection research.

RQ1: What is the Current Trend in Advanced Fault Detection Methods for Wind Turbines?

With the prosperous development of new energy power generation worldwide, scholars researching early fault detection in wind turbines have rapidly increased. Researchers have explored diverse approaches, including strategy design optimization and enhanced sensor deployment, to pre-emptively identify potential faults. The scope of wind turbine early fault detection research is remarkably broad, encompassing areas such as wind speed-active power curve fitting, temperature signal modeling of rotating components, and the development and threshold optimization of early fault detection indicators. While each of these research domains merits a dedicated review, this paper focuses specifically on wind turbine fault research directions. The subsequent analysis synthesizes the research trends in early fault detection of wind turbines, concentrating on modeling algorithms and fault typologies.

Modeling Algorithm. Based on the analysis of previous modeling methods, it is evident that deep learning and machine learning remain the predominant research approaches for early fault detection in wind turbines. Specifically, the rapid advancements in deep learning have enabled the accurate characterization of nonlinear data, proving highly effective in early fault detection. However, the poor explainability of deep learning inevitably

poses challenges in the field of early fault detection for wind turbines. Machine learning approaches maintain a predominant position in this domain, primarily leveraging SVM and related algorithms, regression-based methods, and Boost-related techniques. These approaches offer clear principles and straightforward implementations, contributing to their widespread adoption in wind turbine fault detection research.

Fault type. Wind turbine fault type studies can be broadly categorized into two primary domains: temperature-related and electrical-related faults, which dominate the landscape of wind turbine fault detection research. More attributes are included in fault detection research with the development of SCADA systems. Notably, temperature-related faults typically manifest as gradual processes rather than sudden occurrences, aligning their study with the research paradigm of concept drift algorithms.

Furthermore, analysis of data sources for wind turbine fault detection reveals a trend towards increasing sampling frequencies in SCADA systems, potentially enhancing fault detection accuracy. The literature demonstrates a wide range of sampling frequencies, spanning from 10 minutes to 1 second, indicating that the operation and maintenance of current wind power are developing rapidly, and there is an urgent need for a high-precision early detection model.

RQ2: What is the Current Research Status of Concept Drift Methods in Wind Turbine Fault Detection?

The concept drift methods have laid a solid foundation for early fault detection in wind turbines, although the approaches to research vary significantly among studies. The literature on concept drift has been reviewed, and the findings are summarized in Table 5.

The following conclusions can be drawn from the aforementioned literature review.

- (a) Several studies characterize wind turbines' normal operating state and employ algorithms to identify "new" data or "novel" types. These approaches detect states that differ from the normal operating conditions in wind turbines but do not explicitly address the issue of concept drift (Bilendo et al., 2021; Du et al., 2022).
- (b) Some detection methods integrate machine learning techniques with concept drift algorithms to create comprehensive strategies for identifying potential faults. For instance, some researchers utilize KNN and SVM in their research approach (Hu et al., 2021). Others employ Dynamic AdaBoost as their modeling method (Lin et al., 2019).
- (c) The concept drift method has not yet become a primary research focus in early fault detection for wind turbines. Moreover, the screened literature does not prominently feature typical concept drift algorithms such as EDDM (Early Drift Detection Method) and ADWIN (ADaptive WINdowing).

Problem	Aim/Objective	Main Research methods	Result	References
Detection of the data shift with unlabeled data	Fault diagnosis in an evolving environment	K-nearest neighbor (KNN) classifier SVM classifier	Classification accuracy, parsimony and easiness	Hu et al., 2021
Monitoring ball- bearings without previous ball-bearing RTF data	Online fault detection and prognosis	Hidden Markov models polynomial regression model	Online predictive health assessment	Puerto- Santana et al., 2022
Gearbox fault diagnosis	Fault Severity Diagnosis	Distance metric and the concept detection	KL divergence has been the appropriate metric	Peña et al., 2021
Modeling deteriorated because of the non- stationarities of industrial data	Labeling the potential concept to detect a fault	Statistical detectors and window-based approaches	Different types of drifts – sudden, gradual, recurrent – can be classified	Martinez et al., 2018
Hard fault detection with Big Imbalance Industrial IoT Data	An Ensemble Learning Method of Offline Classifiers	Dynamic AdaBoost	High accuracy rate, over 94%	Lin et al., 2019
Traditional incremental learning model high update frequency	Controlling the incremental update by detecting the concept drift	Shared nearest neighbors (AILSNN)	Higher accuracy than 1DCNN with less training time	Wang, Sun et al., 2021
Wind turbine degradation evaluation	Using information granules to indicate the health state	Concepts extraction using fuzzy c-means clustering	Deterioration was most visible for higher wind speeds	Jastrzebska et al., 2022
Anomaly detection and novel fault discrimination for WTs	Unsupervised method from anomaly detection to novel fault discrimination.	Sparse isolation encoding forest	High diagnostic accuracy	Du et al., 2022
Fault detection by the "drive-train" signal	Effectively detect faults without any prior knowledge	K-means + LDA + ANN	High accuracy by processing the fault-candidates concept	Bilendo et al., 2021
Industrial radial fans predictive maintenance	Identify wear and tear	Linear Regression (LR), Random Forest Regression (RF), Symbolic Regression (SR)	Sufficiently large forecast horizon, predict the drift early	Zenisek et al., 2019
Concept classification for data streams under complex	Built upon an evolving classifier	pENsemble	High accuracy and complexity	Pratama et al., 2018

Table 5Literature related to concept drift

environments

RQ3: What are the Advantages of Distance Metrics for Wind Turbine Fault Detection and Concept Drift?

Distance metrics play a significant role in both early fault detection and concept drift research. In studies of early fault detection based on concept drift algorithms, various types of data, including values, datasets, and indicators, are frequently compared and analyzed. The choice of distance metric is fundamental to the effectiveness of this research. An analysis of literature related to distance metrics has been conducted, and the results are presented in Table 6.

Different distance metric methods exhibit distinct advantages in wind turbine fault detection. KL divergence performs well in comparing data distributions, and it is particularly suitable for diagnosing the severity of faults. Hellinger distance plays a crucial role in concept drift detection. Mahalanobis distance shows advantages in anomaly detection in high-dimensional spaces. The diversity of these distance measurement methods allows researchers to select the most suitable method based on specific problems, thereby enhancing the accuracy and efficiency of fault detection.

After summarizing the literature from Table 6, the following conclusions can be drawn:

- (a) Distance metrics are employed in diverse ways across the reviewed literature. For example, some researchers measure different data distributions through KL divergence (Peña et al., 2021). Other researchers obtain better accuracy by measuring the distance between different patterns (Hu et al., 2021).
- (b) The role of distance metrics in early fault detection based on concept drift strategies varies. For instance, Mahalanobis distance can be applied to the original data in the preprocessing stage (Renstrom et al., 2020). Additionally, distance metrics can serve as performance indicators in the residual processing stage after modeling (Jastrzebska et al., 2022).

Distance metric plays a crucial role in wind turbine fault detection. They provide the foundation for data analysis and directly influence the accuracy and efficiency of fault detection. By choosing appropriate distance metric methods, researchers can identify changes in data patterns more accurately, thereby detecting potential faults promptly.

State-of-the-Art Performance in Wind Turbine Fault Detection

Reviewing and summarizing the current state-of-the-art research performance is essential before exploring emerging trends and future directions in wind turbine fault detection. This approach provides readers with an overview of the latest achievements in the field and establishes a foundation for subsequent discussions. This discussion will be on comparative analysis of recent, highly representative studies encompassing various fault detection methods and their effectiveness across different fault scenarios.
Table 6 Metric distance analysis					
Problem	Aim/Objective	Main Research Methods	Distance Metric Application	Result	References
Detection of the data shift with unlabeled data	Fault diagnosis in an evolving environment	K-nearest neighbor (KNN) classifier SVM classifier	Euclidean distance for pattern similarity measurement	Classification accuracy, parsimony and easiness	Hu et al., 2021
Monitoring ball-bearings without previous ball-bearing RTF data	Online fault detection and prognosis	Hidden Markov models polynomial regression model	Page test and the Chernoff bounds to detect the new data pattern	Online predictive health assessment	Puerto- Santana et al., 2022
Gearbox fault diagnosis	Fault severity diagnosis	Distance metric and the concept detection	KL divergence for comparing data distributions	KL divergence has been the appropriate metric	Peña et al., 2021
Modeling deteriorated because of the non-stationarities of industrial data	Labeling the potential concept to detect a fault	Statistical detectors and window-based approaches	Hellinger distance for concept drift detection	Different types of drifts, sudden, gradual, and recurrent, can be classified	Martinez et al., 2018
Early warning for gearbox failure	Anticipate failure events with a good lead time	Combination of the use of LoMST and a CUSUM approach	Improved CUSUM method is applied to early warning	Average warning lead time is 55 days	Latiffianti et al., 2022
Wind turbine degradation evaluation	Using information granules to indicate the health state	Concepts extraction using fuzzy c-means clustering	Euclidean distance in fuzzy clustering for health state evaluation	Deterioration was most visible for higher wind speeds	Jastrzebska et al., 2022
System-wide anomaly detection for WTs	Monitor the whole component with only one model	Deep autoencoders	Mahalanobis distance processed by EWMA	Code sizes 18 and 24 were the most capable with the detection ability	Renstrom et al., 2020
Fault detection for WTs	Wind-power curve- related NBM	Boosted stacked regressor	Performance metric, MAE is applied	5 types of faults are detected	Bilendo et al., 2022

Concept Drift Early Fault Detection in Wind Turbine

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Table 7 summarizes the key performance indicators of the representative studies.

Through performance analysis of these state-of-the-art methods, it can draw the following observations:

- (a) Various advanced modeling techniques show excellent performance across different fault types. For instance, the dual-stage attention-based recurrent neural network (Yang, Liu et al., 2022) achieves the highest accuracy for generator bearing faults, while the Joint Variational Autoencoder (JVAE) (Yang & Zhang, 2021b) demonstrates high F1-Score and low false positive rate for gearbox lubricant pressure anomalies.
- (b) Different performance criteria are used across studies, making direct comparisons challenging. Common metrics include accuracy, F1-score, detection rate, and specific measures such as ICS and CRR for certain fault types.
- (c) Some methods show promising results for specific fault types. For example, the LoMST and CUSUM approach (Latiffianti et al., 2022) achieves a 100% detection rate for gearbox bearing damage, while the SS-ELM algorithm (Tong et al., 2022) performs well on imbalanced datasets for blade icing fault detection.
- (d) Despite these advancements, challenges remain in practical applications. These may include the need for large amounts labeled data and real-time processing capabilities.

Fault type	Modeling type	Performance criteria	reference
Generator bearing	Discrete digital model	Best ICS, CRR achieved	Tang et al., 2022
Fault	Dual-stage attention-based recurrent neural network	Highest accuracy (Acc), recall (Rec), and F_{β} -score among the compared algorithms	Yang, Liu et al., 2022
Gearbox lubricant pressure anomaly	Joint variational autoencoder (JVAE)	F1-Score: 0.914 PR > 97%, FPR < 1%	Yang & Zhang, 2021b
Gearbox bearings damaged	Combination of the use of LoMST and a CUSUM approach	100% detection rate	Latiffianti et al., 2022
Pitch system fault	Adaptive neuro-fuzzy inference system (ANFIS) technique	F1-score 86% F1-score of Pitch faults detection task	Korkos et al., 2022
Blade icing fault	Semi-supervised extreme learning machine (SS-ELM) algorithm	MCC, G-mean, F1_score. Bset imbalance dataset test performance	Tong et al., 2022
Multitask fault detection	Continual Learning, digital twin	F1_score, RMSE Best continual task performance	Yang, Wang et al., 2022

State-of-the-art performance in wind turbine fault detection methods

Table 7

Emerging Trends and Future Directions

As wind turbine technology continues to advance and data science rapidly evolves, the field of wind turbine fault detection is undergoing a significant transformation. In recent years, several emerging technologies and methods have shown great potential to further improve the accuracy and efficiency of fault detection.

Firstly, the application of digital twin(Feng, Ji, Zhang, et al., 2023) technology in wind turbine fault detection is on the rise. As demonstrated by the continuous learning framework proposed by Wang (Yang, Wang et al., 2022), digital twins can provide a unified platform for multiple modeling tasks, including gearbox fault detection, blade fracture detection, and wind power prediction. This approach enhances model generality and improves its adaptability under various operating conditions.

Secondly, the integration of physics-informed and data-driven methods is becoming an important trend (Feng, Ji, Zhang, et al., 2023). While currently primarily applied to vibration data analysis, the concept of this approach can be extended to SCADA data analysis. For instance, incorporating knowledge from physical models into deep learning networks could potentially improve model interpretability and generalization capabilities.

Furthermore, multi-scale feature fusion and novel deep-learning neural network structures (such as gated recurrent units) have shown promising results in bearing health management (Mohammadi et al., 2020; Ni et al., 2024; Xiao et al., 2022). These techniques have the potential to be applied to wind turbine SCADA data analysis to enhance fault detection accuracy and predictive capabilities.

Lastly, with the development of 5G technology and edge computing, the prospects for real-time big data processing and analysis in wind turbine fault detection are broad. It could lead to faster and more precise fault detection systems, reducing maintenance costs and improving wind turbine reliability.

These emerging trends indicate future directions in wind turbine fault detection. Researchers should closely monitor these areas to drive further advancements in the field.

CONCLUSION

This paper provides a comprehensive overview of the current state of wind turbine fault detection research. Fault detection is an important field of study in the wind turbine industry, as it has the potential to reduce operational and maintenance costs.

This paper uses the PRISMA method to select 65 relevant wind turbine fault detection literature. The paper presents essential information by analyzing the literature, including literature type, publication year, and author nationality. Furthermore, by thoroughly analyzing and synthesizing these 65 literature items, the study investigated fault detection components, modeling methods, and data sources. From this comprehensive review, the following conclusions are drawn:

- (a) In the component analysis of wind turbine early fault detection, it can be concluded that most research focuses on the abnormal temperature attributes of generators and gearboxes. Research on blade faults is also common, while studies on other component faults are less prevalent.
- (b) In current wind turbine fault detection research, modeling methods primarily rely on machine learning and deep learning techniques. Most studies focus on combining algorithms and parameter optimization. However, research on improving the algorithms themselves is relatively scarce.
- (c) Most of the research literature relies on real SCADA data for analysis, with a significant proportion originating from China. In contrast, studies utilizing open datasets and other sources are comparatively scarce.

After thoroughly reviewing and organizing the literature, this paper addresses research questions regarding research trends, concept drift, and distance metrics in wind turbine fault detection.

- (a) Wind turbine fault detection primarily relies on machine learning and deep learning techniques, with temperature and electrical faults being the predominant focus. As SCADA systems have evolved, a broader range of attributes has been incorporated into early fault detection research.
- (b) Concept drift algorithms represent a minor portion of wind turbine early fault detection research. They typically achieve fault detection objectives through integration with other methods. These algorithms show considerable potential and suitability for studying early fault detection in wind turbines.
- (c) The distance metric plays a fundamental role in modeling and is one of the key elements for early fault detection. Improving the distance metric can enhance the effectiveness of early fault detection.

Research Gaps and Future Work

As the wind turbine fault detection field rapidly evolves, it is crucial to identify existing research gaps and outline future directions. This discussion synthesizes the key challenges that emerged from comprehensive literature review and proposes potential avenues for future research.

This study employs the PRISMA method to systematically review existing literature, revealing several key research gaps and future challenges in wind turbine fault detection.

(a) Data Quality and Availability

The paucity of openly accessible, high-quality, large-scale SCADA datasets significantly impedes cross-method comparisons.

Current research predominantly utilizes data from specific wind farms, resulting in limited generalizability across diverse geographical regions and turbine types.

(b) Algorithm Adaptability and Robustness

Existing methodologies demonstrate insufficient adaptability to diverse operational conditions and environmental fluctuations.

The current state-of-the-art exhibits limited efficacy in detecting and identifying rare or novel fault types.

(c) Multi-source Data Fusion
 Comprehensive approaches are lacking for effectively integrating SCADA data, vibration data, meteorological data, and other multi-source information.
 Inadequate research on how to collaboratively analyze data with different sampling frequencies and characteristics.

(d) Real-time Capability and Computational Efficiency Numerous advanced deep learning algorithms exhibit substantial computational complexity, thereby challenging their feasibility and efficacy for real-time monitoring applications in wind turbine fault detection systems.

Lack of research on lightweight fault detection algorithms suitable for edge computing environments.

(e) Interpretability

The inherent opacity of deep learning methodologies, often referred to as the "black box" phenomenon, significantly impedes their credibility and interpretability in practical fault detection applications.

There is a notable deficiency in research on effectively synthesizing domain knowledge from physical models with data-driven approaches.

Further analysis shows that it cannot cover the current status of wind turbines' overall fault detection research. The aspects that need to be improved are as follows.

- (a) There are few horizontal comparisons of relevant literature on temperature parameter modeling, and relevant horizontal comparison research plans to carry out. The research focuses on data preprocessing methods, selecting suitable SCADA attributes for different faults, and threshold determination methods.
- (b) Early fault detection for wind turbines based on SCADA data often focuses on temperature and electrical signals, while pressure and torque signals have received less study and analysis.
- (c) The literature on wind turbine early fault detection based on non-parametric methods needs to be further studied.
- (d) Current literature on the fusion of SCADA data and other data for fault detection should be studied
- (e) Further literature review and summarization of its developmental characteristics are necessary to incrementally update the model for early fault detection in wind turbines.
- (f) The classification method and modeling method need to be further improved.

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Short Communication

An Updated Checklist of Fish Species in the Sultan Idris Shah Forestry Education Centre, Puchong, Selangor, with Notes on the Occurrence of Invasive Species

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ABSTRACT

This study presents an updated fish checklist of the Sultan Idris Shah Forestry Education Centre (SISFEC), Puchong, Selangor, Malaysia. Fish samples were collected using gill nets, cast nets, scoop nets, baited lines, and electrofishers at eight sites within SISFEC, including Rasau River, Bohol River,

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mnamal@upm.edu.my (Mohammad Noor Azmai Amal) *Corresponding author and several lentic water bodies. There are 29 fish species, representing 13 families of freshwater fish, with the family Danionidae (six species) dominating the list. Of the 29 species recorded, six were non-native, including *Oreochromis niloticus, Barbonymus gonionotus, Puntigrus tetrazona, Pterygoplichthys disjunctivus, Oreochromis* sp. (red), and *Poecilia reticulata*. In addition to the non-native species recorded, the Australian red claw crayfish, a non-native invasive invertebrate, was also encountered. Despite the increase in recorded native species compared to past reports, potential threats from invasive species remain a concern. Regular

monitoring and strict regulation are recommended to ensure the conservation and sustainable use of SISFEC's aquatic biodiversity.

Keywords: Aquatic conservation; ecosystem health; environmental management; fish biodiversity; freshwater fish; introduced species

INTRODUCTION

The freshwater biodiversity crisis is a global issue characterized by the rapid decline in the biodiversity of naturally rich freshwater ecosystems like lakes, rivers, streams, and wetlands, which provide essential services to human societies and other living organisms (Albert et al., 2021). Human activities, such as agriculture, industrialization, and urban development, are accelerating the degradation of these ecosystems, posing significant threats to their ecological integrity and benefits (Reid et al., 2018). Emerging threats such as climate change, invasive species, infectious diseases, pollution, and habitat modification exacerbate the vulnerability of freshwater biodiversity and lead to ecosystem-level changes that disrupt ecological balances and diminish the services they provide (Ottoni et al., 2023).

The Sultan Idris Shah Forestry Education Centre (SISFEC), also known as Ayer Hitam Forest Reserve (AHFR), Puchong, Selangor, which falls under research and education, is a permanent forest reserve that was granted to Universiti Putra Malaysia (UPM). It covers an area of 1182 hectares (Faculty of Forestry and Environment, 2024). It is a reduction from the previous area of 4271 hectares with a total of 22 compartments in the year 1906 (Hussein et al., 2020). SISFEC has a river system that may be classified as having an upstream portion, where the gradients are quite steep with fast-flowing water, and it is made up of a network of interconnecting rapids and waterfalls. Two significant rivers, the Rasau River on the southern half and the Bohol River on the northern side, divide the SISFEC (Nuruddin et al., 2007). Many development projects have already been finished in the area surrounding the SISFEC, and these circumstances most likely had an impact on the SISFEC's fish population and stock (Awang et al., 2007; Hussein et al., 2020). Fortunately, the limited exploitation of its resources, which is guaranteed by its status as a protected area, may have increased the replacement rate in the population. Apart from Abit et al. (2012), who reported 11 fish species from the SISFEC over 15 years ago, no research has updated the checklist and diversity of fish species in the protected area (Table 1). This study has two main goals: (1) to present a preliminary checklist of fish species in the SISFEC's riverine system and (2) to report on the occurrence of non-native invasive species in SISFEC.

S/N	Family	Species
1	Cyprinidae	Puntius binotatus (Valenciennes 1842) *
2		Clupeichthys sp.
3		Rasbora einthovenii (Bleeker 1851) *
4		Rasbora heteromorpha (Duncker 1904) *
5		Rasbora sumatrana (Bleeker 1852) *
6	Hemiramphidae	Hemirhamphodon pogonognathus (Bleeker 1853) *
7	Luciocephalidae	Luciocephalus pulcher (Gray 1830) *
8	Anabantoidei	Sphaerichthys osphromenoides Canestrini 1860 *
9		Betta pugnax (Cantor 1849) *
10	Gobiidae	Glossogobius giuris (Hamilton 1822)
11	Clariidae	Clarias macrocephalus Günther 1864

List of fish species recorded from the study area in a previous study (Abit et al., 2012). * = species that are also recorded in this study

MATERIALS AND METHODS

Study Area

Table 1

The SISFEC, Puchong, Selangor, is a secondary disturbed forest logged a few times since the 1930s. The forest is a production forest belonging to the lowland dipterocarp (Awang et al., 2007). The SISFEC is located between 15 m and 233 m above sea level, with the forest slopes between 10% and 20% (Aditya et al., 2020; Top, 2016). The SISFEC is one of Selangor's few remaining lowland forest reserves. It was leased to UPM through a memorandum of understanding signed in 1996, which gives "custody" of the reserve for 80 years for use in education and research (Awang et al., 2007).

In SISFEC, the central terrain appears to be a haven for many wildlife species, particularly small mammals and birds. It is also a location that offers the people of the Klang Valley a green space for outdoor enjoyment in the forest. Land development, however, has seriously harmed the forest's aquatic biodiversity. During the dry season, the water's color usually changes to a yellowish emerald; during the wet season, it turns bluish-turquoise (Hussein et al., 2020).

Sampling Site

The sampling site was mainly divided into two categories: lotic and lentic ecosystems. Fish sampling was conducted for three days, specifically from 29th to 31st May of 2023, at eight sites within the SISFEC, including Rivers Rasau, Bohol River, and lentic water bodies (pond and swampy area) (Figure 1 and Table 2).



Figure 1. Map of Peninsular Malaysia showing the Sultan Idris Shah Forestry Reserve Education Centre (SISFEC), Puchong, Selangor, and the fish sampling sites within SISFEC

Table 2 Coordinates of sampling sites within SISFEC, Puchong, Selangor

Site	Sampling site	Coordinates
Rasau River and its tributary	ST1	3°01'14.5" N, 101°38'48.9" E
	ST2	3°01'02.2" N, 101°38'51.9" E
	ST3	3°00'33.2" N, 101°38'38.6" E
	ST6	2°59'50.6" N, 101°38'39.9" E
Swamp	ST7	3°00'16.8" N, 101°38'39.4" E
Bohol River and its tributary	ST4	3°01'29.1" N, 101°39'56.5" E
	ST5	3°01'48.7" N, 101°39'53.4" E
Lake	ST8	3°02'04.4" N, 101°38'32.1" E

Stations 1, 2, and 3 in the Rasau River are characterized by shallow, slow-moving streams with natural structures and a dense canopy, promoting aquatic plant growth. Station 4 in the Bohol River's upstream section is narrower with a clear water stream and is

influenced by human disturbances such as jungle trekking. Downstream, Station 5 showed murky, contaminated water with debris and foul odors influenced by human disturbances such as fishing and residential areas. Station 6 on the downstream Rasau River had rapid water movement, influenced by human activities from nearby residential areas. Station 7 in the Rasau River swamp had a serene environment with slow-moving, stagnant water, a dense canopy, and natural structures. Station 8, in a lake, had stagnant water with vast open areas and depths but was vulnerable to human disturbance due to submerged tree structures and illegal fishing activities. A pictorial overview of the habitats in the SISFEC is provided in Figure 2. The Faculty of Forestry and Environment, Universiti Putra Malaysia, approved the accessibility and sample collection (Reference number: UPM.FHAS.SSA.100-3/5).



Figure 2. Photographs of the sampling sites within SISFEC

Fish Sampling and Identification

A combination of a fish electro-shocker (Model EFGI 650, BSE Bretschneider, Chemnitz, Germany), scoop nets, gill nets, cast nets, and baited lines equipped with hooks were used for fish sampling, depending on the habitat suitability in each sampling site. During the sampling, efforts were made to promptly identify and release fish back into their habitat whenever feasible and two effort hours were spent in each sampling site. A representative sample of each fish species was preserved in a 10% formalin solution and subsequently transferred to 70% alcohol for long-term preservation. All specimens were cataloged in the fish collection of the Zoology Museum, Department of Biology, Faculty of Science, Universiti Putra Malaysia (UPMZM F).

Taxonomic identification of all captured fish was conducted up to the species level using established taxonomic keys referenced from Kottelat et al. (1993), Rainboth (1996)

and Zakaria-Ismail et al. (2019), while the systematic arrangement of fish followed by Kottelat (2013) and Lann et al. (2014). The taxonomic classification followed Fricke et al. (2024a, b), and species names and authors were confirmed with Fricke et al. (2024b). The International Union for Conservation of Nature (IUCN) status for all fish species was based on The IUCN Red List of Threatened Species (IUCN, 2023).

For the fish invasion risk, we referred to previous studies that designated introduced species in Malaysia as having a high, medium, or low risk of invasion based on the outcome of the Fish Invasiveness Screening Kit (FISK) and the Aquatic Species Invasiveness Screening Kit (AS-ISK) (Saba et al., 2020a, 2021).

RESULTS

A total of 29 fish species representing 13 families of freshwater fish were recorded in SISFEC (Table 3 and Figure 3). The family Danionidae (six species) dominated the list of fish species in SISFEC, followed by Oshphronemidae (five species), Channidae (four species), and Cyprinidae (four species). Only one species was encountered in each of the following families: Loricariidae, Siluridae, Clariidae, Synbranchidae, Nandidae, Poecilidae, Zenarchopteridae, and Pristolepididae. *Hemirhamphodon pogonognathus* was the most occurring species recorded in seven sampling sites. This species exhibited a notable prevalence, suggesting a robust presence within the aquatic ecosystem of SISFEC. It is followed by *Rasbora vulgaris* and *Betta pugnax*, recorded at six sampling sites, while *Barbodes sellifer* was recorded at five sites. Fish species belonging to the family Gobiidae were reported in a previous study but were not encountered in the current study.

Non-native species, including Oreochromis niloticus, Barbonymus gonionotus, Puntigrus tetrazona, Pterygoplichthys disjunctivus, Oreochromis sp. (red), and Poecilia reticulata were recorded. In addition to the recorded non-native fish species, the non-native Australian red claw crayfish, Cherax quadricarinatus, was also encountered.

DISCUSSION

This study provides an updated checklist of fish species in the SISFEC, Puchong, Selangor and additional information on the occurrence of invasive species in the protected area. Among the families recorded in this study, Danionidae was the most abundant, as opposed to Cyprinidae, which is reportedly the most dominant fish family in most of Malaysia's freshwater bodies (Azahar et al., 2021; Cheok & Soo, 2022; Khaironizam et al., 2021; Sharir et al., 2019). Previously, Danionidae was considered a subfamily under the Cyprinidae based on the old classification for fish species (Cheok & Soo, 2022). Therefore, many species previously classified as belonging to the Cyprinidae now belong to the Danionidae.

A chec STI - M NA = 1	klist of fish species was recorded ST8 = Sampling stations, * = int. Vot available, DD = Data deficie	t in Sultan Idris Shah F roduced fish species, # ency, LC = Least conce	orestry Education Centre = sighted species (not cc :rn.	e, Puchong, , aptured), ⁺ =	Selango sampli	or, inclu ing sites	ding the with oc	e IUCN curreno	Red Lis se of im	st Status troduce	d fish sp	species. ecies,
No.	Species	Local name	Catalog number	IUCN Red List Status	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8
	Order Cypriniformes Family Cyprinidae											
1	Barbodes sellifer Kottelat & Lim 2021	Tebal sisik	UPMZM F 101-1107	NA		+		+	+	+	+	
7	Barbonymus gonionotus (Bleeker 1849)*	Lampam Jawa	UPMZM F 1108	LC						+		
\mathfrak{c}	Hampala macrolepidota Kuhl & van Hasselt 1823#	Sebarau		LC					+			
4	Puntigrus tetrazona (Bleeker 1855)*# Family Danionidae	Pelampung Jaring Palembang	UPMZM F 1109	LC								+
ı		-		(
2	Esomus metallicus Ahl 1924	Seluang Janggut	UPMZM F 1110	ГC			+					
9	Rasbora bankanensis (Bleeker 1853)	Seluang Bangka	UPMZM F 1111	LC					+			
٢	Rasbora einthovenii (Bleeker 1851)	Seluang Sambas	UPMZM F 1112 - 1114	LC		+	+			+		
8	Rasbora vulgaris Duncker 1904	Seluang Malaysia	UPMZM F 1115 - 1121	LC	+	+		+	+	+	+	
9	Trigonopoma gracile (Kottelat 1991)	Seluang Pinyuh	UPMZM F 1122 -1124	LC					+			
10	Trigonostigma heteromorpha (Duncker 1904)	Seluang Semenyih	UPMZM F 1125 - 1127	LC		+	+					

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Table 3

+ + + + +++ + + + ++ + + ГС ГС DD ГС С С С ГС ГС UPMZM F 1128 -Tapah Bemban Jawa UPMZM F 1130 **UPMZM F 1132 UPMZM F 1132 UPMZM F 1131 UPMZM F 1132 UPMZM F 1132** UPMZM F 1132 **UPMZM F 1132** 1129 Laga Pulau Pinang Tembok Tebing Sepat Indonesia Gorami Coklat Keli Sambas Bandaraya Karim Jawa Belut Jawa Indonesia Malaya osphromenoides Canestrini disjunctivus (Weber 1991)* **Order Synbranchiformes** Trichopodus trichopterus Trichopsis vittata (Cuvier **Order Anabantiformes** Family Osphronemidae Family Synbranchidae Monopterus javanensis Luciocephalus pulcher Betta pugnax (Cantor Family Loricariidae Silurichthys hasseltii **Order Siluriformes** Clarias leiacanthus Family Clariidae Family Siluridae Pterygoplichthys Lacepède 1800 Sphaerichthys Bleeker 1851 Bleeker 1858 Pallas 1770) (Gray 1830) (849) (831) 1860 12 13 4 15 16 17 <u>∞</u> 19 11

Abdulwakil Olawale Saba, Muhammad Darwish Nazhan Ismail, Muhammad Fadhlil Hakimi Abdull Jamil, Frasier Hoo Anak Steward, Muhammad Rasul Abdullah Halim, Mohd Lokman Ilham-Norhakim, Mohammad Amirul Faiz Zulkiply, Kamarulizwan Kamaruddin, Fazli Shariff and Mohammad Noor Azmai Amal

Table 3 (continue)

Table 3 (continue)

	Family Channidae										
20	<i>Channa limbata</i> (Cuvier 1831)	Haruan Jawa	UPMZM F 1145	NA					+		
21	<i>Channa lucius</i> (Cuvier 1831)	Bujuk Jawa	UPMZM F 1146	LC					+		
22	Channa melasoma (Bleeker 1851)	Haruan Sambas	UPMZM F 1147 - 1148	LC	+						
23	Channa striata (Bloch 1793)	Haruan Tharangambadi	UPMZM F 1149 - 1150	LC				+		+	
	Family Nandidae										
24	Nandus nebulosus (Gray 1835)	Daun Kering Indonesia	UPMZM F 1151 - 1153	LC	+	+		+			
	Family Pristolepididae										
25	Pristolepis fasciata (Bleeker 1851)#	Patung Banjarmasin		LC							+
	Order Cichliformes										
	Family Cichlidae										
26	Oreochromis niloticus (Linnaeus 1758)*	Tilapia Hitam	UPMZM F 1154 - 1155	LC			+	+			
27	Oreochromis sp. (red)*#	Tilapia Merah		NA					+		
	Order Cyprinodontiformes Family Poeciliidae										
28	<i>Poecilia reticulata</i> Peters 1859*	Gapi	UPMZM F 1156	LC						+	
	Order Beloniformes										
	Family Zenarchopteridae										
29	<i>Hemirhamphodon</i> pogonognathus (Bleeker 1853)	Jolong-Jolong Merawan	UPMZM F 1157 - 1163	+ +	+	+	+	+	+	+	

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Figure 3. Freshwater fishes recorded in SISFEC. (1) *Barbodes sellifer*, 43.2 mm SL; (2) *Barbonymus gonionotus*, 103.5 mm SL; (3) *Hampala macrolepidota*, 63.6 mm SL; (4) *Puntigrus tetrazona*, 28.1 mm SL; (5) *Esomus metallicus*, 37.1 mm SL; (6) *Rasbora bankanensis*, 14.2 mm SL; (7) *Rasbora einthovenii*, 23.7 mm SL; (8) *Rasbora vulgaris*, 34.1 mm SL; (9) *Trigonopoma gracile*, 16.4 mm SL; (10) *Trigonostigma heteromorpha*, 12.8 mm SL; (11) *Pterygoplichthys disjunctivus*, 238.31 mm SL; (12) *Silurichthys hasseltii*, 61.2 mm SL; (13) *Clarias leiacanthus*, 81.3 mm SL; (14) *Monopterus javanensis*, 192.7 mm SL; (15) *Betta pugnax*, 54.6 mm SL; (16) *Luciocephalus pulcher*, 88.5 mm SL; (17) *Sphaerichthys osphromenoides* 25.2 mm SL; (18) *Trichopodus trichopterus*, 47.1 mm SL; (19) *Trichopsis vittata*, 40.6 mm SL; (20) *Channa limbata*, 63.3 mm SL; (21) *Channa lucius*, 201.3 mm SL; (22) *Channa melasoma*, 227.1 mm SL; (23) *Channa striata*, 237.1 mm SL; (24) *Nandus nebulosus*, 30.2 mm SL; (25) *Pristolepis fasciata*, 42.1 mm SL; (26) *Oreochromis niloticus*, 183.5 mm SL; (27) *Oreochromis* sp. (red), 49.6 mm SL; (28) *Poecilia reticulata*, 20.1 mm SL; (29) *Hemirhamphodon pogonognathus*, 52.7 mm SL

The number of recorded species from this study is 29, higher than the previous report with 11, where *Clupeichthys* sp. had been recorded in SISFEC (Abit et al., 2012). It may have been a miss-identified species because fish belonging to the genus *Clupeichthys* usually inhabit the habitat of large rivers, and in Peninsular Malaysia, it is only recorded in the Perak River and Pahang River (Zakaria-Ismail et al., 2019). Advancements in science and technology, especially in taxonomy, have led to updates in species names. *Puntius binotatus*, previously reported in SISFEC, is now known as *Barbodes sellifer*, as *Barbodes binotatus* is restricted in Java Island (Kottelat & Lim, 2021). Meanwhile, *Rasbora sumatrana* is only found in Sumatra, and the species that occurs in SISFEC is *Rasbora vulgaris*. The old literature frequently listed the harlequin rasbora as *Rasbora heteromorpha*, but it is now known as *Trigonostigma heteromorpha*.

Approximately 70% of the previously reported species were recorded in the current study. The increase in the number of fish species in the SISFEC, as presented in this study compared to the previous report, shows that the ecosystem has been well preserved. It may also be due to the efficiency of the sampling technique (fish electro shocker) and the number of fish sampling sites in this study. However, the occurrence of non-native species, with three of them (*P. disjunctivus, O. niloticus,* and *Poecilia reticulata*) known to be of high invasion risk, shows that there is a threat of future invasion of these water bodies. It is also indicative of the possibility of anthropogenic impacts on the forest through aquarium releases of alien fish (Saba et al., 2020a).

Several routes of translocation include the release and/or escape from fish farms, the use of non-native fish as fish bait, and the dumping of unwanted aquarium fish for specific reasons such as unmanageable size and, in some cases, religious purposes may have contributed to the spread of non-native fish species into Malaysian aquatic ecosystems (Rahim et al., 2013; Saba et al., 2020b). In addition, the use of some non-native species, like *Poecilia reticulata*, for mosquito control is more harmful than beneficial to the ecosystem (Azevedo-Santos et al., 2016).

Tilapia (*Oreochromis* spp.) is well known to compete with its native counterparts for food, while sailfin catfish are known to disrupt and dominate the river environment (Kang et al., 2023; Hossain et al., 2018). Based on the previous fish invasion risk assessments for Peninsular Malaysia, *P. disjunctivus*, *O. niloticus*, and *Poecilia reticulata* were confirmed to be invasive (high risk), while *Puntigrus tetrazona* and *Barbonymus gonionotus* were reported to be of medium invasion risk (Saba et al., 2020a; 2021).

None of the species encountered was under any form of threat based on the IUCN's list of endangered species. In this study, more intensive sampling may increase the chances of the discovery of additional fish species. In the Ulu Muda Forest Reserve, Kedah, Khaironizam, et al. (2021) reported four introduced species, *Barbonymus gonionotus, Pangasianodon hypophthalmus, O. niloticus* and *Toxabramis houdemeri* with *O. niloticus*

being the most dominant. Ahmad et al. (2020) also reported the dominance of *O. niloticus* from selected freshwater bodies in Selangor after recording a total of 15 species, with five of them being non-native. Notably, in this study, the non-native fish are recorded at sites located nearby or next to human settlements (Stations 4, 5, 6, 7, and 8) and not in the middle of the forest—indicating the importance of human interference in the non-native fish species problems.

The Australian red claw crayfish has been reported to have established populations in West and East Malaysia. It is supported by the reports of studies on Benut River in Johor and Suai River in Sarawak and drainage systems in Felda Tenang, Besut, Terengganu (Naqiuddin et al., 2016). Norshida et al. (2021) suggested that red claw crayfish in certain locations are likely due to releases by aquarium hobbyists rather than aquaculture practices. Like other recorded invasive fish species, it is crucial to develop strong mitigation plans to prevent the further introduction of red claw crayfish to the SISFEC aquatic ecosystem.

In this study, it is unclear how these non-native species got into the SISFEC tributaries. Still, aquarium releases are suspected as the non-native fish are recorded from sites close to human settlement, indicating the high possibility of human influence in introducing non-native fish species.

CONCLUSION

This study gave a comprehensive list of fish species, an update to the existing species list published over 15 years ago. Future research should consider a comprehensive assessment of the fish community structure in this forest spanning the different seasons. It could provide a more detailed insight into the community dynamics of SISFEC. Besides, the presence of invasive species necessitates continuous monitoring of the fish community to avoid the possibility of expansion of their population.

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Experimental Investigation on a Trailing Edge Morphing Airfoil (TEMA) with Zigzag Rib Structure at Low Speed

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ABSTRACT

Camber-morphing wing technology enables adaptive adjustments to wing curvature by optimizing aerodynamic performance and efficiency for varying flight conditions. This study emphasizes the novel Trailing Edge Morphing Airfoil (TEMA) design and analysis, showcasing its noteworthy aerodynamic characteristics. The design uses the parabolic morphing method to obtain TEMA profiles for deflection angles. The different shapes of the TEMA and base airfoil were analyzed using the XFOIL solver with a linear-vorticity stream function formulation. TEMA with a flexible zigzag section was developed using a 3D printing technique with TPU material. The rectangular wing model was developed using TEMA and tested in a low-speed subsonic wind tunnel with Reynolds numbers of 1.19×10^5 , 2.54×10^5 and 3.18×10^5 for different angles of attack. The test cases had a combination of different Reynolds numbers, deflection angles, and angles of attack. The aerodynamic characteristics were calculated by measuring the pressure coefficient around the TEMA using an advanced pressure scanner. The results show that TEMA with a moderate deflection

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Keywords: Additive manufacturing, aerodynamics, morphing wing, structural analysis, thermoplastic polyurethane (TPU)

INTRODUCTION

The morphing wings signify a notable technological advancement in Unmanned Aerial Vehicles (UAVs), delivering enhanced efficiency, improved maneuverability, and increased adaptability in a spectrum of applications. Continuous advances in materials, design, and control systems are poised to enhance feasibility and encourage widespread adoption of morphing wing technology in the foreseeable future. The experimental study on a trailing edge morphing airfoil (TEMA) involves deriving changes in the pressure distribution and their effects on the flow physics around it. Interestingly, a morphing wing can improve aerodynamic characteristics and aircraft performance. Aircraft with large-scale, high-lift morphed wings optimize aerodynamic characteristics during take-off and landing, demonstrating effective changes in the shape of the wings (Auteri et al., 2022).

Various studies have reported that the use of a local, flexible membrane on the WASP airfoil reduces separation bubble size and mitigates vortex-induced vibrations and have proved that WASP airfoils improve performance (Açıkel & Genç, 2018; Koca et al., 2022). Özkan and Genç (2023) have demonstrated a novel ABC-BEM algorithm that optimizes small-scale turbine blades for improving power output and aerodynamic performance. It has also been noted that flexible airfoil demonstrates high-power efficiency by suppressing laminar separation bubbles and shrinking wake regions, and vortex generators enhance aerodynamic performance and delay stall for wind turbine blades (Genç et al., 2020). Several investigators have reported that the active deformation concept of morphing wings has allowed inventors to develop suitable mechanisms, structures, optimization methods and efficient topology parameterization, and they could prove its effectiveness in using in UAVs (Dexl et al., 2022). Various studies have also been conducted using Computational Fluid Dynamics (CFD) analysis to estimate aerodynamic parameters for a morphed wing, comparing favorably with conventional wings. Studies indicate that a trailing edge morphing configuration can effectively enhance performance characteristics with a finite trailing edge deflection angle and various flight missions (Pecora, 2021; Siddalingappa et al., 2022). Genç et al., 2011 and Karasu et al., 2018 have reported the transition models' performance on 3D wing flow, showing the aspect ratio's significant effect. The investigation reported that lower ratios had wingtip vortices, while higher ratios showed dominant flow separation and blowing or suction reduces bubbles, improving lift-to-drag ratios.

The NASA SCRAT airplane, equipped with an adaptive compliant trailing edge wing, has been studied, and its effectiveness has been predicted for large deflections. However, the selection of skin materials plays a crucial role in developing the morphing wing, as its deformation should be accurate and resemble a deformed airfoil with a suitable deflection angle. Most of the skin materials are composite laminates of glass fiber-reinforced plastics and honeycomb core shape-memory polymer composite, and they pose many manufacturing difficulties (Cumming et al., 2016; Yang et al., 2021). It is also observed that the corrugated

skin, cosine beams and flexible corrugated skin have the potential to support the morphing wing under various load and deformed conditions (Bai et al., 2017; Liu et al., 2013, 2017). Also, the aeroelastic analysis (Andersen et al., 2007) and topology optimization techniques (Chang et al., 2020) of composite materials and cellular structures (Tsushima et al., 2019) for sandwich morphing wings and sliding morphing skins (Yu et al., 2018) were adopted to minimize the stiffness in the direction of deformation.

The studies have also reported 3D wing rib topologies printed using polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). The results indicated that the stiffness of the wing rib was increased with enhanced structural efficiency (Carneiro & Gamboa, 2019). Various researchers explored the morphing mechanism and the required stiffness to resist deformation with the necessary flexibility, and the delay in stall with controlled deflection was established (Ferede & Gandhi, 2020; Kan et al., 2020). Along with this, the fishbone active camber (Ajaj et al., 2013), the variable camber concept (Burdette & Martins, 2019), morphing, elastically LofteD transition (Woods et al., 2016), the zigzag wing box (Ajaj et al., 2013), and trapezoidal corrugated cores (Mohammadi et al., 2015) also contributed to the effective morphing technology of the wing.

However, very few studies have been reported on utilizing TEMA for designing rib structures, and there is a need for more investigations to study the effectiveness of utilizing TEMA as a wing rib structure of a UAV. From the literature, it was observed that there were many existing camber morphing technologies, but the present research has innovatively explored the aerodynamics of the TEMA with a zigzag rib. The study aims to examine various TEMA profiles using a parabolic morphing method and analyze flow physics with the XFOIL solver. XFOIL was often preferred over CFD tools for certain aerodynamic analyses due to its efficiency and accuracy in predicting airfoil behavior. The selection of material was a crucial aspect of the study. TPU was found suitable among various materials studied due to its appropriate characteristics, such as flexibility and strength. TEMA with a zigzag flexible section was developed using 3D printing and thermoplastic polyurethane (TPU) material, demonstrating flexibility and safety up to a $+15^{\circ}$ deflection angle. Experimental studies were carried out on rectangular wing models to analyze the aerodynamic parameters, highlighting TEMA's aerodynamic efficiency and suggesting the potential for enhancing aircraft performance.

METHODOLOGY

Trailing-Edge Morphing Airfoil (TEMA)

In this study, a unique cambered morphing method was designed to provide differential camber variation with two-row zigzag rib patterns. NACA 2412 was used as a base airfoil with a zigzag rib structure as it is a common choice in research due to its well-known aerodynamic behavior, geometry, and applications in morphing wings (Amini et al., 2015;

Guerrero, 2009; Shen et al., 2023). The zigzag rib structure makes the rib flexible and reduces the force applied to the change in the camber. The camber was changed with a deflection angle of $+15^{\circ}$ at the trailing edge. 0 to 45% of the chord 90mm from the leading edge is the rigid section, and the remaining 45% to 100% of the chord 110mm is the flexible section, as shown in Figure 1.



Figure 1. Zigzag rib of TEMA with rigid and flexible section

Structural Analysis

Structural analysis was carried out using ANSYS under linear static conditions. The effect of rib thickness, rib material and force on the change of the deflection angle on its structural behavior was analyzed, without considering the skin. Three different thicknesses of the ribs (2.5, 5 and 7.5mm), three different deflection angles ($+5^\circ$, $+10^\circ$ and $+15^\circ$), and two different materials were considered, thermoplastic polyurethane (TPU) and polylactic acid (PLA). The downward force was applied to the trailing edge perpendicular to the chord to achieve the required deflection angle.

The mesh convergence study was carried out for different tetrahedral mesh element sizes (0.0002m to 0.001m). A finer mesh was obtained from a mesh size of 0.0005 m in the higher stress concentration region. Refinement of the mesh was done at the corners of the zigzag structure. It was found that a tetrahedral element less than 0.0005 m in size (1020367 number of nodes) could achieve mesh convergence. Figure 2 shows the results of von Misses stress induced in TEMA at $+10^{\circ}$ deflection angle with a thickness of 5mm made of TPU, using different mesh sizes of TET10 elements. The corresponding data, such as total deformations, directional deformations, equivalent stresses, and safety factors, were calculated based on the force required to achieve the required deflection angle at the trailing edge.

Figure 3 shows that the stiffness of the rib increases with thickness. The PLA-made rib has a higher stiffness value than the TPU-made rib. The TPU gives very close stiffness values for different thicknesses. Higher stiffness requires greater force to achieve the

required deflection angle. Figure 4 shows the effect of the thickness of the ribs on the safety factor for the deflection angle $+5^{\circ}$, $+10^{\circ}$, and $+15^{\circ}$. The TPU rib has a slightly lower safety factor than the PLA rib. The 5mm thick rib has moderate stiffness and safety factor compared to the 2.5mm and 7.5mm ribs.



Figure 2. Von Mises stress induced in TEMA for different mesh sizes



Figure 3. Effect of Thickness on Stiffness for TPU and PLA Materials

The equivalent stress (von-Mises) induced in the rib made of TPU (a, b, and c) and PLA (d, e, and f) for the deflection angle $+5^{\circ}$, $+10^{\circ}$ and $+15^{\circ}$, respectively (Figure 5). The equivalent stress induced depends on the thickness and material used for the rib. More stress is induced in the PLA-made rib than in TPU. The stress concentration is greater at the corners of the zigzag structure (at the mid chord). For both materials, no failure occurred for different deflection angles. Taking into account stiffness, safety factor and induced stress, it was concluded that the TPU-made rib with a thickness of 5mm can achieve a deflection angle of $+15^{\circ}$ without structural failure.



Figure 4. Effect of thickness on safety factor for TPU and PLA materials



Figure 5. Equivalent stress (von-Mises) induced in the rib made of TPU (a,b,c) and PLA (d,e,f)

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Aerodynamic Analysis

The parabolic morphing of the trailing edge was adopted and modeled (Hunsaker et al., 2019; Kaul & Nguyen, 2015). The TEMA was modeled by maintaining a constant thickness value and a camber distribution. The pivot point was on the camber line at 45% of the chord from the leading edge. The neutral line, a straight line, passed through the pivot point and the trailing edge. The angle between the neutral line and the base airfoil's chord line was 2° from the geometrical parameter of the base airfoil. The coordinates of the trailing edge ((x/c)- Δx , Δy) with the change in the deflection angle (Equation 1) were found using the trajectory Equation 2 for the mean camber line, keeping the length of the neutral line unchanged. Where Δx is the change in x coordinates, Δy is the change in the coordinates y with respect to the deflection angle, and c is the length of the chord. The comparison between the base airfoil and the TEMA with a deflection angle of +5° is shown in Figure 6.

$$\tan \delta = \frac{\Delta y}{(x/c) - \Delta x}$$
[1]

$$\frac{y}{c} = -\frac{\tan \delta}{(x/c) - \Delta x} x^2$$
[2]



Figure 6. Comparison between the base airfoil and TEMA at +5° deflection angle

The aerodynamic characteristics were determined using the XFOIL panel method for the base airfoil and TEMA. XFOIL is often preferred over CFD tools for certain aerodynamic

analyses due to its efficiency and accuracy in predicting airfoil behavior, particularly at low Reynolds numbers (Morgado et al., 2016). Linear vorticity stream function and highorder panel method were employed to predict inviscid flow characteristics (Drela, 1989). In this analysis, the program generates an inviscid airfoil flow, incorporating a freestream flow, a vortex sheet, and a source sheet on the airfoil and the wake. The equation for the stream function is given in Equation 3.

$$\Psi(p) = (u_{\infty}y - v_{\infty}x) + \frac{1}{2\pi}\int\gamma(s) \times \ln r(s;p)\,ds + \frac{1}{2\pi}\int\sigma(s) \times\theta(s;p)\,ds \qquad [3]$$

In the equation, *s* represents the coordinate along the surface of the airfoil, i.e., the vortex sheet, *r* denotes the distance between the point in *s* and any point, p(x,y) in the flow, and θ signifies the angle of the vector. The x and y components of the free stream velocity are $u_{\infty} = V_{\infty} \cos \alpha$ and $v_{\infty} = V_{\infty} \sin \alpha$. The airfoil geometry is divided into *N* straight panels, and the wake has N_w nodes, with linear vorticity distribution, as $\gamma_i (1 \le i \le N)$ and source strength of constant value as $\sigma_i (1 \le i \le N + N_w - 1)$.

The vortex strength (γ_{TE}) and source strength (σ_{TE}) are defined at the finite angle trailing edge. γ_{TE} and σ_{TE} must be related to the local airfoil surface vorticity with the following Equations 4 and 5 to make the flow leave smoothly at the trailing edge.

$$\gamma_{TE} = \frac{1}{2} (\gamma_1 - \gamma_N) |\hat{s} \cdot \hat{t}|$$
^[4]

$$\sigma_{TE} = \frac{1}{2} (\gamma_1 - \gamma_N) |\hat{s} \times \hat{t}|$$
^[5]

Where \hat{s} and \hat{t} are the unit vectors bisecting and along the trailing edge panel. The stream function at any point (*p*) in the flow field can be obtained as Equation 6

$$\begin{split} \Psi_{p} &= (u_{\infty}y - v_{\infty}x) + \frac{1}{4\pi} \sum_{j=1}^{N_{w}+N-1} \Psi_{j}^{\sigma}(p) 2 \times \sigma_{j} + \frac{1}{4\pi} \sum_{j=1}^{N-1} \Psi_{j}^{\gamma+}(p) \\ &\times \left(\gamma_{j+1} + \gamma_{j}\right) + \Psi_{j}^{\gamma-}(p) \times \left(\gamma_{j+1} - \gamma_{j}\right) + \frac{1}{4\pi} \left(\Psi_{N}^{\sigma}(p) | \hat{s} \times \hat{t} | \right. \end{split}$$

$$\left. \begin{array}{c} \left[6\right] \\ &+ \Psi_{N}^{\gamma+}(p) | \hat{s} \cdot \hat{t} | \right) \times (\gamma_{1} - \gamma_{N}) \end{split}$$

Establishing the unit stream functions using local panel coordinates and equating the stream function to a constant value on the airfoil at each node yields the following Equation 7:
$$\sum_{j=1}^{N} a_{ij} \times \gamma_{j-\Psi_0} = (-u_{\infty}y_i + v_{\infty}x_i) - \sum_{j=1}^{N_w+N-1} b_{ij} \times \sigma_j \quad ; \quad 1 \le i \le N$$
[7]

The coefficient matrices a_{ij} and b_{ij} represent the system's coefficients, while x_i and y_i denote the nodes along the airfoil panels. Equation 8 results from combining the Kutta condition and the linear system, which gives the following Equation 8:

$$\gamma_1 + \gamma_N = 0 \tag{8}$$

Hence, the surface velocity is the surface vorticity, given as Equation 9:

$$\gamma_i = V_i \tag{9}$$

From Bernoulli's equation, the pressure coefficient at any point on the airfoil can be given as Equation 10:

$$c_p = 1 - \left(\frac{V_i}{V_{\infty}}\right)^2 \tag{10}$$

The normal force coefficient (cn) and the axial force coefficients (ca) from the pressure distribution are calculated using the following Equations 11 and 12:

$$c_n = \frac{1}{c} \int_0^c (c_{p,l} - c_{p,u}) dx$$
[11]

$$c_a = \frac{1}{c} \int_0^c \left(c_{p,u} \frac{dy_u}{dx} - c_{p,l} \frac{dy_l}{dx} \right) dx$$
^[12]

Where and are pressure coefficients on the upper and lower surfaces of the airfoil, respectively. The coefficient of lift and drag can be obtained from the following Equations 13 and 14:

$$c_l = c_n \cos \alpha - c_a \sin \alpha \tag{13}$$

$$c_d = c_n \sin \alpha - c_a \cos \alpha \tag{14}$$

The aerodynamic characteristics were calculated at different angles of attack up to and beyond the critical angle of attack for up to a moderate thickness of the boundary layer. The coordinates of the base airfoil with a chord length of 0.2 m and the TEMA coordinates at the deflection angles $+5^{\circ}$, $+10^{\circ}$, and $+15^{\circ}$ were calculated and imported to XFOIL. The analysis was carried out on three different Reynolds numbers of 1.91×10^{5} , 2.54×10^{5} , and 3.18×10^{5} at different angles of attack. Aerodynamic characteristics such as the lift coefficient, the drag coefficient, the moment coefficient, and cl/cd were obtained. A suitable number of nodes required for the XFOIL analysis was found by conducting a convergence study; cl/cd was determined for different numbers of nodes at various angles of attack at a Reynolds number of 2.54×10^{5} and $+5^{\circ}$ deflection angle. It was found that 150-panel nodes were sufficient for accurate results with minimum errors (Figure 7).



Figure 7. Convergence study from XFOIL

Experimental Setup

A rectangular wing model with a span of 0.6 m and a chord of 0.2 m was developed to determine the aerodynamic characteristics in the low-speed subsonic wind tunnel. The specifications are given in Table 1. The pressure data were measured using AMS 5612, an advanced multichannel pressure scanner, and an electronic differential pressure measurement with a \pm 200mm H₂O pressure range; each pressure port had an array of silicon piezoresistive pressure sensors. The process parameter is displayed with -digit accuracy. Provision exists for the linearization of input data by means of lookup, which can be preprogrammed in EPROM. The smart spike filter filters out spiky pickups from the input signals. Signal noise can be damped by specifying a damping factor that averages the input data for a specified number of samples. Nonlinearity and Pressure hysteresis were found to be \pm 0.3% and \pm 0.2% full span output, respectively, from the calibration certificate. NI USB-6001 is a low-cost multifunction I/O device manufactured by National Instruments (NI) and was used as a data acquisition system. It had a Sampling Rate of 20 kS/s and was compatible with NI LabVIEW. The experimental setup includes a low-speed subsonic wind tunnel and data acquisition system, as shown in Figure 8. The conditions under which the experiment was carried out are given in Table 2.



Figure 8. Low-speed subsonic wind tunnel with data acquisition system

Parameter	Value		
Wind Tunnel type	Low speed, open circuit, and suction type.		
Test section size	Square cross-section: 0.6m height, 0.6m width		
Test section Length	2m		
Contraction ratio	9: 1		
Velocity range	0 to 50 m/sec		
Max axial fan speed	1500 rpm		
Drive	AC motor 20Hp		
Power requirement	AC, 3Phase, 440 volts, 64 amps		
Turbulence level	0.3% to 0.7%		

Table 1Specifications of wind tunnel

The zigzag rib structure was 3D printed using TPU, a flexible and elastic 3D printing material. Unlike PLA and other materials, TPU had lower stiffness and provided good mechanical flexibility after 3D printing. The rib for the morphing wing consisted of rigid and flexible sections, as shown in Figure 1. The flexible section had a zigzag pattern with four subsections to change the different camber-based deflection angles. The wing model consisted of 13 zigzag rib structures, each 0.05m in the span direction, as shown in Figure 9. Each zigzag rib structure had a thickness of 0.005 m and consisted of a hole, the center

of which was located at 27.5% of the chord to place the main circular spar with a diameter of 0.022 m. Another hole was located at 43.5% of the chord, which was used to place the secondary spar. Two stringers (rectangular) were placed at 35% of the chord on the upper and lower surfaces, and one stringer (triangular) at 82% of the chord. The triangular stringer was connected to the secondary spar using inflexible threads, which were used to control the airfoil camber by rotating the secondary spar. The main and secondary circular spars were hollow stainless-steel tubes. A simple gear and chain mechanism was utilized to operate the secondary spar so that it rotated and could control the camber of the airfoil using inflexible threads connected to the triangular stringer, as shown in Figure 10. The rotational motion of the secondary spar was converted into the translational motion of the triangular spar. This motion acted on the flexible ribs to change the camber.

Parameter	Value
Altitude	920m above sea level
Freestream density (ρ_{∞})	1.133 kg/m ³
Dynamic viscosity (μ_{∞})	1.7e ⁻⁵ Ns/m ²
Freestream velocity (V_{∞})	15, 20 and 25m/sec
Reynolds number (Re)	1.91x10 ⁵ , 2.54x10 ⁵ , and 3.18x10 ⁵
The angle of attack (α)	0, 3, 6, 9, 12 and 15 degrees
Deflection angle (δ)	0, 10 and 15 degrees

Table 2Experimental conditions

The secondary spar's rotation angle was based on the required deflection angle and was ensured with the data obtained from the mathematical modeling of TEMA. The 0.5mm thick aluminum sheet covered the wing's rigid section, providing the airfoil's actual shape at the leading edge. The morphing section of the wing was covered with a laminated sheet, which was able to change its shape based on the camber change, as shown in Figure 9. The laminated sheet was flexible, ensuring that the shape of the airfoil for any deflection angle matched the shapes obtained for aerodynamic analysis. The pressure ports of 0.0008m diameter measured the local static pressure (P_i) were in one plane at the mid-span of the wing model at 15 different locations (i = 1-15). Freestream static pressure (P_{∞}) was found using a drilled port on the wall of the wind tunnel. The test was repeated ten times to collect pressure data at each deflection angle, Reynolds number, and angle of attack. The standard deviation (S) was calculated using Equation 15.

$$S = \sqrt{\frac{\sum (p - \overline{p})^2}{n - 1}}$$
[15]

Where p – static pressure, – mean value and n – number of samples. The standard deviation was less than 3% of the full scale. The average value of these pressures was taken to calculate the aerodynamic characteristics further. The pressure coefficient was calculated using the following Equations 16 and 17.

$$c_p = \frac{P_i - P_\infty}{q_\infty} \tag{16}$$

$$q_{\infty} = \frac{1}{2} \rho_{\infty} V_{\infty}^2 \tag{17}$$

Where q_{∞} is the dynamic pressure, is the freestream density.

Using the pressure data, the aerodynamic coefficients were calculated using Equations 11 to 14 and compared with the XFOIL results.



Figure 9. Structural Members of the Wing Model and Sliding Skin Mechanism



Figure 10. Trailing edge deflection mechanism

RESULTS AND DISCUSSION

Pressure Distribution

The comparison of the pressure coefficient obtained from XFOIL and experiments at a Reynolds number of 1.91×10^5 for different deflection angles with respect to various angles of attack was shown in Figure 11. The pressure distribution was observed on the base airfoil and TEMA with deflection angles of $+5^\circ$, $+10^\circ$, and $+15^\circ$ at different angles of attack.

There was good agreement between the results from XFOIL and the experiments. The top surface of all the configurations studied generally experienced an increased negative pressure coefficient. In contrast, the bottom surface experienced a positive pressure coefficient, resulting in improved aerodynamic efficiency with increased angles of attack. This region's pressure coefficient was most affected by variations in the deflection angle at the trailing edge. The negative peak pressure coefficient values were higher for TEMA with a deflection angle of $+15^{\circ}$ compared to other configurations. Additionally, the area under the pressure coefficient curves was enhanced near the trailing edge with increased angles of attack. The trend remained consistent for all the configurations studied.



Figure 11. Comparison of pressure coefficient at Reynold number of 1.91×10^5

To observe the effect of increased Reynolds number on the pressure distribution, the comparison of the pressure coefficient obtained from XFOIL and experiments for different deflection angles with respect to various angles of attack was shown in Figures 12 and 13 for Reynolds numbers of 2.54×10^5 and 3.18×10^5 , respectively. The trend of the graphs remained like that observed earlier for a Reynolds number of 1.91×10^5 . It was also noted that the pressure coefficient on the surface of all the configurations studied improved with the increased Reynolds number.



Figure 12. Comparison of pressure coefficient at Reynold number of 2.54×10^5



Figure 13. Comparison of pressure coefficient at Reynold number of 3.18×10^5

Aerodynamic Coefficients

The comparison of aerodynamic characteristics at a Reynolds number of 1.91×10^5 for different deflection angles with respect to different angles of attack is shown in Figure 14. An increase in the deflection angle caused an increase in the camber of the airfoil, resulting in an increase in the maximum lift coefficient and a decrease in the critical angle of attack. From Figure 14(a), the base airfoil had a critical angle of attack of $+12^\circ$ and a maximum lift coefficient of 1.2, while TEMA with a deflection angle of $+5^\circ$ had 1.3; this was due to the



Figure 14. Comparison of aerodynamic performance at Reynold number of 1.91×10^5

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increase in the slope of the lift curve and the camber. However, the trend in the variation of the coefficient of lift remained similar for a further increase in the deflection angle. It was observed that for TEMA with $+10^{\circ}$ and $+15^{\circ}$ deflection angles, the stall occurred at $+11^{\circ}$ and $+10^{\circ}$ angles of attack, respectively. Therefore, using TEMA, the lift coefficient was increased to higher numbers, i.e., 17% and 33% with $+10^{\circ}$ and $+15^{\circ}$ deflection angles, respectively.

It could be observed from Figure 14(b) that the base airfoil and The TEMA with a $+5^{\circ}$ deflection angle had almost a similar drag coefficient below the $+6^{\circ}$ angle of attack. The trend remained the same even at higher angles of attack. Increasing the angle of attack caused an increased coefficient of drag for the TEMA with a $+10^{\circ}$ deflection angle compared to the base airfoil and The TEMA with a $+5^{\circ}$ deflection angle. An extreme increase in drag could be observed near the critical angle of attack of all airfoil configurations due to flow separation.

TEMA, with a deflection angle of $+5^{\circ}$ and $+10^{\circ}$, was aerodynamically more efficient than the base airfoil, and TEMA had a deflection angle of $+15^{\circ}$ at attack angles below $+5^{\circ}$. TEMA with $+5^{\circ}$ and $+10^{\circ}$ deflection angles had a higher cl/cd at the $+5^{\circ}$ and $+3^{\circ}$ angle of attack, respectively. The corresponding increase in cl/cd was 13% and 12% for TEMA with a deflection angle of $+5^{\circ}$ and $+10^{\circ}$, respectively, compared to the base airfoil. TEMA with a $+5^{\circ}$ deflection angle experienced a small cl/cd due to increased drag with increasing camber and flow separation (Figure 14(c)).

All airfoil configurations examined had similar trends in the variation of the pitching moment with respect to the angles of attack, as shown in Figure 14(d). TEMA with a $+15^{\circ}$ deflection angle exhibited a different trend, reducing the pitching moment beyond a $+12^{\circ}$ angle of attack. This behavior was attributed to high-camber morphing, leading to a nose-down pitching moment and increased drag.

Figure 15 shows a comparison of the aerodynamic characteristics at Reynold number 2.54×10^5 for different deflection angles with respect to different angles of attack. It could be seen from Figure 15(a) that for an increase in the Reynolds number, there was a slight increase in the lift coefficient, but the trend remained like that of the Reynolds number 1.91×10^5 case. The improvement of the lift coefficient could be observed at low angles, that is, below the +6 ° angle of attack for TEMA with the +10° deflection angle. The slope of the lift curve was small for TEMA with +10° and +15° deflection angles compared to the flow with a Reynolds number of 1.19×10^5 .

The trend of the drag coefficient with respect to the angle of attack for the base airfoil and the TEMA with $+10^{\circ}$ and $+15^{\circ}$ deflection angles is similar (Figure 15(b)). The TEMA with $+15^{\circ}$ deflection angle experienced more drag than other airfoil configurations examined again in this study due to the increased camber and the increased Reynolds number.



Figure 15. Comparison of aerodynamic performance at Reynold number of 2.54×10^5

Aerodynamic efficiency improved for all airfoil configurations studied with increased Reynolds number, as shown in Figure 15(c). It was observed that TEMA with a $+5^{\circ}$ deflection angle had the highest cl/cd value of 80 at the $+5^{\circ}$ angle of attack, TEMA with a $+10^{\circ}$ deflection angle had the highest cl/cd value of 75 at the $+2^{\circ}$ angle of attack. The base airfoil had the highest cl/cd value of 72 at the $+6^{\circ}$ angle of attack. It was due to a decrease in drag and a delay in the flow separation to the trailing edge of the TEMA. Therefore, TEMA with a deflection angle of $+5^{\circ}$ and $+10^{\circ}$ could be operated at a low angle of attack



Figure 16. Comparison of aerodynamic performance at Reynold number of 3.18×10^5

with good aerodynamic efficiency compared to the base airfoil. Figure 15(d) shows a similar trend for the base airfoil, TEMA, with $+5^{\circ}$ and $+10^{\circ}$ deflection angles; the increased Reynolds number had little effect on the pitching moment of these airfoils.

The comparison of aerodynamic characteristics at a Reynolds number of 3.18×10^5 for different deflection angles with respect to different angles of attack. As observed in Figure 16(a), the increase in Reynolds' number caused a slight improvement in the maximum lift coefficient for all the airfoils discussed. However, the trend remained similar compared

to previous cases. A decrease in the coefficient of drag could be observed for all airfoil configurations compared to the previous cases. The drag coefficient values were very close in the case of the base airfoil and the TEMA with a deflection angle of $+5^{\circ}$. The increase in camber with a $+5^{\circ}$ deflection angle caused a slight increase in drag at moderate and higher angles of attack compared to the base airfoil, as shown in Figure 16(b).

Enhanced cl/cd was observed in Figure 16(c). At an angle of attack below $+5^{\circ}$, there was an improvement in aerodynamic efficiency by 15% and 29% for TEMA with $+5^{\circ}$ deflection angle compared to the flow at Reynolds number of 2.54×10^{5} and 1.19×10^{5} , respectively. Similarly, for TEMA with $+10^{\circ}$ deflection angle, an improved aerodynamic efficiency could be observed below $+5^{\circ}$ angle of attack compared to the base airfoil. Figure 16(d) shows a reduction in pitching moments beyond a $+12^{\circ}$ angle of attack, akin to the pitching moment coefficients observed for TEMA with a deflection angle of $+5^{\circ}$ and $+10^{\circ}$.

CONCLUSION

The newly designed TEMA's aerodynamics were thoroughly examined through XFOIL simulations and experiments conducted in a low-speed subsonic wind tunnel at Reynolds numbers of 1.19×10^5 , 2.54×10^5 , and 3.18×10^5 . TEMA was manufactured using the 3D printing technique with TPU material. It allowed the TEMA to alter its camber under applied loads more effectively. Structural analysis indicated that a 5mm TPU rib achieved the required deflection angle without failure. Parabolic morphing of the trailing edge method was used and modeled to perform aerodynamic characterization of the base airfoil (NACA2412) and TEMA using XFOIL. A rectangular wing model with 13 TEMA ribs was developed and tested in the experimental phase. The model maintained a uniform airfoil shape with an aluminum sheet on the rigid section for an ideal leading edge. In contrast, the flexible section used a laminated sheet to preserve the shape of TEMA at varying deflection angles. Analysis of the results indicated improved aerodynamic coefficients with increased deflection angles, leading to enhanced camber in the TEMA. TEMA exhibited a higher lift-to-drag ratio of around 30% than the base airfoil at various Reynolds numbers and angles of attack. Consequently, it was concluded that TEMA with +5° and +10° deflection angles demonstrated superior aerodynamic efficiency in these Reynolds numbers compared to the base airfoil and TEMA with a $+15^{\circ}$ deflection angle.

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Influence of Drying Temperature in the Oven on Physical, Morphology and Mechanical Properties of Mycelium Composite

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ABSTRACT

Mycelium, a root-like fungi network, possesses distinctive characteristics that render it an appealing contender for replacing polystyrene (PS). Drying in the oven is one of the most commonly used methods for producing mycelium composites. However, achieving its desired properties requires proper control of the drying temperature. This research aims to develop a mycelium-based composite by utilising an edible mushroom, specifically *Pleurotus ostreatus* (oyster mushroom), as an alternative to non-biodegradable materials for packaging applications. The composite is developed by inoculating *Pleurotus ostreatus* fungi into the substrate, mainly consisting of kenaf, wheat bran and CaCO₃. Afterwards, the composite was incubated for 20 days and then subjected to drying at different oven temperatures (e.g. 40°C, 60°C, and 80°C) for 24 hours. Our findings indicate that the desirable mechanical properties of mycelium composite were found at 60°C, where flexural strength, flexural modulus and impact strength were obtained at 0.11 MPa, 4.15 GPa and 635.8 N, respectively. The moisture content was 26.13%, and the shrinkage was 20.73%. The obtained density of 0.15 g/cm³ was compared to the density of PS, which is 1.04 g/cm³. This research indicates that a lightweight composite material, consisting of a network of interconnected hyphae that function as a

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Keywords: Drying temperature, fungi, mechanical property, mycelium, *Pleurotus ostreatus*

INTRODUCTION

The subterranean network of fungi, known as mycelium, has garnered attention as a

potentially valuable bio-based material due to its widespread presence, ability to regenerate and minimal environmental impact. It has led to the development of mycelium-based composites, a type of bio-composite material formed by the interaction between mycelium, the vegetative part of a fungus and lignocellulosic substrate. These substrates, derived from plant matter (such as agricultural waste or wood chips), provide nutrients for the mycelium to grow and bind the material together. The resulting composites are lightweight and strong and exhibit excellent thermal and acoustic insulation properties, making them attractive for various applications, including packaging, textiles, construction and furniture (Brudny et al., 2024; Madusanka et al., 2024).

Mycelium composites offer a promising sustainable alternative to polystyrene (PS) derived from petroleum, a non-renewable resource. They exhibit distinctive characteristics, including low weight, biodegradability, and the capacity to be shaped into diverse forms (Sydor et al., 2021). The lightweight of mycelium composites can alleviate physical strain in handling, which is beneficial in applications where weight reduction is crucial. Unlike PS, which can linger in the environment for centuries, mycelium composites are naturally biodegradable. They can be broken down by microorganisms over time, returning to the earth without leaving harmful residues, thus reducing long-term waste and minimising their ecological footprint. Additionally, mycelium composites exhibit a remarkable ability to be moulded into various shapes during their growth phase. This property allows for creating custom-designated products with intricate geometries and tailored functionalities. Moreover, their non-toxic nature makes them suitable for use in a range of products, unlike PS, which can release harmful chemicals.

While mycelium composites can be engineered to exhibit good mechanical properties, they may not always match the strength and durability of PS, especially in applications requiring high load-bearing capacity. Apart from that, mycelium composites are naturally hygroscopic, meaning they have the ability to absorb moisture. It can affect their dimensional stability and mechanical properties, limiting their use in humid environments or applications requiring water resistance. Apart from that, the production of mycelium composites a longer biological growth phase (15-20 days) compared to the rapid production of PS. Despite their limitations, development efforts are crucial to improve the performance and applicability of mycelium composites, further establishing their position as a viable and environmentally friendly alternative to PS.

Various factors, including the choice of mycelium species and the type of lignocellulosic substrate, influence mycelium composites' properties. For example, *Ganoderma lucidum* is known for its rapid growth and dense hyphal network, while *Pleurotus ostreatus* is valued for its ability to degrade (Akromah et al., 2024). Process variables such as incubation time, temperature, humidity and pressure during the growth phase significantly affect the composite's final properties. Among these factors, drying temperature is particularly

critical in determining the ultimate characteristics of mycelium composites. Various drying methods are accessible, each exerting unique impacts on the composite material, including air, freeze, supercritical, and oven drying. Air drying is a straightforward and economically efficient approach in which mycelium composites are allowed to undergo natural drying in the surrounding environment (Jones et al., 2020). However, it often leads to inconsistencies due to uncontrolled environmental conditions. The process of freezedrying, scientifically referred to as lyophilisation, entails freezing mycelium composites followed by exposure to reduced pressure, resulting in the direct sublimation of frozen water from ice to vapour. This method preserves the microstructure but is more expensive and time-consuming. Supercritical drying employs a supercritical fluid, such as carbon dioxide (CO_2) , to eliminate moisture from composites (Piskov et al., 2020). Although this method exploits the distinctive characteristics of supercritical fluids, which function as solvents and drying agents, it also increases complexity and cost. Mycelium composites are placed in a controlled temperature environment during oven drying, typically utilising convection furnaces. When comparing air and freeze-drying, using elevated temperatures in oven drying expedites the drying procedure. Although oven drying is a common method for removing moisture and offers better control over temperature, it can also lead to inconsistencies due to variations within the oven.

As mycelium grows, it forms a network of branching hyphae, primarily composed of chitin, that extend from the substrate into the air. It creates a fluffy skin covering the substrate and a vast three-dimensional matrix. Fungal growth in colonised substrates can be stopped through drying or heating. While frying induces a dormant state in the mycelium, allowing for potential regrowth under favourable conditions, heating deactivates the strains permanently, preventing further growth and detoxifying potentially harmful strains (Alemu et al., 2022). Managing the drying temperature within the mycelium composite presents a significant challenge in this situation. Inconsistencies in the properties of the dried composite may arise due to uneven moisture removal caused by variations in temperature and airflow within the oven. When subjecting mycelium composites to low-temperature drying, it is feasible to maintain the structural integrity and mitigate excessive shrinkage.

However, there exists a potential drawback of inadequate moisture elimination, leading to elevated moisture levels and reduced mechanical strength (Santos et al., 2021). Frying mycelium composites at elevated temperatures can accelerate drying by promoting rapid moisture removal. However, this method may also result in significant shrinkage, distortion and decreased porosity (Jones et al., 2018). In another study, Attias et al. (2020) developed a mycelium composite using three fungi species: *Colorius versicolor* (also known as *Trametes versicolor*), *Trametes ochracea* (the current scientific name for *Trametes multicolor*) and *Ganoderma sessile*. After incubation, the composites were oven-dried at 40°C for 72 hours, but as fungal growth was not yet fully terminated, an additional heat treatment of

100°C for 2 hours was conducted. Hence, expanding the investigated temperature range is crucial to fully comprehend the behaviour of mycelium composites, particularly in terms of terminating mycelium growth, rendering the material biologically inactive and achieving desired material properties (Islam et al., 2018).

Prior research may have focused on a restricted range of oven temperatures, omitting a comprehensive examination of the effects of temperature on mycelium composites. For example, Bagheriehnajjar et al. (2023) investigated using bamboo fibres as a renewable lignocellulosic substrate in mycelium composites, drying all samples at 70°C for 10 hours in an oven. Sakunwongwiriya et al. (2024) produced a mycelium composite from water hyacinth using four fungal species (Pleurotus ostreatus, Pleurotus sajor-caju, Auricularia auricula-judae and Schizophyllum commune). The samples were placed in an oven at 90°C until a constant weight was achieved, but the authors did not report the drying duration. Gaff et al. (2024) created a mycelium composite from Ganoderma lucidum spawn, employing a two-step drying process: initial air drying at room temperature for 2 days and oven drying at 120°C for 3 hours. Sim et al. (2017) examined the effects of vacuum and oven drying on the radical scavenging activity and nutritional content of Maitake (Grifola frondosa) mycelia. Their findings indicated that vacuum drying at 70°C and 1000 mBar was more effective in preserving these properties compared to direct oven drying at 105°C for 24 hours. Kim et al. (2016) investigated the drying characteristics of medicinal (Ganoderma lucidum, Phellinus linteus) and edible (Pleurotus eryngii, Lentinus edodes) mushrooms using a hot-air dryer at 50°C and 70°C. They found that the drying rate was highest at 70°C but concluded that 50°C was the most efficient drying method for both types of mushrooms. Mandliya et al. (2022) investigated the effects of vacuum drying at various temperatures (40°C-60°C) and pressures (60-260 mmHg) on the microstructure and physicochemical properties of pressed Pleurotus eryngii mycelium. They found that drying at 60°C and 60 mmHg resulted in the lowest water activity (0.215 ± 0.004) and browning index (28.946) \pm 0.066) while maximising the water absorption index (5.365 \pm 0.046 g/g).

Based on the literature review, the existing studies have focused on vacuum drying, which may not directly translate to the effects of oven drying due to differences in pressure and heat transfer mechanisms. They have often focused on limited temperature ranges and primarily investigated the influence of drying on nutritional content, drying rates, or specific physicochemical properties rather than the full range of properties relevant to mycelium composites. Additionally, there is no standardised drying method, as these processes' effectiveness depends on the specimens' dimensions. Hence, there remains a gap in the research regarding the influence of a wider range of oven temperatures on mycelium composite's physical, morphological and mechanical properties. Further research is needed to elucidate the microstructural changes occurring during drying and their correlation with observed mechanical properties. Hence, this research aims to address these gaps by

fabricating mycelium composites using *Plerotus ostreatus* as spawn and kenaf as a substrate and systematically investigating the effects on a larger range of drying temperatures (e.g. 40°C, 60°C, and 80°C) in determining the composite's properties.

MATERIALS AND METHODS

Fabrication of Mycelium Composite

Figure 1 shows the step-by-step fabrication process of the mycelium composite, encompassing substrate preparation, inoculation and moulding, incubation, and finally, the drying process. The substrate was supplied by Fungitech Sdn Bhd, Pulau Pinang and was prepared in accordance with the formulation specified in Table 1. The substrate for the mycelium composite was formulated by combining 80% kenaf, 19% wheat bran and 1% CaCO₃. The liquid was spawned from *Pleurotus ostreatus* (oyster mushroom) and grown on the substrate. The substrate was sterilised at a temperature of 100°C to eliminate the possibility of contamination by bacteria, fungus, and other potential pathogens.



Figure 1. The fabrication process of mycelium composite: (a) Substrate collected, (b) Packing in acrylic mould, (c) Incubation, (d) Harvest mycelium composite, (e) Drying in the oven for 24 hours at 40°C, 60°C, 80°C, and (f) Characterisation of mycelium composite

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Table 1Formulation of mycelium composite

Materials	Kenaf	Wheat bran	CaCO ₃
Percentage of weight mixture (%)	80	19	1

When the mycelium began to grow in the substrate, it was evenly distributed and compacted into the acrylic moulds measuring $155 \times 155 \times 10$ mm (length x width x height). After filling the mould with the substrate, pressure was applied to the substrate to compact it further. This step promoted denser growth and improved adhesion between substrate particles, resulting in a stronger final product. Once the moulds were filled, they were placed in a container for incubation.

After filling and compacting the substrate within the moulds, they were placed in a closed container for incubation. The fungi thrive and produce mycelium optimally within a temperature range of 25° C- 30° C and a humidity level of 60% - 65%. The incubation lasted for 20 days, during which the mycelium colonised the substrate, binding the particles together and forming a solid composite structure.

After incubation, the former mycelium composites were then subjected to a drying process using an oven (model: Protech GOV-50D). The drying process involved three different temperatures (e.g. 40°C, 60°C, and 80°C). Each composite was dried for 24 hours at its designated temperature. Following 24 hours of drying, the composites were removed from the oven and allowed to cool at room temperature. The dried composites were subsequently inspected for testing and characterisation.

Characterisation of Mycelium Composite

Density Measurement

Density evaluation was performed using an electronic densimeter (Biobase, model: BK-DME 3005). A sample measuring 10×10 mm was prepared for the test. The sample was carefully placed onto the densimeter, and the densimeter measured the mass and volume of the sample to determine its density. The density of the sample was determined by dividing the mass of the sample by its volume. The densimeter determined the sample's mass through a scale, while the volume was assessed by analysing the displacement of the material within the container. The determined density was displayed on the digital screen of the densimeter. Each sample was subjected to an average of three readings.

Moisture Content

The moisture content test determines the quantity of water present in the sample. This test was essential for evaluating the quality and efficacy of mycelium composites, as the

moisture content of the composites significantly impacted their mechanical properties. The samples were weighed using an analytical balance. The weight of the sample was recorded at various oven temperatures before and after placing the sample in the oven. The moisture content was then calculated using the formula given in Equation 1.

Moisture content (%) =
$$\frac{Wet weight - Dry weight}{Wet weight} x 100\%$$
 [1]

The wet weight represents the sample's initial weight, whereas the dry weight indicates the sample's final weight after drying. The moisture content results were recorded for each sample, and the average moisture content was calculated.

Shrinkage Measurement

The shrinkage test is important to target the specific product dimension. The initial dimensions of the sample were $155 \times 155 \times 10$ mm. The sample was placed in an oven (model: Protech GOV-50D). As drying progresses, the moisture content of the sample decreases, causing the sample to shrink. Once the drying period was finished, the final dimensions of the sample were measured. Excessive shrinkage could lead to deformations, fractures and dimensional inconsistencies, all of which could affect the performance and suitability of the material. The formula shown in Equation 2 is used to determine the percentage of shrinkage for each dimension. Five readings were taken for each sample, and the average was recorded.

Shrinkage (%) =
$$\frac{Initial \ dimension-Final \ dimension}{Initial \ dimension} x \ 100\%$$
 [2]

Macroscopic Observation

A macroscopic observation was conducted to observe the physical alteration of the sample. The photos were taken to document the transformation of mycelium composites, from their state prior to drying to their state after drying (as final products).

Scanning Electron Microscope (SEM)

The sample, which measures 10 x 10 mm, was cut to expose its internal structure, thus ensuring a clean and flat surface. Subsequently, the prepared sample was subjected to a Scanning Electron Microscope (SEM), specifically the TM3030 Tabletop Microscope with SwiftED3000. The SEM images obtained were subsequently analysed to assess the sample's microstructural properties.

Flexural Test

Samples measuring 72×13 mm from various oven temperatures were cut to perform a flexural test. A universal testing machine (UTM) Shimadzu AG-IS was utilised and fitted with a three-point bending test configuration. A constant crosshead speed of 2 mm/min and a clamp support distance of 80 mm were used. Following the conclusion of testing, the collected data were analysed. The flexural stress, flexural strain and other relevant mechanical properties, such as the modulus of elasticity and flexural strength, were determined and measured. The test was repeated five times, and the average value was recorded.

Impact Test

An impact test was carried out using a Dynatup 8250-drop weight impact machine to measure the maximum load of mycelium composite. The specimen was 100×100 mm.

RESULTS AND DISCUSSION

Density and Weight Measurement

Figure 2 depicts the density and weight of mycelium composite as a function of oven temperature. The density measurement followed the same pattern as the weight measurement.

The density of the mycelium composite decreased as the oven temperature was raised from 40°C to 60°C but then slightly increased at 80°C. The highest density was 0.17 g/cm³ at 80°C and the lowest was 0.15 g/cm³ at 60°C. Increasing the oven temperature caused moisture within the composite to evaporate, reducing weight. The composite's mass and volume decreased due to the loss of moisture and other volatile components, resulting in a lower density. When the composite is dried at 80°C, the water content of the mycelium hyphae rapidly evaporates. It causes the cell walls of the hyphae to contract and come into closer contact, which lowers porosity and boosts the density of the composite. The density of the prepared mycelium composite was found to be 0.15 to 0.17 g/cm³, which was close to the results of 0.094 to 0.350 g/cm³ reported in some literature (Elsacker et al., 2019; Peng et al., 2023). It was lower than the density of PS (1.04 g/cm³), which was used as traditional packaging (Manan et al., 2021).

In terms of volume measurement, as moisture is removed during drying, the volume of the composite decreases due to the contraction of the composite as water evaporates. The degree of volume reduction depends on the initial moisture content and the drying temperature. Higher temperatures led to faster moisture removal and, consequently, greater shrinkage and volume reduction. It is evident in Table 3, which shows a decrease in the final volume of the composite as the drying temperature increases from 40°C to 80°C.

Meanwhile, for density measurement, the density of the sample is influenced by its mass and volume. While the mass decreases due to moisture loss, the volume also decreases due to shrinkage. The net effect of these changes on density depends on the relative mass and volume reduction rates. In this study, the composite density decreased as the oven temperature increased from 40°C to 60°C, indicating that the volume reduction outpaced the mass reduction. However, at 80°C, the density slightly increased, suggesting that the mass reduction became more significant than the volume reduction at this higher temperature. It could be attributed to the collapse and compaction of the hyphal structure due to excessive drying.



Figure 2. Density and weight of mycelium-based composite at various oven temperatures

Moisture Content

The oven's temperature plays a crucial role in determining the moisture content of the mycelium composite. Figure 3 displays the moisture content of the mycelium composite at different oven temperatures. A clear trend of decreasing moisture content was observed as the oven temperature increased. The composite subjected to 40°C exhibited the highest moisture content, which measured 63.53%. The moisture content decreased to 26.13% and 24.06%, respectively, as the oven temperature was increased to 60°C and 80°C. Inadequate moisture elimination during low-temperature drying of mycelium composite causes the mycelium composite to retain more moisture, thereby becoming wet. It slows down the rate of moisture evaporation, thereby reducing the loss of water from the composite. It causes

the composite to become soft and pliable, increasing the risk of contamination because bacteria and other pathogens thrive in damp environments (Yang et al., 2021). Furthermore, a slower dying process, low temperatures, and high moisture content resulted in moisture expansion within the composite. The expansion can result in internal stresses, ultimately decreasing the composite's mechanical properties. It is evident in the study where the composite dried at 40°C exhibited the highest moisture content (63.53%) and the lowest values for impact load (335.80 N), flexural strength (0.05 MPa) and stiffness (2.66 GPa).

As the temperature increases to 60°C, higher temperatures promote faster evaporation of moisture, which leads to a decrease in moisture content. Increasing the oven temperature transfers heat energy to the water molecules within the composite, elevating their kinetic energy and facilitating faster evaporation. The moisture content decreased as the drying temperature increased, increasing stiffness and strength. However, excessive drying at 80°C accelerates moisture evaporation from the composite, rapidly removing water from the hyphal cell walls. It can cause the cell walls to shrink and collapse, weakening the overall structure. The weakened cell walls are less able to withstand mechanical stress, leading to a decrease in the mechanical properties of the composite. The loss of structural integrity can make the composite more brittle and prone to cracking or fracturing under stress.



Figure 3. The moisture content of the mycelium composite was measured after drying at various oven temperature

The above result shows that high moisture content decreased mechanical strength and increased susceptibility to contamination, while excessively low moisture content made the composite brittle. Therefore, controlling the drying temperature is essential for achieving an optimal moisture content and optimising the mechanical properties of mycelium composite.

Shrinkage Measurement

Shrinkage is important for controlling the dimensions during drying, affecting the composite's dimensional stability. The shrinkage of the composite increased as the oven temperature extended, as presented in Figure 4. The sample subjected to 80°C observed the highest shrinkage, which was 23.2%. However, the shrinkage progressively decreased as lower oven temperatures were used. For example, the composite exposed to a temperature of 60°C showed a shrinkage percentage of 20.73%, whereas the composite exposed to a temperature of 40°C experienced a shrinkage of 13.49%. The trend aligns with the measurement of moisture content. As moisture evaporates, the composite contracts, leading to shrinkage and changes in the overall dimensions that potentially cause warping or cracking. At lower temperatures (40°C), the mycelium composite undergoes minimal shrinkage, indicating that it retains its original dimensions relatively well. Lower temperatures slow down the rate of moisture loss and decrease the likelihood of substantial contraction in the material. As the temperature increases to 60°C, shrinkage increases to 20.73%, and at 80°C, it peaks at 23.2%. This progressive increase in shrinkage with temperature indicates a loss of dimensional stability as the composite undergoes greater contraction due to moisture loss. When the composite is exposed to high temperatures, the moisture contained within it may start evaporating faster, causing it to dry.



Figure 4. Shrinkage of a mycelium-based composite at various oven temperatures

As the moisture content increases rapidly, the spaces left behind by the evaporated water may become squeezed, resulting in the contraction of the composite and causing a reduction in its overall dimension. The decrease in the volume of the composite contributes to higher shrinkage. Moreover, elevated temperature can enhance the occurrence of particular chemical reactions, leading to the decomposition of specific constituents in the mycelium composite. These chemical reactions result in the production of volatile by-products, the emission of gases, or the reconfiguration of molecular structures, thereby causing a slight increase in shrinkage (Sydor et al., 2022). The increased shrinkage at higher temperatures can lead to warping, cracking and internal stresses, which can compromise the structural integrity and functionality of the composite. Therefore, while higher temperatures may accelerate the drying process, they also negatively impact the dimensional stability of the composite due to increased shrinkage.

The relationship between drying temperature and shrinkage in mycelium composite is directly proportional. While higher drying temperatures can expedite the drying process, they also lead to increased shrinkage, which can negatively affect the dimensional stability and structural integrity of mycelium composite.

Macroscopic Observation

Table 2 displays the image of the mycelium composite both before and after undergoing drying, with an increase in oven temperature. Drying the composite in an oven at a lower temperature causes it to shrink less, whereas drying it at higher temperatures can cause it to shrink more. When the moisture evaporates, the volume occupied by water decreases, which causes it to shrink. The reduction in volume is due to contraction. As a result, shrinkage causes a reduction in the volume of the composite, resulting in alterations in the dimensions of the composite, as shown in Table 3. The trend aligns with the measurement of shrinkage. At lower temperatures (40°C), the drying process is slower, allowing for gradual moisture removal and minimal shrinkage. This results in less internal stress within the composite, reducing the likelihood of warpage. However, as the drying temperature increases, the rate of moisture evaporation also increases. At 80°C, the rapid moisture loss causes significant shrinkage and internal stresses, making the composite more susceptible to warping.

Additionally, the high temperature can lead to the degradation of the hyphal cell walls, which are essential for the material's structural integrity. This degradation results in a decrease in flexural strength and flexural modulus, making the composite weaker and less resistant to bending forces. Additionally, thermal degradation can cause discolouration (yellowish) and warping of the composite, further compromising its mechanical performance and aesthetic appeal. At the same time, warpage is also observed, which causes the composite to deviate from its intended flat form. This warpage is a result of the composite's low stiffness. Warpage can increase stress on the mycelium composite, causing it to shrink more during drying. As a result, to keep the shape and dimensions of the composite, the oven temperature should not be raised any more.

Oven temperature (°C)	Before drying in the oven (After incubation)	After drying in the oven
40		
		NOT THE OWNER
60		
80		

Table 2Mycelium composite at various oven temperatures: (a) 40°C, (b) 60°C, and (c) 80°C

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Table 3

Oven temperature	Sample	Final length (mm)	Final width (mm)	Final height (mm)	V (olume (mm ³)
(°C)					Initial (Before drying)	Final (After drying)
40	1	145	150	10	240250	217500
	2	140	145	10	240250	203000
	3	140	145	10	240250	203000
Average		141.67	146.67	10	240250	207833
60	1	138	135	10	240250	186300
	2	140	140	10	240250	196000
	3	138	137	10	240250	189060
Average		138.67	137.33	10	240250	190453
80	1	135	140	10	240250	189000
	2	135	140	10	240250	189000
	3	132	133	10	240250	175560
Average		134	137.67	10	240250	184520

The dimensional and volume changes of the mycelium composite were observed after drying at various oven temperature

Remarks. The initial length*width*height of sample = $155 \times 155 \times 10$ mm

Scanning Electron Microscope (SEM)

Figure 5 shows the morphological modifications to the structure of the composite between the network structure of hyphae at various oven temperatures. Drying at low temperatures preserves the structure of the mycelium composite. At 40°C, the SEM images (Figure 5a) show a loosely packed hyphal network with low interconnectedness. The hyphae strands appear thin, with visible gaps and voids between them. Lower temperatures slow the drying process, leading to higher moisture retention in the mycelium. This results in a less interconnected hyphal network with a lower degree of fusion between hyphae strands. The hyphae appear less densely packed, resulting in a porous structure contributing to the lower strength of the mycelium composite, as evidenced by the low flexural strength (0.05)MPa) observed in the study. Increasing the drying temperature to 60°C leads to a denser and more interconnected hyphal network (Figure 5b). The hyphae strands appear thicker and more tightly packed, with fewer voids and gaps. As the drying temperature increases to 60°C, the rate of moisture removal accelerates, which results in a significant removal of water from the cell walls. It leads to a denser packing of hyphae and a higher degree of interconnectedness within the network. The high packing of hyphae creates a more interconnected structure, as high shrinkage causes the hyphae to come into closer contact.

As a result, the cell walls may start to fuse, resulting in a stronger and more compact composite structure. This improved the mechanical properties observed at this temperature,



Figure 5. SEM image of mycelium showing the surface layer on composite at a magnification of $300 \times$ and $1000 \times$ at various oven temperatures: (a) 40° C, (b) 60° C, and (c) 80° C



Figure 6. Morphology of mycelium composite at 80 °C with magnification of 2000×

with flexural strength increasing to 0.11 MPa and flexural modulus to 4.15 GPa. The higher magnification image (Figure 6) further reveals the fusion of hyphae strands, creating a more continuous and robust network that can effectively distribute stress and resist deformation, resulting in high mechanical properties. It also reduces localised strain and minimises the occurrence of warping. At higher drying temperatures, the rapid moisture loss causes significant shrinkage and further fusion of the hyphae strands, forming an interconnected network of hyphae. When the hyphae strands fuse and become tightly packed, primarily due to the substantial water loss, they decrease the porosity and occupy a smaller volume, resulting in increased composite density. The increased density affects the weight of the composite. However, excessive drying can lead to the degradation of the hyphal cell walls, potentially compromising the structural integrity of the composite and further increasing the temperature to 80°C, resulting in an even denser hyphal network with signs of degradation (Figure 5c).

The hyphae strands appear fused and compacted, but some have collapsed or broken. This degradation is likely due to the excessive heat causing damage to the hyphal cell walls. The cell walls of mycelium shrink more and contract due to the removal of water, resulting in intense drying. These cell walls, primarily composed of polysaccharides like chitin, glucans, or cellulose, are essential for maintaining the composite's structure and strength. Cell walls experience a loss of turgidity and undergo inward compression due to decreased internal pressure. When turgor pressure is decreased, the cell walls undergo degradation, resulting in reduced rigidity and a tendency to collapse. This phenomenon has the potential to result in the deterioration of its inherent structural integrity. While the composite still exhibits relatively high flexural strength (3.64 MPa) and modulus (0.09 MPa), the slight decrease compared to the 60°C suggests that the structural damage caused by the high temperature begins to outweigh the benefits of increased density. Therefore, properly controlling the drying temperature is essential to preserve the mycelium's structural integrity.

Flexural Test

Figure 7 shows the relationship between oven drying temperature and the flexural properties (strength and modulus) of mycelium composites. An initial increase in both flexural strength and modulus is observed as the temperature rises from 40°C to 60°C. However, a further increase in temperature to 80°C leads to a slight decrease in both properties. At lower drying temperatures (40°C), the flexural strength (0.05 MPa) and flexural modulus (2.66 MPa) are relatively low. It is attributed to the loose packing of hyphae and a low degree of interconnectedness within the hyphal network. The gaps and voids between the hyphae strands weaken the overall structure, making it less resistant to bending forces. The flexural strength (0.11 MPa) and flexural modulus (4.15 GPa) peak at 60°C indicate a strong bond between the mycelium and substrate particles, enhancing interfacial adhesion. This bonding has the potential to increase the flexural strength and modulus. This can be explained by the fact that mycelium and its associated compounds are more likely to diffuse at higher temperatures during drying. It allows the mycelium to penetrate deeper into the substrate particles and promotes intimate contact between the mycelium and the substrate surface. Mycelium's increased diffusion and penetration into the substrate results in a larger contact area and stronger bonding.

Additionally, a denser and more interconnected hyphal network, with increased fusion between hyphae strands, helps to distribute the stresses and loads uniformly. However, when it reached 80°C, the mycelium composite's flexural strength (0.09 MPa) and modulus (3.64 GPa) decreased. This decrease is likely due to the excessive heat causing degradation of the hyphal cell walls, reducing its load-bearing capacity and structural integrity. The degradation of mycelium composites can also be attributed to various factors, including thermal degradation of both mycelium and the matrix material and moisture loss. The flexural strength and modulus obtained in this study exhibited a significant similarity to the results reported by Appels et al. (2019), who found flexural strengths ranging from 0.05 MPa to 0.29 MPa and flexural modulus varying from 1 GPa to 9 GPa in their investigation of mycelium composite.



Figure 7. Flexural strength and modulus of mycelium-based composite at various oven temperature

Impact Test

The impact test results provide information about the ability of mycelium composites to withstand sudden loads, a key consideration for applications like packaging materials where impact resistance is vital. As shown in Figure 8, the impact strength of the composite significantly increases as the drying temperature rises from 40°C to 60°C. It suggests that higher temperatures enhance the material's ability to absorb and dissipate impact energy due to improved interfacial bonding and a more integrated structure. However, a slight decrease in impact strength is observed at 80°C compared to 60°C. It indicates that while higher temperatures initially improve impact resistance, excessive heat may lead to degradation within the composite, slightly reducing its ability to withstand impacts. The heat can cause degradation of the composite's molecular structure (hyphal degradation), resulting in the breakdown of intermolecular bonds and changes in the arrangement of its constituents. This degradation can weaken the composite and negatively reduce the load-bearing capacity of the mycelium composite.



Figure 8. Maximum load of a mycelium-based composite at various oven temperatures

CONCLUSION

Significant morphological and mechanical changes were observed upon drying the mycelium composite at various oven temperatures (e.g. 40°C, 60°C, and 80°C).

The optimal drying temperature for mycelium composites is 60°C. This temperature strikes a balance between effective moisture removal and preservation of the composite's structural integrity.

At 60°C, the mycelium composite exhibits the highest flexural strength (0.11 MPa), flexural modulus (4.15 GPa), and maximum load (635.80 N) for impact test, indicating superior mechanical properties compared to composites dried at lower or higher temperatures. The drying process at 60°C resulted in a decrease in density. It is supported by the decrease in the density value from 0.16 g/cm³ to 0.15 g/cm³. The reduction in density can be attributed to removing moisture content during the drying process. It is corroborated by the finding that the mycelium composite's moisture content decreased from 63.53% to 24.06% after 24 hours of drying at 40°C and 60°C, respectively.

Although drying at higher temperatures, such as 80°C, contributes to faster moisture evaporation, the volume changes caused by rapid water removal can lead to greater shrinkage and the occurrence of warpage. It causes thermal stress, leading to the denaturation of polysaccharides and subsequent degradation and collapse of the hyphae. Discolouration also occurs due to thermal degradation at higher drying temperatures. In addition, a higher drying temperature of 80°C may contribute to an increase in density and weight as well as a decrease in mechanical properties.

FUTURE RECOMMENDATIONS

Based on this research's findings, several potential future research directions can be pursued to further optimise the drying process of mycelium composite.

Optimising the oven's drying temperature, duration, and airflow achieved the desired balance between moisture removal, shrinkage and mechanical properties. It could involve developing predictive models or using machine learning algorithms to identify optimal drying conditions for specific applications.

Investigating alternative drying methods, such as microwave drying, vacuum drying, or hybrid approaches, could lead to more effective drying techniques.

Investigating pre-drying or pre-heating could improve the uniformity of the oven-drying process and influence the final properties of the mycelium composite.

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Acoustic Emission Partial Discharge Localization in Oil Based on Artificial Bee Colony

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ABSTRACT

This study explores the application of an artificial bee colony (ABC) to locate partial discharge (PD) in a test tank based on acoustic emission (AE) approach. Data from a previous AE PD experimental study, which includes the coordinates of 3 AE sensors and the time difference of arrival (TDOA), were used to construct the nonlinear localization equations. It is known that localization algorithms are among the factors that can affect PD localization accuracy, and the ongoing research in this area underscores the need for further advancements in this topic. Therefore, the ABC was proposed to estimate the PD location through a colony of 120 bees, evenly divided into 60 employed and 60 onlooker bees. The employed bees explored the bounded search space, and onlooker bees refined PD locations found by the employed bees through local search. Scout bees were set out whenever a bee exceeded the limit of abandonment to discover possible PD locations in new areas of the search space. After 500 iterations, the optimal solution was the estimated PD location produced by ABC. Comparisons with the genetic algorithm (GA), particle swarm optimization (PSO) and bat algorithm (BA) revealed that the distance error, maximum deviation and computation time for AE PD

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Keywords: Acoustic emission, artificial bee colony, localization, partial discharge, time difference of arrival

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INTRODUCTION

Partial discharge (PD) can affect the integrity of power transformers since it can gradually deteriorate dielectric insulation and potentially lead to failure over time (Ilkhechi & Samimi, 2021; Liu, 2016). Therefore, PD detection and localization are crucial to maintain the reliability of power transformers (Wang et al., 2017). Conventional electrical measurement based on IEC 60270, ultra-high frequency (UHF), acoustic emission (AE) and dissolved gas analysis (DGA) are well-known methods for PD detection. PD in the insulation of a transformer results in various physical phenomena such as high-frequency electric current pulses, electromagnetic (EM) wave emissions, mechanical vibrations, chemical reactions and liberation of heat and light energies (Rathod et al., 2022). Mechanical vibrations generate AE signals, typically covering frequencies ranging from 20 kHz to 1 MHz (Rathod et al., 2022). These AE signals can be detected, denoised, and used to estimate the PD location through localization equations (Liu & Liu, 2014).

AE-based PD localization has recently gained significant attention due to its nondestructive nature (Liu, 2016). AE sensors, particularly the piezoelectric transducers, can be easily placed on the external walls of a transformer tank via magnetic holders (Hussain et al., 2021; Wang et al., 2017). AE is immune to electromagnetic interference and cost-effective (Faizol et al., 2023). However, AE is sensitive to external mechanical noise, which can introduce errors in PD localization (Al-Masri et al., 2016). It is known that the accuracy of AE PD localization relies on the localization algorithms (Liu, 2016). Iterative methods such as least square and Newton's methods are previously utilized to solve the nonlinear equations inherent in the time difference of arrival (TDOA) method for PD localization (Howells & Norton, 1981; Kundu et al., 2009; Punekar et al., 2012). These algorithms are computationally intensive and require initial guesses to perform PD localization (Howells & Norton, 1981; Kundu et al., 2009; Punekar et al., 2012). Noniterative algorithms proposed by Kundu et al. (2009) and Antony and Punekar (2018) can provide faster computation times than Newton's method with generations of 2 solutions.

Advanced approaches such as genetic algorithm (GA) are also implemented for AE PD localization (Veloso et al., 2006, 2007, 2008). GA can estimate the PD location without any initial guesses, but it can be subjected to complicated optimization issues related to premature convergence phenomena (Liu, 2016). A quantum GA (QGA) is introduced to improve the accuracy of AE PD localization with complex computation (Liu, 2016). The bat algorithm (BA) produced less error than the QGA and GA for AE PD localization (Chakravarthi et al., 2017). The particle swarm optimization (PSO) is also utilized for AE PD localization, whereby apparent reductions of PD localization errors are found compared to the least square algorithm (Ri-cheng et al., 2008; Tang et al., 2008). Hybrid differential evolution PSO (DE-PSO) can further enhance the accuracy of AE PD localization with a longer iteration time than PSO (Cai et al., 2020). The adaptive grey wolf optimizer is

known for its ability to adjust search parameters during optimization; it also shows promise in enhancing AE PD localization (Dudani & Chudasama, 2016).

Despite these advancements, research on the algorithms for AE PD localization is still ongoing, which has prompted further study on this aspect (Dudani & Chudasama, 2016). One key challenge is balancing exploration and exploitation in the search process to avoid premature convergence and enhance PD localization accuracy. The artificial bee colony (ABC) serves as a potential candidate to address this gap since it can effectively prevent premature convergence in multi-dimensional problems, such as AE PD localization (Karaboga & Akay, 2009). Therefore, this paper presents an investigation into the application of the ABC for AE PD localization. The study aims to explore the application of ABC for AE PD localization and comprehensively compare its performance against BA, GA, and PSO. The AE PD signals used in this study are collected through 3 AE sensors placed on the surface of a steel tank filled with mineral oil. The time of arrival (TOA) for each AE PD signal is determined through the first peak method from the denoised AE PD signals (Hashim et al., 2022; Sinaga et al., 2012). Next, the TDOAs between the 3 AE signals are computed based on the TOAs. PD localizations are then carried out based on the ABC algorithm, and its performance in terms of distance error between the actual and estimated PD locations, maximum deviation of estimated PD location and average computation time is compared with BA, GA, and PSO.

METHODOLOGY

Experimental Setup and Mathematical Model of Acoustic Emission PD Localization

This study's experimental setup and data were based on the previous study (Hashim et al., 2022, 2023, 2023b). The nonlinear localization equations employed in this investigation were formulated based on the configuration shown in Figure 1, which comprised a PD source and 3 AE sensors mounted on the walls of the test tank. The spatial Cartesian coordinate system was established with one of the bottom corners of the test tank serving as the reference point, known as the origin O (0, 0, 0). The actual PD location is represented by the coordinates P (x, y, z), while the positions of the 3 AE sensors S₁, S₂, and S₃ are denoted by (x_1, y_1, z_1) , (x_2, y_2, z_2) , and (x_3, y_3, z_3) . The needle and plane electrodes were used to create PD at 2 distinct locations in the test tank: PD location A (0.07, 0.08, 0.18 m) and PD location B (0.32, 0.09, 0.08 m), respectively. The TDOA was employed for PD localization to avoid the need to determine the actual time of arrival for the AE PD signals at each of the sensors (Liu, 2016). S_1 was specified as the reference sensor. The time difference in receiving the AE PD signals between sensor S_1 and sensor S_2 , τ_{12} , was defined as $t_1 - t_2$, as depicted in Figure 2. Similarly, the difference between the arrival times of the AE PD signal at sensors S1 and S3 was defined as the TDOA between the 2 sensors, τ_{13} , which was mathematically expressed as $t_1 - t_3$.

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Figure 1. Schematic of AE sensors placement and actual PD location



Figure 2. Difference in arrival times of acoustic emission PD signals

The system of nonlinear equations that govern the AE localization of PD in the test tank can be expressed by Equations 1, 2 and 3. These equations were obtained from the spherical distance calculations between the actual PD location and the 3 AE sensors, in

conjunction with the TDOA principles illustrated in Figure 2 (Liu, 2016; Sinaga et al., 2012; Veloso et al., 2006). The parameter v_e in these equations represented the equivalent speed of sound in oil, which was defined as 1415 m/s (Hashim et al., 2022; IEEE, 2019). Conversely, the quantity T in the equations denotes the time taken for the AE signal to travel from the actual PD location to the reference sensor S₁, which is unknown in this case.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = (v_e T)^2$$
[1]

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = [v_e(T + \tau_{12})]^2$$
^[2]

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = [v_e(T + \tau_{13})]^2$$
[3]

To reduce the number of variables to be optimized in the nonlinear localization equations, Equations 2 and 3 can be rewritten in the alternative form shown in Equation 4, whereby i = 2, 3 (Liu, 2016; Ri-cheng et al., 2008; Tang et al., 2008).

$$\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} - v_e \tau_{1i} = 0$$
[4]

Equation 4 represents an over-determined situation, which indicates that the precise solution is difficult to acquire (Liu, 2016; Liu & Liu, 2014). Hence, the common approach is to seek the optimal solution of Equation 4 for AE PD localization (Liu, 2016; Liu & Liu, 2014). Overall, the mathematical model for the AE PD localization based on the TDOA can be summarized as a constrained optimization problem, as shown in Equations 5, 6, 7, and 8 (Liu, 2016; Liu & Liu, 2014; Tang et al., 2008).

$$\min\{D_f(x, y, z)\} = \sum_{i=2}^{3} \left| \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} - v_e \tau_{1i} \right|$$
[5]

subjected to

 $0 \le x \le (x_{\max} = 0.40 \text{ m})$ [6]

$$0 \le y \le (y_{\max} = 0.25 \text{ m})$$
 [7]

$$0 \le z \le (z_{max} = 0.25 \,\mathrm{m})$$
 [8]

Here, (x, y, z) represents the estimated PD location, $(x_{\nu}, y_{\nu}, z_{1})$ is the coordinate of the reference sensor, S₁, and $(x_{\nu}, y_{\nu}, z_{i})$ are the coordinates of the other AE sensors. For each PD location A and B, 10 combinations of AE sensor positions were used to acquire the

AE PD signal. Each combination consists of the coordinates for 3 AE sensors (S_1 , S_2 , and S_3), as shown in Table 1.

PD	AE Sensors	AF	AE Sensor S ₁ AE Sensor S ₂		$\cdot \mathbf{S}_2$	S ₂ AE Sensor S ₃				
Location	Combination	x ₁ (m)	y ₁ (m)	z ₁ (m)	x ₂ (m)	y ₂ (m)	z ₂ (m)	x ₃ (m)	y ₃ (m)	z ₃ (m)
	A1	0.15	0.10	0.00	0.15	0.05	0.00	0.15	0.15	0.00
	A2	0.20	0.10	0.25	0.20	0.05	0.25	0.20	0.15	0.25
	A3	0.25	0.05	0.00	0.25	0.15	0.00	0.35	0.10	0.00
А	A4	0.25	0.05	0.00	0.30	0.10	0.00	0.35	0.15	0.00
(0.07,	A5	0.25	0.15	0.25	0.25	0.05	0.25	0.25	0.10	0.25
0.08,	A6	0.30	0.15	0.25	0.30	0.05	0.25	0.30	0.10	0.25
0.18 m)	A7	0.40	0.05	0.20	0.40	0.10	0.10	0.40	0.15	0.20
	A8	0.40	0.05	0.20	0.40	0.15	0.15	0.40	0.05	0.10
	A9	0.40	0.15	0.10	0.40	0.15	0.20	0.40	0.05	0.15
	A10	0.40	0.15	0.15	0.40	0.05	0.15	5 0.40 0	0.10	0.05
	B1	0.00	0.05	0.05	0.00	0.15	0.05	0.00	0.10	0.15
	B2	0.15	0.05	0.25	0.15	0.15	0.25	0.05	0.10	0.25
	B3	0.20	0.15	0.25	0.20	0.10	0.25	0.15	0.15	0.25
в	B4	0.25	0.05	0.00	0.20	0.15	0.00	0.15	0.05	0.00
(0.33,	В5	0.25	0.05	0.25	0.00	0.05	0.10	0.15	0.15	0.00
0.09,	B6	0.25	0.10	0.25	0.15	0.05	0.25	0.15	0.15	0.25
0.08 m)	B7	0.30	0.10	0.00	0.15	0.05	0.00	0.10	0.15	0.00
	B8	0.35	0.15	0.00	0.40	0.15	0.10	0.35	0.15	0.25
	B9	0.40	0.05	0.05	0.20	0.15	0.00	0.00	0.05	0.20
	B10	0.40	0.05	0.10	0.35	0.05	0.00	0.15	0.10	0.25

Table 1Combinations of sensors for each of the PD locations

Implementation of Optimization Algorithms for PD Localization

To assess the performance of the ABC for AE PD localization, GA, PSO and BA were also applied to solve the same optimization problem for comparative analysis (Chakravarthi et al., 2017; Ri-cheng et al., 2008; Tang et al., 2008; Veloso et al., 2006). For each algorithm, Equation 5 serves as the objective function for the AE PD localization. Equations 6, 7 and 8 define a 3-dimensional search space that confines the estimated PD locations produced by each algorithm. This confined search space represents the actual dimension of the experimental test tank. The AE sensors' coordinates (x_i , y_i , z_i) and reference sensor coordinates (x_i , y_{ν} , z_1) were pre-defined and listed in Table 1. The detailed processes to obtain the TDOAs used in this study were outlined in (Hashim et al., 2022). Table 2 shows the TDOAs for each AE sensor combination in Table 1. The optimal solution for each algorithm is the estimated PD location for the given combinations of TDOAs and AE sensors' coordinates.

PD Location	AE Sensors Combination	TDOA, $ au_{12}$ (μs)	TDOA, $ au_{13}$ (μs)
	A1	1.237	7.449
	A2	1.406	9.943
	A3	4.883	54.155
	A4	25.420	58.664
А	A5	1.081	7.774
(0.07, 0.08, 0.18 m)	A6	0.876	6.318
	A7	-0.148	5.703
	A8	4.459	6.318
	A9	1.000	10.000
	A10	3.000	15.594
	B1	5.000	4.000
	B2	4.999	54.000
	В3	6.000	29.000
	B4	34.000	59.000
В	В5	0.000	5.997
(0.33, 0.09, 0.08 m)	B6	41.000	45.000
	B7	75.000	115.000
	B8	0.000	61.000
	B9	50.000	189.000
	B10	8.000	118.000

 Table 2

 TDOAs for the combinations of AE sensors in Table 1

Genetic Algorithm

A real-coded GA was implemented for the AE PD localization with reference to (Veloso et al., 2006, 2007). Hence, the genes for all 120 chromosomes in the population are real numbers. The important parameters that are used in GA are summarized in Table 3. The GA started with the random initializations of 120 chromosomes. Each chromosome consists of 3 genes representing the (x, y, z) coordinates of the estimated PD locations.

To estimate the PD location for each of the AE sensor combinations in Table 1, the coordinates of the 3 AE sensors (x_i , y_i , z_i), along with the corresponding TDOAs in Table 2 (τ_{1i}), were used as inputs for the GA. The AE PD signals captured by the AE sensors during the PD experiment were first denoised by the moving average (MA) technique (Hashim et al., 2022; Hashim et al., 2023b). The TOAs of the 3 AE sensors were then determined from the denoised AE PD signals based on the first peak method (Hashim et al., 2022; Sinaga et al., 2012). These TOAs represent the moments when the AE PD signals emitted from the actual PD location arrive at the respective AE sensors. The TDOAs were computed based on the concept illustrated in Figure 2. For AE PD localization, the cost value for each chromosome was obtained by substituting the 3 genes in each chromosome

into the objective function of the GA, given by Equation 5. A total of 500 generations of chromosomes were produced. In each generation, 84 new chromosomes were produced through the crossovers among 42 pairs of selected parent chromosomes. The probability of each chromosome being selected as a parent through the roulette wheel selection was computed based on Equation 9, where $cost_i$ is the cost of the ith chromosome obtained from the objective function (Heris, 2015).

$$P = e^{-0.8 \times \left(\frac{\cos t_i}{\text{worst cost value of the generation}}\right)}$$
[9]

The exponential conversion in Equation 9 assigned a higher probability of selection to chromosomes with smaller absolute cost values and vice versa. The smaller the absolute cost value of a chromosome, the closer the estimated PD location that is represented by the genes of the chromosomes to the actual PD location. Furthermore, 36 new chromosomes were produced through creep-type mutation of 36 chromosomes in the current generation. The mutation operation enabled GA to explore different locations in the test tank for the estimated PD location by injecting diversity into the gene pool. Next, the 120 chromosomes generated by crossover and mutation operations were merged with the existing chromosome population. Elitism was applied whereby only 120 chromosomes with the best cost values were retained to constitute the subsequent generation. This selective retention strategy ensured that each successive generation of chromosomes comprised estimated PD locations with higher probabilities of proximity to the actual PD location. After the elitism process, the GA proceeded with the next iteration. The output of the GA was obtained from the best chromosome in the 500th generation. The 3 genes of this best chromosome resulted in the lowest absolute cost value when substituted into the objective function. It means that the estimated PD location (x, y, z) represented by the genes was closest to the actual PD location in the test tank.

Table 3Parameters of the GA for acoustic emission PD localization

Parameter	Value
Size of the population	120
Maximum number of generations	500
Probability of mutation	0.05
Percentage of offspring produced by crossover (%)	70
Percentage of offspring produced by mutation (%)	30

Particle Swarm Optimization Algorithm

A standard PSO was employed for the AE PD localization based on the methodology outlined in (Ri-cheng et al., 2008; Tang et al., 2008). All parameters of the PSO were set

the same as in (Ri-cheng et al., 2008; Tang et al., 2008), except for the inertia factor or the inertia weight, denoted by w. Initially, the inertia weight was set to 1 and reduced in every subsequent iteration based on Equation 10, with the damping factor, w_{damp} , held constant at 0.99 (Heris, 2015). The crucial parameters the PSO needs to perform the AE PD localization task are tabulated in Table 4.

Equation 5 was employed as the objective function of the PSO to predict the actual PD location within the test tank. The coordinates of the 3 AE sensors (x_i, y_i, z_i) listed in Table 1 served as the inputs to the PSO. The corresponding TDOAs, listed in Table 2, were also utilized as inputs to the PSO to estimate the actual PD location based on Equation 5. In each iteration of the PSO, each swarm particle's velocity and location were updated based on the same equations given in (Ri-cheng et al., 2008; Tang et al., 2008). The output of the PSO was obtained from the g_{Best} parameter, which was updated whenever a particle found an estimated PD location closer to the actual PD location than the previously recorded best location. This parameter contained the (x, y, z) coordinates of the estimated PD location nearest to the actual PD location, as found by the particles in the swarm.

$$w(k+1) = w(k) \times w_{damp}$$
^[10]

Table 4

Parameters	of the	PSO fo	r acoustic	emission	PD	localization
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Parameter	Value	
Size of particle swarm	120	
Maximum number of iterations	500	
Initial inertia factor (w_0)	1	
The damping factor of inertia factor (W_{damp})	0.99	
Personal learning factor (C_1)	2	
Global learning factor (C_2)	2	

Bat Algorithm

The AE PD localization based on BA was implemented according to the procedures in (Chakravarthi et al., 2017; Yang, 2010).. The important parameters of the BA for AE PD localization are summarized in Table 5. The locations of the bats represented the estimated PD locations based on BA in the confined search space defined by Equations 6, 7, and 8. This confined search space restricted the movements of the bats so that the estimated PD locations produced by the BA were always within the test tank. The BA can be regarded as a modified version of PSO with additional parameters involved in the search for the actual PD location. These parameters included the velocity (v_i), pulse frequency (f_i), pulse emission rate (r_i), and loudness (A_i) for each of the bats in the population (Chakravarthi et

al., 2017; Yang, 2010). These parameters were computed and updated in each iteration of the BA based on the equations provided by Chakravarthi et al. (2017) and Yang (2010). Equation 5 serves as the objective function of the BA for AE PD localization. The inputs of the BA included the coordinates of the 3 AE sensors (x_i, y_i, z_i) as listed in Table 1 and the corresponding TDOAs given in Table 2. The cost value for each bat in the population was obtained by substituting the 3 coordinates in the bat's location into the objective function. A small absolute cost value indicates that the bat's location is relatively closer to the actual PD location. Therefore, the bat's location with the lowest absolute cost value in the population represents the estimated PD location closest to the actual PD location in terms of the Euclidean distance. The output of the BA was taken from the best bat location identified in the bat population over 500 iterations of computation.

Table 5	
Parameters of the BA for acoustic emission PD localization	

Parameter	Value	
Size of the bat population	120	
Maximum number of iterations	500	
The frequency range of each bat $[f_{min}, f_{max}]$	[0, 1.5]	
Initial loudness of each bat (A_0)	1	
Initial pulse emission rate (r_0)	0.6	
Loudness decay constant (α)	0.9	
Pulse emission rate constant (γ)	0.9	

Artificial Bee Colony Algorithm

An ABC was implemented for AE PD localization with reference to (Karaboga, 2005; Karaboga & Akay, 2009; Kulkarni & Desai, 2016). The bee colony utilized 120 bees, divided into 60 employed and 60 onlooker bees. The group of employed bees was tasked to search for certain locations within the confined 3-dimensional search space defined by Equations 6, 7, and 8 for the actual location of PD. The bee's location, represented by 3 coordinates (x, y, z), together with the coordinates of the AE sensors in Table 1 and the corresponding TDOAs in Table 2, were set as inputs for the objective function given by Equation 5. These TDOAs were computed from the differences among the TOAs of the AE PD signals acquired by each AE sensor.

The output from the objective function was the cost value of the bee. It indicates how close the location of a bee is to the actual PD location, whereby the lower the absolute cost value of a bee is, the closer its location is to the actual PD location. The onlooker bees were employed to perform local searches around the locations of the employed bees with higher fitness values. The fitness values of the employed bees were computed based

on Equation 11, which assigned a higher fitness value for a bee with a lower absolute cost value and vice versa (Kulkarni & Desai, 2016). In Equation 11, f_i and c_i represented each employed bee's fitness and cost values, respectively. Subsequently, a greedy selection process was executed to determine whether to retain the employed bee's location or replace it with the onlooker bee's location based on the proximity of the 2 locations to the actual PD location. Each bee in the colony was assigned a crucial parameter known as the limit of abandonment (Karaboga, 2005; Karaboga & Akay, 2009). This parameter was increased by 1 whenever the greedy selection process resulted in no replacement of a bee's location, and it was reset to 0 once a replacement occurred. Once a bee exceeded its limit of abandonment, it was sent out as a scout bee to explore new areas within the confined search space to pinpoint the actual PD location. The transition of a bee into a scout indicated that the vicinity of the bee's location was adequately examined, without any new location found to be closer to the actual PD location than the bee's current location. In this study, the limit of abandonment for the bees was set to 180 based on Equation 12 (Karaboga & Akay, 2009), where $N_{employed_bees}$ is the number of employed bees in the colony, and D represents the dimension of the AE PD localization problem, which in this case is 3. At the end of each iteration, the location of the bee with the lowest absolute cost value in the current iteration was compared to the best location identified by the bee colony, denoted as g_{Best} . This comparison was made to ascertain if the current best location was closer to the actual PD location than the previously established best location, g_{Best} . Specifically, g_{Best} was updated only if the absolute cost value of the newly discovered best location in the current iteration proved to be smaller than that of g_{Best} . The ABC was terminated upon completing 500 iterations, and the output was the 3 coordinates (x, y, z)of the estimated PD location in the g_{Best} parameter. The important parameters used for the ABC are tabulated in Table 6.

$$f_{i} = \begin{cases} \frac{1}{1+c_{i}}, & \text{if } c_{i} \ge 0\\ \frac{1}{1+|c_{i}|}, & \text{if } c_{i} < 0 \end{cases}$$
[11]

$$Limit = N_{employed_bees} \times D$$

 Table 6

 Parameters of the ABC for acoustic emission PD localization

Parameter	Value
Size of bee colony	120
Maximum number of iterations	500
Limit of abandonment	180

[12]

PD Localization Analysis

To ensure a fair comparison, all four algorithms employed in this study were carried out over 500 iterations with 120 search agents in each population. For each of the estimated PD locations, the distance error and the maximum deviation were computed based on Equations 13 and 14, respectively (Chakravarthi et al., 2017; Dudani & Chudasama, 2016; Liu, 2016). ΔR in Equation 13 represents the distance error between the estimated PD and actual PD locations based on the Euclidean distance (Hashim et al., 2022). x_{act} , y_{act} and z_{act} in Equations 13 and 14 represent the actual PD location in the test tank, whereas x_{cal} , y_{cal} and z_{cal} signify the estimated PD location by each algorithm. The maximum deviation is denoted by , as shown in Equation 14.

$$\Delta R = \sqrt{(x_{act} - x_{cal})^2 + (y_{act} - y_{cal})^2 + (z_{act} - z_{cal})^2}$$
[13]

$$D_{max} = \max \begin{cases} |x_{act} - x_{cal}| \\ |y_{act} - y_{cal}| \\ |z_{act} - z_{cal}| \end{cases}$$
[14]

RESULTS AND DISCUSSION

Figures 3 and 4 show the PD localizations based on the GA, PSO, BA, and ABC for PD locations A and B, respectively. Each of the estimated PD locations represents the mean of 20 estimates obtained from 20 independent applications for each algorithm. According to the Figures 3 and 4, the estimated PD locations based on ABC are the closest to the actual PD location, followed by BA, PSO and GA.

The ABC consistently demonstrates the highest PD localization accuracy regardless of the arrangement of AE sensors and PD locations A and B, as shown in Figures 5(a) and 5(b). The good balance among the local search mechanism that is provided by the artificial onlooker and employed bees and the global exploration process that is managed by the scout bees allows the ABC to produce good results for the multi-variable PD localization task, with the lowest average distance errors of 0.0481 m for PD location A and 0.0959 m for PD location B (Karaboga & Akay, 2009). In terms of Euclidean distance, the average distance error for PD location A that the ABC obtained is 37.04%, 55.55%, and 48.61% lower than the BA, PSO, and GA, respectively. For PD location B, the average distance error that the ABC produces is 32.27%, 43.15%, and 51.61% lower than the BA, PSO, and GA. Apart from the ABC, the BA performs better than the GA and PSO for the AE PD localization at PD locations A and B, which is a constrained optimization problem (Yang, 2010). It is evident from Figure 5(a) for PD location A, where the average distance error of the estimated PD location by BA is 0.0764 m, which is 29.39% and 18.38% lower than the PSO and GA, respectively. Similarly, from Figure 5(b), the average distance error of the



Figure 3. PD localization for PD location A based on (a) GA (red); (b) PSO (green); (c) BA (blue); (d) ABC (purple)

estimated PD locations for PD location B by BA is 0.1416 m, which is 16.06% and 28.55% lower than the PSO and GA, respectively. The PD localization accuracies of GA and PSO show inconsistency for both PD locations A and B, possibly due to the implementation of probabilistic modeling to change a part of the existing solutions in the search for a better estimated PD location (Karaboga & Akay, 2009; Kulkarni & Desai, 2016). For PD location A, the GA demonstrates more effective exploration and exploitation of the search space than PSO. The average distance error of the estimated PD locations by GA is 0.0936 m, which is 13.50% lower than that produced by the PSO. The PSO showcases a better ability to avoid local convergence and better global search ability for the cases of PD location B because the average distance error of the estimated PD locations produced by the PSO is 0.1687 m, which is 14.88% lower than the GA. The PD locations estimated by both the GA and PSO for both PD locations A and B are farther away from the actual PD location as compared to the ABC, most likely because of the local convergence problem (Karaboga & Akay, 2009; Kulkarni & Desai, 2016; Tang et al., 2008).

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Figure 4. PD localization for PD location B based on (a) GA (red); (b) PSO (green); (c) BA (blue); (d) ABC (purple)



Figure 5. Distance errors of the estimated PD locations by GA, PSO, BA, and ABC for (a) Location A and (b) Location B

The maximum deviations of the estimated PD locations based on the ABC for PD location A are between 0.019 m and 0.069 m, as shown in Figure 6(a). For PD location B, the maximum deviations of the estimated PD locations based on the ABC are from 0.026 m to 0.179 m, as illustrated in Figure 6(b). Based on the BA, the maximum deviations of the estimated PD locations are from 0.025 m to 0.108 m for PD location A and from 0.038 m to 0.207 m for PD location B. The maximum deviations of the estimated PD locations based on the PSO are between 0.061 m to 0.131 m for PD location A and between 0.062 m and 0.232 m for PD location B, as depicted in Figures 6(a) and 6(b). For PD location A, the maximum deviation range for the estimated PD locations based on the GA is from 0.046 m to 0.143 m. On the other hand, for PD location B, the maximum deviation range for the estimated PD locations based on GA is from 0.044 m to 0.261 m. For PD location A, the average of the maximum deviations of the estimated PD locations produced by the ABC algorithm is 0.0387 m, which is 38.77%, 57.14%, and 51.38% lower than the BA, PSO, and GA. For PD location B, the average value of the maximum deviations of the estimated PD locations based on the ABC is 0.0818 m, which is 37.70%, 47.53%, and 48.23% lower than the BA, PSO, and GA. These findings indicate that the estimated PD locations produced by the ABC deviate less from the actual PD location as compared to the BA, PSO, and GA. This consistency in the average of the maximum deviations aligns with the findings of the average distance errors, which highlight the good accuracy and reliability of the ABC for PD localization as compared to the other algorithms.



Figure 6. Maximum deviation of the estimated PD locations by GA, PSO, BA, and ABC for (a) PD Location A and (b) PD Location B

The average computation times for the GA, PSO, BA, and ABC to estimate the PD locations for PD location A are presented in Figure 7(a). Each average computation time in Figures 7(a) and 7(b) represents the mean value of 20 computation times for each AE sensor combination. The average computation time for the ABC is the shortest, with an

average of 0.7556 s. For PD location A, the average computation time by BA is 0.88 s, which outperforms GA, with 1.1509 s and PSO, with 0.9195 s. A similar trend is observed in Figure 7(b) whereby for PD location B, the average computation time for ABC is the fastest with 0.7713 s followed by BA, PSO and GA with 0.8965 s, 0.9375 s and 1.1486 s, respectively. Overall, the ABC takes the shortest time to estimate the PD locations for both PD locations A and B. For PD location A, the average computation time of the ABC is 14.13%, 17.83%, and 34.35% faster than the BA, PSO, and GA. For PD location B, the average computation time of the ABC is 13.97%, 17.73%, and 32.85% faster than the BA, PSO, and GA. The ABC's fastest average computation time to obtain an estimated PD location is probably attributed to its inherent advantage. This advantage stems from the fact that ABC has only 1 control parameter, which is the limit for abandonment. In comparison, other algorithms such as GA, PSO, and BA have at least 2 parameters to be updated for the computation (Karaboga & Akay, 2009).



Figure 7. The average computation time of GA, PSO, BA, and ABC for (a) PD Location A and (b) PD Location B

CONCLUSION

In conclusion, it is found that the ABC outperforms the BA, GA, and PSO in AE PD localization regardless of the AE sensor arrangements and PD locations within the test tank. The distance errors between estimated and actual PD locations by ABC range from 0.0202 m to 0.0831 m for PD location A and from 0.0300 m to 0.1875 m for PD location B, representing the smallest errors obtained in the study. The high PD localization accuracy of the ABC is attributed to its effective search mechanism, which balances local search by onlooker bees with global exploration by scout bees. The ABC exhibits the shortest average computation time to estimate the PD locations in 500 iterations by optimizing the nonlinear localization equations. This is likely due to the algorithm's inherent advantage of requiring only one control parameter. The BA performs better than the GA and PSO, with relatively

lower distance errors for AE PD localization and shorter computation time to obtain the estimated PD locations. GA and PSO show inconsistency in PD localization accuracy, but the average computation time needed by the PSO to give estimated PD locations is shorter than that of the GA. While the ABC shows promise in AE PD localization, its performance might vary with different types and levels of noises or interferences during on-site testing. Future studies could address this by testing the algorithm under different noise conditions and more complex scenarios, such as accounting for the effect of temperature, moisture and pressboard.

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Classification of Bearing Degradation Stage Based on Automatic Label Assignment and Multi-scale Channel-attention Network

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ABSTRACT

Predicting bearing degradation is crucial for precise maintenance. However, accurately predicting the degradation stages of bearings to achieve appropriate maintenance has always been challenging. To address this problem, we propose a network architecture based on automatic label assignment called FAEK and a multi-scale channel-attention classification (MCC) prediction model to predict the degradation stage of bearings at a given time. Our method achieved outstanding performance on the FEMTO dataset with an accuracy of 0.9665. This approach provides an efficient and reliable solution for the predictive maintenance of bearings.

Keywords: Automatic label assignment, bearing degradation prediction, classification prediction model, deep learning, predictive maintenance

INTRODUCTION

Today, with the rapid development of technology and the continuous advancement of industrialisation, the reliability and performance of equipment and systems have become important focal points across various fields. Prognostics and health management (PHM) (Xia & Xi, 2019), an advanced technology and approach, offers an effective means for predicting equipment failure, optimising maintenance, and enhancing reliability through

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E-mail addresses: 21010282@siswa.unimas.my (Xiuyu Li) jtshirley@unimas.my (Shirley Johnathan Tanjong) *Corresponding author real-time monitoring, diagnostics, and prognostics of equipment health.

PHM utilises operational data from equipment to predict health conditions and enable precision maintenance. Compared with traditional methods involving routine inspections and regular checkups, PHM provides an intelligent maintenance

ISSN: 0128-7680 e-ISSN: 2231-8526 approach. In conventional maintenance, determining the optimal timing for maintenance can be challenging; however, with PHM, the stage of the life cycle of the equipment can be predicted, enabling the implementation of appropriate maintenance strategies. This precise maintenance approach significantly enhances equipment maintenance's efficiency and cost-effectiveness while extending its operational lifespan. PHM technology offers equipment managers a more intelligent and efficient maintenance approach to managing large-scale equipment and complex operational requirements.

This paper focuses on bearing components, critical parts of many rotating devices. Their failure can result in equipment downtime and production interruptions, causing significant business losses. PHM technology can establish fault prediction models by collecting and analysing vibration data from bearings. Monitoring changes in the bearing's condition can predict its remaining lifespan. Currently, two main methods exist for predicting the remaining lifespan of bearings. First, the direct prediction method, which relies on machine learning models to directly predict a bearing's lifespan (Li et al., 2019; Wang et al., 2019; Ruan et al., 2023). By inputting feature data into the model, the model directly outputs the predicted value of the remaining lifespan. This approach requires selecting and extracting appropriate features and demands a high level of expertise in feature engineering. However, it cannot explain the bearing's degradation and failure mechanisms. Second, the health indicator method predicts the time when the bearing reaches its failure threshold by monitoring its degradation process (Wang et al., 2021; Ren et al., 2018; Sanakkayala et al., 2022). Subsequently, it calculates the remaining useful life. This approach requires the prior determination of suitable health indicators and thresholds, which relies on understanding the system's characteristics and degradation behaviour, making it challenging.

In the PHM of bearings, the regression problem of predicting the remaining life of a bearing is transformed into a classification problem. Rather than solely predicting the remaining life of the bearing, we are more interested in determining the current stage of the bearing's lifecycle. It enables us to conduct more effective maintenance and management procedures. To achieve this, we can divide the entire lifespan of the bearing into different stages, and with the given bearing data, we can predict the current stage of the bearing life. It can aid in identifying appropriate maintenance strategies and operational measures, enabling us to implement suitable preventive maintenance or repair actions at different stages.

Based on this, this paper proposes a method for the early prediction of bearing degradation. This method combines a convolutional autoencoder segmentation network with a high-performance classifier to effectively differentiate and accurately classify bearing degradation processes. It provides more comprehensive and reliable support for the health assessment of bearings and maintenance decision-making. The contributions of this study are as follows:

- We propose a model based on convolutional autoencoders that can selectively distinguish different stages of bearing degradation. The network learns a low-dimensional representation of the input data and uses reconstruction to segment the data into different stages of degradation. By utilising a convolutional autoencoder segmentation network, we can extract crucial features from bearing vibration data and employ them for subsequent classification tasks.
- We propose a high-performance classifier for classifying and identifying the different stages of bearing degradation. To better adapt to the bearing degradation classification task, we extract both frequency and time-domain features based on the vibration data of the bearings used to train the classifier.
- The classifier architecture is based on multi-branch parallel convolution and attention mechanisms, enabling it to capture long-distance dependencies within sequential data and learn the correlations between features. Consequently, our classifier achieves high accuracy in classifying the bearing degradation stages.

RELATED STUDIES

Existing research on bearing fault prediction has largely focused on predicting the remaining useful life (RUL). However, in PHM for bearings, we are more concerned with accurately determining a bearing's current life stage at a given time. Therefore, this section discusses research related to the segmentation of bearing degradation stages.

In the PHM domain of bearings, accurate segmentation of the bearing degradation stages is crucial for achieving precision maintenance and management. Unlike solely predicting the RUL, accurately segmenting the degradation stages of bearings enables appropriate maintenance strategies and actions to be identified, such as implementing preventive maintenance or corrective measures at different stages. Researchers have proposed various methods and techniques to precisely segment bearing degradation stages. Among them, approaches based on image segmentation, deep learning, and unsupervised learning have played a significant role in research on bearing degradation stage segmentation.

Methods based on image segmentation transform vibration data into an image format and utilise image segmentation algorithms, such as threshold segmentation and edge detection, to separate degraded regions from normal regions in the vibration images (Liao et al., 2022; Wang et al., 2017). However, this approach can only achieve segmentation for two stages and may not accurately differentiate complex bearing degradation processes, such as the early stages of degradation. Deep learning-based methods using convolutional neural networks (CNNs) (Wang et al., 2021; Zhou et al., 2019) and RULNet (Gamanayake et al., 2023) have been used for feature learning and segmentation on vibration signals. These approaches can automatically learn feature representations and complex relationships, enabling precise bearing degradation segmentation. Nonetheless, deep learning methods typically require a large amount of labelled data for supervised learning, which poses challenges in engineering applications. Manually annotating a large-scale vibration dataset is time-consuming and labour-intensive, demanding domain expertise and experience correctly labelling samples of different degradation stages.

Segmentation methods based on unsupervised learning enable the segmentation of bearing degradation stages without requiring labelled data. For instance, methods such as generative adversarial networks (Mylonas & Chatzi, 2020) and variational auto-encoders (Hong et al., 2014) can learn the latent representation and distribution of data, enabling the segmentation of bearing degradation and dividing degraded areas into different categories. In unsupervised learning approaches, the key lies in modelling bearing degradation. Based on the nature of the degradation process, bearing degradation modelling methods can be categorised into continuous degradation and discrete degradation stage models.

The continuous degradation model aims to establish a single model to describe the gradual deterioration of the bearing's life. This model type is typically based on physical principles, statistics, or machine learning. The continuous degradation model considers the progressive changes in the bearing life and can capture the trends of bearing degradation based on various indicators (e.g. vibration features, temperature, and load). Common continuous degradation models include physical models (Cui & Su, 2021; Li et al., 2023), Markov processes models (Gu et al., 2023; Kou et al., 2022), and regression models (Chen et al., 2022). By estimating and predicting the parameters of a continuous degradation model, the model can forecast and assess the remaining life of a bearing. The establishment and prediction of the continuous degradation model are based on existing bearing degradation data and the assumption that the degradation process is continuous and gradual. However, the actual bearing degradation process may be influenced by multiple factors, such as working conditions, load variations, and environmental factors. These factors may result in discrepancies between the model and actual scenarios.

In the discrete degradation stage model, the bearing lifespan is divided into multiple discrete stages, based on which the bearing conditions are modelled and predicted. This model can adapt better to the nonlinearity and uncertainty of degradation processes in practical scenarios. Common discrete degradation stage models include hidden Markov models (Aggab et al., 2022) and time-series models (Cao et al., 2021; Zhu et al., 2023). These models can better describe and identify the different stages in the bearing degradation process, thereby assisting in determining appropriate maintenance strategies and operational measures.

The bearing discrete degradation stage model proposed by Juodelyte et al. (2022) transforms the life prediction into a classification problem. However, this model fails to identify effective features, resulting in lower accuracy in predicting early-stage bearing

degradation. In contrast, our proposed approach introduces a convolutional autoencoder. It combines it with a domain-knowledge-based automatic data labelling strategy and a classifier based on a multi-scale attention network architecture. This model is suitable for predicting degradation throughout a bearing's lifespan.

METHODS

Bearing degradation can be categorised into four stages based on the observed physical manifestations and features in the frequency and time domains. This classification helps us better understand the changing trends and status evolution of bearing life. Each stage exhibits different degradation characteristics and requires specific maintenance strategies to prolong the lifespan of the bearing and ensure reliable equipment operation. Table 1 summarises the characteristics and corresponding maintenance strategies for each stage.

Stage	Physical Characteristics	Time-domain Characteristics	Frequency-domain Characteristics	Maintenance Strategy
Healthy	The bearing is in normal operating condition.	It is manifested as stable periodic oscillations.	Normal operating frequency components are displayed in the spectrum.	Monitor and record the baseline condition and performance parameters of bearings.
Early degeneration	Minor signs of degradation, e.g. scratches, tiny cracks, or slight wear.	Minor non- periodic variations may occur, e.g. slight changes in amplitude.	High-frequency components related to early-stage faults appear in the spectrum.	 Monitor spectrum data and observe early signs of fault variations. Perform regular vibration analysis and diagnosis. Timely lubricate and clean.
Severe degeneration	More significant and severe degradation.	Manifests as evident non-periodic fluctuations, potentially accompanied by more amplitude variations and waveform distortion.	The spectrum has more high-frequency components and wide- band noise associated with bearing faults.	 Strengthen vibration analysis and fault diagnosis. Implement appropriate maintenance and replacement measures. Inspect lubrication conditions and the performance of lubricants.

Table 1Bearing degradation stage classification

Stage	Physical Characteristics	Time-domain Characteristics	Frequency-domain Characteristics	Ma	intenance Strategy
Failure	Severe fault state	Significant mutations, shocks, or irregular fluctuations may occur.	More high-frequency components and wide-band noise may appear in the spectrum, possibly causing impact frequencies.	1.	Inspection and replacement of bearings and their related components. Root cause analysis to prevent similar failures from occurring again.

Table 1 (continue)

This paper collects time-domain vibration data during the operation of bearings for bearing life-stage prediction. The problem is divided into two stages. Assuming the input is $X \in Rk, t = (0, 1, \dots, T)$, where T is the time step. X contains the complete life cycle data of the bearings. The data transformed into the frequency domain is represented as $F(X) \in Rm$, where m is the dimension of frequency domain features. The model maps the frequency domain features to bearing life-stage labels $L \in \{0,1,2,3\}$ to form life labels, reflecting different degradation states of the bearings. Equation 1 represents Stage I:

L = M(F(X))^[1]

M represents the model function for Stage I.

Assuming the input data are $X \in Rk$, and $L \in \{0,1,2,3\}$, representing different life-stage labels of the bearings, the model takes input data X, which include the frequency and time domain features of the bearings, along with life-stage labels L. The output is the predicted life-stage label of the bearings, denoted as $P \in \{0,1,2,3\}$. Equation 2 represents Stage II:

P = G(X,L)^[2]

G represents the classifier for Stage II.

The functions M in Stage I and G in Stage II can be used to classify and predict the degradation stage of the bearing vibration data. This aids in determining the bearing life stage at a given time point and provides corresponding maintenance strategies. Figure 1 shows the workflow of our model, which is divided into two parts based on the description of the aforementioned problem. In the following, we discuss each submodel in detail.

Classification of bearing degradation based on FAEK and MCC



Figure 1. Bearing life-stage workflow

Bearing Degradation Model

The proposed bearing degradation model, FAEK, consists of data pre-processing, a convolutional autoencoder, and a clustering operation. The architecture of the FAEK network is shown in Figure 2.



Figure 2. FAEK network architecture

First, the bearing vibration data are subjected to a fast Fourier transform (FFT) to determine the vibration signal's dominant frequency components and energy distribution, thereby extracting features related to bearing degradation. These features can be used to divide the degradation stages. Assuming that the bearing vibration data are represented as a time series x(t), where t represents the time, the frequency-domain transformation can be expressed as Equation 3:

$$X(f) = ABS(FFT(x(t)))$$
^[3]

X(f) is the frequency-domain representation of the vibration data, f denotes the frequency, and ABS is the absolute value.

The frequency-domain signals of the bearings are fed into the convolutional autoencoder to learn the feature representation of the data through unsupervised learning. The convolutional autoencoder consists of an encoder and a decoder. The encoder compresses the input data into a latent representation, and the decoder decodes the latent representation into the reconstructed input data. In contrast to traditional fully connected autoencoders, convolutional autoencoders utilise convolutional operations in the encoding and decoding processes. In the bearing degradation model, the encoder uses 32, 64, and 128 convolutional kernels to sample the pattern information thrice. Then, it samples 64, 32, and 1 convolutional kernel in the decoder to recover the data thrice. The convolution kernel size for both the encoder and decoder is 3.

The encoder takes the input data and processes them through convolution and activation operations. It gradually reduces the size of the feature maps through maxpooling operations and extracts and compresses feature information from the input data. The results of the convolutional and pooling layers are denoted as h and p, respectively, in Equations 4 and 5:

$$h = ReLU(Conv1D(W,b)(x))$$
[4]

$$p = MaxPooling1D(h)$$
^[5]

Conv1D represents a one-dimensional convolution operation; *W* and *b* are the weights and bias parameters corresponding to the convolutional layer; *ReLU* represents the activation function; *MaxPooling* represents a one-dimensional max-pooling operation.

The decoder gradually restores the size of the feature maps through upsampling operations, followed by convolution and activation operations, to obtain the reconstructed output. *UpSampling* can be represented as u in Equation 6:

F < 7

$$u = UpSampling1D(h)$$
^[6]

UpSampling 1D represents the one-dimensional up-sampling operation.

Using a convolutional autoencoder, we can capture meaningful features from bearing vibration data and transform them into a meaningful representation. The convolutional autoencoder is trained in an unsupervised learning manner, eliminating the necessity for manual labelling of the bearing data's life stages and avoiding reliance on handcrafted feature engineering. The design of the convolutional autoencoder enables it to perform exceptionally well in processing the time-series data of bearing vibrations, enabling it to extract temporal correlations and local features from the data.

Finally, by mapping the learned features into a clustering space, the bearing data can be effectively grouped into different degradation stages, generating the corresponding labels. It provides essential guidance for subsequent maintenance decisions. This data-driven approach exhibits a good generalisation performance and can adapt to various types and scales of bearing data, making it a viable solution for practical engineering applications.

Prediction Model

Early signs of bearing degradation are only visible in the frequency domain (Qiu et al., 2023). We propose a multi-input classification network architecture, which we refer to as the multi-scale channel-attention classification (MCC) model, to capture both the frequency-domain features associated with early degradation signs and time-domain features that intensify with the progression of degradation. Figure 3 shows a schematic of this architecture.

In this architecture, we simultaneously input the time domain, frequency domain, and degradation signals. Time-domain signals provide more detailed temporal information, whereas frequency-domain signals can better capture the frequency characteristics. By combining these two inputs, we can fully exploit their complementarities. The network has three layers: multi-scale processing, channel attention, and classification. The substructures are discussed in detail in the following.

The multi-scale processing layer consists of a multi-branch parallel convolution, utilising four parallel convolutional branches to extract different frequency domain features. Each branch extracts a set of feature maps, capturing distinctive aspects of the input data. These feature maps are then fused to obtain a more comprehensive representation of the features. This approach provides a richer and more diverse feature representation, enabling the network to adapt to various bearing degradation patterns and enhance its ability to extract complex features.

If the input data are denoted as X, the number of convolution kernels is N, the size of each convolution kernel is $K \times K$, the number of input data channels is C, and the number of output feature maps is M. The weight matrix of each convolution kernel $I (1 \le i \le N)$ is represented as W_n with the shape $K \times K \times C$, and its bias term is b_n . The output of the

multi-path convolution operation for the m-th feature map of the input data X can be calculated using Equation 7:

$$Y_{\rm m} = \sum^{n} f(\operatorname{conv}(W_{\rm n}, X) + b_{\rm n})$$
^[7]

Here, $conv(W_n, X)$ denotes the convolution operation of input data X with convolution kernel W_n , b_n denotes the bias term of the *n*-th convolution kernel, and *f* denotes the ReLU function.

During the bearing degradation process, the frequency spectrum characteristics of the vibration signal change. Traditional single convolutional kernels often struggle to capture subtle variations across frequency bands. By contrast, multiple parallel convolutions, known as multi-branch parallel convolutions, employ several parallel convolutional kernels, each corresponding to a different frequency band. It enables better extraction of signal features in the frequency domain. Moreover, multi-branch parallel convolution increases the depth and width of the network, providing more parameters and nonlinear expressive power. Consequently, the model can better adapt to complex vibration signal features, improving its bearing degradation research performance.



Figure 3. MCC architecture

Channel Attention Layer

The channel attention network won the championship in the ImageNet classification task in 2017 (Hu et al., 2019). It can enhance the attention mechanism of CNNs by adapting the importance of features across channels to improve network performance.

The channel attention module comprises two key steps: squeezing and excitation. In the squeezing step, the input feature map undergoes global pooling along the channel dimensions to obtain global information regarding each channel. In the excitation step, a nonlinear function is learned to transform the squeezed features into channel attention weights that adjust each channel's importance in the input feature map. Figure 4 shows the structure of the channel attention module.



Figure 4. Channel attention module (Hu et al., 2019)

Squeezing: If the input feature map has dimensions H, W, and C, the compression operation applies global average pooling to the input feature map, resulting in a C-dimensional vector that represents the global average value for each channel. This vector indicates the overall importance of each channel in the input-feature map. The output result Z can be represented as Equation 8:

$$Z = F_{sq}(X) = \frac{1}{H \times W} \sum_{i=1}^{H} \sum_{j=1}^{W} X(i,j)$$
[8]

Excitation: The excitation operation generates channel attention weights by learning a nonlinear mapping function. The mapping function can be learned using a fully connected or one-dimensional convolutional layer. Given an input feature vector Z, the result of the excitation operation, denoted as S, can be represented as Equation 9:

$$S = \sigma(W2 * \delta(W1 * Z))$$
^[9]

S is a C-dimensional vector, representing the attention weights for each channel, W1 and W2 are weight matrices, denotes the ReLU activation function, and represents the sigmoid function.

Scale: The channels of X are reweighted by performing element-wise multiplication between S and X. Thus, the weighted feature map Y is calculated as Equation 10:

$$Y = Fscale(S, X) = S * X$$
^[10]

By learning the weights of each channel, the channel attention network can adaptively enhance important features. The vibration frequency-domain signals of the bearings can be used to extract the most representative and discriminative frequency-domain features, which is beneficial for accurately analysing the degradation of bearings. Moreover, the channel attention network can significantly improve the network performance without introducing additional parameters. It is particularly important for large-scale data processing in bearing degradation research because bearing vibration signals are typically high-dimensional timeseries data. The network can efficiently and accurately extract features without increasing the network complexity.

Classification Layer

In bearing fault diagnosis, the time-domain features are crucial for capturing fault conditions. Skewness and kurtosis are commonly used time-domain features that reflect vibration signals' symmetry and impulsive characteristics. These features are essential for predicting the degradation of bearings. When the bearings are faulty, the pulse components in the vibration signal typically increase, making these features valuable for bearing fault diagnosis. Additionally, dimensionless parameters can mitigate the influence of operating conditions and other factors on the model. Common dimensionless parameters include the clearance, waveform, impulse, peak, and kurtosis indices. The clearance index is often used to indicate wear conditions. In contrast, the peak, impulsion, and kurtosis indices are used to describe the impact characteristics of the signal, aiding in better characterising early degradation. Table 2 presents the 13 time-domain features that we extracted (Zhu et al., 2014).

To identify bearing degradation more accurately, the feature dimensions of the vibration signal were reduced after performing feature extraction with the aforementioned two-layer structure. By combining frequency-domain and time-domain features and then applying linear layers and softmax for degradation-stage prediction, this fusion approach enables comprehensive utilisation of information from both feature categories, thereby enhancing diagnostic and predictive accuracy. Thus, to predict the bearing stage model, the convolution operation of the input layer uses 32 convolution kernels for sampling, all with a size of 3 and an activation function of ReLU.



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RESULTS AND DISCUSSION

We used a publicly available bearing dataset to validate the proposed model's performance. We evaluated automatic label assignment and compared the classification results for different bearings under various operating conditions. Additionally, we assessed the accuracy of predicting the bearings' degradation stages and made comparisons to demonstrate the effectiveness of our model in predicting bearing degradation. We aimed to understand the effectiveness of the model in generalising across different types of bearings and operating conditions.

Datasets Description

This study employed the FEMTO-ST bearing dataset for training and evaluation (Zhang et al., 2018). This dataset contains horizontal and vertical vibration measurement data of ball bearings with rolling elements collected through experiments. The bearings were tested under pressure exceeding the recommended load to accelerate the degradation process. As shown in Table 3, 17 bearings were tested under three different load and speed conditions. For safety reasons, the experiment stops when the accelerometer reading exceeds 20g, indicating that the bearing has reached the final degradation stage. Due to the high variability of bearing life (from 28 minutes to 7 hours), the FEMTO bearing dataset is challenging (Figure 5). There is no specific explanation for the bearing malfunction. Even worse, the data challenge description mentions that bearings may have multiple defects occurring simultaneously. During the experiment, the vibration data of the bearing was sampled every 10 seconds at a frequency of 25600Hz for 0.1 seconds. As a result, each sample contained 2560×2 data points.

Table 3FEMTO-ST dataset (Zhang et al., 2018)

Working conditions	Load force (N)	Speed (r/min)	No. of training sets	No. of test sets
1	4000	1800	2	5
2	4200	1650	2	5
3	5000	1500	2	1

Data Preparation and Experimentation

First, we pre-processed raw data from the FEMTO-ST dataset. We independently separated and processed the data for each direction because the dataset contains vibration signals for horizontal and vertical directions. We applied an FFT to convert the vibration signal in each direction into the frequency domain and extract the frequency-domain features. Additionally, we extracted the time-domain features for each direction's vibration signal
based on the feature list provided in Table 2, described their statistical and impulsive characteristics, and then fused the features from horizontal and vertical directions to obtain comprehensive and integrated bearing features. Because each bearing may have different operating conditions and degradation patterns, we performed all the above operations separately to capture its unique vibration characteristics and degradation patterns.

We used cross-entropy as the loss function and the Adam optimiser to train the model. During the iterations, we employed gradient clipping techniques to prevent gradient explosions. The batch size for all the networks was 64, and the learning rate was 0.01. All the experiments were conducted on a Windows 10 operating system with an Intel i5-12490F CPU and an NVIDIA RTX 3060 12 GB GPU. Our code was written in Python 3.8 using PyTorch.

To evaluate the effectiveness of the automatic label assignment of the model, we compared automatically generated stage labels with manually assigned stages from for the training set (Sutrisno et al., 2012). Smaller differences indicated better accuracy in the model label assignment. Additionally, to assess the performance of the bearing stage prediction classifier, we compared the predicted stages with the stages automatically labelled by our model for the test set to evaluate the prediction accuracy. As bearing PHM requires predictions to follow the actual degradation sequence over time, we also considered the overlap between predicted and actual stages when predictions were made in chronological order, which aided in gauging the model's reliability.

Experimental Results

Data labelling: We automatically assigned degradation stages to the six bearings in the training set and compared the results with those of the manually labelled stages. As shown in Figure 5, the model's automatically assigned bearing degradation stages were in good agreement with the manually labelled stages, indicating that the model performed well in identifying the bearing degradation stages. Although some overlap was observed between adjacent stages, this was reasonable because of the continuity of the degradation process and variations in the signals, which may have resulted in some degree of overlap between neighbouring degradation stages. The model demonstrated excellent performance in distinguishing between healthy and faulty stages, which is crucial for early maintenance and timely identification of failed bearings. The FEMTO-ST dataset was collected under extreme operating conditions, resulting in relatively short healthy stages for all bearings, which aligned with real-world scenarios.

However, for bearing1_2, the model's performance was relatively poor. This was owing to the excessive amplitude of the smoothest maximum acceleration in the vertical direction, which resulted in strong interference in the signal. Despite this, the model exhibited good accuracy and robustness in automatically assigning bearing degradation stages.



Figure 5. The training set degradation labels: Top: Smoothed maximum acceleration obtained by averaging the five highest absolute acceleration measurements in the time domain (Sutrisno et al., 2012). Bottom: Automatically assigned labels obtained using the FAEK model. The vertical lines represent the manually assigned results

Classifier

After automatically labelling the training set for the six bearings using the FAEK model, we compared the performances of the AE model (Juodelyte et al., 2022), 1DCNN model (Wang et al., 2021), and our proposed MCC model in predicting the bearing degradation stages (Figure 6).



Figure 6. Accuracy of different classification models

The results indicated that the MCC model outperformed the other two with remarkable classification accuracy for the bearing degradation classification task, reaching approximately 0.9665. The superiority of the MCC model can be attributed to its innovative design and feature extraction techniques. The model adopts multi-path convolution and attention mechanisms to effectively extract meaningful features. Additionally, we simultaneously trained the model on both the horizontal and vertical data of the bearings and ultimately fused the frequency- and time-domain features.

The AE and 1DCNN models exhibited similar performances, with maximum accuracies of 0.8471 and 0.8763, respectively. Notably, our proposed MCC model achieved an accuracy greater than 0.9 after only 30 epochs, indicating its high convergence speed. This efficiency makes the MCC model more effective in solving the bearing degradation classification task, thereby providing timely and accurate solutions for bearing fault diagnosis and prediction.

To validate the accuracy of our model in predicting the bearing degradation stages further, we compared the results of the MCC and 1DCNN models on the test set (Figure 7). The left-hand figure shows the prediction accuracy of the 1DCNN model. The box plot reveals that the 1DCNN model had a lower classification accuracy in stages 1 and 3, with the median line of the boxes being relatively low and the boxes narrow, indicating a significant dispersion of data in these two stages. In particular, the performance was poor in bearing degradation stage 1. The right-hand figure in Figure 7 shows the results of our MCC model, indicating a high classification accuracy at all stages. The median line of the boxes was higher, and the boxes were flatter, suggesting a higher concentration of data at each stage. Therefore, the MCC model exhibited more stable performance and superior results.



Figure 7. Test set accuracy of the models (based on FAEK labels). Left: 1DCNN model. Right: MCC model

Figure 8 shows the statistics on the overlapping rates between the adjacent stages of all 11 bearings in the test set. Our model's predicted results had a low overlapping rate, indicating the MCC model's ability to distinguish different degradation stages and better identify the distinctive features of each stage in the bearing degradation classification task.



Figure 8. Overlap rate of adjacent stages for the models. Left: 1DCNN Model. Right: MCC Model

We presented the prediction results using a smoothing classifier to reduce prediction fluctuations at individual time points and obtain more stable predictions. Specifically, we generated the posterior probabilities for five predictions for each time point in the test set. We calculated their average within a fixed sliding window, resulting in smooth classifier predictions.

Figure 9 shows the prediction results for three different operating conditions for the test set containing 11 bearings. The graphs show that the predicted bearing degradation stages aligned well with the actual bearing degradation progress over time, indicating that our predictions were highly accurate and consistent with the actual degradation processes of the bearings.



Figure 9. Prediction results for bearings 1_5 (top), 2_4 (middle), and 3_3 (bottom)

CONCLUSION

This study focused on the problem of predictive maintenance for bearings, aiming to classify bearings into four degradation stages to predict at a given time point when the bearing is in the degradation stage and to provide corresponding maintenance strategies for different stages. We propose a method based on a FAEK automatic label assignment and an MCC prediction model to achieve this. This model has the following characteristics: (1) automatic label assignment: We use a convolutional autoencoder-based approach to segment the full-lifetime vibration signals of bearings into different stages. The FAEK automatic label assignment effectively distinguishes different degradation stages of bearings, avoiding the laborious and subjective nature of manual label assignment, and (2) prediction model: We input both time- and frequency-domain features of bearing signals into the MCC

classification model, which includes multiple convolutional modules and channel attention modules. These modules aid in better extracting signal features and achieving a precise prediction of the bearing degradation stages. With this prediction model, we can accurately predict the degradation status of bearings and promptly perform corresponding maintenance measures. We validated this network architecture using the FEMTO dataset. The results revealed excellent performance. The automatically assigned labels highly overlapped with the manually assigned labels, successfully distinguishing different degradation stages. For degradation-stage prediction, our model architecture achieved an accuracy of 0.9665.

The bearing dataset used in this study is relatively clean, whereas in practical industrial applications, bearing data may be subject to various types of interference and noise. Additionally, the accuracy of the automatically assigned labels requires further discussion and improvement. Future research should explore better segmentation methods to improve the quality of labels. Only by improving the quality of the labels can our classification prediction results become more trustworthy and reliable, thereby providing more effective support for the predictive maintenance of bearings.

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Review Article

Machine Learning Precision for Mangosteen Maturity: A Comparative Analysis of Conventional Classifiers

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ABSTRACT

Identifying mangosteen maturity stages pre-harvest is crucial for postharvest quality, as fruit disease and pest infestation often occur at specific stages. Deep learning, while popular for classification, struggles with false negatives. Conversely, conventional machine learning methods now effectively handle false negative issues. The main goal of this research is to determine the significant comparison between different conventional classifiers, namely Random Forest (RF), Decision Tree (DT), Support Vector Machine (SVM) and K-Nearest Neighbour (K-NN), in terms of their accuracy, validity, and False Negative Rate (FNR) in predicting six distinct classes. Image samples of 253 mangosteens across six maturity stages were used, with 20 regions of interest (ROIs) each. 112 Gray-level Co-Occurrence Matrix (GLCM) and colour features were extracted to train models using texture, colour, and combined features. The evaluation metrics used for assessing the validity of predictions

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for colour, and 1.00 for combined features. In conclusion, the RF classifier outperforms other classifiers in accuracy, validity, and mean FNR across six classes with three category features, achieving statistical significance in the Friedman Test.

Keywords: Conventional machine learners, decision tree, fruit maturity, K-Nearest Neighbour, random forest, support vector machine

INTRODUCTION

Mangosteen, technically known as Garcinia mangostana, is a tropical fruit native to Southeast Asia, notably Malaysia, Indonesia, and Thailand. Mangosteen is grown extensively in Malaysia's Pahang, Johor, and Perak states. Malaysia is a significant supplier of mangosteen worldwide, and the demand for this tropical fruit is growing, particularly in the United States, Europe, Japan, the Arab region, and ASEAN countries. Mangosteen is one of the nine premium fruits targeted by the Malaysian government, and mangosteen exports have increased by 65% since 2020 (IndexBox, 2024). The conventional method of assessing and identifying fruit quality through manual inspection by trained professionals is time-consuming and impractical for efficiently categorising large volumes of fruits intended for export within a limited time frame. To optimise the efficiency of fruit sorting and elevate the quality of categorisation and filtering, leveraging image processing and machine learning (ML) algorithms proves advantageous, as highlighted in studies by Pandey et al. (2013) and Liakos et al. (2018).

Recent trends employ deep learning (DL) in many aspects, including prediction and classification research areas, including crop grading, maturity or ripeness classification, and crop-yielding prediction (Khan, Nauman et al., 2022, Khan, Faheem et al., 2022; Joshua et al., 2022; Bashir et al., 2023; Orchi et al., 2023). Other studies which utilised DL in classifying leaf disease by Parashar and Johri (2024) and fruit maturity and defective fruits are by Al-Mashhadani and Chandrasekaran (2021), Mohtar et al. (2019), Kim et al. (2023), Ashtiani et al. (2021), Benmouna et al. (2022), Gao et al. (2020), Tan et al. (2020), Muñoz et al. (2022), Azizah et al. (2017) and Sudana et al. (2020). Nevertheless, according to Rushing (2022), the No Free Lunch (NFL) theorem claims that no particular ML algorithm is always the most effective for a given situation. Regardless of the contrasting notion among researchers, this work tends to agree that research utilising traditional machine learners should be continued so that improved techniques can be discovered in conventional machine learners to be, at the minimum, on par with deep learners' performance. Orchi et al. (2023) revealed that, despite the superior performance of the InceptionV3 network in terms of accuracy, precision, and recall, the Random Forest (RF) classifier demonstrated a markedly lower False Negative (FN) rate compared to other experimented models. Their findings are crucial for achieving heightened accuracy and mitigating misclassification rates.

In combining texture and coloured features, Phothisonothai and Tantisatirapong (2019) achieved 88% accuracy for mangosteen maturity stages within 3 classes. Whidhiasih et al. (2012) reached 85% accuracy across 6 maturity stages. Riyadi et al. (2020) achieved 94.16% accuracy, focusing on skin defects, not maturity stages. In addition, Parashar and Johri (2024) resulted in 94.76% accuracy in determining 4 classes of apple leaf disease. Several studies advocate for the incorporation of coloured features in fruit grading, as proposed by Khojastehnazhand et al. (2010) and Liming and Yanchao (2010). Damarjati et al. (2017) aced 80.8% accuracy using statistical features from mangosteen, but it focused on skin defects. Indeed, Afandi et al. (2021) scored 96.67% accuracy using texture features extracted via the Gray-level Co-Occurrence Matrix (GLCM) and executed using Extreme Learning Machines (ELM) for mangosteen. Nevertheless, the work detects skin defects. Another study by Riyadi et al. (2018) attained an accuracy of 92.5% utilising Discrete Cosine Transform (DCT) extracted texture features. However, the work detected mangosteen binary classes for skin defects unrelated to the fruit's maturity stages.

In a different category where numerical data were used, Khan, Faheem et al. (2022) achieved an accuracy of 96% and Joshua et al. (2022) with 97%, respectively. Khan, Nauman et al. (2022) and Bashir et al. (2023) gained accuracy of 78% and 91.44%, respectively, also using numerical data. These studies attempted to match the shape of the standard irrigation model.

The primary goal of this research is to compare the significance of various conventional classifiers, namely RF, DT, SVM and kNN, in terms of their accuracy and validity across various metrics such as accuracy, precision, recall, F1-score, and Cohen's Kappa when predicting six distinct classes. Next, this study aimed to analyse the processing power of the traditional machine learning models in relation to the false negative rate. In this area, deep learning models may fall short. This work attempts to understand the inherent strengths and limitations intrinsic to the classification methods implemented throughout this study, thus contributing to the advancement of knowledge not only of mangosteen maturity classification but also of other agricultural studies.

MANGOSTEEN CHARACTERISTICS

Mangosteen maturity is defined by various parameters such as size, colour, texture, and flavour, traversing through six discernible phases, each with unique characteristics. The first phase, Index Class 1, is marked by an immature yellowish-green colour, small size, and high mucus content. In Index Class 2, the fruit is half-developed green, continuing to mature with reduced mucus. Moving on to Index Class 3, the fruit's colour transitions to mature red-brownish, and the flesh becomes separable. Index Class 4 signifies ripeness, with the fruit maturing into red-purple hues, and the flesh is ready for consumption. Fully ripe in Index Class 5, the reddish mangosteen offers the finest flavour for immediate

consumption. Finally, Index Class 6 indicates an overripe state, characterised by a purpleblack colour, with mushy flesh. A visual representation of this multiclass progression of mangosteen maturity stages is depicted in Figure 1, as documented by Acharya et al. (2018) and Thammastitkul and Klayjumlang (2021), providing valuable insights into the intricacies of mangosteen development.



Figure 1. Mangosteen Maturity (a) Index Class 1; (b) Index Class 2; (c) Index Class 3; (d) Index Class 4; (e) Index Class 5; (f) Index Class 6

MACHINE LEARNING TECHNIQUES

The K-NN method, a supervised learning technique, evaluates new datasets by measuring their proximity to the k-nearest data points within the training set. It involves storing the training data and calculating the distance between each new and existing data point. Then, the K-NN algorithm identifies the k closest data points and assigns the new data point to the class containing most of these k nearest neighbours. Widely used for classification and regression tasks (Riyadi et al., 2020; Kim et al., 2023), the algorithm determines the projected label for a test sample in classification by selecting the label that predominates among the target labels of the k-selected training samples, as illustrated in Figure 2. K-NN's

simplicity and effectiveness make it a popular choice in various fields, including pattern recognition, image recognition, and recommendation systems.



Figure 2. How K-NN determines classes (a) calculating distance (b) new data is classified

A Decision Tree (DT) serves as a tree-based methodology for decision-making and predictive modelling. It recursively partitions the data into subsets based on the most influential attribute and its corresponding value. This process continues until a decision or leaf node that denotes a prediction is reached. Each division in the tree represents a decision, and the path from the root to a leaf node delineates a sequence of decisions leading to a prediction. DTs exhibit versatility in handling categorical and numerical data, making them applicable to classification and regression tasks. Employing a hierarchical tree structure, the DT algorithm characterises datasets and computes discrete target-valued functions, as illustrated in Figure 3. The classification is accomplished by organising tree instances from the root to a leaf node. Meanwhile, each node of the tree corresponds to an attribute, and each branch signifies the value of that attribute. DTs stand as a robust tool widely employed across diverse domains for their interpretability and effectiveness in decision-making processes.

The Support Vector Machine (SVM) is a powerful supervised learning technique applicable to classification and regression endeavours. Its fundamental aim revolves around identifying the hyperplane that effectively segregates the data into separate classes or predicts target values accurately. This hyperplane's placement hinges on maximising the margin between it and the nearest data points, commonly known as support vectors. These support vectors, known as support vectors, serve as pivotal elements in delineating the hyperplane. These support vectors serve as pivotal elements in delineating the hyperplane and exert significant influence in making predictions for novel data points. The intricacies of SVM's operation and reliance on support vectors are vividly portrayed in Figure 4,



Figure 3. Construction of Decision Trees



Figure 4. How a class is determined in Support Vector Machine (SVM)

elucidating its practical implementation and theoretical underpinnings (Kim et al., 2023). Notably, SVM's versatility extends beyond linear separation, encompassing non-linear relationships through techniques like kernel methods.

It is a cornerstone in various domains, including image recognition, bioinformatics, and financial forecasting, underscoring its indispensable role in modern machine learning paradigms.

In contrast, Random Forest (RF) emerges as an ensemble learning framework meticulously crafted for classification and regression tasks. Unlike singular decision trees, RF constructs numerous Decision Trees (DTs), amalgamating their predictions to yield a comprehensive outcome. Each tree within the forest stands as a unique entity, fashioned from a random subset of the dataset and a random selection of features. This diversity among the trees fortifies the model's resilience and predictive prowess, mitigating the risk of overfitting. The ultimate prediction is forged by amalgamating outcomes from all constituent trees in the random forest, elucidated in Figure 5 (Goel & Abhilasha, 2017; Ashtiani et al., 2021). RF's versatility extends beyond linear separations, facilitating the discernment of complex, non-linear relationships present in data. Its efficacy and adaptability render it a cornerstone in modern machine learning, finding applications in domains ranging from finance to healthcare, underpinning its status as a quintessential tool in predictive analytics.



Figure 5. Concept of Random Forest

METHODOLOGY

Image Acquisition

The mangosteen samples for this study were provided by the Malaysian Agriculture Research Development Institute (MARDI) in Changlun, Kedah, Malaysia. Postharvest, these specimens underwent photographic documentation at the Post Harvest Department, as seen in Figure 6a and Figure 6b. Image acquisition employed a Do-It-Yourself (DIY) mini-studio setup, outlined in Figure 6c, capturing the external surface of the mangosteen. A light source ensured optimal visibility. Despite a limited number of images, 20 regions of interest (ROIs) were extracted from each, standardised to 512 x 512 pixels. Table 1 outlines the distribution of images and ROIs across different maturity classes: Class 1 contributed 25 images and 525 ROIs, Class 2 had 14 images and 294 ROIs, Class 3 contained 48 images and 1008 ROIs, while Class 4 comprised 62 images and 1302 ROIs. Classes 5 and 6 included 51 and 53 images, contributing 1071 and 1113 ROIs, respectively. From each image, textured and coloured features were extracted, resulting in 5313 ROIs or instances.

This study embraced a hybrid approach to feature extraction, drawing from methodologies proposed by Afandi et al. (2021) for textural features and leveraging coloured feature extraction techniques outlined in several studies (Khojatesnazhand et al., 2010; Leemans et al., 2002; Liming & Yanchao, 2010). Textural feature extraction commenced with converting each image into grayscale and then extracting 20 Regions of Interest (ROIs) from each rendition. Conversely, for coloured feature extraction, a comprehensive strategy unfolded, tapping into four distinct colour models: RGB, hue, saturation, value (HSV), CIE Lab, and CIE LUV. Each image transformed its designated colour model, with 20 ROIs extracted from each colour channel within every model. This dual-pronged approach facilitated an exhaustive examination of textured and coloured attributes, enriching subsequent analysis. By amalgamating these techniques, the study aimed to provide a nuanced understanding of the intricate interplay between texture and colour characteristics in the dataset under scrutiny.



Figure 6. Activities of image acquisition

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Class	Images	ROI	
1	25	525	
2	14	294	
3	48	1008	
4	62	1302	
5	51	1071	
6	53	1113	

Table 1Number of images and ROIs for each maturity class

Extracted Features from Mangosteen Images

Textured features were meticulously extracted using the Gray-Level Co-occurrence Matrix (GLCM) method pioneered by Haralick et al. (1973), encompassing 13 distinctive features. These included Energy, Contrast, Correlation, Variance, Homogeneity, Sum average, Sum variance, Sum entropy, Entropy, Difference Variance, Difference Entropy, Measure of Correlation 1, and Measure of Correlation 2. Each textured attribute was derived from four directional angles: 0, 45, 90, and 135 degrees, resulting in 52 textured features per Region of Interest (ROI). Conversely, coloured features encompassed mean, standard deviation, variance, entropy, and Root Mean Square (RMS) extracted from each ROI across every colour channel and colour model. Consequently, 60 coloured features were obtained, summing up to 112 features from textured and coloured domains for every ROI. This comprehensive feature extraction approach aimed to capture diverse characteristics embedded within the dataset, laying the groundwork for in-depth analysis and exploration of intricate patterns and correlations.

Experimentation Setup

The experimentation process encompassed three distinct feature modes: textured features only, coloured features only, and a fusion of both textured and coloured features. This comprehensive approach aimed to dissect the significance of each feature type within the designated classifiers, facilitating a better understanding of their respective contributions. Table 1 delineated a substantial dataset comprising 5313 Regions of Interest (ROIs) or instances amassed for this study. The experimental protocol comprised a bifurcated approach, with 70% of the instances allocated for training purposes, while the remaining 30% constituted the test set. Instances were meticulously selected across various maturity classes to ensure a representative distribution within training and testing subsets. Consequently, 3,719 mangosteen ROI images spanning maturity class 1 through maturity class 6 were earmarked for testing. Figures 7a to 7f showcase sample ROIs representing mangosteen maturity classes 1 through 6 in grayscale. Figures 7g to 7l present analogous



Figure 7. Samples of ROIs for each maturity class 1-6 respectively (a-f) in grayscale and (g-l) in RGB colour model

maturity stages in the RGB colour model, offering insights into the visual characteristics across different maturity levels.

The comprehensive processes delineated in Figure 8 encompass various stages, commencing with image acquisition, which involves the meticulous capture and subsequent conversion of images into grayscale and coloured formats. Following this, images undergo precise cropping to predefined dimensions, yielding Regions of Interest (ROIs) as an integral part of the image pre-processing pipeline, paving the way for subsequent analyses. Feature extraction ensues, wherein a rich array of both textured and coloured features is meticulously acquired and catalogued, subsequently categorised into three distinct datasets.



Figure 8. The flow of processes in the experiment

Modes: texture-only, colour-only, and a hybrid amalgamation of textured and coloured features. Each dataset undergoes rigorous training utilising four distinct classifiers: K-Nearest Neighbours (K-NN), Support Vector Machine (SVM), Decision Tree (DT), and Random Forest (RF). Remarkably, each classifier is adeptly leveraged across all three dataset modes, signifying the versatility and adaptability of the approach. This meticulous selection of classifiers is underpinned by their demonstrated efficacy in addressing multiclass problems, as underscored by previous research endeavours (Giuntini et al., 2023; Boateng et al., 2020), highlighting their suitability for the present study's objectives.

In this study, the specified classifiers accessible within the Matlab tool were employed for analysis. Furthermore, each type of the remaining dataset underwent thorough testing utilising the K-Nearest Neighbours (K-NN), Support Vector Machine (SVM), Decision Tree (DT), and Random Forest (RF) classifiers, respectively. Each machine learner performs the experimentation based on the parameter setting described in Table 2. The research findings are meticulously presented based on a comprehensive analysis of a testing dataset, employing diverse evaluation metrics to ensure a robust assessment. These chosen evaluation metrics encompass a broad spectrum, including accuracy, precision, recall, F1score, Cohen's Kappa, and false negative rate (FNR), allowing for a multifaceted classifier performance evaluation. Particularly in the context of FNR analysis, a detailed examination was conducted by constructing confusion matrices for each feature mode. Within these matrices, the counts of false negatives and true positives were meticulously tallied for each maturity class across all the aforementioned classifiers, providing invaluable insights into the classification outcomes and performance metrics.

	N_estimators	100	Decision Tree	Criterion	Gini
Random Forest	Criterion	Gini		Splitter	Best
	Random state	None			
	Kernel	RBF		Number of neighbours	Default=5
SVM	Probability	False	kNN	Weight	Uniform
	Random state	None		Leaf size	Default=30
	Stratify	Yes		Metric	Default = 'Minkowski'

Table 2Parameter setting for experimented machine learners

Evaluation Metrics

In addition to accuracy, as defined in Equation 1, this study incorporated diverse evaluation metrics. Following the recommendations of Powers (2020), precision, recall, F1-score, and Cohen's Kappa were chosen as suitable metrics for assessing classifier performance in multiclass scenarios. Equation 1 quantifies accuracy, representing the ratio of true cases to overall cases. Precision, detailed in Equation 2, measures the quality of results by evaluating true positives against the sum of true positives and false positives. Equation 3 defines recall as the ratio of true positives to the sum of true positives and false negatives, with precision gauging quality and recall gauging quantity. A higher precision indicates a model returning more relevant results than irrelevant ones, while a higher recall signifies a model retrieving the most relevant results irrespective of irrelevant ones. The F1-score, depicted in Equation 4, serves as the harmonic mean of precision and recall, providing a balanced evaluation of both metrics.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$
[1]

$$Precision = \frac{TP}{TP + FP}$$
[2]

$$Recall = \frac{TP}{TP + FN}$$
[3]

$$F1 \ score = \frac{2 * (Precision * Recall)}{Precision + Recall}$$
[4]

The F1 score also represents the model's accuracy on a dataset. F1-score ranges between 0 and 1. The closer it is to 1, the better the model. Cohen's Kappa measures the level of agreement between two raters who each classify items into mutually exclusive categories. In other words, the measure tests interrater reliability. The rater reliability represents the extent to which the data collected in the study are correct representations of the variables measured. Cohen's Kappa, namely k, is described in Equation 5. Cohen's Kappa always ranges between zero and one, with zero indicating no agreement between the two raters and one indicating perfect agreement between the two raters.

$$k = \frac{P_o - P_e}{1 - P_e} \tag{5}$$

where P_o: relative observed agreement among raters

P_e: hypothetical probability of chance agreement

The False Negative Rate (FNR) denotes instances where a true condition is inaccurately identified as false. For example, it quantifies how often instances are wrongly predicted as non-class 1 when they indeed belong to class 1 in the dataset. The FNR is calculated using Equation 6, whereby a smaller FNR is a better value given that false negative (FN) and true positive (TP) cases have been determined from the confusion matrix. A true positive signifies the model's accurate prediction of a specific class.

$$FNR = \frac{FN}{FN + TP}$$
[6]

According to Rainio et al. (2024), a suitable statistical test for multiclass classification that determines significant differences among several models is the Friedman Test. Given that X^2 is chi-square, N is a number of instances, df is the degree of freedom, and the p-value is the area under the density curve of the chi-square distribution to the right of the value of the test statistic. If the p-value is less than the significance level, there is enough evidence to conclude that at least one mean of the chosen metric is different among the multiple methods. This work chooses 0.05 as the significance level because it is common in classification. The lowest mean ranks signify the best statistically significant method. It is calculated by taking the sum of the ranks and divided by N.

RESULTS

Results Related to Accuracy

The study found that most learners achieved less than 50% accuracy, as evidenced by the results from the texture features testing data in Table 3. Random Forest (RF) and Decision Tree (DT) precisely detected class 1 maturity within the range of 0.58 to 0.61. Support

Classifier	Class	Precisi	uo		Recall			F1-Sco	re		Accur	acy		Cohen	's Kappa	
		Texture	Colour	Combined	Texture	Tout	Combined	Texture	Colour	Combined	lexture	Colour	Combine	Texture	Colour	Combined
Random	-	0.58	0.78	0.76	0.58	0.9	0.9	0.58	0.84	0.82	0.46	0.75	0.76	0.33	0.69	0.70
Forest	2	0.41	0.64	0.68	0.22	0.5	0.45	0.29	0.56	0.55						
	ю	0.55	0.8	0.78	0.61	0.76	0.8	0.58	0.78	0.79						
	4	0.45	0.65	0.68	0.47	0.66	0.67	0.46	0.66	0.67						
	5	0.34	0.65	0.67	0.35	0.67	0.69	0.35	0.66	0.68						
	9	0.44	0.93	0.94	0.42	0.91	0.9	0.43	0.92	0.92						
Decision	1	0.61	0.84	0.74	0.58	0.77	0.78	0.59	0.8	0.76	0.4	0.69	0.67	0.26	0.62	0.59
Tree	2	0.29	0.49	0.42	0.29	0.58	0.47	0.29	0.53	0.44						
	ŝ	0.47	0.71	0.66	0.47	0.68	0.63	0.47	0.69	0.65						
	4	0.4	0.59	0.56	0.39	0.59	0.54	0.39	0.59	0.55						
	5	0.33	0.61	0.61	0.36	0.62	0.62	0.34	0.62	0.62						
	9	0.36	0.87	0.88	0.35	0.9	0.88	0.35	0.88	0.88						
SVM	1	0	0.71	1	0	0.77	0.01	0	0.74	0.01	0.26	0.66	0.26	0.03	0.57	0.04
	2	0	0	0	0	0	0	0	0	0						
	З	0.33	0.65	0.4	0.01	0.74	0.01	0.01	69.0	0.01						
	4	0.25	0.56	0.25	0.87	0.75	0.86	0.39	0.64	0.39						
	5	0.32	0.63	0.3	0.21	0.3	0.22	0.26	0.41	0.25						
	9	0	0.78	0.7	0	0.92	0.04	0	0.84	0.08						
K-NN	1	0.18	0.6	0.32	0.17	0.76	0.31	0.17	0.67	0.32	0.28	0.64	0.36	0.09	0.55	0.19
	2	0.1	0.41	0.22	0.07	0.36	0.17	0.08	0.38	0.19						
	Э	0.33	0.65	0.41	0.33	0.65	0.42	0.33	0.65	0.42						
	4	0.28	0.59	0.32	0.39	0.56	0.44	0.33	0.57	0.38						
	5	0.3	0.57	0.31	0.3	0.54	0.31	0.3	0.56	0.31						
	9	0.26	0.8	0.48	0.18	0.83	0.3	0.21	0.81	0.37						

 Table 3

 Results analysed from testing data using various metrics from texture, colour and combined texture-colour features

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Vector Machine (SVM) excelled in class 4 detection, achieving a recall value of 0.87. RF and DT performed well in detecting stages other than class 2, with recalls ranging from 0.58 to 0.22, which is understandable due to SVM's binary class inclination. Considering accuracy and Cohen's Kappa, RF outperformed other classifiers.

Moving forward, Table 3 offers a comprehensive overview of the results garnered from testing data, utilising an array of metrics derived from colour features. Random Forest (RF) exhibited exceptional performance, boasting an accuracy of 0.75 and a Cohen's Kappa value of 0.69. RF showcased its superior ability in pinpointing both class 1 and class 6, achieving recall values that surpassed 0.90. Intriguingly, nearly all classifiers demonstrated proficiency in determining class 6 using colour features, highlighting the significance of colours within this category. Furthermore, RF displayed precision in identifying each class, with values ranging from 0.64 to 0.93. However, it is noteworthy that Decision Tree (DT) outperformed RF in detecting class 1, achieving a precision value of 0.84 compared to RF's 0.78. Nevertheless, the overall performance of RF remains justified, given its voting approach to determine specified classes.

Table 3 provides a detailed overview of the results from analysing testing data, utilising a blend of texture and colour features. The findings prominently showcase the Random Forest (RF) model's superiority, boasting an impressive accuracy of 0.76 and a Cohen's Kappa value of 0.70. RF's outperformance across F1 scores for each class is noteworthy, indicating its effectiveness in distinguishing various mangosteen maturity classes through the harmonic mean of combined precision and recall. Conversely, the Support Vector Machine (SVM) falls short, with a lower accuracy rate of 0.26 and a Cohen's Kappa value of 0.04. SVM notably struggles in accurately identifying maturity class 2.

Statistical Test Result Based on F1-score

Table 4 presents the Friedman Test result to discover the p-value and mean rank for 3 categories of features across 6 classes of maturity stages based on F1-score metrics. Instead of accuracy, the F1-score was chosen to perform the statistical test because it represents a balanced evaluation of precision and recall. The p-value for texture features is 0.00235, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean F1-score is different among the multiple classifiers under the texture features category. The mean rank for texture features using classifiers RF, DT, SVM, and kNN are 3.75, 3.16, 1.25, and 1.83, respectively. On the other hand, the p-value for colour features is 0.00235, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean F1-score is different among the multiple classifiers RF, DT, SVM, and kNN are 3.75, 3.16, 1.25, and 1.83, respectively. On the other hand, the p-value for colour features is 0.00235, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean F1-score is different among the multiple classifiers under the colour features category. The mean rank for colour features using classifiers RF, DT, SVM, and kNN are 4.00, 2.75, 1.91, and 1.33, respectively. The p-value for a combination of texture and colour features is 0.00071, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean F1-score is different among the multiple classifiers and the number of texture and colour features is 0.00071, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean F1-score is different among the multiple classifiers under the combined features category.

The mean rank for combined features using classifiers RF, DT, SVM, and kNN are 4.00, 3.00, 1.16, and 1.83, respectively.

	Classifier	Sum of Ranks	X2	df	Ν	p-value	Mean Rank
	RF	22.50					3.75
Toutuno	DT	19.00					3.16
lexture	SVM	7.50	14.45	3	6	0.00235	1.25
	kNN	11.00					1.83
	RF	24.00					4.00
Calarra	DT	16.50					2.75
Colour	SVM	11.50	14.45	3	6	0.00235	1.91
	kNN	8.00					1.33
	RF	24.00					4.00
Combined	DT	18.00					3.00
texture	SVM	7.00	17.00	3	6	0.00071	1.16
	kNN	11.00					1.83

Friedman Test resi	ult based on F1	-score related to	o texture. colour	and combined f	, eatures

Results Related to Confusion Matrix and FNR

Figure 9 presents the confusion matrix depicting the results of testing textured features using various classifiers. Figure 10 illustrates qualitative measures, specifically the FNR derived from the confusion matrix in Figure 9. Random Forest (RF) exhibits the lowest false negative rate among the six maturity classes. Support Vector Machine (SVM) shows proficiency in determining maturity stages for classes 3, 4, and 5, with false negative rates ranging between 0.6 and 0.8. However, SVM performs badly in other classes.

The overall misclassification rate for the textured features scheme generated by RF, DT, SVM and kNN was 53.8%, 59.6%, 74.2% and 72.5%, respectively. The overall accuracy for the coloured features scheme using RF, DT, SVM and kNN were 75%, 69.4%, 65.6% and 63.6%, respectively. The overall accuracy for the combined texture-colour features scheme using RF, DT, SVM and kNN were 76%, 66.9%, 26.5% and 35.5%. The gap based on FNR between RF-DT and SVM-kNN scheme based on textured features in Figure 10 was huge because of the higher misclassification rate between them.

Figure 11 presents the confusion matrix depicting the results of testing-coloured features using various classifiers. Figure 12 provides a visual representation of the FNR derived from the confusion matrix in Figure 11. Random Forest (RF) emerges as the standout performer within this visualisation, boasting the lowest FNR across all classes, with rates between 0.1 and 0.4. The Support Vector Machine (SVM) encountered difficulties accurately detecting the class 2 maturity stage. Undoubtedly, RF distinguishes itself as the

Table 4

most promising learner for discerning the various maturity classes of mangosteen within the dataset under scrutiny. This assertion finds support in its impressive accuracy, Cohen's Kappa scores, and its consistently low false negative rates. Although SVM and kNN missed the 0.60 acceptance value based on Cohen's Kappa, all the classifiers in the study achieved more than 0.60 accuracies. These findings suggested that colour features better describe mangosteen multiclass maturity. Gaps based on FNR between RF, DT, SVM and kNN based on coloured features in Figure 12 were reduced compared to the one in Figure 10, which employed textured features because of the lower misclassification rate among them.

Figure 13 presents the confusion matrix depicting the results of testing combined features using various classifiers. Figure 14 illustrates qualitative measures, specifically the FNR derived from the confusion matrix in Figure 13. Notably, the Random Forest (RF) exhibits the lowest FNR across classes, ranging from 0.05 to 0.32. This exceptional performance by RF, characterised by consistently low FNR values, complements the overall evaluation based on accuracy and Cohen's Kappa. In contrast, the Support Vector Machine (SVM) faces challenges in determining class 1 and class 2 maturity, which is evident in its higher FNR. Intriguingly, despite SVM having the lowest FNR across classes compared to kNN, it surprisingly outperforms kNN in determining class 6. The gap based on FNR between RF-DT and SVM-kNN scheme based on combined texture-colour features in Figure 14 was huge because of the higher misclassification rate between them.



Figure 9. Confusion matrix with results analysed from the testing data of textured features executed via various classifiers



Figure 10. False negative rates analysed from the testing data of textured features executed via various classifiers



Figure 11. Confusion matrix with results analysed from the testing data of coloured features executed via various classifiers

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Figure 12. False negative rates from the testing data of coloured features executed via various classifiers



Figure 13. Confusion matrix with results analysed from the testing data of combined textured and coloured features executed via various classifiers



Figure 14. False negative rate from the testing data of combined textured and coloured features executed via various classifiers

Statistical Test Result Based on FNR

Table 5 presents the Friedman Test result to discover the p-value and mean rank for 3 categories of features across 6 classes of maturity stages based on FNR metrics. The p-value for texture features is 0.00134, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean FNR is different among the multiple classifiers under the texture features category. The mean rank for texture features using classifiers RF, DT, SVM, and kNN are 1.16, 1.83, 3.75, and 3.25, respectively. On

	Classifier	Sum of Ranks	X2	df	Ν	p-value	Mean Rank
	RF	7.00					1.16
Toyturo	DT	11.00					1.83
Texture	SVM	22.50	15.65	3	6	0.00134	3.75
	kNN	19.50					3.25
	RF	7.00					1.16
Colour	DT	12.50					2.08
Colour	SVM	20.50	12.55	3	6	0.00572	3.42
	kNN	20.00					3.33
~	RF	6.00					1.00
Combined	DT	12.00					2.00
texture	SVM	23.00	17.00	3	6	0.00071	3.83
	kNN	19.00					3.17

Table 5Friedman Test result based on FNR related to texture, colour and combined features

the other hand, the p-value for colour features is 0.00572, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean FNR is different among the multiple classifiers under the colour features category. The mean rank for colour features using classifiers RF, DT, SVM, and kNN are 1.16, 2.08, 3.42, and 3.33, respectively. The p-value for a combination of texture and colour features is 0.00071, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean FNR is different among the multiple classifiers under the colour features is 0.00071, which is less than 0.05 level of significance. Thus, there is enough evidence to conclude that at least one mean FNR is different among the multiple classifiers under the combined features category. The mean rank for combined features using classifiers RF, DT, SVM, and kNN are 1.00, 2.00, 3.83, and 3.7, respectively.

DISCUSSION

Discussion Related to Accuracy

The analysis of various metrics indicates a notable similarity in the accuracy of Random Forest (RF) and Decision Trees (DT) when utilising coloured features alone and in combination with textured features. The experimental findings strongly suggest that the use of colour features alone is sufficiently robust for characterising mangosteen maturity classes. Specifically, incorporating thirteen out of fourteen textural features from GLCM and five essential colour features—mean, standard deviation, variance, entropy, and RMS—from each colour channel and model (RGB, HSV, CIE Lab, and CIE LUV) significantly contributes to accurate maturity class determination for mangosteen. RF is a superior classifier to DT, SVM and kNN due to its less biased nature—RF's performance benefits from majority voting across multiple sub-tree iterations.

The results based on the F1-score among all the compared machine learners are statistically significant for each type of feature scheme, as the p-value for all feature schemes is less than the 0.05 significance level. However, RF is not the most statistically significant method based on the mean rank values in Table 6. This finding is consistent with the methods compared to other works that employed deep learning (DL), as shown in Table 6. For instance, Sudana et al.'s (2020) work determined mangosteen maturity for seven classes using coloured features and achieved 97.10% accuracy. Another study by Mohtar et al. (2019) achieved 91.90% accuracy using Inception V3 to determine six classes of mangosteen maturity via coloured features. Although the work by Parashar and Johri (2024) is not directly comparable because it determined four classes of apple leaf disease, the Inception V3 model achieved an accuracy of 94.76%.

Traditional machine learning methods for determining maturity, skin defect, or ripeness have not performed as well as most deep learning results. Referring to Table 6, for example, Phothisonothai and Tantisatirapong (2019) conducted a study to determine mangosteen ripeness for three classes using texture and coloured features via GMM, achieving 86.67% accuracy. Riyadi et al. (2020) studied mangosteen binary classes of skin defects using

texture and coloured features, scoring 94.16% accuracy via LDA. Whidhiasih et al. (2012) achieved 85% accuracy in determining three classes of mangosteen maturity using textured and coloured features classified via Fuzzy NN.

As observed in Table 6, many studies did not report precision and recall, leaving insufficient information to conclude the FNR performance. Orchi et al.'s (2023) work compared DL and traditional learners, including Inception V3, RF, SVM, and K-NN, but did not determine FNR and focused on binary classes of crop leaf disease. In his work, RF achieved a competitive accuracy of 97.54% compared to Inception V3 accuracy of 98.01%.

Regardless of RF's ability to classify multiclass instances, the instances acquired from textured features did not really represent the overall characterisation of the mangosteen maturity stages. Besides texture, mangosteen maturity is also characterised by their skin colour. DT performed worse than RF but was much better than SVM and K-NN, using textured features only. It is supported by the fact that DT suffers a bias problem. However, because the classifier is suitable for multiclass problems, the DT recognition rate is much better than that of SVM and K-NN. It is observed that having textured features only is insufficient to characterise the mangosteen maturity classes.

It was mentioned earlier that the overall accuracy for the textured features scheme using RF was 46.2%. Meanwhile, when coloured features were employed, the recognition rate increased to 75% using the same classifier. This result indicates that coloured features are significantly better at characterising mangosteen maturity stages compared to textured features. A similar trend was observed with the remaining classifiers. The overall accuracy for the coloured features scheme using both SVM and K-NN ranged between 63% and 66% for the six mangosteen maturity classes. From earlier findings, RF and DT achieved an overall accuracy of 69% and 75% for the coloured features scheme. It suggests that coloured features are essential for characterising mangosteen maturity classes regardless of the classifier used, though some classifiers perform better or worse depending on their processing capabilities.

The combined coloured texture feature was 76% using the same type of classifier. Coloured features or a combination of colour texture features are suggested to characterise mangosteen maturity classes.

Surprisingly, the overall accuracy of the coloured features and combined texturecolour features scheme using the same DT classifier was 69.4% and 66.9%, respectively. Indeed, the use of coloured features and combined texture-colour features are adequate to characterise mangosteen maturity stages.

The overall accuracy for the colour features scheme and combination of texture-colour using SVM was 65.6% and 26%, respectively. Meanwhile, the overall accuracy for the colour features scheme and combination of texture-colour using K-NN was 63.6% and 35.5%, respectively. There is a huge decrease in the overall accuracy when combined texture-colour features are used and executed using SVM and K-NN. These findings may

be because those classifiers have less ability to handle high dimensional data, thus less processing power.

Based on the experimentation result, this work suggests that using colour features is sufficient to characterise mangosteen maturity classes. Alternatively, combined texturecolour features are better executed using an RF classifier to determine mangosteen maturity classes. Indeed, five coloured features, namely mean, standard deviation, variance, entropy, and RMS from each colour channel and each colour model of RGB, HSV, CIE Lab, and CIE LUV, are essential to determine maturity classes for mangosteen. RF classifier can handle multiclass problems, which is a valuable notion in this kind of work. In addition, RF lessens the overfitting problem in DT and reduces the variance, improving accuracy. On top of that, non-linear parameters are handle efficiently, and RF is robust to outliers.

Discussion Related to FNR

The False Negative Rates (FNR) for RF, whether using coloured features alone or combined texture and coloured features, exhibit consistent similarity, ranging from 0.02 to 0.40. It suggests that determining mangosteen multiclass maturity stages can be effectively achieved using either coloured features or a combination of texture and colour features. From another perspective, combined features are not the factor degrading SVM and K-NN multiclass detection capability. The competitive accuracy values support it, as Cohen's Kappa and FNR were obtained from RF and DT. RF achieved an accuracy of 0.76 and DT of 0.67. Both RF and DT Cohen's Kappa readings are above 0.59, with RF having a higher reading of 0.70. The FNR for RF is more than 0.60 but is considered competitive when it falls between 0.02 and 0.40.

Due to their inherent limitations, SVM and K-NN are less effective in determining multiclass mangosteen maturity. SVM is more suited for binary classification, while K-NN, although supporting multiclass cases, struggles to differentiate them effectively using the proximity concept. K-NN does not require training before classification, whereas accurately differentiating among mangosteen maturity classes necessitates a learning process.

This observation aligns with the results presented in Table 3, where RF's performance is rooted in the majority voting concept. SVM is known to better suit binary classification. In this work, kNN, as a lazy learning algorithm, falls short in finding the similarity of new and existing points in specified classes.

Once again, RF's commendable performance can be attributed to its robust computing capability, which employs a voting mechanism among subtrees during iteration. This unique approach mitigates bias and proves highly effective in accurately classifying multiclass cases.

This anomaly can be attributed to SVM's nature as a binary classifier. It distinguishes between class 2 and non-class 2 categories, potentially contributing to its superior

performance in certain instances. This nuanced understanding of classifier behaviour enhances our insights into their strengths and limitations in differentiating various maturity classes.

Regardless of the FNR rate, RF and DT classify better in all feature schemes. SVM and K-NN have less processing power to classify when only textured and a combination of texture-colour features are used. Regardless of the feature scheme, RF is always the best classifier compared to DT. Additionally, RF is the best at classifying maturity stages among all the classifiers.

Results based on FNR among all the compared machine learners in Table 5 are statistically significant for each type of feature scheme because the p-value for all feature schemes is less than the 0.05 significance level. RF is also the most statistically significant method, scoring the lowest mean rank values in Table 5.

The competitive performance of FNR using the RF classifier across multiple classes highlights its adeptness in handling multiclass problems, a crucial attribute in this context. Furthermore, RF effectively mitigates the overfitting issues associated with DT, reduces variance, and thereby enhances overall accuracy. Its proficiency in managing non-linear parameters and resilience to outliers make RF a robust choice for this analytical task.

When comparing the experimented methods with previous work on statistically significant methods based on FNR, there is insufficient information to conclude because many previous works did not compute precision and recall metrics.

CONCLUSION

RF is deemed the best method based on its accuracy in determining six mangosteen maturity classes compared to the experimented methods. A statistical test, the Friedman Test, was conducted using the F1-score, and it was found that at least one method is statistically significant and differs among the multiple methods, with a significance level of 0.05. Nevertheless, SVM is the best statistically significant method via texture and combined texture-colour features based on Table 4.

Compared to the work by Orchi et al. (2023) in Table 6, RF is competitive against Inception V3 based on F1-score reading even though Orchi et al.'s (2023) work experiments with binary class crop leaf disease. Given a huge dataset, RF has the potential to beat DL classifiers, and the number of instances in each class is more proportionate. In the future, this study recommends improving RF by incorporating an enhanced dynamic weighted function to regularise the voting mechanism to classify.

Either colour features or a combination of texture and colour features are suitable for determining mangosteen maturity stages. This finding is also applicable to previous works, as shown in Table 6 (Al-Mashhadani et al., 2021; Kim et al., 2023; Muñoz et al., 2021; Parashar & Johri, 2024).

Table 6 Summary of previous works p	erformance							
Article	Dataset	Type/Classes	Feature	Classifier	F1-score	Recall	Precision	Accuracy (%)
Orchi et al. (2023)	Crop leaf	Leaf disease/2	Colour	Inception V3	0.9652	0.9753	0.9652	98.01
				CNN	0.9132	0.9139	0.9157	93.89
				Resnet50	0.9169	0.9164	0.9241	93.57
				VGG16	0.8977	0.9017	0.9043	87.50
				VGG19	0.8668	0.8694	0.8818	86.70
				RF	0.9771	0.9747	0.9792	97.54
				CART	0.9418	0.9406	0.9424	94.45
				KNN	0.9227	0.9226	0.9196	91.67
				SVM	0.8440	0.8437	0.8438	84.10
				LDA	0.7993	0.7994	0.8001	80.28
				NB	0.5474	0.5995	0.6865	60.09
Al-Mashhadani et al. (2021)	Tomato	Ripeness/4	Colour	AlexNet	1.0000	1.0000	1.0000	99.80
Mohtar et al. (2019)	Mangosteen	Maturity/6	Colour	Inception V3	0.9200	0.9600	0.8800	91.90
Kim et al. (2023)	Tomato	Maturity/4	Colour	DNN	0.9100	0.8900	0.9300	97.00
Miraiei et al. (2021)	Mulberry	Ripeness/2	Colour	DenseNet	N/A	N/A	N/A	98.67
				Inception V3	N/A	N/A	N/A	98.55
				ResNet-18	N/A	N/A	N/A	98.65
				ResNet-50	N/A	N/A	N/A	96.33
Benmoana et al. (2022)	Fuji apple	Ripeness/4	Hyperspectra	CNN	0.9646	0.9651	0.9659	96.50
				ANN	0.8807	0.8837	0.8941	89.50
				SVM	0.9590	0.9607	0.9592	95.93
				kNN	0.9192	0.9186	0.9205	91.18
Gao et al. (2020)	Strawberry	Ripeness/2	Hyperspectra	AlexNet	N/A	N/A	N/A	98.60
Tan et al. (2022)	Beef	Quality/8	Colour	Inception V4	0.6040	0.6130	0.6280	90.00
Muñoz et al. (2021)	Bluberry	Ripeness/5	Colour	CNN	0.9008	0.9092	0.8926	90.74
Azizah et al. (2017)	Mangosteen	Surface defect/2	Colour	CNN	N/A	N/A	N/A	97.50

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Table 6 (continue)

Article	Dataset	Type/Classes	Feature	Classifier	F1-score	Recall	Precision	Accuracy (%)
Sudana et al. (2020)	Mangosteen	Maturity/7	Colour	CNN	N/A	N/A	N/A	97.10
Phothisonothai and Tantisatirapong (2019)	Mangosteen	Ripeness/3	Texture, Colour	GMM	N/A	N/A	N/A	86.67
Whidhiasih et al. (2012)	Mangosteen	Maturity/3	Texture, Colour	Fuzzy NN	N/A	N/A	N/A	85.00
Riyadi et al. (2020)	Mangosteen	Skin defect/2	Texture, Colour	LDA	N/A	N/A	N/A	94.16
Khojastehnazhand et al. (2010)	Lemon	Quality/3	Colour	Machine Vision	N/A	N/A	N/A	94.04
Liming and Yanchao (2010)	Strawberry	Quality/4	Colour	K-Means cluster	N/A	N/A	N/A	88.80
Damarjati et al. (2017)	Mangosteen	Skin defect/2	Texture	LDA	N/A	N/A	N/A	77.43
Afandi et al. (2021)	Mangosteen	Skin defect/3	Texture	ELM	N/A	N/A	N/A	96.67
Riyadi et al. (2018)	Mangosteen	Skin defect/2	DCT feature	ELM	N/A	N/A	N/A	92.50
Leemans et al. (2002)	Apple	Quality/4	Colour	DA,NN	N/A	N/A	N/A	75.00
Bashir et al. (2023)	Irrigation	Quality/2	Shape	Ensemble ANN	N/A	N/A	N/A	91.44
				ANN (all parameter)	N/A	N/A	N/A	88.36
				ANN(one parameter)	N/A	N/A	N/A	87.84
Joshua et al. (2022)	Environmental	Quality/2	Numerical	BPNN	N/A	N/A	N/A	89.00
				SVM	N/A	N/A	N/A	93.00
				GRNN	N/A	N/A	N/A	97.00
Parashar and Johri (2024)	Apple	Leaf disease/4	Texture, Colour	Inception V3	0.85	0.87	0.84	94.76
Khan, Nauman et al. (2022)	Irrigation saline soil	Quality/2	Shape	Embedded LSTM	N/A	N/A	N/A	78.00
				LSTM	N/A	N/A	N/A	70.00
Khan Faheem et al. (2022)	Soil and fertility	Quality/2	Numerical	LR	N/A	N/A	N/A	92.00
				SVM	N/A	N/A	N/A	94.00
				GNB	N/A	N/A	N/A	96.00
				kNN	N/A	N/A	N/A	93.00

RF also generated the lowest FNR across texture and colour and combined texturecolour feature schemes for almost all six classes, as presented in Figures 10, 12 and 14. The FNR were computed based on FN and TP reading in the confusion matrix for each feature scheme. RF achieved the best statistically significant method among the experimented methods based on the lowest mean rank value analysed using the Friedman Test with a 0.05 significance level. Apparently, RF is the best method to handle FNR-related analysis in mangosteen six multiclasses's maturity stages study. Nevertheless, there is not enough information to claim that other classifiers from agricultural-related studies are able to handle FNR because many studies have not analysed the related metric. In future work to improve weighted function in an enhanced RF algorithm, it is recommended that FNR analysis be incorporated with other machine learners to justify its computational capability. This work is limiting the work among traditional machine learners. Thus, the next work will extend the experimentation using DL instead of comparing it with traditional machine learners.

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Reverse Engineering of Aneurysm Clip Using Metal Forming

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ABSTRACT

Aneurysm clip is widely used as the primary treatment of complex brain aneurysm, primarily in a haemorrhage stroke due to cerebral blood vessel blockages or ruptures, leading to severe neurological deficits. In some developing countries, such as Indonesia, open surgical clipping is sometimes unaffordable and causes a financial burden to the state. This study aims to reproduce the commercial aneurysm clip using metal forming to be more independent in providing medical equipment throughout the country. The metal forming employed rolling and bending techniques, utilizing a base and a jig system to press the Ti6Al4V wire into the desired shape of an R-shaped contour. Our investigation confirmed their structural integrity, fine-grain structure, and mechanical properties. The density of the aneurysm clip shows 4.3 g/cm3 after the forming process. The chemical composition of the aneurysm clip tested with a scanning electron microscope equipped with an

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Keywords: Fenestrated clips, metal machining, neural implant, remanufacturing, stroke haemorrhage

INTRODUCTION

An aneurysm clip is a metal surgery clip with a function to block the aneurysm, particularly in the brain (Louw et al., 2001). The history of the aneurysm clip began in 1937 when Walter Dandy introduced the V-shaped malleable silver clip during brain surgery. In this modern era, the commercial brands of Yasargil, Sugita, and Spetzler dominate the production of aneurysm clips worldwide. Aneurysm clip is commonly utilized as a procedure in the treatment of several brain diseases, including cerebrovascular accident (CVA), called a stroke, and particularly with a type of haemorrhagic stroke. The haemorrhagic stroke is due to bleeding into the brain by the rupture of blood vessels, which is associated with severe morbidity and high mortality (Montaño et al., 2021). In a specific case of spontaneous subarachnoid haemorrhage, it is due to the rupture of a brain aneurysm. Neurosurgeons, primarily conducting craniectomy, attach a clip to the neck of the aneurysm so that it can ultimately reduce pressure on the aneurysm wall and prevent the risk of aneurysm rupture (Oppong et al., 2020). Aneurysm clipping is one of the most promising treatments available, besides a coiling treatment, for brain aneurysms and eventually solves the problems in stroke patients (Jumah, Quinoa et al., 2020).

The manufacture of the aneurysm clip has been developed and equipped with its applier or installation tools by many inventors (Jumah, Quinoa et al., 2020). In 1911, the Cushing silver clip, well known as the Olivecrona clip, was manufactured by winding the silver wire in a tight could around an oval or diamond-shaped rod, followed by cutting each clip with a wire cutter, then forming the shape of a U-wire. This model was then modified by McKenzie, Duane, and Drew (Duane, 1950). The Mayfield aneurysm clip, which had been improved to overcome surgical problems using previous clips, was designed with a togetherness between the clip and the forceps to meet most anatomical situations and using the material of stainless steel 301 (van der Meulen et al., 2009; Mayfield & Kees, 1971). The Drake fenestrated clip, first introduced in 1969, has the proximal portion of the legs. The Drake clip design was expected to manage the basilar bifurcation aneurysm. The first production of Drake's idea was still controlled by Mayfield and the engineer of Kees (Del Maestro, 2000). The Lougheed-Kerr clip has a unique configuration that gains its spring action from an attached ring, and it can be moved to change the force of the spring. Another advantage is that the Lougheed-Kerr clip can also be swivelled in any direction in the clip holder; this configuration was also found in the Scoville-Lewis aneurysm clip and the McFadden aneurysm clips (Fox, 1976). The Heifetz clips, commercialized by Weck Corporation, were introduced in 1968 as a pivot-type, a stainless-steel aneurysm clip that could self-close. This clip has biconvex blades to prevent tissue laceration, minimize slippage, and maximize clipping force (Jumah, Ginalis et al., 2020). The Sundt encircling graft clip is a metallic spring with the primary function of pressuring a Teflon of Dacron synthetic graft, available in several lengths and diameters and designed to repair significant defects in vessels (Park & Meyer, 2010). The Yasargil clip was first introduced in 1968 and has been implanted in more than 1.5 million global in clipping procedures, made from a high-grade cobalt-chromium alloy and titanium alloy and manufactured by Aesculap, Germany (Dujovny et al., 2010; Jumah, Quinoa, et al., 2020). It is an alpha-type clip with solid, narrow blades and high closing pressure. The Sugita clip, introduced in the late 1970s and manufactured by Mizuho, Japan, had an external bridging between the blade and body that could reduce misalignment or uncrossing of the clip arm (Jumah, Quinoa et al., 2020; Sugita et al., 1982; 1984). The Spetzler clip, introduced in the late 1970s, was made of pure titanium and has interlocking sinusoidal grooves. It could enhance the contact area with the aneurysm neck and reduce the slippage (Jumah, Quinoa, et al., 2020; Shellock & Shellock, 1998). The discovery of titanium clip presented no magnetic attraction, less heating, and the artefacts involved a small signal void. Overall, the information about how others could manufacture them was still limited by all the inventors of the mentioned aneurysm clips. There are a lot of patents available under the theme of aneurysm clips as well as their surgical instruments. Most of them revealed the configuration designs of each component using aneurysm clips and delivered medicinal reasons and urgencies behind every development of aneurysm clips and their applicability. However, only a few patents declared the production phases of the aneurysm clip (Kim & Lee, 2020; Pleil et al., 2023).

The epidemiology of haemorrhagic stroke revealed that the incidence is extremely high in low and middle-income countries and Asians. The fatality rate is approaching 30% to 48% in low-to middle-income countries (Unnithan et al., 2023). Indonesia, also classified as a lower-middle income country that has a Gross National Income (GNI) of about \$4050 per capita based on World Population Review, contributes a prevalence of around 10.9% or about seven hundred thousand stroke patients annually, spending the National Health Insurance Fund approximately 15.37 trillion Rupiahs or almost one billion US dollars annually (https://worldpopulationreview.com/Country-Rankings/Gniper-Capita-by-Country). To tackle the high dependency on imported medical devices, some middle-income countries, including Indonesia, attempt to provide and produce their medical equipment needs. However, the production stages of aneurysm clips remain unfamiliar as one of the high demands for imported medical devices, particularly for implant urgencies and stroke prevention. Moreover, the available information, both in patents regarding the manufacturing process of the aneurysm clip and the commercial video of shortened methods in aneurysm clip manufacturing and evaluation process by Yasargil's official channel, presents the whole manufacturing process requires much-sophisticated equipment, high-skilled labour both in production and quality and control stages. The original idea of this research comes from a well-reputable Indonesian neurosurgeon who conducted over two hundred craniectomies for attaching aneurysm clips. His idea led to a research collaboration among metallurgists, biomedical engineers, medical experts, and an

industrial representative. This study aims to employ a metal-forming method to reproduce the commercial aneurysm clip in Siloam Hospital Karawaci, Tangerang, Indonesia. Previously, three-dimensional (3D) printing had been used to reverse engineer the aneurysm clip (Asmaria et al., 2021; Walker et al., 2019). However, the reverse engineering method using additive manufacturing needs to improve the critical ability of the closing force as well as the ability to equalize the dimensions. In the attempt to remanufacture a specimen or other reverse engineering approaches, an investigation needs to be done to measure how far the attempt is successful and how to improve the attempt to reach the desired aim (Fegade et al., 2015; Poswal et al., 2022; Singhal et al., 2018).

The objective of this research is to investigate the replication process of the commercial aneurysm clip, with no prior detailed information or any catalogue from the brand, that is used broadly by neurosurgeons in Indonesia. This reverse engineering process is expected to provide medical equipment throughout the country. The investigation of the reverse-engineered aneurysm clip includes several factors, such as the physical appearance, the closing force, and the material used.

MATERIAL AND METHODS

The main methods of the remanufacturing process consist of 3D model scanning and construction, the remanufacturing process, material analysis, and characterization to investigate the remanufacturing results.

3D Model Scanning and Construction

Initially, the available clip, a fenestrated Sugita aneurysm clip, was scanned using a Cairnhill 3D scanner. The 3D model of the fenestrated aneurysm clip results from the scan was then processed using Uni Graphics parametric design software, the object surface was fixed, and the file was saved as a step file (.stp). In refabricating the existing 3D model, 3D scanning followed by creating the copy model or its modification is the most effective way rather than drawing from a sketch (Szwedziak et al., 2022). Figure 1 describes the scanning aneurysm 3D model and the detailed drawing dimensions, viewed from above and from the side. Figure 1A is the 3D model of the Sugita aneurysm clip after 3D scanning. Figures 1B and 1C are the line data to build detailed drawing dimensions from the scanned aneurysm clip and seen from an above view and a side view, respectively. Figure 1D describes the properties of a commercial fenestrated Sugita aneurysm clip. The chosen commercial fe



Figure 1. A fenestrated aneurysm clip model. (A) 3D scanning from the aneurysm clip; (B) A detailed drawing dimensions of the scanned aneurysm clip from an above view; (C) An aneurysm clip dimension viewed from the side; (D) Properties of commercial fenestrated Sugita aneurysm clip

Remanufacturing Process

The raw material in producing the aneurysm clip consists of Ti6Al4V wire with a 1.20 ± 0.02 mm diameter. Since we did not receive any information or catalogue info on this product, we decided in this study to use the Ti6Al4V material because today, it is commonly used as implant material. Besides that, Ti6Al4V has some advantages, such as high strength properties, low density, and non-toxic to the human body. Firstly, the wire is subjected to compression using a mould combining SKD-11 hardened steel and carbon steel S45C materials to create an R-shaped form. This combination base and jig are custom-made to accommodate the need for an R-shape to the wire. In this stage, we pressed the wire into the R-shape. Subsequently, the R-shaped wire is rolled into a coil configuration with a pressing angle of 22 ° and a free angle of 34 °. The initiation of these angles is based on the scanning and 3D model reconstruction of the aneurysm clip. Finally, the aneurysm clip is bent to obtain a 90 ° blade angle. The process was then followed by bending the blade part of the clip to create an L-shaped blade. Figure 2 illustrates a detailed metal forming from design, the wire moulding, pressing the wire to R-shaped, and rolling the wire.

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Figure 2. Metal forming diagram to reproduce the Ti6Al4V aneurysm clip. From the design of the aneurysm clip, we chose a material and formed the wire with customized moulding. The wire is pressed to form an R-shaped contour. The pressed wire is then rolled with determined angles of 22° and 34° before being bent 90° into an L-shaped

Closing Force Measurement

This study utilized a measurement setup comprising a force sensor and a microcontroller to quantify the closing force exerted by the aneurysm clip. Figure 3 describes the scheme for the closing force measurement. The two blades on the aneurysm clip are attached to the load cell and the linear actuator, respectively, and those are pulled towards each other, with a minimum distance set to 2mm. The blade distance was set to 2 mm, corresponding to the size of the arteries being considered (Asmaria et al., 2021). The force will be measured as the blades are pulled. The purpose of this self-manufacture measurement system is to provide an aneurysm clip tensile force measuring device consisting of a load cell equipped with a strain gauge pressure sensor connected to a microcontroller, a keypad connected to a microcontroller; a linear actuator connected to the motor; the motor connected to a 9V battery as a power supply for the motor; the motor connected to a microcontroller; which is characterized by a hook mounted on the end of the load cell which is equipped with a

strain gauge pressure sensor; a hook mounted on the end of the linear actuator; and a keypad which functions to adjust the movement distance of the linear actuator.

Figure 3. Closing force measuring device for aneurysm clips. The blades on the aneurysm clip are attached to the load cell and the linear actuator. The measured distance when the blades are pulled converts to a closing force through other equipment assistance, such as strain gauge pressure sensor and microcontroller

The Material Analysis and Characterization

This evaluation consists of physical analysis, a density test of aneurysm clips, a metallography test, a scanning electron microscope with energy dispersive spectroscopy (SEM-EDS), and a Vickers hardness test to acquire information regarding the reverse-engineered aneurysm clip's material characteristics.

The physical analysis refers to the gross analysis of the physical measurements and appearance between the scanned Sugita aneurysm clip and the reverse-engineered one.

The density of the aneurysm clip was determined using the Archimedes method following the ASTM B962-17 standard. A Radwag analytical balance, equipped with a density kit, was employed for the measurements.

Metallographic preparation was conducted to examine its microstructure. The clip sample was cut, mounted, ground with SiC paper ranging from grit 120 to 1500, and polished using colloidal silica. The polished samples were then etched with a mixture of Nitric Acid, Fluoric Acid, and water at a ratio of 6:2:92% vol to observe the microstructure and chemical composition of the clip using the SEM-EDX Jeol. As part of microstructure analysis, average grain size will be measured using the image resulting from metallurgy test microscopy. ImageJ software was used to calculate the grain size of the aneurysm clip. The line intercept method will be used to calculate the grain size. A line will be superimposed on the image, and the number of grains intercepting the line will be counted. The formula can be described as Equation 1. It must be noted that the line length must be adjusted to scale or magnification.

A Mitutoyo Micro hardness tester assessed the aneurysm clip's hardness with utmost precision. A 0.3 N load was applied with a 12-second dwell time, ensuring accurate measurement. The hardness was measured at five different points, and the average value was subsequently determined, providing a reliable indication of the clip's hardness.

RESULTS AND DISCUSSION

The primary outcome of this study is the reverse-engineered prototype of an aneurysm clip. To analyse whether this attempt is a success, this study conducts several evaluations: the physical analysis of the aneurysm clip prototype, the closing force measurement, and the material analysis and characterization.

Physical Analysis

Figure 4 indicates nine parameters to compare: the total length, the blade length, the inner diameter of the fenestration side, the blade tip, the wire diameter, the wire width of the spring, the inner and outer diameter of the spring, and the arm length, which then all summarized in Table 1.

A reverse-engineered aneurysm clip is more prominent in size than a commercial aneurysm clip. The wire used for the reverse-engineered aneurysm clip has a diameter of 1.20 ± 0.02 mm, which is only 0.04mm bigger than the commercial aneurysm clip. However, the wire thickness along the commercial aneurysm clip is more dynamic than the re-verse-engineered one. For instance, as shown in Figure 4(A), the wire tends to be flatter at the blade and spring area before reverting to a rod-like shape in its transitional or fulcrum area. The commercial one is different from the reverse-engineered aneurysm clip, which generally has uniform wire thickness throughout the body of the clip. The reason can

be the lack of fine machining in the reverse-engineered aneurysm clip. The uniformity in wire thickness in the reverse-engineered aneurysm clip causes the overall dimension to be bigger and bulkier compared to the commercial aneurysm clip. The bulkiness, especially in the spring portion of the clip, may affect force exertion upon closure.

Based on the website of the commercial Yasargil aneurysm clip official, the total length, the blade length, and the arm length of aneurysm clips have been varied (Figure 4 no 1, no 2, and no 9) and been adjusted to the application on the size of patient's aneurysm. The metal forming in this reverse-engineering experiment produced the inner diameter of fenestration, blade tip, and the wire width of the spring inner and outer diameter of the spring (Figures 4 no 3, no 4, no 6, no 7, and no 8), which more significant in size than the commercial Sugita. These larger areas affect the performance of the reversed engineering aneurysm clip, making the blade more brittle when opening and closing.



Figure 4. (A) The commercial Sugita aneurysm clip; (B) the reverse-engineered aneurysm clip

Table 1

No.	Parameters	Commercial Sugita (mm)	Reverse Engineering (mm)
1	Total Length	16.50	19.28
2	Blade Length	10.00	10.41
3	Inner Diameter of Fenestration	5.00	6.02
4	Blade Tip	1.45	1.27
5	Wire Diameter	1.16	1.20
6	Wire width of spring	0.37	1.00
7	Inner Diameter of Spring	2.26	2.81
8	Outer Diameter of Spring	3.01	5.09
9	Arm Length	7	8

Physical measurement between the Sugita aneurysm clip and the reverse engineering prototype of the aneurysm clip

Closing Force Results

The reverse-engineered Ti6Al4V aneurysm clip prototype developed in this study showed a closing force of 1.689 N, above double the closing force exerted by a commercial aneurysm clip, which is 0.791 N. The findings of another study suggest that the closing force magnitude is directly proportional to the distance by which the blade of the aneurysm clip opens, indicating that greater blade opening distances result in higher closing forces (Horiuchi et al., 2013; Tsutsumi et al., 2017).

The Material Analysis and Characterization

Since the reverse-engineered aneurysm clip has a higher closing force than the commercial Sugita aneurysm clip, the material analysis and characterization results are crucial to answering the microstructural and chemical reasons behind the issue.

Based on the measurements conducted using the Archimedes method, the density of the reverse-engineered aneurysm clip was determined to be 4.3 g/cm³ after the forming process. However, the raw Ti6Al4V wire for the reverse-engineered aneurysm clip comes with a specification sheet from PT. Agru Solusi Industri, as the manufacturing company, and the sheet shows that the density of the Ti6Al4V wire is 4.42 g/cm³. The Archimedes method used in this study also found that the density of the sample of the commercially available wire Ti6Al4V alloy is 4.4 g/cm³. It can be observed that the density of the reverseengineered aneurysm clip in this study closely approximates that of the wire (Tevet et al., 2022). Overall, the density test results show that the commercial aneurysm clip has a 7.9581 g/cm³ density, whereas the reverse-engineered aneurysm clip has a 4.3424 g/cm³ density. The density test result may be attributed to the overall bulkiness of the reverse-engineered aneurysm clip compared to the commercial one. Since there is no information regarding material density for commercial aneurysm clips, the commercial aneurysm clip would be tested using SEM-EDS. Figure 5 shows the SEM-EDS test on the commercial aneurysm clip that the material alloy of CoCr Mo, which, in the 1990s, most Sugita aneurysm clips were made from (Brothers et al., 1990). The commercial aneurysm clip's density test results of 7.9581 gr/cm³ were close to the literature that the density of CoCr Mo by 8.3 g/cm³.

This theoretical value sits closely with the value obtained from measurement for reverse-engineered aneurysm clip. Commercial aneurysm clip has nearly twice the density of the remanufacturing prototype, which may indicate that there is a difference in material specifications between the reverse-engineered clip and commercial aneurysm clip or that the two aneurysm clips are made from entirely different materials. Based on the literature, titanium alloys are magnetic resonance (MR) safe implantable medical devices since the susceptibility of Ti is about 1/10 that of the Co-Cr-Ni alloy, which was previously claimed to be the preferred MR-safe material (Tang et al., 2020). For this reason, there is no need to change the titanium alloy materials in the next reverse engineering aneurysm clips.

The microstructure of the Ti6AlV used in the reverse-engineered aneurysm clip will be thoroughly analysed using a metallography test. The chemical composition and hardness of the Ti6AlV will be determined through SEM EDX and Vickers hardness test results, which will be compared to the literature for validation. Figure 6 provides a detailed view of the microstructure of the Ti6Al4V aneurysm clip, demonstrating the thoroughness of our analysis.



Figure 5. SEM image and EDS of the commercial aneurysm clip

It can be observed that the Ti6Al4V aneurysm clip consists of α and β Ti phases with fine grain size. The fine grain structure observed in clip aneurysm manufacturing can be attributed to the utilization of rolling and bending processes. Gurau et al. (2020) also stated that subjecting titanium alloys to severe plastic deformation through cold rolling can form refined grains. This process has an impact on the biocompatibility of the implant material. Kim et al. (2007) reported that a reduction in grain size is associated with increased surface energy, significantly enhancing cell proliferation. Cell proliferation is a basis for evaluating the in vitro biocompatibility of materials used for the metal implant. Menik Dwi Kurniatie, Talitha Asmaria, Fendy Rokhmanto, Joko Triwardono, Galih Senopati, Dita Ayu Mayasari and Wulan Tsabita Anandisa



Figure 6. Microstructure of Ti6Al4V Aneurysm Clip

Figure 7 demonstrates grain size calculation using profile plotting. Average grain size will be measured using the image acquired through the metallography test. Nine different line segments will be superimposed on the enhanced image, which is the profile plot of the number 1 coloured in yellow in Figure 7. Due to the irregularities in shape, counting the number of grains using eyesight is difficult. Profile plotting is utilized to help with this problem. The α -primary phase tends to be darker in colour, and the β -phase boundary tends to be lighter. Using the intercept line method (Equation 1), the average grain size is calculated and showed the result of 10.48µm. It is known that with the decrease in grain size, tensile strength will increase at the expense of decreasing elongation (Chong & Tsuji, 2016).

The grain size becomes smaller than $1\mu m$, and early necking happens shortly after yielding, which indicates the early plastic instability due to the limited work-hardening

ability of the ultra-fine grain (UFG) equiaxed microstructure (Peng et al., 2014). It means that the material used in the reverse-engineered aneurysm clip has good workability, especially in the range of 10 to 25µm (https://www.copper.org/applications/industrial/DesignGuide/ props/grain_size.html). This workability is based on the industrial recommendation by the Cooper Development Association, which mentioned that metal with typical operations and a grain size of 10 to 25µm, such as stampings, the parts will exhibit high strength (https:// www.copper.org/applications/industrial/DesignGuide/props/grain_size.html). Bazner and Copponnex also wrote that a rule of thumb for good mechanical strength is when the thinnest object dimension is at least ten times larger than the grain size, a condition fulfilled by the reverse-engineered aneurysm clip (Baltzer & Copponnex, 2014).



Figure 7. Profile plot of line number for grain size measurement. Line number 1 is coloured in yellow

Figure 8 shows the SEM micrograph and EDS Spectra of the alloying element of Ti6Al4V Aneurysm Clip. The SEM micrograph shows a similar structure to the optical microscope (OM) result. The EDS result shows that Ti6Al4V consists of Ti (91.22 \pm 0.28 wt.%), Al (5.25 \pm 0.21 wt.%), and V (3.53 \pm 0.36 wt.%). Lastly, the Vickers hardness value of the re-verse-engineered aneurysm clip was taken at different points along the clip with each of the five indentations. The test was done with a load of 0.3 N or 0.031-kilogram force. The aneurysm clip has a Vickers hardness mean of 330.64 HV \pm 6.56. The value is close to the theoretical value of Ti6Al4V hardness, 300 \pm 2 HV (Ma et al., 2017).

As the manufacturing process tends to be a trade secret, no in-detail aneurysm clip manufacturing process is published online. However, one renowned medical supply company, B. Braun, which produces aneurysm clips under the name Yasargil, does publish a corporate video about making their aneurysm clip. Yasargil commercial aneurysm clip uses a machining similar process to the reverse-engineered aneurysm clip in this study that involves pressing the wire into an R contour using the metal jig and rolling the wire to create the spring part on the aneurysm clip (https://www.youtube.com/watch?v=jlGleP8d7W8).

One note-worthy process featured in the video but not on the reverse-engineered aneurysm clip in this study is the manual polishing of the Yasargil clips. Manual clip polishing is a process for smoothing implant material surfaces apart from chemical polishing, electropolishing, and laser polishing.



Figure 8. SEM image and EDS result of the Ti6Al4V aneurysm clip

Moreover, on a patent by Florida Hospital Supply Inc., the manufacturing process of aneurysm clip is described as having a cylindrical metal wire made out of titanium or titanium alloy prepared, cold drawing the wire, cutting the wire, winding the wire around a mandrel to form the spring part, bending the arms next to the spring part into designated deflection angle, shaping the blades or clamping jaws and its connecting elements or fulcrum, coining the blades or clamping jaws at 9000–10,000° F and bending the blades or clamping jaws into parallel position (World Patent No. EP0724406A4, 1993) (Schmidt & Maughan, 1993). While the patent describes many processes that were also done in the re-verse-engineered aneurysm clip in this study, there are particular metal treatment processes, such as cold drawing and coining, which were not done in this remanufacturing of aneurysm clip prototype. Cold drawing of the starting wire was done to reduce the diameter of the wire and increase strength, while coining was needed to form raised sections, serrations, and other fine details. These key processes can be added to achieve closer results to commercial aneurysm clips.

Overall, to the best of our knowledge, the attempts of remanufacturing or mastering the technology behind aneurysm clip production still need to be understood. Previous research studies have used metal additive manufacturing to reproduce aneurysm clips (Asmaria et al., 2021; Walker et al., 2019). The first study could produce the aneurysm clip similarly and precisely in size compared to the commercial one; however, it lacked the closing force (Asmaria et al., 2021). The idea from the second study was remarkable for producing the patient-specific geometry of an aneurysm clip; however, the results from additive manufacturing are far different from their intended models of aneurysm clip, and there was no measurement of closing force (Walker et al., 2019). Compared to this study, our cold forming method could be better in aneurysm clip geometry and the measured closing force. Furthermore, reviewing the existing brain aneurysm models defines five main groups: sidewall, bifurcation stump, terminal, natural and artificial bifurcation, and complex aneurysm models (Marbacher et al., 2020).

The brain aneurysm also could appear in different locations of brain vessels of various sizes and has plenty of branches. Based on their geometries, the aneurysm could be categorized as fusiform and saccular (Pineda-Castillo et al., 2021). Current commercial metal clips, produced by several medical companies, have designed more than 300 configurations and sizes to accommodate uncertain forms, sizes, and locations of brain aneurysms (https://www.aesculapusa.com/en/healthcare-professionals/or-solutions/ aneurysm-clips-for-neurosurgery.html). Significantly, the effort of remanufacturing aneurysm clip will not only help to reproduce the technology to be more independent in providing their medical equipment for Indonesia or other countries but also will be a fundamental knowledge of how to produce the aneurysm clip with a slight modification, particularly on the blade side in a purpose to overcome the occurrence of the patient-specific aneurysm geometries.

CONCLUSION AND OUTLOOK

In this study, the remanufacturing process was executed to reconfigure the aneurysm clip material, which underwent comprehensive characterization. Subsequent analysis involved a comparative assessment between the reconstituted aneurysm clip and their commercially available counterparts.

There is an apparent difference in the morphology of the two samples. The commercial aneurysm clip has a more dynamic wire shape where the spring and the blade part tend to be flatter and thinner than the transitional or fulcrum area, which tends to be more rodlike. The commercial one differs from the reverse-engineered aneurysm clip, where the wire shape is generally uniform with a rod-like shape. The reason can be the lack of fine machining on the reverse-engineered aneurysm clip. The dimension measurements of the reverse-engineered clip are considerably bigger than the existing commercial clip. For its application, the reverse-engineered clip could work, open, close, and clip as intended. However, performance deficiencies exist, such as the prototype being too brittle.

There is a significant divergence between the reverse-engineered aneurysm clip and the commercial aneurysm clip for the value of closing force, 1.689N and 0.791N, respectively. The possible main reason for the difference in the closing force is that the physical appearance of the reverse-engineered aneurysm clip is far from the detailed configuration of the commercial aneurysm clip, meaning both have different manufacturing processes.

In material analysis, the density of the remanufacturing prototype of an aneurysm clip conforms to the density of medical grade Ti6Al4V, which is 4.3424 g/cm³. However, the commercial aneurysm clip's experimental density is 7.9581 g/cm³. This value is far higher than the density of Ti6Al4V, which indicates that the commercial aneurysm clip may be manufactured using different materials. The SEM-EDS examination of the commercial aneurysm clip reveals the presence of CoCr Mo.

Furthermore, the material analysis is also concerned with the sample's micro-structural and chemical composition aspects. The reverse-engineered aneurysm clip shows an equiaxed microstructure, apparent from the metallurgy test results and SEM images. The microstructure result indicates a superior microhardness and ductility in the reverse-engineered aneurysm clip. The grain size calculation using the intercept line method shows the result of 10.48 μ m, indicating good metal workability. Therefore, it is possible to emulate the dynamic shape of the commercial aneurysm clip on the reverse-engineered aneurysm clip through further machining. As for chemical composition, the result shows the typical value of Ti6Al4V. Vickers hardness test shows a close number to the theoretical Vickers hardness of Ti6Al4V.

Manufacturing analysis compares the reverse-engineered aneurysm clip and commercial aneurysm clips. Both share a similar machining process, which involves pressing the wire into an R contour using a metal jig and rolling the wire to create the spring part on the aneurysm clip. However, commercial aneurysm clips undergo more fine machining and manual polishing, which results in their dynamic wire shape and fine detailing compared to the bulkiness and lack of fine detailing of reverse-engineered aneurysm clips.

Despite the suspicion of material difference, changing the material of the next selffabrication of aneurysm clip may not be required as Ti6Al4V is commonly used to fabricate aneurysm clips. The grain size of the reverse-engineered aneurysm clip shows that further working and detailing of the wire is possible. Therefore, the best recommendation that can be proposed is to do a more meticulous shaping of the raw wire to emulate the dynamic shape of commercial aneurysm clips.

These findings contribute to advancements in clip design and installation techniques. Cold metal forming and coining of the raw wire should be incorporated in the future.

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A Supervised Genre-based Recommendation Model for Game Review

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ABSTRACT

The gaming industry is becoming more and more popular as the number of players increases. Game recommendations allow players to quickly decide if it is worth playing. This article explores how reviews of players who have played the game can be used to decide whether the game should be recommended. Nevertheless, genre-oriented models have not been incorporated in the recommendation. Since different genres have different characteristics that attract different groups of players, generalized recommendation models may not be effective enough in dealing with specific genres of games. This article proposes a genre-based recommendation model using a supervised machine learning model. All game datasets will be divided into six genres (Action, RPG, Adventure, FPS, Horror, and Strategy). Each game genre is trained separately with three feature selection methods (Bag of Words, N-Gram and Part of Speech) and three classification algorithms (Naive Bayes, Support Vector Machine and Decision Tree). The experiment results found that genre-based models mostly outperform the general model (without differentiating by genre). The best feature selection and combination of classification algorithms is also obtained for each genre, with Bag of Words and Naive Bayes topping most genres. For example, the accuracy achieved by the FPS model is 0.854 compared to the general (all genres) model with an accuracy of 0.828.

Keywords: Feature selection, game review, machine learning, recommendation

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INTRODUCTION

In recent years, the need for recommendations has arisen in domains like online selling, academia and entertainment. This need stems from information overload, which causes users to be overwhelmed by choices when buying products, choosing courses and picking movies. Providers must assist users in making better decisions. In gaming, game quality is vital for player experience. Game review content offers hints about the game's quality. Analyzing the contents helps players grasp game aspects and playability, aiding the decision of whether a game is worth playing. This task is treated as classification. The models will predict whether a game will be recommended based on the supervised learning of previous players' reviews.

Steam, a major digital distribution platform, allows players to buy, discuss, and share games and software. With millions of users and 47 million active players daily, Steam has been developed for 20 years to improve the player experience. Players often review games and express whether they would recommend them. The percentage of recommendations affects others' perceptions and buying decisions. Figure 1 shows reviews posted on the Steam gaming platform.



Figure 1. Game review on the Steam platform (https://store.steampowered.com/)

Nevertheless, not all game discussion forums have a recommendation feature, making it difficult for players to judge a game's playability. For example, discussions about games on Twitter do not indicate whether the game is recommended (Figure 2).



Figure 2. Game review on Twitter

In this context, players must rely on reviews to assess the games. The game recommendation model would be useful for automating the process of processing the reviews and suggesting a recommendation. Recommendations benefit players by allowing

them to swiftly take others' feedback as their reference. Game developers can also learn from the non-recommended reviews to understand complaints, overcome shortcomings, identify needs, and create better work.

In the domain of gaming, each game will have different characteristics and different ways of playing, so they will have their own genres. Some games may also span multiple genres, incorporating multiple play styles and elements. For example, The Legend of Zelda: Breath of the Wild, a game that contains both Action and Adventure genres, focuses on exploring an open world and upgrading characters by completing quests. Therefore, some genre-based keywords, such as combat and backstory, may appear in the review. In other games from other genres, there will be different feature words; for example, horror games will appear as scary, frightening, and so on.

A classifier is constructed to understand players' written reviews to create a game recommendation model. These reviews are categorized as recommended or not. Zuo (2018) presented a similar classifier for Steam reviews, categorizing them as positive (recommended) or negative (not recommended). Naïve Bayes and Decision Tree (with N-Gram features) were used. Decision Trees outperformed Gaussian Naive Bayes with about 75% accuracy on the Steam Review Dataset. However, there's room for improvement due to limited feature selection methods and algorithms.

Player-written descriptions play a pivotal role in training a recommendation model. For instance, "scared with creepy voices" indicates recommendation, while "repetitive without excitement" indicates not recommended. Previous research explored enhancing recommendation models using machine learning or rule-based methods. Viggiato et al. (2021) used Stanford CoreNLP, Sentistrength, and self-trained Naïve Bayes to analyze sentiment, with modest and poorly performing results on game reviews. Accuracy ranged from 0.37 (Stanford CoreNLP) to 0.61 (NLTK). Zuo (2018) reported higher accuracy (0.7495) using Decision Tree and N-Gram features. Therefore, exploring different textual features like Bag of Words, N-Gram, and Part of Speech (POS) could be valuable.

Viggiato et al. (2021) identified the root causes of poor classification, including negative terminology causing misinterpretation of positive words. They proposed a stratified training process based on the game genre for their sentiment analysis classifier. The results show a positive outcome.

As far as we are concerned, no related work combines game genres with various feature selection methods and classification algorithms applied to sentiment classification. Therefore, Therefore, we propose a genre-based model for game recommendation. Our proposed model will be compared with a general recommendation that will be trained based on reviews from all games (without separating by genre). Three feature extraction methods (BOW, N-Gram and POS) and three classification algorithms (NB, SVM and DT) that have been shortlisted from the literature will be used in the model training.

LITERATURE REVIEW

The literature related to game recommendations is mostly related to the sentiment expressed in the review text. This discussion covers three main areas of work: game recommendation, genre classification and sentiment classification.

Game Recommendation

Bais et al. (2017) conducted a sentiment analysis study using Steam reviews as a dataset to detect sarcasm in reviews. Methods including Lexicon Score Aggregation, Multinomial Naive Bayes, Modified Turney's Algorithm, Logistic Regression and Linear SVM were evaluated in the experiment. According to the reported results, linear SVM performed best with an accuracy of 0.935. Britto and Pac'ífico (2020) used the Portuguese language game data set and BOW as the feature extraction method for the training of three classifiers, which are Random Forest, Support Vector Machines and Logistic Regression, respectively. The best-performing model is the SVM model, with an accurate rate of 82.54%.

Genre Classification

Another class of work related to the game domain would be genre-related research. Jiang and Zheng (2023) utilized the cover image, description text, title text and genre information of 50,000 video games as a dataset and divided them into 21 game genres. The authors thoroughly evaluated image—and text-based state-of-the-art models in classification and developed an efficient image—and text-based multimodal framework.

Puppala et al. (2021) classified music into ten different genres by extracting the Mel Frequency Cepstral constant (MFCC) value in music as a feature and using a convolutional neural network to train the model. The final model training accuracy rate is as high as 97%.

Besides the game domain, genre-based research has also been conducted in domains like books and movies. Biradar et al. (2019) used book covers and titles as features for genre classification. The authors used a logistic regression model for training and prediction. In the end, the accuracy of using both the cover and the title as features was 87.2%.

Chu and Guo (2017) propose to implement movie genre classification based only on movie poster images. A deep neural network is constructed to jointly describe visual appearance and object information and classify a given movie poster image into genres. Simoes et al. (2016) proposed a novel deep neural architecture based on Convolutional Neural Networks (ConvNets) to perform multi-label movie trailer genre classification. It encapsulates an ultra-deep ConvNet with residual connections and utilizes special convolutional layers to extract temporal information from image-based features before performing movie trailer-to-genre mapping.

Sentiment Classification

Since the problem of game recommendation resembles the problem of sentiment classification, techniques used in sentiment classification are important baselines and references, especially in the identification of algorithms and feature selection methods. Hadwan et al. (2022) proposed an improved sentiment classification method that used machine learning methods with feature engineering and SMOTE techniques to measure user satisfaction with government service mobile applications. The authors used a total of six feature engineering methods and five machine learning algorithms. Among them, the NB classifier outperformed the other models (74.25% accuracy) when using the original Arb-Apps Review dataset and extracting features by BOW.

Chakraborty et al. (2021) researched the Bangla dataset, predicted text polarities (positive, neutral, negative) using N-Gram as feature extraction, and two ML algorithms (SVM, Random Forest). The results showed that SVM outperformed, especially with unigram, achieving a 68% F1 score.

Shahzad et al. (2022) proposed a framework for analyzing global perceptions and attitudes towards the COVID-19 vaccines AstraZeneca, Pfizer, Sinovac, Moderna, and Sinopharm, respectively. Different machine learning classifiers, such as Random Forest (RF), Parsimonious Bayes (NB), Decision Trees (DT), Logistic Regression (LR) and Support Vector Machines (SVM), were used. DT performed the best results on five different datasets.

A review on exploring the impact of embedding models on text analysis was published (Asudani et al., 2023). It introduces a number of word representation approaches, including traditional methods such as the bag-of-words model, n-gram, TF-IDF, and word embedding models Word2Vec, GloVe, and so on. It also shows the performance of these word representation models in different tasks. They explored the performance of word embeddings in deep learning models in text analysis tasks and concluded that combining domain-specific word embeddings and LSTM models can improve the performance of text analysis tasks.

Based on the literature review, many achievements have been captured in the field of genre classification (Puppala et al., 2021). However, genre-based research is lacking, especially genre-based recommender systems. Genre is important in differentiating the characteristics or types of the domain's objects. Hence, the genre-based model is often used to capture specific characteristics. Therefore, we explore whether recommendation models in the gaming domain can benefit from a genre-based setting.

Since the feature selection method can also affect the model's accuracy, this article chooses three common feature selection approaches in the field of text classification: BOW, N-Gram and POS. BOW explores the effect of individual words on the model, N-Gram explores the effect of sequences on the model, and POS explores the effect of actions or sentiments on the model.

As for machine learning algorithms, previous studies provide mixed results. According to Hadwan et al. (2022), NB performed best when BOW was the feature selection method, so NB was also chosen. SVM was chosen because it performed better compared to LR and RF in the game dataset (Britto & Pac'ifico, 2020). DT was chosen because Zuo (2018) used both NB and DT in his method and performed better. In similar tasks, NB, SVM and DT algorithms have achieved better results than other machine learning algorithms, such as random forest and logistic regression. Therefore, we have chosen NB, SVM and DT as the algorithms for machine learning.

In contrast to previous work, our study will systematically compare multiple feature selection methods and classification algorithms to construct recommendation models in the gaming domain. Figure 3 summarizes the related literature, which shows the gaps in research and highlights the methodology that is the focus of this paper. This approach addresses the identified gaps and provides a robust analysis of genre-based recommendations, thereby advancing the field.



Figure 3. Literature gap in game recommendation

METHODS

A classification model is created to achieve the classification goal on the game review dataset. Firstly, games are classified by genre, and the dataset is split accordingly. Various text preprocessing steps are applied based on different feature extraction methods: Bag of Words (Punctuation removal, lowercase, lemmatization, and stop word removal), N-Gram (Punctuation removal, lowercase, and lemmatization), Part of Speech (Punctuation removal and lowercase).

After text preprocessing, the respective feature extraction processes are carried out. Extracted features are then fed into various classifier models, including Naive Bayes, Support Vector Machines, and Decision Trees.

Subsequently, each model's performance is evaluated in terms of accuracy, precision, recall, and F1 score. The models for each game genre are compared, and the best-performing model is chosen. Figure 3 is the framework of the model.



Figure 4. The framework of the genre-based game recommendation model

Dataset

This dataset is from Kaggle. The link is https://www.kaggle.com/datasets/arashnic/gamereview-dataset, and reviews originate from the Steam gaming platform. The dataset includes 44 games, encompassing various genres, resulting in 157 different game genres represented.

For the sake of practicality in conducting experiments, six specific game genres were selected for analysis. These genres were chosen because all 44 games included at least one of these six genres, with many games falling under two of these categories. The six selected game genres are as follows: Action (Act), Role-playing game (RPG), Adventure (Adv), First-person shooting game (FPS), Horror (Hor) and Strategy (Str).

Upon categorizing the games into these genres, the dataset provides information for all genres collectively and for each genre (Table 1). It's worth noting that since many games belong to two genres simultaneously, the total number of data sets for these six game genres will exceed the original number of data sets in the dataset.

Genre	Number of games	Number of reviews	Recommended	Not recommended
All	44	17436	9933 (57.0%)	7503 (43.0%)
Act	28	10852	6871 (63.3%)	3981 (36.7%)
RPG	15	4681	2802 (59.9%)	1879 (40.1%)
Adv	11	4916	2435 (49.5%)	2481 (50.5%)
FPS	12	5330	3051 (57.2%)	2279 (42.8%)
Hor	5	1747	845 (48.4%)	902 (51.6%)
Str	19	6496	3324 (51.2%)	3172 (48.8%)

 Table 1

 Data set information of all genres and each genre

Text Preprocessing

Text preprocessing is a series of processing of source data to extract more useful features. Here is how the text was preprocessed for this article.

Punctuation removal	:	Strip punctuation from reviews so that a space precedes each word.
Stop word removal	:	Stop words are words that appear frequently in the text and are of little value in indicating the content of the text. Eliminating some meaningless and ineffective words can avoid the interference caused by these words.
Lowercase	:	Convert all letters to lowercase, aiming to improve feature extraction so that words with different cases are not treated as different.
Lemmatization	:	Lemmatization is the reduction of a language vocabulary of any form to its general form. It will remove the word's affixes and extract the word's main part.

Feature Selection

Feature selection is a critical process aimed at choosing the most relevant features from the original set of features to reduce data dimensionality and enhance the performance of machine learning algorithms. For the task of this article, the feature selection methods of word embedding, such as Word2Vec and GloVe, are not used. It requires a large amount of data and computational resources to train and generate vectors dependent on pre-trained data. Meanwhile, traditional feature extraction approaches are simpler and computationally efficient for tasks with small data. Therefore, the following three feature selection methods are used in this article. They are Bag of Words, N-Gram and Part-of-Speech, respectively.

Bag-of-words is a basic and well-known text representation technique (Deniz et al., 2021). Each word of the bag-of-words model occurs independently in the text. The frequency of all words is counted, and a part of the words with the highest frequency is selected as the word bag. BOW can investigate how individual words impact the model. BOW is widely used for tasks such as text analysis and sentiment classification because it captures the word frequency information in the text very well and is easy to compute. It can be used as input to various machine learning algorithms.

N-Gram is an algorithm based on statistical language models (Cavnar & Trenkle, 1994). N-Gram is enough to capture more semantic information and relationships between words and can delve into how word sequences affect the model. In this article, 2-gram and 3-gram will be chosen.

Part-of-speech tagging involves classifying and tagging words in a sentence, assigning part-of-speech tags to each word based on its grammatical role. After tagging, this article will extract verb phrases, nouns, and adjective phrases from the text as features. POS tagging can capture actions through verb phrases and sentiments through adjective phrases. These features related to actions and sentiments can be leveraged to explore their impact on the model. It can also reduce noise since words with specific lexical properties may be more important than others. Verb phrases and adjective phrases have specific extraction rules, as outlined in Table 2.

Phrases	Extraction rules
Verb phrases	verb + preposition
	verb + adverb
	verb + adverb + preposition
Adjective phrases	adjective + coordinating conjunction + adjective
	adjective + adverb
	adverb + adjective

Table 2Extraction rules with POS

After extracting the corresponding phrases, the frequency of their occurrence was calculated, and the part with the highest frequency was used as a feature. Comparing BOW, N-Gram and POS, machine learning models can capture textual features at different dimensions, thus exploring the ability of the models to understand and process textual data when using different feature selection methods.

Classification Algorithm

Three classification algorithms are used in this article, namely Naive Bayes (Raschka, 2014), Support Vector Machine (Gaspar et al., 2012) and Decision Tree (Patel & Prajapati, 2018). NB is based on Bayes' theorem and assumes that features are independent of each other. It is computationally simple, fast in training and prediction, and suitable for large-scale text data. SVM has strong generalization ability, can effectively avoid overfitting, and performs well in dealing with binary classification problems. DT is good at capturing the nonlinear relationship between features and categories and is suitable for complex sentiment classification tasks. Combining the advantages of these three classifiers and their excellent performance in related work, they were considered suitable for this study and were finally selected as the classification algorithm for this article.

Experiment Setup

The dataset for each game genre will be split into a training set and a test set, with a ratio of 8 to 2. Following this division, the parameters for feature extraction will be explored. Given the substantial size of the dataset, only the most frequently occurring features will be extracted. Different parameter values will be tested for various feature selection methods. In this context, the parameter refers to the number of features with the highest frequency ranking.

These parameters will be established using all data sets for the various game genres. The experimental results from this comprehensive analysis will serve as a reference for standardizing the parameters for the models of each game genre. Their parameters will be set to be identical to ensure a fair comparison between classification algorithms.

Ultimately, the parameters for each feature selection method will be determined separately by selecting the values that yield the highest average accuracy across the three models. The experiments will lead to the selection of the most suitable parameters, which are summarized in Table 3.

After confirming feature extraction parameters, a baseline was specified. In this article, the results of the model trained with all game genres as the data set are selected as the baseline. Not only was the model trained on all game genres on all datasets tested, but the datasets for each genre were also tested separately. This result was used to compare with the model of each game genre. The model evaluation metrics are accuracy (A), precision (P), recall (R), and F1 (F) score.

Feature selection method	Parameter
Bag of Words	1500
2-Gram	3000
3-Gram	4000
Part of Speech	2000

 Table 3

 Parameters for each feature selection method

RESULTS

Statistical Significance Tests

Before the experiment, we did statistical significance tests to confirm that the three machine learning algorithms are different. Here, all genre datasets are used. The method used is a t-test, and since a t-test can only validate two models at a time, we did three t-test validations. We set the alpha value to 0.05 for the experiment and used 5×2 cross-validation to validate. That is, we repeated the 2-fold cross-validation five times. The results of the experiment are shown in Table 4.

Table 4Results of statistical significance tests

Models for comparison	NB/SVM	NB/DT	SVM/DT	
p-value	0.004	< 0.001	< 0.001	
Result	Reject	Reject	Reject	

Based on each of the results above, the null hypothesis was rejected. Therefore, the three models show variability, proving that the experiment is feasible.

Results for Bag of Words

When BOW is used as a feature selection method, the accuracy results are shown in Table 5.

Table 5 shows that using BOW as the feature selection method generally yields higher accuracy with the NB classification algorithm. Additionally, when training NB and DT models based on game genres, most accuracy rates surpass those of models trained on all genres. Furthermore, performance is suboptimal when applying the all-genres model to individual genre datasets. Precision, recall and F1 results are detailed in Table 6.

Table 6 shows that when BOW is used as the feature selection method, the precision, recall and F1 of NB as the classification algorithm are generally higher. The Horror genre NB model's precision value is much higher than that of all the other genres, reaching 0.883. The highest recall is in the Adventure genre, reaching 0.844. The highest F1 scores were observed for NB in the Adventure and FPS genres, both at 0.831.

	Classifier	NB	SVM	DT				
Target & Model								
All	All	0.828	0.822	0.688				
A at	Act	0.851	0.802	0.719				
Act	All	0.564	0.523	0.514				
DDC	RPG	0.812	0.732	0.693				
KPU	All	0.488	0.522	0.509				
A .l	Adv	0.832	0.804	0.669				
Adv	All	0.543	0.567	0.508				
EDC	FPS	0.854	0.776	0.698				
FPS	All	0.519	0.520	0.468				
II	Hor	0.797	0.697	0.720				
Hor	All	0.506	0.529	0.471				
C.t.,	Str	0.832	0.766	0.676				
Str	All	0.535	0.520	0.528				

Table 5Accuracy of all and genre-based models with BOW

Table 6

Precision, recall and F1 of all and genre-based models with BOW

$\overline{}$	Classifier		NB			SVM			DT	
Target & Mo	t del	Р	R	F	Р	R	F	Р	R	F
All	All	0.822	0.786	0.804	0.783	0.797	0.790	0.627	0.637	0.632
A	Act	0.820	0.793	0.806	0.736	0.739	0.737	0.630	0.628	0.629
Act	All	0.639	0.446	0.526	0.585	0.409	0.481	0.551	0.397	0.461
DDC	RPG	0.742	0.751	0.746	0.676	0.631	0.653	0.625	0.581	0.602
RPG	All	0.585	0.378	0.459	0.421	0.374	0.396	0.533	0.385	0.447
A 1	Adv	0.818	0.844	0.831	0.788	0.816	0.802	0.646	0.679	0.663
Adv	All	0.572	0.543	0.557	0.620	0.563	0.590	0.588	0.510	0.546
EDC	FPS	0.833	0.829	0.831	0.738	0.742	0.740	0.664	0.647	0.655
FPS	All	0.538	0.452	0.492	0.592	0.457	0.516	0.538	0.411	0.467
	Hor	0.883	0.748	0.810	0.620	0.721	0.667	0.690	0.724	0.707
Hor	All	0.895	0.497	0.639	0.725	0.512	0.600	0.772	0.475	0.588
G.	Str	0.797	0.842	0.819	0.720	0.775	0.747	0.653	0.664	0.659
Str	All	0.248	0.531	0.338	0.178	0.496	0.262	0.569	0.506	0.536

Results for 2-Gram

When 2-gram is used as a feature selection method, the accuracy results are shown in Table 7.

	Classifier	NB	SVM	DT
Target & Model				
All	All	0.816	0.764	0.663
Aat	Act	0.825	0.756	0.684
Act	All	0.513	0.550	0.491
DDC	RPG	0.819	0.724	0.655
KPG	All	0.505	0.472	0.508
4.1	Adv	0.826	0.725	0.691
Auv	All	0.535	0.504	0.510
EDC	FPS	0.839	0.721	0.662
FPS	All	0.479	0.500	0.492
Hom	Hor	0.757	0.694	0.697
пог	All	0.503	0.469	0.551
C.	Stra	0.817	0.758	0.664
Stra	All	0.514	0.520	0.505

Table 7Accuracy of all and genre-based models with 2-gram

Table 8

Precision, recall and F1 of all and genre-based models with 2-gram

$\overline{}$	Classifier		NB			SVM			DT	
Target & Moo	lel	Р	R	F	Р	R	F	Р	R	F
All	All	0.816	0.768	0.791	0.733	0.721	0.727	0.601	0.608	0.605
Ast	Act	0.786	0.760	0.772	0.670	0.680	0.675	0.549	0.589	0.568
Act	All	0.563	0.398	0.466	0.393	0.403	0.398	0.683	0.399	0.504
RPG	RPG	0.785	0.743	0.763	0.605	0.636	0.620	0.590	0.534	0.561
	All	0.542	0.383	0.449	0.734	0.389	0.508	0.665	0.403	0.502
۰.۱.	Adv	0.861	0.807	0.833	0.679	0.750	0.713	0.687	0.695	0.691
Adv	All	0.527	0.538	0.533	0.485	0.504	0.496	0.572	0.512	0.540
FPS	FPS	0.779	0.837	0.807	0.644	0.691	0.667	0.592	0.613	0.603
	All	0.445	0.407	0.425	0.371	0.413	0.391	0.521	0.429	0.470
	Hor	0.819	0.722	0.767	0.760	0.663	0.708	0.725	0.678	0.701
Hor	All	0.485	0.491	0.488	0.474	0.458	0.466	0.620	0.535	0.575
C 4	Str	0.783	0.825	0.804	0.717	0.762	0.739	0.658	0.646	0.652
Str	All	0.465	0.491	0.478	0.318	0.497	0.388	0.579	0.485	0.528

From Table 7, when 2-Gram is employed as the feature selection method, the accuracy of SVM and DT models for each game genre fluctuates, sometimes surpassing and other

times falling below the accuracy of the all-genres model. Conversely, most NB genrespecific models achieve higher accuracy than the all-genres models. The highest accuracy value was for the FPS genre NB model, which exceeded the value for all genres of models, reaching 0.839. Table 8 shows the precision, recall and F1 results.

It can be seen from Table 8 that when 2-Gram is used as the feature selection method, the precision, recall, and F1 of each game genre model of NB, SVM, and DT fluctuates up and down the value of all game genre models. Among them, the precision of the NB model of Adventure reached 0.861. The recall of the NB model of FPS reached 0.837, which is the highest. The F1 of the NB model of Adventure reached 0.833, which is the highest.

Results for 3-Gram

When 3-gram is used as a feature selection method, the accuracy results are shown in Table 9.

	Classifier	NB	SVM	DT
Target & Model				
All	All	0.779	0.696	0.659
Apt	Act	0.792	0.704	0.656
Act	All	0.514	0.532	0.481
DDC	RPG	0.761	0.670	0.670
KPU	All	0.540	0.489	0.475
A .l	Adv	0.762	0.646	0.618
Adv	All	0.552	0.558	0.494
EDC	FPS	0.771	0.682	0.639
FPS	All	0.516	0.508	0.482
II	Hor	0.723	0.637	0.597
Hor	All	0.489	0.500	0.449
<u>S</u> .t.,	Str	0.768	0.664	0.633
Str	All	0.502	0.497	0.477

 Table 9

 Accuracy of all and genre-based models with 3-gram

It can be seen from Table 9 that when 3-Gram is used as the feature selection method, the accuracy of the models for each game genre for NB, SVM and DT fluctuates around the value of the models for all game genres. The highest accuracy was achieved by the Action Genre NB model with 0.792. In addition, when the models trained by all game genres are put into the data sets of each genre, the models of each genre do not perform well. Next, precision, recall and F1 results are in Table 10.
$\overline{}$	Classifier		NB			SVM			DT	
Target & Mode	el	Р	R	F	Р	R	F	Р	R	F
All	All	0.770	0.729	0.749	0.649	0.643	0.646	0.606	0.601	0.604
A = 4	Act	0.724	0.725	0.724	0.618	0.606	0.612	0.619	0.539	0.576
Act	All	0.471	0.384	0.423	0.424	0.391	0.407	0.486	0.361	0.415
DDC	RPG	0.702	0.671	0.686	0.539	0.560	0.549	0.570	0.556	0.563
КI Ü	All	0.539	0.410	0.466	0.473	0.358	0.407	0.484	0.351	0.407
Adv	Adv	0.794	0.749	0.771	0.574	0.675	0.620	0.529	0.647	0.582
	All	0.505	0.561	0.531	0.479	0.572	0.521	0.481	0.497	0.489
EDC	FPS	0.664	0.775	0.715	0.564	0.653	0.605	0.566	0.585	0.576
FP5	All	0.449	0.441	0.445	0.456	0.435	0.445	0.527	0.421	0.468
TT	Hor	0.789	0.689	0.736	0.596	0.638	0.616	0.649	0.578	0.612
Hor	All	0.538	0.479	0.507	0.520	0.489	0.504	0.485	0.441	0.462
C 4	Str	0.732	0.771	0.751	0.627	0.655	0.641	0.598	0.621	0.609
Str	All	0.482	0.479	0.481	0.511	0.476	0.493	0.474	0.455	0.465

 Table 10

 Precision, recall and F1 of all and genre-based models with 3-gram

Table 10 shows that when using the 3-Gram as the feature selection method, the precision, recall and F1 of the models for each game genre for NB, SVM and DT fluctuate around the value of the models for all game genres. The highest precision was for the Adventure genre NB model, which reached 0.794. The highest recall was for the FPS-type NB model, which reached 0.775. Among them, the highest F1 is the Adventure genre NB model, reaching 0.771.

Results for Part of Speech

The experiment results are shown in Table 11 according to the feature extraction rules.

It can be seen from Table 11 that when POS is used as the feature selection method, the accuracy of the models of each game genre of NB and DT fluctuates up and down the value of the model of all game genres. Among them, the NB model with the highest accuracy is the FPS game genre, reaching 0.827. In addition, when the models trained by all game genres are put into the data sets of each genre, the models of each genre do not perform well. Table 12 shows the precision, recall and F1 results.

From Table 12, when POS is used as the feature selection method, the precision, recall, and F1 of each game genre model of NB, SVM, and DT fluctuate up and down in value. The highest precision is the NB model of the Horror game genre, reaching 0.930. The Adventure genre NB model has the highest recall and F1, 0.808 and 0.821.

	Classifier	NB	SVM	DT
Target & Model				
All	All	0.812	0.775	0.645
Act	Act	0.822	0.767	0.668
Act	All	0.500	0.569	0.555
DDC	RPG	0.785	0.719	0.642
RPG	All	0.493	0.549	0.485
A .l	Adv	0.817	0.737	0.634
Adv	All	0.503	0.505	0.480
FPS	FPS	0.827	0.751	0.628
	All	0.508	0.518	0.534
TT	Hor	0.734	0.663	0.614
Hor	All	0.486	0.483	0.494
C4	Str	0.805	0.737	0.639
Str	All	0.477	0.529	0.498

Table 11Accuracy of all and genre-based models with POS

Table 12

Precision, recall and F1 of all and genre-based models with POS

	lassifier		NB			SVM			DT	
Target & Mode	el	Р	R	F	Р	R	F	Р	R	F
All	All	0.814	0.762	0.788	0.717	0.746	0.732	0.575	0.587	0.581
Act	Act	0.783	0.755	0.769	0.682	0.696	0.689	0.516	0.567	0.540
Act	All	0.839	0.419	0.559	0.463	0.434	0.448	0.523	0.428	0.470
DDC	RPG	0.756	0.695	0.724	0.659	0.615	0.636	0.504	0.521	0.512
KFU	All	0.621	0.388	0.477	0.536	0.417	0.469	0.570	0.374	0.452
A day	Adv	0.834	0.808	0.821	0.705	0.755	0.729	0.624	0.640	0.632
Adv	All	0.705	0.504	0.588	0.675	0.506	0.578	0.471	0.482	0.476
EDC	FPS	0.796	0.803	0.800	0.720	0.709	0.715	0.555	0.571	0.563
rrs	All	0.696	0.455	0.550	0.479	0.446	0.462	0.358	0.451	0.399
II	Hor	0.930	0.663	0.774	0.649	0.657	0.653	0.620	0.602	0.611
Hor	All	0.784	0.484	0.598	0.532	0.474	0.501	0.234	0.465	0.311
S.t.	Str	0.780	0.807	0.793	0.740	0.719	0.729	0.630	0.618	0.624
Su	All	0.831	0.473	0.603	0.693	0.506	0.585	0.526	0.478	0.501

DISCUSSION

Based on the results presented in this study, it's clear that models trained on datasets encompassing all game genres perform reasonably well when applied to the same genre of dataset. However, their performance significantly lagged behind models trained specifically in individual game genres. The primary reason for this disparity lies in feature extraction. Models trained in all genres extract features that encompass elements from all six game genres, whereas models trained in a specific genre extract feature tailored to that genre alone. Consequently, the performance gap becomes substantial when both models are applied to the same genre-specific dataset.

For instance, when both models are applied to the Action dataset with identical test data, the models trained using all game-genre datasets (using BOW and NB) achieve an accuracy, precision, recall, and F1 score of 0.564, 0.639, 0.446, and 0.526, respectively. In contrast, the models trained using the Action dataset achieve much higher results, with an accuracy of 0.851, precision of 0.820, recall of 0.793, and F1 score of 0.806. This illustrates that models tailored to specific game genres significantly outperform those trained in all genres.

Table 13 summarizes all the above results and provides a concise overview of the highest accuracy, precision, recall, and F1 for different combinations of feature extraction methods and classifiers for each game genre. Figure 4 illustrates the results in a bar chart, providing a more visual view of the gap between each result.

Referring to Table 13 and Figure 5, it's apparent that, for most game genres, the combination of BOW and NB achieved the best performance, followed by 2-Gram and NB. Also, models based on specific game genres generally perform better than those trained in all genres. However, there are still individual game genres where the results of the models are not as good as the models trained on all game genres, and it is possible that this occurs due to an insufficient dataset, which prevents the models from being adequately trained. Notably, the FPS game genres like horror and RPG have relatively lower performance, possibly due to their small dataset sizes, hindering the training of more robust models.

In summary, Table 13 reveals that when employing the combination of BOW and NB, the accuracy of the all-genres model reaches 0.828. However, most genre-based models surpass their accuracy, including FPS, Action, Adventure, and Strategy, which achieve accuracy values of 0.854, 0.851, 0.832, and 0.832, respectively. It implies that genrespecific models consistently outperform the all-genres model in accuracy. This result is an improvement over previous similar tasks in the literature, e.g., (Zuo, 2018) (accuracy: 0.75), (Britto & Pac'ıfico, 2020) (accuracy: 0.825).

The Action game genre models were used as a reference for text features, and Table 14 summarizes the experimental results.

	Ac	curacy	Pr	ecision		Recall		F1
Genre	Value	Feature & Classifier						
Act	0.851	BOW&NB	0.820	BOW&NB	0.793	BOW&NB	0.806	BOW&NB
RPG	0.819	2-G&NB	0.785	2-G&NB	0.751	BOW&NB	0.763	2-G&NB
Adv	0.832	BOW&NB	0.861	2-G&NB	0.844	BOW&NB	0.833	2-G&NB
FPS	0.854	BOW&NB	0.833	BOW&NB	0.837	2-G&NB	0.831	BOW&NB
Hor	0.797	BOW&NB	0.930	POS&NB	0.748	BOW&NB	0.810	BOW&NB
Str	0.832	BOW&NB	0.797	BOW&NB	0.842	BOW&NB	0.819	BOW&NB
All	0.828	BOW&NB	0.822	BOW&NB	0.797	BOW&SVM	0.804	BOW&NB

Table 13Summary of all top-performing models



Figure 5. Results for all top-performing models

As indicated in Table 14, within the Action game genre, each classifier delivers the best performance when employing BOW as the feature selection method. They consistently outperform 2-Gram, 3-Gram, and POS across all evaluated metrics. Consequently, it can be inferred that BOW is the most effective among the three feature selection methods.

The subsequent step is to determine the best-performing classification algorithm. Table 15 summarizes the results for the Strategy game genre.

Classifier	Feature	Accuracy	Precision	Recall	F1
	BOW	0.851	0.820	0.793	0.806
ND	2-Gram	0.825	0.786	0.760	0.772
NB	3-Gram	0.792	0.724	0.725	0.724
	POS	0.822	0.783	0.755	0.769
	BOW	0.802	0.736	0.739	0.737
SVM	2-Gram	0.756	0.670	0.680	0.675
	3-Gram	0.704	0.618	0.606	0.612
	POS	0.767	0.682	0.696	0.689
	BOW	0.719	0.630	0.628	0.629
DT	2-Gram	0.684	0.549	0.589	0.568
DI	3-Gram	0.656	0.619	0.539	0.576
	POS	0.668	0.516	0.567	0.540

Table 14Summary of results for the Action game genre

Table 15Summary of results for the Strategy game genre

Feature	Classifier	Accuracy	Precision	Recall	F1
	NB	0.832	0.797	0.842	0.819
BOW	SVM	0.766	0.720	0.775	0.747
	DT	0.676	0.653	0.664	0.659
2-Gram	NB	0.817	0.783	0.825	0.804
	SVM	0.758	0.717	0.762	0.739
	DT	0.664	0.658	0.646	0.652
	NB	0.768	0.732	0.771	0.751
3-Gram	SVM	0.664	0.627	0.655	0.641
	DT	0.633	0.598	0.621	0.609
	NB	0.805	0.780	0.807	0.793
POS	SVM	0.737	0.740	0.719	0.729
	DT	0.637	0.630	0.618	0.624

As evident from Table 15, among the Strategy game genre models, NB consistently outperforms both SVM and DT in all evaluation metrics when feature selection methods are consistent. This trend is also observed across the other game genre models, with NB emerging as the best-performing classification algorithm. The model performance is notably enhanced when the most effective feature selection method is paired with the top-performing classifier.

The above results may be because BOW can learn valid sentiment tokens from a large amount of data very well, and it does not focus on word order and structural information, making it robust to certain noisy data. In addition, NB assumes conditional independence between features, an assumption that often provides a valid approximation in sentiment categorization since many sentiment words independently reflect sentiment tendencies. It can handle high-dimensional data well, whereas the features of game reviews are usually high-dimensional. Therefore, the results of combining BOW and NB outperform other combinations.

After the above experiments, we chose the most accurate FPS genre for prediction, and the combination of the models was BOW and NB. We selected 10 game reviews from Twitter without labels. After the prediction was completed and manually verified, 8 out of 10 predicted reviews were correct. The accuracy is relatively high. The model can help users quickly realize the number of positive and negative reviews of a game and thus help them decide whether to play.

The model still exists with some limitations. The current model can only show recommendations and non-recommendations but no justification for the reason for the recommendation. A more specific recommendation can be provided by supporting the decision recommendation with evidence such as phrases related to the recommendation or otherwise. For example, aspect and evidence extraction can be carried out when a game called "Spooky" is recommended. For example, because the music is so scary, it can be extracted as music and scary. Players can determine whether their needs are fulfilled based on the words extracted. The dataset used for training is relatively small and has a limited variety of game genres, with only six considered. There are multiple genres for each game, and it is not possible to consider all of them. It is possible that as games are updated or new games appear, new features or genres will appear, which will require the model to be constantly updated. This article also discusses only three feature extraction methods and classification algorithms. Better results could be obtained by exploring more feature selection approaches or more machine school models.

CONCLUSION

In this article, we introduce a game genre-based model for assessing the recommendation of reviews across different game genres. Our approach involves identifying the genre of the game and then experimenting with various feature extraction methods and classification algorithms to create an effective model. We compare three feature extraction techniques, Bag of Words (BOW), N-Gram, and Part of Speech (POS), in conjunction with three classification algorithms: Naive Bayes (NB), Support Vector Machine (SVM), and Decision Tree (DT), selecting the most suitable combination for each game genre.

Our evaluation results reveal the optimal models for each game genre. BOW emerges as the top-performing text feature selection method, while NB stands out as the best-performing classification algorithm. The most effective combination is BOW and NB. In comparison to the accuracy of the model encompassing all genres (0.828), our proposed

models achieve improved accuracy rates, specifically 0.854 for FPS, 0.851 for Action, and 0.832 for both Adventure and Strategy.

The player can figure out the game's recommendation rate after the model determines whether other players recommend it. If there are 100 player reviews and the model results in 80 recommendations, then the game has an 80 percent positive rating, which can greatly help other players in their decision-making and can also help the game developer monitor whether the game is successful or not.

By demonstrating the effectiveness of specific model genres, we emphasize the importance of tailored approaches in improving recommendation accuracy. Our approach provides new perspectives on the combination of feature extraction and classification algorithms and sets a precedent for future research exploration and improvement.

More datasets will be collected, and more game genres will be involved in model training to overcome the limitations. More feature extraction methods will be evaluated, such as feature extraction by TD-IDF, word embedding, and some optimization algorithms to find the right features, such as the Reptile Search Algorithm (RSA) (Abualigah et al., 2022). After that, deep learning models such as CNN and BiLSTM can be combined. Aspects of sentiment analysis will also be considered, listing the strengths and weaknesses of each game in order to be more helpful to players and game developers. For example, in one review, the action is smooth, but the plot is confusing. Through aspect sentiment analysis, it can be extracted that its strength is the action, and its weakness is the plot.

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Inorganic Phosphorus Fractions and Sorption Capacity of Sediments Correlated with Physicochemical Parameters of Water in Langat River, Selangor Malaysia

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ABSTRACT

This study investigates the physicochemical parameters of water, their association with inorganic phosphate fractions, and the sorption capacity of sediments. Water and sediment samples were collected from upstream, midstream, and downstream sections between November 2022 and June 2023. The water samples were analysed according to the American Public Health Association (APHA) guidelines for physicochemical parameters. Inorganic phosphate fractions in the sediments were quantified using the molybdenum blue colourimetric method. Sediment phosphate sorption capacity was assessed by measuring the resulting filtrate and applying regression correlation and Langmuir isotherm models to determine the relationships among the sediment samples. Sediment analysis of inorganic phosphorous fractions revealed varying percentages of Ca-P (32.6%), Rs-P

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Keywords: Anthropogenic, adsorption, correlation, fractions, isotherm

INTRODUCTION

Rivers are important sources of freshwater, satisfying the daily water demands essential for human consumption and various industrial and agricultural applications (Baggio et al., 2021). Unfortunately, these freshwater sources are threatened by pollution with orthophosphates from many anthropogenic sources (Kaushal et al., 2021). Phosphorous pollution in rivers, primarily from agricultural runoff, industrial discharge, and sewage treatment plant effluents, can lead to water quality deterioration, biodiversity loss, and ecosystem imbalances, posing a significant concern as rivers serve as water consumption sources (Giri, 2021; Khalil et al., 2023). This pollution accelerates the ageing of water bodies through eutrophication caused by excess nutrients, especially phosphorus (Kakade et al., 2021). Phosphorous pollution of rivers leads to the proliferation of algae and aquatic plants, reduced water clarity, unpleasant taste and odour, decreased oxygen levels, and changes in the visual attractiveness of river landscapes (Bozorg-Haddad et al., 2021). In addition, algal blooms fuelled by phosphorus pollution can produce toxins that are harmful to humans, leading to skin irritation, liver and kidney damage, neurological disorders, and respiratory complications (Sha et al., 2021).

The Langat River in Malaysia is an important water body known for its ecological importance and various land uses within its watershed, including urban, agricultural, and forested areas (Yusof et al., 2021). This makes it an ideal model for studying phosphorus dynamics in different environmental conditions. The choice of the Langat River as a model for this research is influenced by several factors. First, several studies reported that the Langat River receives phosphorus inputs from multiple sources, such as agricultural runoff, urban discharges, and natural weathering processes (Al-Odaini et al., 2013; Ahmed et al., 2022), reflecting the common challenges faced by many rivers worldwide. In 2006, the Department of Environment (DOE) in Malaysia announced that the Langat River was polluted due to the rapid industrialisation along the Langat River, which caused river pollution (Basheer et al., 2017). Furthermore, the Langat River has been the focus of environmental monitoring and management efforts due to concerns over water quality degradation, including eutrophication and algal blooms (Basheer et al., 2017). Additionally, it is a vital water resource for domestic, agricultural, and industrial purposes (Juahir et al.,

2011), highlighting the importance of managing phosphorus inputs to ensure sustainable water use and ecosystem health (Loi et al., 2022).

Despite the Langat River being the water source for treatment plants, the river faces significant threats from phosphorus pollution from various anthropogenic activities. This pollution disrupts the well-being of river ecosystems, leading to eutrophication and the formation of harmful algal blooms. Although numerous studies have identified the Langat River as polluted, there is still a lack of comprehensive understanding of the extent and sources of phosphorus pollution. Moreover, the implications of this pollution on water quality, ecosystem health, and the sustainability of water use remain unclear. Therefore, there is a pressing need for research investigating the dynamics of phosphorus pollution in the Langat River, including its sources, transport pathways, and environmental impacts. Hence, this study aimed to determine the physicochemical parameters of water, their association with inorganic phosphorus fractions, and the sorption capacity of sediments in the Langat River.

MATERIALS AND METHODS

Study Area

The Langat River is the longest in the Malaysian State of Selangor (LUAS, 2015). It is located at 101°50″E, 3° 45″N, 101 °10″ E, 3 °15″ N, and is approximately 60 km long and 30 km wide, covering a total area of 1820 km². Figure 1 indicates the map of the study



Figure 1. Map of Selangor, showing the sampling sites along the Langat River

location, showing the sampling sites, while Table 1 presents the list of Langat River study locations. The activities taking place by the river differ depending on the specific location. Small villages, orchards, and eco-tourism resorts predominantly occupy the upstream portions. The riverbanks are highly vulnerable to the possibility of collapsing. This region is susceptible to deforestation, intensified agriculture, and soil erosion (Basheer et al., 2017). The middle and downstream sections of the river are occupied by residential, industrial, and plantation areas. However, these areas are susceptible to pollution from several causes, including industrial, agricultural, and urban activities, both natural and human-induced (Zubir et al., 2016; Ahmed et al., 2022).

Table 1Sampling locations of the Langat River

Location	Area	Latitude	Longitude	Sampling site
Upstream	Lui village	3.5931° N	101.8498° E	Pangsun recreational area and Sungai Congkak recreational forest.
Midstream	Kajang	3.2193° N	101.905° E	Dusun Tua, Long quarry road, Sg. Balak, Bangi and Dengkil.
Downstream	Banting	2°49'0"N	101°30'0"E.	Bukit Changgang, Labohan Dagang and Jugra

Sample Collection

Water samples from the Langat River were collected using a Van Dorn Vertical Sampler, and sediment samples were collected (~10 cm) using an Ekman grab sampler between November 2022 and June 2023 with designated points as UP1 and UP2 (upstream), M1-M5 (midstream), and D1-D3 (downstream). The glass bottles used for the water samples were acid-washed and rinsed with deionised water and then disinfected using five drops of an aqueous sodium thiosulfate solution to remove residual chlorine. Afterwards, the screw caps were loosely attached and covered with aluminium foil to prevent sticking during sterilisation (Wang & Ji, 2024). The bottles were placed in a dry oven heated to 170 ± 0.5 °C for an hour and then cooled. Sterile zip plastic bags were used for the sediment samples. All the samples were labelled according to the collection site and kept in a different cool box at 4°C before being transported to the Plant Systematic and Microbe Laboratory at the Department of Biology, Universiti Putra Malaysia. The water samples were immediately used for the determination of physicochemical parameters, while sediment samples were immediately freeze-dried and stored at -20°C (Chuang et al., 2021),

Determination of Water Physicochemical Parameters

The physicochemical parameters of the water samples were assessed following the American Public Health Association guidelines (APHA, 2005). On-site measurements of

pH, electrical conductivity (EC), and dissolved oxygen (DO) were conducted with a Hach Multiparameter (HD401 probe meter). Other physicochemical parameters such as biological oxygen demand over five days (BOD₅), chemical oxygen demand (COD) and the soluble reactive phosphorous (SRP) were measured in the laboratory according to the methods of Nuruzzaman et al. (2017), Ma et al. (2016) and Murphy and Riley (1962), respectively.

Extraction of Inorganic Phosphate Fractions from Sediment Samples

The inorganic phosphate fractions of the sediment samples for exchangeable phosphate (Ex-P), iron-bound phosphate (Fe-P), reductant-soluble phosphate (Rs-P) and calciumbound phosphate (Ca-P) were sequentially extracted as described by Zhang (2009). The concentration of each fraction was determined using the molybdenum blue colourimetric method established by Murphy and Riley (1962) according to Equation 1:

$$Inorganic concentration (mg/kg) = \frac{Concentration of phosphorous (mg/L) \times Volume of extractant (L)}{Mass of sediment (kg)}$$
[1]

Determination of Phosphate Sorption of Sediment

The phosphate sorption of the sediment samples was determined as outlined by Cui et al. (2018), and the resulting filtrate was quantified using the molybdenum blue colourimetric method by Murphy and Riley (1962). A regression correlation coefficient model was used to assess the linear relationship between the adsorption capacity of the sediments at equilibrium. The Langmuir isotherm equation model was used to determine the sorption capacity of the sediment and assess the relationship between the standard phosphate concentrations and the phosphate adsorbed at equilibrium in the sediment as in Langmuir Isotherm Equation 2:

$$\frac{i}{ge} = \frac{\frac{1}{kl \times gmax} \times \frac{1}{ce}}{\frac{1}{gmax}}$$
[2]

Statistical Analysis

All the samples were analysed in triplicate. The data were statistically analysed for descriptive statistics, analysis of variance (ANOVA) and regression correlation using JASP (Jeffreys's Amazing Statistics Programme) version 0.18.1 statistical software. Graphs were generated using Originlab and licenced under the GNU Affero General Public Licence.

RESULTS AND DISCUSSION

Physicochemical Parameters

The pH, DO, BOD, EC, COD, and SRP values of the water samples from the three sections of the Langat River are provided in Table 2, showing differences in the physical and chemical characteristics which impact the water quality. The pH range (pH 6.5–pH 7.23) observed in all locations was higher than that of pH 6.39 to pH 6.62 reported by Juahir et al. (2011). The marginal pH increase observed 23 years apart indicates that the Langat River maintains its capacity to regulate acidity and remains within the acceptance range of the World Health Organization. Decreased pH levels in the water downstream may indicate increased human activity or the decomposition of organic substances (Azrina et al., 2006; Aris et al., 2015). A similar pattern was also observed for EC, with slight downstream deterioration. Since this region was urban and bordered by plantations with dissolved ions from tidal impacts and industrial and agricultural discharges such as agricultural runoff, logging, and land clearance, higher EC values downstream were expected (Roy et al., 2018). This variation could result from natural factors such as the geology of the watershed, weathering processes, seasonal changes, and anthropogenic factors, including land use, human activities, and wastewater discharge (Yap, 2013).

Table 2Physicochemical parameters of each section of Langat River

Location	рН	EC (µS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SRP (mg/L)
Upstream	7.23±0.32ac	27.55±2.91ac	9.06±1.97abc	0.45±0.38a	0.95±2.43a	0.13±0.07abc
Midstream	7.22±0.14bc	73.71±11.87bc	6.18±0.59ab	$1.66{\pm}0.70b$	$14.05 \pm 1.17b$	0.53±0.28ab
Downstream	6.87±0.15abc	81.72±10.74abc	2.22±0.43ac	1.97±0.95c	54.33±25.87c	0.64±0.09ac
WHO limit	6.5-8.5	400	5.0	3.0	25.0	0.03

Note. This means that shared letters are significantly different at P < 0.05.

Dissolved oxygen is crucial for river health and overall water quality, and low DO levels can have detrimental effects (Haider et al., 2012); thus, effective management strategies to maintain healthy river ecosystems are needed. The same trend of variations in DO in this study was observed by Abidin et al. (2018), and these changes were attributed to temperature, organic matter, and human activities (Vigiak et al., 2019). Since the upstream region has the shallowest and greatest river flow, which can result in quick reaeration rates and reduced organic matter, more DO is anticipated there. Conversely, higher organic pollution and waterborne microbial activity caused reduced DO downstream (Bozorg-Haddad et al., 2021; Wang et al., 2016). The oxygen content may be reduced by increased organic pollutants, which would be detrimental to the water quality. However, BOD and COD levels were greater downstream compared to the DO. High BOD levels can be caused by organic pollution, microbiological contamination, industrial discharge, and human sewage (Vigiak et al., 2019). However, Chapra et al. (2021) believe that water temperature is the primary variable influencing BOD level, which impacts a river's ability to absorb BOD. The elevated COD levels downstream differ from those reported by Basheer et al. (2017) but are consistent with Loi et al. (2022). According to the DOE (2012), COD levels >25 mg/L fall under Class III (moderately polluted), which can negatively impact the river by depleting oxygen and deteriorating water quality, leading to organic matter loading (Ibrahim et al., 2021). These findings highlight the complex nature of DO, BOD and COD variations in the Langat River, which is influenced by a combination of natural and anthropogenic factors. Given that the Langat River is a major river in Selangor and provides water to several locations (Abidin et al., 2018), the ecology and the water supply may be at risk if no effective mitigation is taken.

The downstream area measured up to 0.64 ± 0.09 mg/l of SRP, and this increase could have resulted from phosphate-containing chemicals associated with urban and agricultural areas, among other sources (Bol et al., 2018). Eutrophication, which can result in excessive algae growth and decreased DO levels, may occur because of increased SRP levels downstream (Billah et al., 2019). Although Simonetti et al. (2019) highlighted that land erosion and subsequent entry into aquatic ecosystems were the cause of the increased phosphorus in water, an interchange of SRP from sediment to water and vice versa cannot be completely disregarded.

Inorganic Phosphate Fractionation

Table 3 displays the average concentration of inorganic phosphate measured from three different sections of the Langat River. According to Yusof et al. (2021), erosion and land use affected the distribution of nutrients in the Langat River. All sampling sites have a modest Ex-P content, suggesting that most inorganic phosphate is indirectly preserved in the sediment by establishing bonds with other elements, with few phosphate ions available for exchange from sediment to water and vice versa.

The bioavailable phosphorus reservoir known as Ex-P can release its contents when the concentration of soluble phosphate decreases. At an average of 11.5 ± 0.09 mg/kg, the downstream sediment had the most Ex-P but only marginally non-extractable phosphorus (Rs-P), suggesting a greater likelihood of a high P concentration in the water in this area. According to Hoffman et al. (2009), farming activities such as dredging and palm oil plantations, along with wastewater discharge from sewage treatment plants, could cause elevated Ex-P concentrations downstream of the Langat River's bed sediments. However, the low Ex-P level in the upstream Langat River segment is more indicative of the silt than a phosphorus deficiency. The rapid water flow from upstream moved most of the Ex-P to midstream and downstream, and sandy sediments unable to absorb P were the defining upstream features (Howell, 2010). In essence, the availability of Ex-P in the water and sediment may be influenced by the internal loading of legacy phosphorus in sediments, particularly in areas with a high sediment P/Fe ratio (Orihel et al., 2017).

Table 3 Distribution of inorganic phosphorous fractions (mg/kg) in the sediment samples for different sections of Langat River

Sampling site	Ex-P	Rs-P	Al-P	Fe-P	Ca-P
Upstream	7.75 ± 0.07ac	$17.75 \pm 0.34ac$	13.5 ± 0.08ac	11.25 ± 0.11ab	24.25 ± 0.15a
	(10.4%)	(23.8%)	(18.1%)	(15.1%)	(32.6%)
Midstream	8.60 ± 0.28b (7.9%)	41.4 ± 0.40 bc (38.3%)	21.4 ± 0.16bc (19.8%)	$16.5 \pm 0.14ab$ (15.2%)	20.3 ± 0.18b (18.8%)
Downstream	11.5 ± 0.09ac	30.5 ± 0.08abc	41.3 ± 0.36abc	111.3 ± 0.16c	35.5 ± 0.11c
	(5.0%)	(13.3%)	(17.9%)	(48.4%)	(15.4%)

Note. This means that shared letters are significantly different at P < 0.05.

The amount of Rs-P acquired by the midstream and downstream was double that of the upstream, with the midstream achieving the highest average of 41.4 ± 0.40 mg/kg. Except for Rs-P, the downstream section maintained the highest overall phosphate fractions, and this may be due to the unique midstream characteristics such as pollution sources, flow dynamics, and sediment characteristics. The midstream has a lot of different streams and runoff sources that come together and mix. It could cause more phosphate to enter the water from agricultural runoff, industrial discharges, and urban waste (Roy et al., 2021). The physical features of the midstream segment, including elevated water flow and turbulence, could have played a pivotal role. Increased water movement enhances the interaction between the water and riverbed sediments, potentially releasing phosphates bound to the sediments and raising the Rs-P concentration midstream (Liao et al., 2020). Turbulence also helps keep the phosphates in suspension, which keeps them from settling and makes them easier to use in their soluble form (Helard et al., 2019). Major agricultural, industrial, and urban areas surround the midstream of the Langat River, providing different sources of Rs-P. These anthropogenic activities in the midstream may have led to more soluble reductant phosphate buildup in the area, potentially contributing to the observed elevated Rs-P levels. Furthermore, the type of land used within this area could potentially introduce organic matter into the river, influencing the Rs-P concentration. Transferring iron and aluminium to deeper sediment profiles involving fresh, less decomposed organic matter could also contribute to midstream accumulation (Tadini et al., 2019). Thus, it significantly influences this distribution by maintaining insoluble phosphorus in the sediment (Van Den Broeck et al., 2004).

Inorganic phosphate linked to aluminium and iron compounds supports appropriate amounts of inorganic phosphate despite Ex-P shortages in every region of Sungai Langat.

The two primary metal-bound bioavailable forms of P are Al-P and Fe-P. Under favourable redox, pH, and other environmental circumstances, these phosphorous forms can be transformed into SRP and released into the surrounding water (Ni et al., 2016). The Al-P concentration increased twofold from upstream to downstream, which is consistent with the findings of Welch et al. (2017). Factors like resuspension and redistribution of alum floc, flood, site-specific hydrodynamics, and geochemical factors transport contaminated sediment, potentially increasing the Al-P concentration downstream (León et al., 2017; Yuan et al., 2019; Hoffman et al., 2009). However, any excess Al-P may have ecological implications, such as nutrient loading and the alteration of phosphorus availability in the river, potentially affecting sediment composition and the abundance and distribution of bottom-dwelling organisms (Emelko et al., 2015; Dadi et al., 2023). In the long term, this may increase the risk of aluminium and nitrate contamination in the Langat River.

The significant iron accumulation caused by industrial and human activities discharging chemical wastes from the surrounding area into the Langat River may have resulted in very high concentrations of Fe-P ($111.3 \pm 0.16 \text{ mg/kg}$) in the downstream sediment (Bing et al., 2013), attributed to iron-bound at lower pH levels and phosphate mobilisation by Ca-P (Gao et al., 2020) but upstream and midstream sections contained approximately 10% of the downstream Fe-P, possibly due to a lack in the sediment's capacity to retain Fe through the reductive dissolution of Fe-P (Chen et al., 2019). The reductive dissolution of iron oxides can cause phosphate release from sediments in low-oxygen environments, such as upstream areas, particularly if the sediments have a high phosphorous/iron ratio (Table 3).

Ca-P is found in upstream and downstream sediments (Table 3), with downstream sediments usually exhibiting the highest Ca-P concentrations (Jalali & Peikam, 2013). Particularly in alkaline conditions of the overlying water in eutrophic lakes, Ca-P is often regarded as very inert and stays buried in sediments for a long period with relatively poor bioavailability (Ni et al., 2016). According to Han et al. (2022), high calcium ions and phosphorus levels in the downstream area can be attributed to various natural and man-made factors that alter nutrient dynamics and sediment composition. While phosphate adsorption onto calcite and carbonate dissolution may contribute to an increase in Ca-P concentration in estuarine environments (Flower et al., 2022), reductive conditions, alkalisation, and human sources are the main causes in urbanised areas (Huang et al., 2020).

This variability in SRP distribution underscores the influence of diverse environmental factors and sediment characteristics on the downstream sediment composition. Most of the P fraction was high in the downstream sediments, demonstrating the impact of both river current and sediment type. Silt containing small particles and resembling clay provides a variety of options for storing P in sediments downstream and has significant implications for the water quality (Basheer et al., 2017). Thus, it emphasises the importance of considering the intricate processes by which phosphorus is stored and transformed in

catchment systems when assessing its availability and possible effects on water quality. The rate at which sediments flush depends on the river flow (Batalla & Vericat, 2008). Particles from upstream and midstream flow downstream, creating a tranquil flow and reducing shear due to the action of water flow (Beltaos & Burrell, 2016), thereby causing high P sedimentation. High phosphorous sedimentation shall be avoided since the Langat River, which is part of the Langat River Basin, is one of the major sources of potable water in Selangor State, supplying drinking water to almost one-third of the population in the state of Selangor (Ahmed et al., 2019).

Correlation Coefficient of Water Parameters and Inorganic Phosphorous Fractions from Sediments

Table 4 illustrates the correlation between SRP fractions and water parameters, showing a positive correlation between Ex-P, Al-P, and Fe-P fractions and EC, COD, and SRP. It suggests that variations in the EC, COD, and SRP levels in water are accompanied by corresponding changes in the Langat River's Ex-P, Al-P, and Fe-P fractions of phosphorus. More focus must be given to trophic status and trophic development content in sediments due to their dual roles (sink or source) under certain environmental conditions to ensure that the Langat River can accommodate life and maintain water quality (Zhou et al., 2001). The Ex-P and Rs-P values can describe the balance and availability of SRP. However, the current study shows that both factors moderately impacted SRP availability in water and sediment.

The EC and COD values have a stronger association with SRP availability than other parameters, suggesting that the equilibrium of the inorganic phosphate fractions in the sediment depends on EC and COD (Saha et al., 2022). EC caused by agricultural runoff or wastewater discharge and COD from microbial decomposition will affect phosphorous chemical bonds and potential nutrient release (Jiao et al., 2021). Nonetheless, these data emphasise the importance of considering both EC and COD on the bioavailability of mobile and less mobile phosphorus fractions to understand the eutrophication potential of water bodies (Lee et al., 2013). EC also contributes to changes in ionic strength and pH which impact the solubility and availability of insoluble phosphorous in the sediment (Wang et al., 2017). It is demonstrated by the moderately positive correlation between Rs-P and EC. Consequently, higher EC levels indicate conditions conducive to releasing Rs-P and Ex-P into the water column, potentially contributing to eutrophication and other water quality issues.

Since the most common form of SRP in sediment is Rs-P, and its concentration is often 1000-fold higher than in water (Pardo et al., 1998), the effect of these parameters is undeniable. Overall, all the data suggested that Rs-P is less influenced by pH, DO, and COD, indicating that Rs-P is strongly bound to iron and aluminium oxides in the sediments,

Table <i>Corr</i> e	e 4 elation matri	ix of inorgani	ic phosphate J	fractions and	ł physicochei	nical parame	eters of Lang	at River wate	er samples			
Par	ameter	Ex-P	Al-P	Fe-P	Rs-P	Ca-P	ЬH	EC	DO	BOD	COD	SRP
	Ex-P	1.00										
5.	Al-P	0.998*	1.00									
з.	Fe-P	0.985	0.973	1.00								
4	Rs-P	0.260	0.319	0.092	1.00							
5.	Ca-P	0.891	0.862	0.955	-0.206	1.00						
6.	рН	-0.790	-0.751	-0.883	0.386	-0.982	1.00					
7.	EC	0.883	0.910	0.790	0.683	0.574	-0.411	1.00				
8.	DO	-0.912	-0.936	-0.829	-0.633	-0.627	0.470	-0.998	1.00			
9.	BOD	0.620	0.667	0.477	0.919	0.197	-0.010	0.916	-0.887	1.00		
10.	COD	.997*	1.000^{**}	0.970	0.330	0.856	-0.744	0.915	-0.940	0.676	1.00	
11.	SRP	0.821	0.855	0.712	0.764	0.473	-0.300	0.993	-0.983	0.957	0.861	1.00
Note.	* p < .05, *	* p < .01.										

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making it less responsive to any changes in pH or any microbial activity and organic matter decomposition (Wang et al., 2017). However, modest correlations between Rs-P and SRP suggest that Rs-P is less dynamic due to its slower release (Zhou et al., 2021). It might be due to microbial activity breaking down organic matter in anoxic environments, as suggested by a moderately negative association between Rs-P and DO (Lin et al., 2020). The moderate correlation of Ex-P to BOD indicated that Ex-P is widely used to support microbial growth, participate in organic matter decomposition, and subsequently increase BOD levels (Reusser et al., 2023). However, the availability of Ex-P can be affected by pH and DO. In low pH conditions, SRP is more likely to be absorbed by aluminium and iron hydroxides. It is more severe in anoxic conditions, ultimately reducing its bioavailability, as evidenced by the negative correlation between Ex-P, pH, and DO.

Phosphate Sorption Isotherm

Phosphate adsorption capacity was tested to ascertain the sediment's capacity to absorb P from the Langat River at different locations along the Langat River (Figure 2). Even though there is a difference in the P adsorption range between the different P standard concentrations for the three streams, there is no significant difference between the streams for each specific P standard concentration. The upstream sediment samples exhibited adsorption capacities ranging from 4.00 to 18.21 mg/g of sediment per mg/L of phosphate. The midstream and downstream sediment samples demonstrated adsorption capacities between 4.36 and 21.10 mg/g and 4.00 to 12.98 mg/g of sediment, respectively. Nonetheless, all sediments showed a phosphate adsorption capacity limit between 20–25 mg/L.



Figure 2. The phosphate adsorption capacity of the sediments collected from different sections of the Langat River

Similar variations in phosphate adsorption capabilities have been found throughout different segments of the Langat River. The Langat River's poor to moderate phosphate

adsorption capacities were initially attributed to sewage sludge, pollutants, sediment properties, and mineral composition. Earlier studies on the Langat River Basin have proposed numerous elements influencing phosphate adsorption capabilities. Kadhum et al. (2015) have identified heavy metal contamination, which affected water characteristics such as pH and subsequently influenced sediment adsorption capacity for phosphate. Zainol et al. (2021) highlighted the unique characteristics of the sediment, particularly the impact of the silty clay's composition on its capacity to adsorb phosphate. However, Ahmed et al. (2022) concluded that the primary factors affecting the phosphate sorption capacities of rivers are water pollution and sewage sludge resulting from various human activities. The variations in phosphate adsorption per unit weight of particulate matter in different rivers imply that specific sediment characteristics contribute to adsorption capacity where phosphorus bonding is weaker in calcareous sediment compared to iron-containing sediments (Yuan et al., 2019; Ji et al., 2022).

The regression parameters for the Langmuir isotherm model for the phosphate adsorption process for Langat River sediments are shown in Table 5, with the R² values for the Langmuir model demonstrating the moderately high relationship between Q_{max} and R_L . It suggests that the Q_{max} and R_L values obtained are statistically valid and reasonably fit the observed data. It implies that the Langmuir isotherm model adequately describes how phosphates adhere to sediment particles in the Langat River. Shafie et al. (2013) and Hafeznezami et al. (2016) suggested that the cation exchange capacity in the Langat River's sediments, which is influenced by pH, salinity, and electrical conductivity, could enhance this correlation. However, the influence of climate change on the capacity and adsorption of sediment must not be ignored, as Ebrahimian et al. (2018) reported that climate change affected the correlation between the different sediments in the Langat River.

Sampling site	Linear equation	Qmax	RL	R2	
Upstream	$y = 23.102 \times + 3.917$	0.269	0.366	0.743	
Midstream	$y = 25.205 \times + 3.860$	0.265	0.416	0.713	
Downstream	$y = 15.720 \times + 2.617$	0.395	0.366	0.797	

Langmuir isotherm parameters for the phosphate adsorption process of the sediments

Table 5

All sediments along the Langat River have a low capacity to adsorb inorganic phosphate, as indicated by the low adsorption capacity (Q_{max}). Other than the sediment type and the river flow, various physicochemical factors, such as the phosphate concentration, temperature, pH, and the presence of other ions or molecules, can influence the phosphate adsorption capacity of sediments (Azam et al., 2019). Del Bubba et al. (2003) emphasised the role of physicochemical properties in adsorption capacity, with the former showing a significant

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relationship between maximum P adsorption capacities and properties such as Ca and Mg content, grain size, and porosity. Tang et al. (2014) showed a strong correlation between maximum phosphorus adsorption capacities and sediment oxalate-extractable ion (Feox), total iron (FeT) and total phosphorus (TP) concentrations. The diminished adsorption capacity of sediment, particularly upstream and midstream, to adsorb phosphorous may be attributed to a reduced attraction between phosphate and sediment or limitations in available adsorption sites (C. Han et al., 2020). Despite these sediments' limited phosphate adsorption capacity, they were ideal for inorganic phosphate adsorption because the R_L value ranged from 0 to 1. The Langat River sediments' low inorganic phosphate absorption capacity (Q_{max}) may increase the risk of eutrophication (Loi et al., 2022). The SRP in the water cannot be stored in the sediment, even though the sediment tends to store it ($R_{\rm L}$) value) because R_1 declines. At the same time, the depth and width increase and the river current diminishes, so there is a greater risk of eutrophication downstream. As a result, the location's SRP content is higher. Previous studies have shown a correlation between lower to moderate sediment phosphate adsorption capacity and increased phosphorus levels in water that have led to eutrophication in rivers (Yin et al., 2017; Pu et al., 2021).

The Langat River's water quality and sediment composition indicate significant spatial variations, with the midstream section experiencing higher water parameters and the downstream section facing greater risks of eutrophication due to elevated SRP and inorganic phosphate concentrations. The correlation between water parameters and phosphate fractions suggests that as EC, COD, and SRP levels increase, the inorganic phosphate levels in the river also tend to rise. The moderate adsorption of phosphate by sediments is mostly affected by changes in their composition, such as the presence of aluminium, iron, and calcium compounds due to human activities, as well as physicochemical factors such as pH, electrical conductivity, and the presence of contaminants.

This study provides valuable insights into the potential risks of phosphorus disposal from agricultural, industrial, and urban runoff into river bodies. This idea is essential for developing sustainable mitigation practices to minimise nutrient pollution, thereby protecting river water quality and ecosystem health (Haque, 2021). The demonstrated inorganic phosphorus fractions in Langat River sediments, as well as their bioavailability, contribute to improving phosphorus recovery processes and reducing environmental impacts associated with the disposal of phosphorus-containing compounds (Kalkhoff et al., 2016). However, the inorganic phosphorus fractions' location along the river's sediments and their relationships with physicochemical parameters explain how water quality parameters affect the phosphate fractions' presence. It is important to create effective conservation strategies to protect biodiversity and keep the ecological balance between river sediments and water (Smits et al., 2019). Furthermore, sediments' low to moderate sorption capacity throughout the river contributes to our understanding of the retention

and release of phosphorus in the river environment. It can improve sediment management practices, such as dredging and sediment capping, to minimise phosphorus release and mitigate its impact on water quality (Yang et al., 2020).

Climate change can also substantially impact sediment dynamics and sorption capacity in rivers such as Sungai Langat (Lim et al., 2013a; 2013b). Elevated temperatures expedite sediments' chemical reactions, which may modify the intensity of phosphorus binding (Costa et al., 2018). Furthermore, increased temperatures stimulate the functioning of living organisms, consequently modifying the decomposition of organic matter and the circulation of nutrients. Amin et al. (2019) found that this modifies the uptake and discharge of phosphorus. Climate change also results in heightened and fluctuating precipitation patterns, which directly affect the movement and behaviour of sediment. Heavy precipitation amplifies erosion and runoff, leading to a greater influx of sediments into the river and modifying their ability to be absorbed (H. Han et al., 2020). Moreover, the variability in river flows can result in the dispersion or accumulation of contaminants, which might impact the sediment's capacity to absorb nutrients such as phosphorus (Zhang et al., 2019). Climate change-induced modifications in hydrological patterns result in diverse impacts on the capacity of sediment to sorb substances. Modifications in fluid movement patterns impact the transportation and settling of sediment, which in turn affects the stability and effectiveness of sediment layers in capturing particles (Azari et al., 2015).

CONCLUSION

The river sediments exhibited varying levels of phosphate adsorption capacity, ranging from low to moderate in both the upstream and downstream sections. However, a higher level of adsorption was reported in the midstream area. The inorganic phosphate fractions exhibited significant positive connections with EC, COD, and SRP, while the pH and DO levels showed substantial negative correlations with the inorganic phosphate fractions. The Langmuir isotherm models precisely determined the differences in adsorption capacities among the research locations, with Ex-P, Al-P, Fe-P, and Ca-P being dominant downstream and Rs-P dominating midstream.

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AI Chatbots in Research: Yes or No? A Self-reflective Exploration

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ABSTRACT

ChatGPT, an artificial intelligence chatbot released in November 2022, is the fastest-growing consumer application in history. As a generative AI that uses Natural Language Processing, it creates a plethora of content with a 'human voice'. Unsurprisingly, ChatGPT garnered much attention from academia as it passed several professional exams and has multiple avenues for potential misuse by students and researchers alike. Therefore, this study addresses the dearth in literature by performing a self-reflection study on the practical usage of AI chatbots in research, with a research question: What is the self-reflection of the authors on the usage of AI chatbots for research? This study was framed under the Technology Acceptance Model to provide a comprehensive discussion covering multiple domains. AI chatbots provide advantages and disadvantages to the end-user, but the resulting outcome lies in the hands of the user; hence, educating existing and future users of the tool to use it responsibly should be first and foremost. As Pandora's AI chatbot box has been opened, ethical issues are also plentiful in chatbots. However, it is up to academia to solve these in multidisciplinary settings because, as history has shown, curtailing the use of new technologies is futile. Overall, this study contributes to the body of knowledge in AI Chatbot research by emphasising their potential and addressing probable issues when using them in research.

Keywords: AI chatbots' ethics, ChatGPT, self-reflection study

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INTRODUCTION

ChatGPT gained significant attention upon its release by OpenAI in November 2022, quickly becoming the fastest-growing consumer application in history, surpassing Instagram and TikTok (OpenAI, 2022; Hu, 2023). As a generative artificial intelligence (AI) Chatbot, ChatGPT engages users in real-time conversations, responding to

ISSN: 0128-7680 e-ISSN: 2231-8526 follow-up questions, addressing inappropriate arguments, and acknowledging errors while declining unsuitable requests. Its launch spurred the development of several other generalpurpose generative AI chatbots like Gemini (Hsiao, 2024) and Claude AI (Anthropic, 2023) and also chatbots tailored for the research community like Consensus (Consensus, 2023) and Scopus AI (Elsevier, 2024).

Universities paid particular attention to ChatGPT's release, especially after it performed well in multiple professional exams (Ault, 2023; Terwiesch, 2023). Concerns emerged regarding students' work's originality, integrity, and plagiarism, which are fundamental educational values (Webber, 2022). Additionally, worries persisted about hallucinations, bias, errors, and misinformation in the content generated by generative AI chatbots (Bang et al., 2023). Despite these concerns, university students embrace AI chatbots as useful tools (Rudolph et al., 2023).

Therefore, this study aims to investigate the practical usage of generative AI chatbots in research through a self-reflection study by the authors, using pragmatism as a lens. It utilises the Technology Acceptance Model (TAM) (Davis, 1989) as a framework. The research question guiding this study is: What is the authors' self-reflection on using generative AI chatbots for research in daily university life?

The Technology Acceptance Model (TAM) elucidates how users accept and utilise new technology. It comprises two fundamental components: Perceived Usefulness (PU) and Perceived Ease of Use (PEOU). PU pertains to the extent to which users believe that technology enhances their job performance. For generative AI chatbots, PU encompasses the perceived benefits of improving research efficiency, accelerating idea generation, and supporting various academic tasks. PEOU, on the other hand, refers to the degree to which users perceive a technology as easy to use. In the context of generative AI chatbots, PEOU involves users' perceptions regarding the ease of learning and utilising the technology and its integration into research processes.

This study applies TAM to examine the factors influencing the authors' acceptance of AI chatbots, including their advantages and disadvantages. Through self-reflection, the authors assess their experiences with AI chatbots in their research activities, offering insights into these tools' practical benefits and limitations.

The study's findings are intended to deepen the understanding of AI chatbots' utility in research and highlight the significance of user perceptions. By employing the TAM framework, this study facilitates a reflective analysis of the authors' experiences with AI chatbots, exploring their practical values and constraints. This approach provides a nuanced understanding of how AI chatbots can be effectively integrated into research practices. The results aim to contribute to the broader discourse on AI chatbots in research, emphasising the critical role of user perceptions in successfully accepting and utilising these technologies.

Background

To understand ChatGPT and, more broadly, AI chatbots, it is essential to grasp the underlying technologies that support them. The term "AI" encompasses various technologies, including machine learning (ML), natural language processing (NLP), large language models (LLMs), and more. This integration of diverse algorithms is often referred to as generative AI. For this article, these technologies will collectively be termed AI chatbots. Products such as ChatGPT and Gemini and academic-focused AI chatbots like SciSpace and Consensus AI leverage similar technological frameworks. These systems involve the development of computer programs capable of performing tasks traditionally reserved for humans, such as reasoning and problem-solving. Essentially, these systems model certain processes of the human brain. The primary goal of AI is to create computer systems that can perform tasks historically requiring human intelligence, including speech recognition, decision-making, and pattern identification (Dellermann et al., 2021; Radanliev, 2024).

A chatbot is an AI program operated like a Human-computer interaction model (Bansal & Khan, 2018), aiming to mimic human interaction (Shum et al., 2018). The system uses NLP and sentiment analysis to communicate with humans and other chatbots in human language via text or verbal formats (Khanna et al., 2015). The key to NLP is tokenisation, which converts unstructured text into structured text, thus rendering it compatible with computing (Hosseini et al., 2023). Notable early examples of AI-integrated chatbots include Eliza (Weizenbaum, 1966), Parry (Colby, 1975), and Alice (Wallace, 2009) in the 1960s.

Furthermore, with the advancement of chip development, as per Moore's Law prediction, the number of transistors that can be installed in the same chip size doubles every two years (Gustafson, 2011). It has enabled exponential growth in computing power, leading to advancements in various fields. Nevertheless, with the advancement of Nvidia technology for Graphics Processing Units (GPUs), also known as Huang's Law (Moore, 2023), the improvement of AI chatbots is occurring even faster than what Moore's Law suggested. Nvidia's GPUs are now faster than five years ago by a factor of 25. According to Moore's Law, it would only be done by a factor of 10 (Perry, 2018). It suggests that Huang's Law can better support the development of AI chatbots than Moore's Law.

Literature Review

AI chatbots like ChatGPT can assist researchers in idea generation and brainstorming in a conversational manner (Jo, 2023). The AI Chatbot excels in research idea generation as it can access billions of parameters and texts, enabling it to use a wide array of knowledge to generate ideas from existing ones (Dowling & Lucey, 2023). It also demonstrates the potential to improve research efficacy and productivity by generating news, stories, or articles and writing essays on various topics, thereby reducing the burden on human capital and allowing them to focus their energy on other tasks. AI chatbots could accelerate

publication, aiding PhD students in completing dissertations, researchers conducting literature reviews for grant proposals, and peer reviewers meeting deadlines, freeing academics to design new experiments and potentially leading to breakthroughs across disciplines (Pavlik, 2023; Thorp, 2023; van Dis et al., 2023). Researchers can also use AI chatbots to edit manuscripts and write or check code (Jo, 2023).

However, AI Chatbot-generated content carries the risk of containing errors, primarily due to its reliance on training datasets and algorithms (Jo, 2023). AI chatbots lack understanding of their output or the questions asked by users. While they produce relevant and coherent responses on many topics, they may also generate inaccurate, irrelevant, or nonsensical outputs (Hosseini et al., 2023). Additionally, AI chatbots are limited by their training data. Hence, data outside their training boundaries affects accuracy (Jo, 2023). They generate output based on existing information and statistical data without a real understanding, motivation, or moral compass (Hosseini et al., 2023).

Moreover, according to Jo (2023), AI chatbots may propagate biases in their training datasets, potentially amplifying biases related to sex, race, gender, or other factors. It can distort historical events if the training data reflects cultural superiority. Despite efforts to include toxicity filters, AI chatbots raise concerns about misinformation, as researchers may unknowingly use false or biased information presented by these systems. Errors may stem from training datasets, as the starting point of AI chatbots is data (World Economic Forum, 2024), while biases could result from unconscious or implicit biases in the underlying code (Jo, 2023).

Furthermore, AI chatbots lack transparency regarding their architecture, dataset construction, and training methods, posing challenges to understanding and addressing biases (Hacker et al., 2023). Although newer versions like ChatGPT-4 claim improvements in reducing errors and hallucinations, concerns remain about bias and transparency (OpenAI, 2023). Enhanced reasoning capabilities notwithstanding, challenges persist in examinations requiring higher-order thinking and advanced mathematical concepts (OpenAI, 2023).

Consequently, there is ongoing debate about AI chatbots' ethical implications and limitations in research integrity. When a user utilises AI Chatbot-generated content, research integrity may be compromised due to factual flaws, fraud, plagiarism, and copyright violations (Gordijn & Have, 2023). This issue has been highlighted in the ongoing "Stable Diffusion" court case (Brittain, 2023). Stable Diffusion AI is a text-to-image AI (Black Technology LTD, 2024). AI chatbots have been implicated in falsifying data, including answers to qualitative study questions (Hosseini et al., 2023). Concerns have also been raised about potential misuse by researchers claiming AI-generated essays as their own (Nature Editorial, 2023). Many papers have attributed authorship to ChatGPT without proper acknowledgement, indicating a lack of transparency and accountability in academic publishing (Nature Editorial, 2023).
The prevalence of machine-generated content, especially in research and academia, raises concerns about cheating, as students may use AI chatbots to write essays (King & ChatGPT, 2023). It poses ethical dilemmas and risks academic penalties if discovered. Moreover, there are grey areas regarding accountability in AI Chatbot-generated content. While AI chatbots excel in generating factual, fluent, and professional content, errors and biases complicate evaluating their reliability. Users may struggle to discern between original and erroneous content, potentially leading to its unwitting use in research (Hacker et al., 2023).

Furthermore, attributing authorship to AI chatbots challenges traditional notions of authorship and responsibility (Yeo-Teh & Tang, 2023). Machines lack the human capacity for accountability, ethics, and integrity, raising questions about their suitability as authors in academic publications. Leading academic publishers have underscored the importance of human authorship, emphasising the unique intellectual contributions and responsibilities associated with it (Elsevier, 2019; Editors, 2023; Springer Nature, 2023; Taylor & Francis Group, 2023; Wiley Online Library, 2023). Consequently, conferences and publishers have implemented policies to address the inclusion of machine-generated text in scholarly work, requiring clear delineation and proper attribution.

Despite these ethical concerns, the academic community is actively seeking solutions. Initiatives include educating students on academic integrity, promoting transparency by disclosing machine-prepared manuscript content and developing robust editorial policies and guidelines for using AI chatbots in research. Policymakers and educators are also urged to develop guidelines and policies to maximise the benefits of AI chatbots while mitigating their drawbacks in education (Hosseini et al., 2023). Developing software tools for detecting machine-written content offers a technological solution to this issue (GPTZero, 2023). UNESCO has guided policymakers on integrating AI into education, emphasising the need for ethical considerations and responsible use of technology (UNESCO, 2019; 2021).

METHODOLOGY

Self-reflection study is employed because this method helps practitioners, in this case, the authors themselves, carefully and critically examine their practices and context in their work, in this context, the usage of AI chatbots in research (Dinkelman, 2003; Hamilton et al., 2008). Reflection is a spontaneous process involving recalling past experiences, self-articulating in various situations, and internalising professional knowledge into real-world contexts and situations (Yip, 2006). This study entails the authors recalling their past experiences and later articulating their usage of AI chatbots in their university research activities. While pragmatism emphasises a problem-solving philosophy, considers realistic human behaviour, highlights the interplay of action and meaning, strives to understand the complexities of problems, and addresses structures and entities (Farjoun et al., 2015).

In this context, structures and entities can be analogised to the authors and AI chatbots. Meanwhile, the exponential increase in AI chatbots like ChatGPT users within a short period, even though ChatGPT and other AI chatbots are not perfect yet, could be linked to the TAM (Davis, 1989). TAM is used to discern end-user behaviours and attitudes in adopting new technology via understanding the effect of perceived ease of use and practicality (Davis, 1989).

Therefore, this study began by identifying a problem articulated through the research question. The subsequent step involved a structured self-reflection process by the authors. This process was interactive, with authors reflecting on their use of AI chatbots in their daily lives, documenting their observations, and engaging in discussions to identify overarching themes from these reflections (Hamilton et al., 2008). This was achieved through discussions between two authors during the drafting phase, leading to the segregation of reflections into various themes. The identified themes were then categorised into two main areas: the advantages of AI chatbots in research and their limitations.

This process, known as coding, began with the initial self-reflections treated as raw data. The data was subjected to open coding, where each segment was assigned a name. It was followed by axial coding, wherein open codes were grouped into two primary categories (Merriam, 2009). Each sub-theme within these categories was further triangulated with relevant literature and secondary data to ensure the credibility and validity of the findings (Lincoln & Guba, 1985). The secondary data included screenshots of users' interactions with AI chatbots for research purposes. The findings of the self-reflection are presented below.

FINDINGS

In February 2023, the authors began their exploration with AI chatbots such as ChatGPT-3.5, followed by ChatGPT-4 in March 2023. Subsequently, they extended their exploration to include other AI chatbots as they were released. Concurrently, AI chatbots tailored for the research community were gradually introduced, prompting the authors to examine these tools for research purposes. The period of this self-reflection extended from February 2023 to August 2024. The themes presented below represent a consensus reached among authors. The data continued to extend after each manuscript review due to the continuous improvement of AI chatbots.

How AI Chatbots can Improve Research

Another benefit of AI chatbots is that they facilitate the personalisation of learning experiences so that users can understand research topics or difficult concepts in chatbots. It can provide recommendations to users to help them understand materials by providing educational resources, tutoring, real-time feedback on their assignments and summarising

their understanding of a particular topic. This is triangulated with Figures 1 and 2 and further with the following literature.

I want you to act as a Socrat and use the Socratic Method to help me improve my critical thinking, logic, and reasoning skills. Ask openended questions to any statement I make and provide constructive feedback before you ask any further questions. Memory updated Absolutely, I'd be happy to help with that! Feel free to start with any statement or topic, and I'll use the Socratic Method to prompt you with questions that encourage deeper thinking and reflection. ChatGPT, an artificial intelligence chatbot released in November 2022, is the fastest-growing consumer application in history. As a generative Al that uses Natural Language Processing, it creates a plethora of content with a 'human voice'. Unsurprisingly, ChatGPT garnered a lot of attention from academia as it was able to pass a number of professional exams and it has multiple avenues for potential misuse by students and researchers alike. Therefore, this study aimed to address the dearth in literature by performing a self-reflection study on the practical usage of Al Chatbots in research, with a research question What is the self-reflection of the authors on the usage of Al Chatbots for research? This study was framed under the Technology Acceptance Model to provide a comprehensive discussion covering multiple domains. The authors find that AI Chatbots are helpful in terms of brainstorming for idea generation, enhancing research productivity, enabling personalized learning, removing writer's block, overcoming language barriers, checking grammar, and enhancing crossdisciplinary research. The downsides are that the generated answers from AI Chatbots might contain errors, exhibit bias, cause misinformation, lack originality, include citation errors, impair scholarly thinking and writing, and raise concerns about data transparency. Furthermore, the authors find that the usage of AI Chatbots in research largely depends on the user, as there are currently no guidelines for the usage of AI Chatbots in research and education. Therefore, user integrity, respect for academic originality, and accountability play an important role when using Al Chatbots for academic purposes. Overall, this study contributes to the body of knowledge in AI Chatbot research by emphasizing their potential and addressing potential issues when using them in research. You've presented a detailed overview of the study on AI Chatbots in research. Let's delve deeper into some of the ideas you've shared. I'll start by asking a question to help you reflect more critically on the content: Ouestion: How do you think the Technology Acceptance Model (TAM) specifically helps in understanding the practical usage of AI Chatbots in research? What might be its limitations in this context? Feedback: You've chosen TAM as a framework, which is valuable for understanding user acceptance and perceived usefulness. It's important to reflect on whether TAM fully captures the complexities of Al Chatbots' integration into research. For instance, TAM focuses on perceived ease of use and usefulness, but does it address ethical concerns, potential biases, or the quality of generated content? Reflecting on these aspects can help you identify both the strengths and limitations of applying TAM to this study.

Figure 1. Learning thinking with ChatGPT (date generated: 1 August 2024)

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Figure 2. Suggestion of reading material from Google Germini (date generated: 1 August 2024)

Dowling and Lucey (2023) added that with AI chatbots, it is possible to reduce the disparity between developed and non-developed countries in terms of research output by offering pertinent advice to the researcher. It is made possible through ChatGPT's academic-related plugins, such as Coursera and a globally recognised Massive Open Online Course (Stein, 2023). Even Coursera offers AI Chatbot support on its website (Goli, 2023). All these plugins reduce the weaknesses of AI chatbots, as discussed in the literature review, and provide more reliable educational materials to the user. Users can use AI chatbots as sources of information for their research because the new function includes referencing. Therefore, users can double-check the accuracy of the information based on the provided references. This function addresses the progression of SDG 4 in certain countries by providing users with an innovative teaching and learning experience through personalised learning made possible with AI chatbots (UNESCO, 2023). Moreover, Lin and Chang (2023) have proposed a framework for using chatbots in personalised learning by integrating personalised chatbot interactions, active learning, and self-regulated learning to enhance student engagement and motivation and improve learning outcomes. It is further triangulated in Figure 2.

Furthermore, ChatGPT has a function known as 'Customise ChatGPT', allowing users to tailor the tool to fit their needs. This tool aids in research and academic learning. As proof of concept, we instructed ChatGPT to function as a linguistic proofreader specifically for grammar, as illustrated in Figure 3.

Furthermore, users can use 'Customise ChatGPT' to practice their argumentative skills for research or other academic settings by keying specific prompts into both columns. This function has enabled users to have a meaningful argument with the AI, assisting them to improve their argumentative skills. With "Customise ChatGPT," the possibilities for learning and growth are truly endless, with a condition whereby users need

to have prerequisite knowledge in the respective debate topic to recognise errors and/or hallucinations from the machine. Put differently, this is also an advantage as it helps users shape their critical thinking as the user needs to detect errors and/or hallucinations from the machine during arguments.

Likewise, AI chatbots also provide grammar-checking functions, which are particularly beneficial for non-native English-speaking researchers. It is further triangulated with literature whereby AI chatbots can check grammar. It enhances the readability of advanced drafts in an editing pass, thus assisting non-native-English speaking researchers (Editorial, 2023; Gordijn & Have, 2023; van Dis et al., 2023). However, users still need a basic understanding of grammar rules, as AI chatbots are not infallible and may not always correctly apply grammar and/or tense rules in specific contexts. This reflection is further triangulated in Figure 3, demonstrating how users can utilise ChatGPT to specify the type of English corrections needed. Furthermore, the authors also used ChatGPT for the IELTS writing test Task 2 practice in Figure 4, and the corresponding feedback from ChatGPT is provided in Figure 5. The authors also used ChatGPT for the IELTS speaking test with the ChatGPT phone application, as shown in Figure 6.

Customize ChatGPT
Custom Instructions ① What would you like ChatGPT to know about you to provide better responses?
I am a Ph.D. student researching educational leadership, and I am using ChatGPT to proofread my English sentences and learn English grammar rules.
146/1500 How would you like ChatGPT to respond?
grammar ERROR ONLY, and also show me what grammar mistake I made and how to improve it.
Enable for new chats Cancel Save

Figure 3. Customizing ChatGPT for a specific function

Chi-Kuan Chia, Avinash Rames and Ahmad Zabidi Abdul Razak



Figure 4. IELTS writing test practice with ChatGPT (date generated: 26 June 2024)



Figure 5. Evaluation for the Figure 4 essay by ChatGPT (date generated: 26 June 2024)

AI Chatbots in Research: Yes or No? A Self-reflective Exploration



Figure 6. IELTS speaking test practice with ChatGPT APP (date generated: 1 August 2024)



Figure 7. Suggestion on starting a topic writing with Claude AI (date generated: 1 August 2024)

AI chatbots can assist in generating initial ideas on a given topic and guide how to begin writing about it. Users simply need to input important keywords related to the topic they want to write about. This capability is triangulated by literature and Figure 7. In academic literature, AI chatbots have been shown to help remove writer's block (Gordijn & Have, 2023; van Dis et al., 2023). Those who fear blank pages can use AI chatbots to create a first draft, which requires a good prompt (Gordijn & Have, 2023). Likewise, AI chatbots are able to summarise long reading materials and automatically generate outlines to easily identify key points (Editorial, 2023; Pavlik, 2023).

Additionally, AI chatbots have positively impacted research as it has made information searching faster and more effective as it can function as a search engine that provides direct answers compared to current search engines in which the user would have to find pertinent information on their own (Gordijn & Have, 2023). For the academic community, AI chatbots and ChatGPT with academic-related plugins (Consensus, 2023; Ought, 2023; Perplexity AI, 2023; PubGenius Inc., 2023; scite_, 2023) provide instant factual answers to specific research questions together with references that are actually available online It is further triangulated with Figures 8 to 10.

Finally, the authors used ChatGPT-4 to develop a computer program based on findings from one of the author's PhD studies when ChatGPT-4 was released in early 2023. The author's research focused on developing a leadership succession planning model for Malaysian public universities using the Grounded Theory Approach. With the assistance of a friend who had very basic knowledge of the Java language but had not worked in the industry for over 10 years, he could only recall how to insert code generated from ChatGPT-4 into Java. The entire process took one week to develop a very basic program version. On the first day, the author and his friend learned to write a prompt into the chatbot to generate the correct code. On the second and third days, they continued learning how to prepare the prompt but encountered persistent errors in the Java code, resulting in no progress. However, they successfully resolved the first square box appeal on the fourth day, marking a significant breakthrough. They realised they could ask ChatGPT-4 for guidance on resolving Java error appeals. With this newfound approach, the program gradually took shape and was successfully developed by the seventh day.

Hence, the authors suggest that AI chatbots might potentially assist researchers in trying out new projects completely outside their field of study. In this case, none of the authors have computer programming degrees. This function is supported in the aforementioned literature review. Figure 11 shows the interface of the Potential Leader Identification System program developed with the assistance of ChatGPT-4. These reflections align with the TAM in terms of being easy and practical for use within the research community (Davis, 1989). AI Chatbots in Research: Yes or No? A Self-reflective Exploration

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		Q Expert v
Acceptability of artificial intelligence (AD-led chatbot services in healthcare: A mixed-methods	s study	
Most internet users are receptive to using Al-led health chatbots, but hesitancy regarding A	N technology may compromis	e engagement.
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d Observational Bludy 5 Reprove Journal 5 Highly Clied		
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"What Can ChatGPT Do?" Analyzing Early Reactions to the Innovative AI ChatGot on Twitter		
ChatGPT, an AI chatbot, can perform various functions, including creative writing, essay we answering questions, impacting both technologies and humans in both positive and negative set of the set	iting, prompt writing, code w	iting, and
Big Data Cogn. Comput. Viriya Tancharungniji et al. 121 charlona 2023		
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Artificial Intelligence Chatbet Behavior Change Medel for Designing Artificial Intelligence Cha	tbots to Promote Physical Acti	uity and a Healthy

Figure 8. Paper searching by Consensus AI (date generated: 1 August 2024)

Papers (10)	Insights ×
prover + 0018 ■ Arhitectual Approach to Drapitoying LLM Chattoots for Humain-Ail Dieterschole Research Neuroshiwes 23 Jan 2020 ■ ROF □ 11 10 Ark Coplex	Yes, Al chatbots in research are beneficial. The paper presents a practical method for deploying Al chatbots in studies, enabling user interaction data collection for human Al research.
Bouk Ongers + 0018 The effect of chatbots on self-disclosure among users Smag te, 11 Jun 2024 The The Coplet	The paper's title matches your query, but it doesn't address your specific question.
artice + 0018 Artice + 0018 Artice + 0018 Artice + 0018	The paper's title matches your query, builit doesn't address your specific question.
Dord Comparing and assessing four AI chatbots' competence in	The paper's title matches your query, but it doesn't address your specific question.

Figure 9. Paper searching by SciSpace (date generated: 1 August 2024)



Figure 10. Paper searching by ChatGPT with Consensus AI plugin (date generated: 1 August 2024)

Potential Dean System	Potential Leader Identification System
	Add Candidate
	Candidate Management
	Evaluate Suitability

Figure 11. Interface of Potential Leader Identification System

Flipside of AI Chatbots in Research

Originality is absent in AI chatbots due to their training dataset dependency. Hence, they cannot be expected to offer original and stimulating ideas or useful insights (Pavlik, 2023). AI chatbots, at their core, merely combine existing data and come up with a statistically average opinion while lacking a real understanding of the world (Editorial, 2023). Even though this statement is debatable, as some researchers suggest that original ideas can be innovated through the combination and synthesis of existing knowledge and ideas (Han & Nickerson, 2015), a question arises: What if an idea is generated by AI chatbots and used in research or writing? In this case, does the idea belong to the user or the AI Chatbot? This issue links back to the authorship discussed in the literature review.

This concern also applies to research work(s) because individuals could quickly formulate research essays without investing time and energy into creating original content. This dependency on AI chatbots may cause researchers to lose their ability to think and write scholarly articles over time, and proponents predict the phenomenon's occurrence (Editorial, 2023; Jo, 2023). Undertaking a research endeavour conventionally (such as now) requires the researcher to search for materials in a myriad of ways. During the process, researchers read and filter material to identify suitable ones, and they learn a variety of information and gain deeper insight. With AI chatbots, the information search process is considerably reduced as AI chatbots provide all the suitable information per the given prompt, and the researcher only has to double-check the content's accuracy. Although researchers save time with AI chatbots, they skip the aforementioned processes; hence, they would not be exposed to other information that could educate and shape their crystallised intelligence. It leads to queries about a researcher's contributions, the ability to express their opinions, and the quality of universities (Jo, 2023; van Dis et al., 2023). Does AI do research still research, granted that it is merely revisiting information it acquired from its

training dataset? Can researchers still call themselves researchers if AI guides their ideas and work(s) either partially or completely? Nonetheless, opponents of this stance argue that AI chatbots may produce hypotheses, establish methodologies, design experiments, analyse and interpret data, and compose papers in the future (van Dis et al., 2023). In the long term, AI chatbots might even examine and review papers in place of human editors and reviewers.

Learning and improving academic writing prior to using AI in research is imperative, particularly for novice researchers and graduate students. It is analogous to mathematical learning, whereby a student is not encouraged to use a calculator prior to mastering basic mathematical skills. A researcher in this era needs to rely more on their writing compared to AI writing, as until now, AI is unable to process information absent from their database. Correspondingly, AI struggles to put concepts such as tacit knowledge, intrinsic values of cultures, morality, and ethics into words. Succinctly, AI chatbots do not understand prompts and their corresponding replies, and they are also unable to differentiate truth from falsehood (Hosseini et al., 2023).

Even though the literature review shows that AI chatbots can help researchers brainstorm, Using AI chatbots to brainstorm poses challenges to the concept of originality. For instance, if an article is published but the generated idea was from a prompt keyed into an AI Chatbot, is it plagiarism or an original work? Likewise, if a researcher had an original idea but used an AI Chatbot to grow it to something usable, is it original or plagiarised? Researchers have suggested that AI chatbots are unable to generate original ideas or concepts because they depend on their training dataset (Dowling & Lucey, 2023; Pavlik, 2023). Therefore, higher education needs to rethink, review and redefine originality and plagiarism. Likewise, this creates a new conundrum on innovation. If research is conducted using AI, which runs solely based on currently available information, innovation will become a thing of the past. It has even been argued that peer review impedes innovation as peers are unlikely to be familiar with ground-breaking discoveries (Riera & Rodríguez, 2022). As previously explained by the TAM, curtailing AI use in research would be difficult; hence, it is critical for academia to instil the concepts of ethics, integrity and originality into the minds of students early on while maintaining a strict code of conduct for AI use in research (Hosseini et al., 2023; Jo, 2023).

Provided that a researcher keys in the appropriate prompt into an AI Chatbot, it will aid the individual in organising or navigating their thoughts and ideas by cross-linking them together (Hutson, 2022). It is akin to a "brainstormer," as discussed in the literature review. It poses the question, "Is it good for researchers to rely on AI to brainstorm?" Proponents would quote savings on time and effort and increased productivity as supporting statements. On the flip side, will the use of AI chatbots in research erode the ability of researchers to think, create and innovate? Revisiting history, prior to the advent of the global positioning system (GPS), humans relied on memory and/or maps to navigate while travelling. After the introduction of the GPS, humans have increasingly relied on the tool for navigation. It is rare for individuals to go anywhere without GPS, and whether they would still be able to navigate without the tool is questionable. Will the advancement of AI chatbots lead to researchers becoming too lazy to think or lose the ability to navigate and cross-link their crystallised intelligence? A premonition exists in Jo (2023); *a further worry is that by offloading thinking to automated chatbots, researchers might lose the ability to articulate their thoughts* (p. 216).

Furthermore, AI chatbots designed for the research community have introduced a new function called "Co-pilot." This function assists users in understanding articles by allowing them to insert the article into the AI Chatbot. The AI Chatbot then answers the user's questions based on the article's content. However, this innovation has raised concerns regarding citation and referencing practices. The issue arises when the AI Chatbot explains the article to the user, as it does not display citations used within the article. As a result, users may inadvertently cite ideas presented by the AI Chatbot instead of attributing them to the original researchers. Certain formulae are widely known in the sciences and can be ascribed to specific individuals; hence, directly citing them is common practice. Case in point, $E=mc^2$ is ascribed to Albert Einstein. However, in social sciences and education, many statements in articles are fact-based opinions drawn from research findings. Distinguishing the origin of these ideas becomes challenging, thus potentially leading to situations where classical theories in social sciences and education are cited as someone else's work rather than acknowledging the original researchers.

As with most innovations, wealthy nations and privileged researchers will likely take advantage of LLM in ways that accelerate their research and widen social disparities (van Dis et al., 2023). The reverse has also been suggested, whereby an AI Chatbot could reduce the disparity by offering pertinent advice to the researcher (Dowling & Lucey, 2023). It raises a question on the access and usability of knowledge in developing countries as not all regions may have internet access, and even if they do, the content available online would likely not be in their native language.

DISCUSSION

Even though AI chatbots still have weaknesses, their strengths outweigh their shortcomings. With full awareness of these weaknesses, the authors have continued using them for research purposes. This decision can be explained by the TAM, which considers factors like PU and *PEOU* from the end-users perspective (Davis, 1989). The benefits of AI chatbots, as discussed in the literature review and findings, align with a domain of TAM related to perceived practicality. Indeed, the authors prefer novel technologies demonstrating high PU and *PEOU*, as Davis (1989) suggested.

Furthermore, ChatGPT allowed one of the authors to transform data collected from his PhD study into a computer program. Even though it is still a prototype, it has opened another opportunity for the authors to delve further into a new realm of research based on data collected from a qualitative research approach. It is aligned with the lens of pragmatism, whereby AI chatbots could potentially solve and improve research output more effectively, which was previously impossible. In the future, AI chatbots may work as the researcher's assistant in solving real-world problems. Owing to their huge training data sets, they may provide perspectives that humans otherwise would not notice. A good example is AlphaFold (Ren et al., 2023).

Meanwhile, a conflict arises with the suggestion of Dowling and Lucey (2023) of reducing the disparity between developed and non-developed countries in terms of research output by AI chatbots. Two important aspects that Dowling and Lucey (2023) missed are the difficulty of accessing the Internet as well as the fact that languages used on the Internet for knowledge might not be the native languages of individuals in some developing or low-income countries. Furthermore, most data used to train AI chatbots was in English, but noteworthily, not every citizen in developing countries would have a good command of the language. Likewise, AI chatbots provide limited support for languages other than English. Consequently, multiple groups of people might miss out on this opportunity to learn new knowledge. It is a significant challenge because citizens' knowledge is linked to a country's gross domestic income (Hanushek & Woessmann, 2020). This substantial disparity might widen the gap between low-income and high-income countries (Alonso et al., 2020; Qiu & Liu, 2023).

One might also inquire if AI chatbots are accessible to university students in poor countries for learning purposes. Even though Dowling and Lucey (2023) argue that AI chatbots present a valuable opportunity to assist universities in research, particularly where there is a lack of expertise, a crucial question arises: Can universities ensure that all students have access to the Internet? At an individual level, disparities may arise between those who can afford subscription-based services and those who cannot. This discrepancy in knowledge accessibility may widen the gap between students from different economic backgrounds. Furthermore, as the development of AI chatbots is primarily driven by capitalistic interests, the knowledge gap between students from poor and rich countries, as well as those from economically diverse family backgrounds, may continue to expand (van Dis et al., 2023).

The authors would like to introduce a model called "The Seven Wave Model," which illustrates the integration of AI technologies into education via a series of waves. The waves are as follows:

- 1. First wave: Companies push AI technologies to ensure wide acceptance.
- Second wave: AI technologies are officially integrated into education, albeit in certain areas.

- 3. Third wave: AI technologies are incorporated into the educational system via the legal system.
- 4. Fourth wave: Education becomes increasingly dependent on AI to function.
- 5. Fifth wave: AI-generated content is no longer distinguishable from human-generated content.
- 6. Sixth wave: AI companies remove the option for using the technology without cost.
- 7. Seventh wave: Disparity in education would worsen as society would be divided into those who can afford it and those who cannot, powered completely by AI.

AI chatbots can facilitate personalisation of learning experiences for users to comprehend research topics or challenging subjects, and their accuracy increases when users repeatedly ask the same question to AI chatbots while verifying certain information (Wang et al., 2022). Suppose hallucinations occur in the initial responses generated by AI chatbots. In that case, these hallucinations persist throughout subsequent conversations (Zhang et al. (2023) because AI chatbots are fundamentally supported by deep machine learning, which still faces unresolved issues related to hallucinations. These issues have been present since the inception of deep machine learning in the field of AI in the mid-20th century, and scientists today still continuously try to solve this problem (Luo et al., 2024; Xu et al., 2023).

Findings by Dziri et al. (2023) suggest that transformers, core technologies in supporting AI chatbots, have been unable to excel in handling high-complexity problems. They have primarily generated responses based on shallow and repetitive learning, lacking a deep and holistic understanding of the tasks. Therefore, for the time being, a comprehensive literature review can only be conducted by humans. Henceforth, this circumstance presents a dual-sided coin, manifesting both merits and demerits concurrently, and only researchers who use it can identify this error. Therefore, with the rise of AI, it is becoming increasingly important for researchers to equip themselves with strong critical thinking skills to differentiate accuracies and inaccuracies, especially given our experiences with the rampant spread of fake news during the Coronavirus Disease 2019 pandemic over the past few years (Kruijt et al., 2022; Puig et al., 2021; Spector & Ma, 2019). Furthermore, researchers are advised to possess prerequisite knowledge in specific subjects before utilising AI chatbots. With these skills, researchers can identify and rectify mistakes generated by AI chatbots and utilise them wisely.

Additionally, the reliability of AI chatbots in furnishing information to university students raises concerns. There is a lack of transparency regarding the data sources for widely utilised AI chatbots such as ChatGPT, Claude AI, and Google Bard/Gemini. Furthermore, the information presented to users is contingent on the preceding prompts

entered by the user, potentially leading to biases that align with user preferences. It may cause students to overlook crucial information, thus creating blind spots in their knowledge and understanding.

Additionally, although Bing AI displays resources, the method by which it prioritises and displays information for users is still undisclosed.

For academic purposes, AI chatbots, such as SciSpace, have limitations in the articles they can present to users, and not all articles originate from high-quality journals. Even though Consensus AI allows users to choose articles from WoS, the criteria for displaying articles to researchers remains unknown. It is unclear whether the selection is based on the highest search, citation or download counts or if it is a medley of these factors. A low download count or citation rate does not necessarily indicate poor paper quality; instead, it could signify a niche research paper. Conversely, high citation counts may result from an already well-cited paper, leading users to continuously cite it, perpetuating its visibility. AI chatbots still struggle to differentiate between good and poor-quality papers, and there is a chance that predatory journal articles will be selected for answer generation. Even though Scopus has its own Scopus AI, the same question arises: How do they present articles to the audience, and on what criteria is this based? These platforms must disclose this information; otherwise, there is a risk of unintentionally creating a situation of bias or injustice in the realm of academic referencing.

Even though many problems regarding AI chatbots still need to be addressed, AI is expected to change the way research is conducted in the long term, as demonstrated by Ren et al. (2023) and Lee and Kumar (2023). Additionally, Tao (2023) predicted that by 2026, AI chatbots will be able to research side by side with mathematicians in solving complex mathematical problems and others. AlphaGeometry can solve Olympiad geometry questions and is nearing the achievement of a gold medallist (Trinh et al., 2024). Grace et al. (2024) even argued, '*If science continues undisrupted, the chance of unaided machines outperforming humans in every possible task was estimated at 10% by 2027, and 50% by 2047* (p. 1)'. Therefore, researchers and policymakers must find ways to utilise and coexist with AI chatbots in future research (Gursoy et al., 2023; Khosravi et al., 2023).

The conceptual framework of this reflection is based on the TAM, and findings on advantages, disadvantages and ethical issues associated with AI chatbots are summarised in Figure 12. The advantages of AI chatbots are perceived through high levels of PU and PEOU. High PU is observed via enablement of personalised learning, idea generation, enhancement of research productivity and removal of writer's block. High PEOU is reflected in the 'Customise ChatGPT' function, which removes language barriers and improves essay readability. Despite existing flaws in AI chatbots, the benefits of PU and PEOU outweigh these shortcomings, provided that users employ the technology judiciously and stay updated with developments from leading AI Chatbot providers, namely OpenAI and

Google. The conceptual framework also outlines the disadvantages of AI chatbots, as well as the associated ethical considerations.



Figure 12. Summary of AI chatbots' pros, cons, and ethical considerations

CONCLUSION

This study investigates the practical usage of AI chatbots in research through a self-reflective study by the authors, framed with the TAM and through the lens of pragmatism. Based on their self-reflection on the use of AI chatbots in daily university life, the authors find that AI chatbots are beneficial in several respects: they aid in brainstorming for idea generation, enhance research productivity, facilitate personalised learning, alleviate writer's block, overcome language barriers, check grammar, and promote cross-disciplinary research. However, there are notable drawbacks. The responses generated by AI chatbots may contain errors, exhibit bias, disseminate misinformation, lack originality, include citation errors, potentially impair scholarly thinking and writing, and raise concerns regarding data transparency.

Furthermore, the authors observe that the effectiveness of AI chatbots in research is highly contingent upon the user, as there are currently no established guidelines for their use in research and education. Consequently, user integrity, adherence to academic originality, and accountability are crucial when employing AI chatbots for academic purposes. Additionally, the accessibility of AI chatbots for all students warrants attention. At present, there is a lack of fairness in access to AI chatbots among university students worldwide. This disparity can create a knowledge gap between students accessing AI chatbots and those without access. The quality of content generated by AI chatbots also varies between paid and free versions. Most pressing is that not every student in every country has equal opportunities to utilise AI chatbots as a learning tool, further exacerbating economic disparities as we advance towards a knowledge-based economy.

The authors find that AI chatbots significantly enhance their productivity (high PU) and are easy to use (high PEOU). Therefore, despite their weaknesses in chatbots, the authors continue to use them in research and education, exercising extra caution with the answers generated by these tools.

In the final part of the author's self-reflection for this essay, it is noted that AI chatbots have significantly shaken society, and Pandora's box is just beginning to be opened in the realm of academia. Since the release of ChatGPT 3.5 in November 2022, AI chatbots have become mainstream, as they are perceived as easy to use and highly practical for research, albeit imperfect, as discussed by the TAM (Davis, 1989). Academia is contending with a variety of discussions on the advantages and disadvantages of AI chatbots in research while grappling with ethical concerns surrounding it. Adding to the nebulous situation, GPT-4 technology has been launched, and successors will be released progressively. Currently, AI chatbots appear to be a double-edged sword, and the edge depends on the user, as evidenced by Urbina et al. (2022). Indeed, on one end, an array of advantages can be harnessed, while on the other, a variety of disadvantages and ethical concerns are present. Nonetheless, academia's panic appears unjustified for now as the current status of AI chatbots is akin to that of an 'interactive Wikipedia' with added breadths of knowledge and conversational capacity. However, this status is bound to change as successors become more refined, but with such change also comes new responsibilities. Academic users need to practice caution when using AI chatbots for research due to known issues in the realms of integrity, originality, and accountability. Likewise, there should be increments in interdisciplinary discussions as academics would have to consistently solve novel issues emerging as AI chatbots become mainstream.

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Factors Controlling Durability of Geopolymer Concretes in Chloride Determined via Growing Self-Organizing Maps

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ABSTRACT

Geopolymer concrete offers a promising alternative to traditional Portland cement concrete, exhibiting comparable mechanical and durability performance while reducing environmental impacts. However, its mechanical and durability properties depend on many factors, such as the water/binder ratios, concentration of activator and curing temperatures. This study proposes using an unsupervised Artificial Neural Network (ANN) Self-Organizing Map (SOM) to predict the factors that control the durability of geopolymer concrete in a chloride environment based on experimental datasets. This research aims to identify the impact of various water-to-binder ratios and molarity of activators on the durability of geopolymer concretes by applying the Growing Self-Organizing Maps (GSOM) model to predict the durability of the design mix. A series of geopolymer concrete mixes with varying water-to-binder (w/b) ratios and activator molarity were prepared to achieve these goals. These cylindrical samples of 100 mm height × 50 mm diameter size were cured for 24 hours at 80°C and subject to chloride migration test at 28-day curing age. The data collected was analyzed and modeled using statistical methods and machine learning techniques, i.e., SOM modeling. This modeling approach effectively revealed patterns and relationships within the dataset, providing

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E-mail addresses: 21020482@siswa.unimas.my (Fong Wen Lee) wui.lee@uts.edu.my (Chang Wui Lee) 21020039@siswa.unimas.my (Teo Siaw Hui) kmtay@unimas.my (Tay Kai Meng) jannisa@unimas.my (Annisa Jamali) jmnazim@unimas.my (Mohamad Nazim Jambli) iidawati@unimas.my (Idawati Ismail) *Corresponding author crucial insights into the chloride migration behavior. Based on the GSOM modeling, this study highlights efficient data analysis, pattern recognition, and optimization of outcomes, such as geopolymer concrete durability prediction in a chloride environment based on the selected parameters.

Keywords: Artificial Neural Network (ANN); durability; geopolymer concrete; Self-organizing map (SOM)

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INTRODUCTION

Geopolymer concrete represents an innovative and sustainable paradigm in construction materials. It departs from the dependency on conventional Portland cement-based concrete by utilizing industrial byproducts, natural sources, or waste materials with high silica and alumina content, such as fly ash, slag, and metakaolin (Cong & Cheng, 2021). The precursors go through a geopolymerization process, where these source materials react with an alkaline activator solution, typically composed of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). During geopolymerization, these constituents undergo a chemical transformation, forming a robust three-dimensional network of interconnected polymeric chains, which serve as the binding matrix for the concrete (Gunasekara et al., 2019). This unique chemistry not only reduces the environmental footprint by diminishing carbon dioxide emissions related to traditional Portland cement production but also offers geopolymer concrete with remarkable attributes, including exceptional fire resistance (Cong & Cheng, 2021), rapid early strength development (Amran et al., 2021), and formidable resistance to chemical aggression (Wong, 2022), making it an eco-friendly and high-performance choice for various construction applications.

Chloride-induced corrosion of steel reinforcement in concrete is primarily attributed to the penetration of chloride ions into the concrete matrix. This penetration is influenced by several factors, including the chloride ion concentration at the surface of steel, with critical levels around 0.4% by weight of cement being a potential threshold for corrosion initiation (Zofia & Adam, 2013). The porosity of concrete plays a pivotal role in facilitating chloride ingress. Chloride ions permeate concrete through three key mechanisms: capillary absorption, hydrostatic pressure, and diffusion. The predominant mechanism is diffusion, driven by concentration gradients and dependent on factors such as ion concentration differences and continuous pore fluid Sirivivatnanon and Khatri (2011), and Shobeiri et al. (2021). It occurs predominantly in submerged conditions, where the concentration disparity between contaminated and uncontaminated surfaces and the diffusion coefficient determine the ingress rate. Concrete, characterized by solids and voids filled with fluid and air, can also experience chloride penetration due to hydraulic pressure caused by the presence of chloride ions at the concrete surface (Halim et al., 2017). Capillary absorption relies on moisture gradients to facilitate chloride ion movement into concrete pores (Titi & Tabatabai, 2018).

Several critical factors influence the durability of geopolymer concrete, and one of the most significant concerns is the risk of chloride-induced corrosion. This corrosion process can be complex and is influenced by several key factors (Chen et al., 2021; Chindaprasirt & Chalee, 2014). The initial chloride concentration in the environment, the exposure duration, the geopolymer concrete's specific mix design, and the prevailing environmental conditions all play vital roles (Tennakoon et al., 2017; Titi & Tabatabai, 2018).

The main aim of this study is to adopt machine learning methods to predetermine the chloride permeability durability of geopolymer concrete. Artificial intelligence (AI) is revolutionizing engineering by streamlining tasks and optimizing the design and maintenance of engineering systems. AI algorithms can efficiently analyze large datasets to recognize patterns and make predictions, offering a wide range of applications, including complex system design, predictive maintenance, and more (Huang et al., 2015). As AI technology continues to advance, it is expected to profoundly impact the field of engineering. In geopolymer concrete durability prediction in chloride-rich environments, machine learning techniques, including artificial neural networks (ANNs), support vector machines (SVMs), random forests, and decision trees, are employed to develop predictive models. These models rely on comprehensive datasets, including concrete composition, preparation techniques, testing conditions, and chloride penetration test results. The successful implementation of machine learning models has the potential to significantly enhance the safety and longevity of concrete structures by providing engineers and designers with precise insights into material behavior under varying conditions (Pavithra et al., 2016). While machine learning models can significantly contribute to our understanding, it's important to acknowledge the complexity of real-world scenarios and the need for continued research and refinement in this field.

In the field of machine learning, two fundamental approaches are supervised and unsupervised learning (Rahmatbakhsh et al., 2021). Supervised learning utilizes labeled data to learn a set of training data samples and classify them based on their labels, which is useful for precise predictions. On the other hand, unsupervised learning (often known as clustering) uncovers the hidden patterns from the set of training data samples and partitions similar patterns into a cluster of similar patterns (Padmapoorani et al., 2023). The self-organizing feature of an AI algorithm has exhibited a remarkable ability to retain the information acquired from the learning of the data samples that are used to adjust responses of presented data samples. While the labeled data samples are hardly (expensive) to be acquired in geopolymer concrete studies, clustering serves as a better alternative in this study.

The Self-Organizing Map (SOM) is adopted for its unique feature of clustering highdimensional data onto a low-dimensional (2D) topological map. While the topological map consists of a number of nodes (clusters) that are self-organized according to the topological relationship among the data samples, visualizing the 2D topological map provides useful insights into the data structure. It potentially reveals the hidden message for knowledge discovery, especially in the geopolymer concrete study. Kalteh et al. (2008) outlined a structured approach involving data gathering and normalization, training the SOM, and extracting information from it. These steps enable visualizing data patterns, grouping data through clustering, and identifying distinct clusters for further analysis. Extracting the hidden message from a SOM model may include deriving a rule-based model at the clusters that precisely describes and/or predicts geopolymer concrete's diffusion coefficient across various mixing designs. Ensuring the consistency of mixed designs with experimental data and assessing the reliability of these designs in guiding specific chloride permeability levels are crucial. It is particularly significant given the potential variations and parameters that may not be explicitly accounted for in the training data (Colantonio et al., 2021).

The adoption of SOM extends to the design of geopolymer concretes, with researchers exploring its structural potential, driven by the growing interest in SOM clustering. The previous focus of the geopolymer concrete study included analyzing micro-scale materials like the composition and structure of aluminosilicate precursors, the distribution of reaction products, and the development of pore structures at the micro level. Based on these findings, current research trends are focused on investigating the performance of nano-silica or nano-alumina additives on the microstructure and properties of geopolymer concrete at a larger scale (Mayhoub et al., 2021). Additionally, there is growing interest in studying the influence of activator solution concentration at the micro level and the impact of curing temperature on microstructural development, as these factors could offer valuable insights into the material's behavior in practical construction applications. Among the researchers, the geopolymer concrete durability characteristics are of most interest, particularly in the impact of chloride attack (Pasupathy et al., 2021) on compressive strength and chloride binding capacity of fly ash geopolymers under varied curing conditions.

Limited research papers reportedly refine the geopolymer concrete parameter settings to enhance strength (Mohammed et al., 2021), durability (Huseien & Shah, 2020) and energy efficiency (Chen et al., 2021). Therefore, the development of the SOM model can reveal the underlying information, such as mixed proportions. The modeling uses geopolymer concrete data, such as compressive strength or penetration depth of ionic species. This paper explores how SOM models predict the durability of fly ash geopolymer concretes in chloride.

EXPERIMENTAL METHOD

Raw Materials

The raw precursor used in this study is Class F fly ash obtained from Sejingkat Power Station, Kuching, Sarawak, Malaysia. The chemical composition of the raw material is shown in Table 1 and was classified according to ASTM C618. Two types of alkaline were used in a combination of NaOH and sodium silicate (Na₂SiO₃) at a 1:0.5 mass ratio. Only coarse aggregates of 20 mm maximum size were used to ensure homogeneity and fine aggregates were also used through a 4.75mm sieve.

Precu	rsor MgO	A1203	Si02	P205	SO3	K20	CaO	TiO2	MnO	Fe2O3	Rb202	SrO	ZrO
Fly A:	sh 0.5	15.7	53	1.44	0.144	4.71	5.21	1.57	0.295	17.1	0.081	0.372	0.000ppm
Table 2													
Mix Pr	oportions for C	Chloride Perme	eability Te.	st									
N0.	Liquid to	Molarity	Sod	ium	Aggregate	Sand	kg,(kg/	Fly Ashes	Na Na	OH (kg)	Na ₂ SiO ₃	(kg)	Water (ml)
	Binder ratio		Hydr to So Silicat	oxide dium e ratio	kg,(kg/m³)	Ĩ	n³)	kg,(kg/m ³					
-	0.3	8	1:().5	12.965(2400)) 6.485	5(1600)	3.23 (540)		0.311	0.155	5	972
7	0.4	8	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.414	0.20	7	1296
3	0.5	8	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.518	0.259	6	1620
4	0.3	10	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.388	0.19	4	972
5	0.4	10	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.518	0.259	6	1296
9	0.5	10	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.648	0.32^{4}	4	1620
7	0.3	12	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	_	0.466	0.23	~	972
8	0.4	12	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)	~	0.622	0.31	_	1296
6	0.5	12	1:().5	12.965(2400)) 6.485	5(1600)	3.23(540)		0.780	0.39(0	1620

Table 1Chemical composition of fly ash by XRF (%)

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Samples and Testing

Table 2 shows the mixed proportions to make the fly ash geopolymer concretes. The geopolymer concrete was mixed using a concrete mixer, cast into a 100 mm \times 200 mm height cylinder mold and vibrated using a vibrator for about 15 s. This vibration process was to ensure that the geopolymer concrete was fully compacted. Then, the samples were cured at 80°C for 24 h in a curing oven. After demolding, the samples were sealed to prevent moisture loss until the age of testing, which is on day 28 for the chloride migration test. A total of 162 samples were prepared as training data sets.

Chloride Diffusion Experiment

The diffusion of chloride was conducted according to non-steady state migration—NT BUILD 492 (Nordic Council of Ministers, 1999). Figure 1 shows the experiment setup, which uses external electrical potential to allow chloride ions to penetrate the specimen. After 24 hours, the specimens were split and sprayed with silver nitrate solution. The white precipitates indicate the presence of silver chloride precipitates at the split surface, indicating chloride penetration.



Figure 1. Nord Test Method Sample Migration Setup

Figure 2 compares chloride penetration depth and chloride diffusion coefficients in geopolymer samples as a function of water-to-binder ratios and molarity. These data sets from 162 samples were used in the SOM prediction model.



Figure 2. Chloride Penetration Depth and Coefficients as a function of w/b ratio and molarity

Self-Organizing Maps (SOM)

In this study, Self-Organizing Maps (SOM) are pivotal in determining the optimal mixing design for geopolymer concrete. The dataset used in this analysis has been meticulously assembled through rigorous experiments and testing procedures. An array of activator mixing design variations was systematically applied to geopolymer concrete samples. In total, this comprehensive approach encompassed a total of 162 individual specimens. Each of these distinct combinations underwent chloride permeability testing after a 28day curing period. This dataset serves as the cornerstone for SOM analysis, enabling in-depth exploration of the intricate relationships between mixing design elements and chloride permeability (Stryhal & Plavcová, 2023). Data preprocessing, a vital step in any analytical process, including SOM modeling, involves meticulous data preparation, quality assurance, and necessary transformations. In this particular study, data preprocessing incorporates a normalization procedure, which scales the data to a standardized range to ensure that all variables contribute equally to shaping the SOM model (Alahakoon et al., 2000). Data preprocessing is instrumental because variables may have dissimilar scales, and normalization mitigates the risk of one variable overshadowing others due to its larger values (Mehta et al., 2017).

Growing Self-Organizing Maps (GSOM) is a variant of Self-Organizing Maps (SOM) that can dynamically adjust their size during learning. Unlike traditional SOMs, GSOMs can grow or shrink in response to the input data, allowing them to adapt and represent complex structures more effectively (Alahakoon et al., 2000). The primary advantage of GSOM is its capability to automatically expand the map size in regions of high data density, thereby enhancing its ability to capture intricate patterns.

The GSOM begins by normalizing a dataset from a collection data sample to a range of [0,1]. Then, a map size of (1×1) is initiated, where the initial prototype weight vector is randomly assigned within the normalized data space. Then, SOM's learning process is conducted by fetching one data sample at a time. Similarity measures are conducted, using Equation 1, on the data sample to determine the best-matching-unit (BMU) among the nodes in the map size. Then, update the BMU node to move the node towards the data sample using Equations 2 and 3. Repeat the SOM's learning process by fetching the next data sample until all data samples are learned. Learning of the normalized data samples is repeated at the next learning epoch(s) until the prototype weight vectors are converged (i.e., no changes after each learning). Determine a hit sample count at all nodes to identify a row (or column) of maximum hit sample counts from the map size. Duplicate the identified row (or column) nodes' prototype weight vectors with a new row (or column) of nodes that are positioned next to the identified row (or column) to increase the map size. Repeat the SOM's learning process until the maximum hit sample counts (in row and column nodes) are less than a preset threshold value.

The proposed GSOM procedure for geopolymer concrete analysis involves mainly nine steps.

In step 1, the GSOM is initialized with two nodes or clusters, where a random valued prototype weight vector, $w_j = [w_{j,1}, ..., w_{j,p}], j = \{1,2\}$, is assigned as the centroid of the cluster.

In step 2, a collected data set is fed for learning on the cluster created. The data set consists of *n* data samples of *p* parameter settings of water/binder ratio, molarity, activator NaOH, activator Na₂SiO₃, water, and chloride diffusion coefficient, where each parameter value is normalized to a range of [0,1] to ease the similarity test in the next step. The normalizing method divides the real parameter value by a maximum constant.

In step 3, the learning of GSOM begins with a similarity test on a data sample, $x_i = [x_{i,1}, ..., x_{i,p}]$, on the available clusters using Equation 1.

$$d(\mathbf{x}_{i}, \mathbf{w}_{j}) = \sqrt[2]{\sum_{k=1}^{p} (x_{i,k} - w_{j,k})^{2}}$$
[1]

Step 9 selects a winner, *J*, among the clusters using Equation 2.

$$J = \arg\min_{j} d(\boldsymbol{x}_{i}, \boldsymbol{w}_{j})$$
^[2]

In step 5, the winner cluster and its adjacent clusters are updated with Equations 3 and 4, where h_{jJ} is the topological-based learning rate that is obtained by calculating the distance between the adjacent *J*-th node (N_J) and winner *J*-th node (N_J) on the topological map. Let j = J of Equation 3 update the winner cluster's prototype weight vector, and h_{jJ} of Equation 4 is at the maximum of the learning rate ($h_{jJ} = \alpha$). At the same time, an adjacent node's prototype weight vector (W_j) is updated with a lower $h_JJ < \alpha$ for the self-organizing feature. $\alpha, \sigma \in [0,1]$ are the learning rate and adjacent width that are monotonically reduced over the period of learning.

$$\boldsymbol{w}_{j} = \boldsymbol{w}_{j} + h_{jJ} \left(\boldsymbol{x}_{i} - \boldsymbol{w}_{j} \right)$$
[3]

$$h_{jJ} = \alpha \exp\left(-\frac{\left(N_j - N_J\right)^2}{2\sigma^2}\right)$$
[4]

In step 6, a hit sample counter of N_J is incremented to determine the size of the cluster.

In step 7, go to step 2 with the subsequent data sample x_{i} , i = i + 1, until i = n.

In step 8, the hit sample counters are evaluated for the growth of nodes. A row or a column of new nodes is inserted to retain the topological feature of the previous map. The row of nodes is inserted to the west side of the row with the maximum total hit sample counts, and their prototype weight vectors are initiated from the rows. Otherwise, a column of nodes is inserted to the north side of the column with the maximum total hit sample counts, and their prototype weight vectors are initiated from the columns.

In step 9, go to step 2 fetch x_i , i = 1.

These steps are recursively conducted until the hit sample count of all nodes does not exceed the maximum count. Figure 3 summarizes the overall steps.



Figure 3. Flow chart of Growing SOM

RESULTS AND DISCUSSION

SOM Simulation

From MATLAB, the SOM model was trained using a 5×5 map size, resulting in a grid of 25 neurons arranged in a hexagonal structure, as shown in Figure 4. Each neuron represented specific combinations of activator dosages and chloride permeability. The hexagonal topology allowed information exchange between adjacent neurons, aiding self-organization and learning.







Figure 4. Self-organizing map (SOM) topology; (a) 5×5 map and (b) hit map

Hit maps were generated, as per Figures 4(a) and 4(b), revealing how the input data was distributed within clusters to assess the model's effectiveness. These maps also assessed the quality of clustering, with clusters 3 and 5 receiving more hits, indicating their better representation of common patterns in the data. However, some clusters lacked associated datasets, suggesting that the chosen number of clusters may not have been ideal for capturing distinct variations in the data. Overall, SOM analysis offered valuable insights into mixing design patterns, emphasizing the importance of precise mix design considerations to achieve durable and structurally sound geopolymer concrete compositions.

Meanwhile, the SOM neighbor weight distance analysis assesses the likeness or disparity between neighboring neuron weight vectors, determining the input's influence on each neuron's output (Figure 5). The weight distances were calculated using the Euclidean distance of Equation 1.

Using the SOM library in MATLAB, these neighbor weight distances are visualized using a colormap, as depicted in Figure 5. The dark shade represents the least relevance between the nodes, while the light shade represents the highest relevance of the nodes. This colormap provides a graphical illustration for identifying clusters of similar information or the relevant geopolymer concrete characteristics. For instance, r_9 and r_10 are the relevant nodes indicated in the colormap figure.



Figure 5. SOM neighbor weight distances

Deriving insights from a trained SOM requires some post-processing to create a cluster "recipe" or mix proportion chosen for its accuracy in predicting the durability of geopolymer concrete under various chloride exposure conditions. Ensuring alignment with experimental data and providing reliable recommendations for achieving specific durability levels is crucial. The recipe's robustness is also considered, aiming to offer reliable suggestions for datasets beyond those used for training.

Prediction from SOM

Table 3 shows the prototype weight vectors of SOM, but Table 4 illustrates their implications. Each element of the prototype weight vectors is interpreted in terms of the water/binder ratio, molarity, water volume in units of ml, NaOH in units of g, and chloride diffusion coefficient in units of m²/s parameters, respectively.

Table 3 Weight vectors of 5x5 nodes rounded to the nearest 4 decimal places from SOM in MATLAB

j	W _{j,1}	<i>W</i> _{<i>j</i>,2}	<i>W_{j,3}</i>	<i>W</i> _{<i>j</i>,4}	<i>W</i> _{<i>j</i>,5}	W _{j,6}
1	1	0.6667	0.6641	0.6641	1	0.8546
2	0.8947	0.6686	0.6115	0.6115	0.8947	0.8678
3	0.8000	0.6667	0.5308	0.5308	0.8000	0.8916
4	0.6909	0.6667	0.4587	0.4580	0.6909	0.8355
5	0.6000	0.6667	0.3987	0.3974	0.6000	0.8174
6	0.9744	0.7564	0.7325	0.7325	0.9744	0.8118
7	0.8000	0.8333	0.6641	0.6641	0.8000	0.8237
8	0.8000	0.7500	0.5974	0.5974	0.8000	0.8127
9	0.6000	0.6667	0.3987	0.3974	0.6000	0.4619
10	0.6000	0.6667	0.3987	0.3974	0.6000	0.6702
11	1	0.8333	0.8308	0.8308	1	0.7429
12	0.8974	0.8675	0.7754	0.7754	0.8974	0.7049
13	0.8000	0.8333	0.6641	0.6641	0.8000	0.6459
14	0.6741	0.8457	0.5666	0.5666	0.6741	0.7314
15	0.6000	0.8333	0.4974	0.4974	0.6000	0.7951
16	1	1	1	1	1	0.4399
17	0.8000	1	0.7974	0.7974	0.8000	0.6032
18	0.8000	0.8333	0.6641	0.6641	0.8000	0.5438
19	0.6000	1.0000	0.5974	0.5974	0.6000	0.6462
20	0.6000	0.8333	0.4974	0.4974	0.6000	0.6525
21	1	1	1	1	1	0.2347
22	0.9034	1.0000	0.9022	0.9022	0.9034	0.3885
23	0.8000	1	0.7974	0.7974	0.8000	0.4155
24	0.6667	1.0000	0.6641	0.6641	0.6667	0.5433
25	0.6000	1	0.5974	0.5974	0.6	0.5404

Cluster	WBR	Molarity	NaOH	Na ₂ SiO ₃	Water (ml)	Chloride Diffusion
		_	(g)	(g)		Coefficient (m ² /s)
1	0.5	10	648	324	1620	1.8170e ⁻¹¹
2	0.5	8.9697	581.0303	290.5152	1620	1.7847e ⁻¹¹
3	0.5	8.0000	518.0000	259.0000	1620	1.8673e ⁻¹¹
4	0.4548	8.0000	471.0323	235.5161	1473	1.9165e-11
5	0.4	8.0000	414	207	1296	1.9443e ⁻¹¹
6	0.5	10.0000	648	324	1620	1.5490e-11
7	0.4658	9.1053	545.3684	272.6842	1509	1.7656e ⁻¹¹
8	0.4567	8.8667	518.0000	259.0000	1479	1.8233e-11
9	0.3452	8.0000	357.5161	178.4839	1118	1.8592e ⁻¹¹
10	0.3452	8.0000	357.5161	178.4839	1118	1.8592e ⁻¹¹
11	0.5	10	648	324	1620	1.3425e ⁻¹¹
12	0.4400	10.5333	600.5333	300.2667	1425	1.5398e ⁻¹¹
13	0.4000	10.000	518.0000	259.0000	1296	1.8148e ⁻¹¹
14	0.3400	9.1000	405.3500	202.4500	1101	1.6593e ⁻¹¹
15	0.3000	8	311.0000	155.0000	972	1.7699e ⁻¹¹
16	0.5000	12	780	390	1620	9.6929e ⁻¹²
17	0.4000	12.0000	622	311	1296	1.3216e ⁻¹¹
18	0.4000	10	518	259	1296	1.3857e ⁻¹¹
19	0.3000	9.7143	377.0000	188.4286	972	1.3776e ⁻¹¹
20	0.3000	10.000	388	194	972	1.7781e ⁻¹¹
21	0.5000	12	780	390	1620	5.3012e ⁻¹²
22	0.4515	12.0000	703.3939	351.6970	1462	8.4333e ⁻¹²
23	0.4000	12	622	311	1296	9.0224e ⁻¹²
24	0.3000	12	466	233	972	1.1914e ⁻¹¹
25	0.3000	12	466	233	972	1.4555e ⁻¹¹

Table 4Predicted chloride diffusion coefficients from SOM 5 × 5 nodes

The SOM reveals suggestions on the lowest possible chloride diffusion coefficient in the formulation of geopolymer concrete. This geopolymer mix has a water/binder ratio of 0.5 coupled with a molarity of 12, as per the above SOM suggested. The optimal combination is cluster 21 (highlighted in bold), as depicted in Table 4, with the lowest chloride penetration depth and diffusion coefficient.

Verification and Validation

The cluster formula obtained from the clustering analysis underwent a 5-fold crossvalidation process to confirm its reliability and evaluate the accuracy of the suggested mixing design and activator dosage in predicting chloride permeability. Two key validation metrics were employed: the mean absolute error (MAE) and the coefficient of determination (R^2) . The MAE and R^2 results were recorded as $1.515e^{-12}$ and 0.77, respectively, demonstrating that the cluster formula effectively forecasts chloride permeability based on the recommended mixing design. These validation outcomes are still confident in the cluster formula's capacity to guide selecting the ideal mixing design and activator dosages, ensuring the desired chloride resistance in geopolymer fly ash concrete. Figure 6 illustrates these validation results.



Figure 6. Performance of the clustering formula generated from the clustering analysis

CONCLUSION

The application of SOM analysis offers a systematic and efficient method to examine a vast dataset comprising formulas and their associated diffusion coefficients. By utilizing AI technology, the analysis can unveil hidden patterns, relationships, and clusters within the data that may not be easily discernible using conventional approaches. This ability to uncover meaningful insights from complex datasets enhances the overall effectiveness and efficiency of the decision-making process.

This study demonstrates the significant advantages of utilizing AI technologies, specifically Self-Organizing Maps (SOM), for efficient data analysis and pattern recognition in material science.

1. Efficient Data Analysis: AI technologies like SOM enable swift and effective processing of large, complex, and multidimensional datasets. It allows for the identification of patterns and relationships that are difficult to detect manually.
- 2. Pattern Recognition: SOM analysis revealed that a 0.5 water/binder ratio combined with 12M NaOH consistently resulted in the lowest diffusion coefficients. This pattern recognition capability aids decision-making by highlighting the most effective factors or combinations.
- Optimization and Resource Efficiency: AI technology helps optimize formulas for desired outcomes, such as reducing diffusion coefficients. It leads to efficient use of materials, reduced costs, and minimized waste, thereby improving overall efficiency and sustainability.

By utilizing SOM in AI training, geopolymer concrete researchers and engineers can gain valuable insights into factors influencing durability, such as chloride diffusion, carbonation, and strength development. The SOM algorithm's ability to visualize and cluster data assists in comprehending the complex interactions within the material, ultimately enhancing the accuracy and effectiveness of AI models in predicting geopolymer concrete durability.

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Effects of Electron, Gamma and Neutron Irradiation on the Superconducting Properties of (Bi,Pb)₂Sr₂Ca₂Cu₃O_x Bulk Samples

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ABSTRACT

In this study, we explored the potential of irradiation techniques to optimize defect concentration and crystal structure in $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223) superconductors, aiming to enhance their practicality by potentially improving their critical temperature (T_c) in high magnetic fields. Bi-2223 superconductors have higher T_c and less stringent cooling requirements than low-temperature types, yet enhancing T_c under high magnetic fields is still challenging. The study meticulously compared the electrical properties of Bi-2223 samples in bulk form, subjected individually to electron, gamma, and neutron irradiations, prepared via the conventional solid-state reaction method. Subsequent analyses of structural properties through X-ray diffraction revealed changes in cell lattice parameters, while electrical resistance and AC susceptibility measurements provided insights into the critical temperature. Interestingly, a significant decrease in T_c was observed across all irradiated samples instead of an enhancement, challenging our initial hypothesis. Electron and gamma irradiations, which correlated with the observed decrease in T_c —22.9% for neutron, 16.7% for gamma, and

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E-mail addresses: zaahidah.atiqah@yahoo.com (Zaahidah A Mohiju) laysheng@uniten.edu.my (Lay Sheng Ewe) ras@ukm.edu.my (Roslan Abd-Shukor) w.yew@hw.ac.uk (Weng Kean Yew) hwoon@uniten.edu.my (Hai Song Woon) abi@nm.gov.my (Abi Muttaqin Jalal Bayar) *Corresponding author 13.5% for electron irradiation. These results highlight the intricate relationship between the type and distribution of defects induced by different irradiations and their varying impacts on superconductor performance. This study illustrates how defects, based on their characteristics, distinctly affect superconducting properties, emphasizing the complexity of defect interactions in superconductors. Our findings highlight the crucial relationship between irradiation-induced defects and the

ISSN: 0128-7680 e-ISSN: 2231-8526 superconducting properties of Bi-2223, suggesting that the impact of T_c reduction on high-temperature superconductor applications needs to be reevaluated.

Keywords: BSCCO-2223, energy, irradiation impact, superconducting properties

INTRODUCTION

There has been a rising interest in conduction-cooled high-temperature superconducting (HTS) magnets for research and industrial purposes, considering their advantages over the traditional low-temperature superconducting magnets requiring liquid helium (Braginski, 2019; Buckel & Kleiner, 2012; Fallah-Arani et al., 2019). This system mainly consists of three phases with the general formula Bi₂Sr₂Ca_nCu_nO2_{n+4+y} where n = 1, 2 and 3, considering the number of CuO₂ layers in the sub-unit cell, respectively. Different methods of preparation, as well as the structural and superconducting properties, have been extensively reported (Amira et al., 2011; Farbod et al., 2016; Hannachi et al., 2018; Salleh et al., 2005; Xu et al., 2010;). Notably, the Bi-2223 phase is preferable due to its highest critical temperature, T_c (~110 K), compared to Bi-2201 (~20 K) and Bi-2212 (~90 K) (Nurbaisyatul et al., 2021). Several techniques have been employed for bulk ceramic superconductor processing, including co-precipitation (Zhang et al., 2021), sol-gel process (Shen et al., 2021), freeze-drying (Jin et al., 2021), and solid-state reaction (Juárez -Lopez et al., 2020).

The solid-state reaction presents a straightforward and cost-effective method. In this study, Bi_{1.6}Pb_{0.4}Sr₂Ca₂Cu₃O₁₀ (Bi-2223) powders were produced via the solid-state reaction method. The distinctiveness of Bi-2223 lies in the added Pb, which enhances phase diffusion, accelerates reaction kinetics, creates nucleation centers, and stabilizes the Bi-2223 phase (Anis-ur-Rehman & Mubeen, 2012). In BSCCO systems, lead (Pb) significantly influences the microstructure, phase composition, and superconducting properties. The presence of Pb in the initial mixture promotes the formation of the Bi(Pb)-2223 phase. However, achieving a pure Bi(Pb)-2223 phase is nearly impossible, as it typically coexists with the Bi(Pb)-2212 phase (Nurbaisyatul et al., 2021). Furthermore, Pb promotes grain growth and improves grain connectivity, leading to an improved transport current density, J_{c} , especially at low fields with a 5 wt% Pb addition (Wang et al., 2010). Also, it induces lattice dislocations within the grains, enhancing the pinning force. It, in turn, leads to an improvement in the critical current density (J_c) (Camargo-Martínez & Baquero, 2016; Lin et al., 2016; Takahira et al., 2015). High critical temperature in superconductors plays a vital role in specific applications such as MRI machines, particle accelerators, and energyefficient technologies.

Before the discovery of high-temperature superconductors, the idea of superconducting cables existed, but the challenge of long-distance cooling with liquid helium made practical

applications difficult. The advent of high-temperature superconducting cables, cooled with liquid nitrogen, transformed these ideas into feasible solutions. Significant progress has been made in commercializing DI-BSCCO wires, leading to their use in practical applications such as current leads (Hayashi, 2020).

Artificial defects introduced by energetic particle irradiation can improve the critical current in high-temperature superconductors (HTS). Energetic particles, including light ions like protons, deuterium, helium, heavy ions, and high-energy neutrons, create displacement defects, cascades, and voids. These changes affect the vortex patterns in the superconducting material, enhancing its performance (Rajput et al., 2022). Thus, it is an efficient method to introduce pinning centers—the elastic collisions between the accelerated particles on the bulk's surface yield many defects. In the Bi-Sr-Ca-Cu-O system, the highly mobile oxygen atoms can be displaced from their ideal locations when impacted by the energy from incident neutrons. These oxygen atom movements generate numerous vacancies and interstitial oxygen atoms (Kitô et al., 2001; Zhang et al., 2007).

The ability of neutrons to penetrate the specimen bulk creates uniformly distributed defects, where the energy spectrum of the fast neutrons is broadened by scattering and resembles the high energy part of the neutron spectrum in the TRIGA MARK II research reactor, thereby enabling the irradiation of microscopic specimens for further experimentations (Fischer et al., 2018; Karkin et al., 2009). This research explores the effects of electron, gamma, and neutron irradiation on the superconducting properties and microstructure of Bi-2223 superconductor bulk samples. Also, it seeks to investigate whether irradiation can improve the superconducting properties by increasing the concentration of defects in the microstructure. However, Sakurai et al. (2024) notes that increasing the volume fraction of the amorphous regions can lead to a loss of superconducting properties, which may outweigh the benefits provided by the pinning centers.

Understanding the connection between irradiation and the material's properties is crucial for gaining valuable insights into the underlying mechanisms driving these changes. In previous research, compression tests on samples demonstrated that the mechanical properties of Bi-2212 superconductor ceramics, such as porosity, are influenced by varying doses of electron irradiation (Mohiju et al., 2015). The microstructure of irradiated samples, characterized by higher grain orientation and porosity, leads to weaker interface bonding between superconducting grains. Generally, the strength of these samples diminishes with exposure to irradiation, resulting in deformation. Despite this, the formation of point defects within the microstructure, while increasing, enhances the critical current density and transition temperature of the samples (Bi-2212) (Mohiju et al., 2017). Enhancing high-temperature superconductors (HTS) typically requires increasing the complexity of their material composition and microstructure. It is often achieved by introducing defects called artificial pinning centers (APCs). However, this method can clash with efforts to develop

mature, cost-effective mass-production technologies. Interestingly, a notable technique has shown that using dominant pinning centers can maintain the stability of current commercial production without complicating the superconductor's chemistry (Molodyk et al., 2021). In addition, a higher critical current density indicates better flux pinning properties in the sample with additional metal compounds. Studying Bi-2223 can uncover its mysteries, boost its performance, and better understand how superconductors work.

METHODOLOGY

Samples Fabrication

The Bi-2223 superconductor samples were prepared using the conventional solid-state reaction technique. The desired compound, $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$, necessitated precise proportions of Bi_2O_3 , PbO, SrCO₃, CaCO₃, and CuO with purity of 99%. The first stage requires mixing Bi_2O_3 , PbO, SrCO₃, CaCO₃, and CuO powders in the proportions needed for the desired composition. The powders were ground, mixed and then heated in a tube furnace at 810°C for 30 h. This step helped to catalyze the formation of the Bi-2223 phase.

The resultant powders, predominantly Bi-2223 phase, were compacted under a pressure of 7 tonnes to form pellets, each measuring 13 mm in diameter and 3 mm in thickness. Replicating the conditions of the original heat treatment, the bulk samples were heated at 850 °C for 48 h. The samples were cooled in the furnace down to room temperature in a controlled manner, enabling the material to solidify and maintain favorable properties. The bulk Bi-2223 samples, including structural, electrical resistance and AC susceptibility, were characterized to evaluate their superconducting attributes and performance.

Irradiation Procedure

The electron irradiation process involved using a 3 MeV beam with a current rating of 10 mA. This procedure was executed utilizing the EPS-3000 electron-beam accelerator. The gamma irradiation was performed at the SINAGAMA Irradiation Plant. This plant employs ionizing energy derived from gamma radiation from a cobalt-60 source. The irradiation operations were performed at the Nuclear Malaysia Agency in Bangi, Selangor, Malaysia. The Bi-2223 superconductor bulk samples were subjected to a cumulative dose of 100 kGray in both the electron and gamma irradiation procedures under an open-air environment. Neutron irradiation was carried out with the aid of the PUSPATI TRIGA MARK II research reactor at the Nuclear Malaysia Agency.

Before irradiation, all the necessary procedures were made, including constructing an aluminum holder for the samples and applying protective coverings using aluminum sheets and boron carbide powder. Forecasts were made to predict the activation of elements after the irradiation process. A neutron flux of 2.0×10^{11} neutrons/(cm²·s) was employed throughout the irradiation, and the samples underwent a 6-hour exposure. As a result, a total fluence of 4.32×10^{15} neutrons/cm² was imparted to the samples, effectively triggering the intended irradiation effects. The introduced defects improve flux pinning at low neutron fluences, increasing the critical currents. However, at a certain defect density, the critical current reaches its maximum and I_c declines upon further irradiation. The ability to engineer a product with a pinning microstructure will face arguments such as the doses or level of exposure that produced the most efficient results, which means the critical current reaches its maximum for different magnetic fields and temperatures. According to Koshelev et al. (2016) the ultimate critical-current optimization can be achieved by the constructive combination of different pinning centers; a natural first step is to determine the best pinning configuration for a relatively simple system with only one type of defects (Koshelev et al., 2016).

As stated in the introduction part, where grain growth helps to improve grain connectivity, Aksenova et al. (1995) also stated that under small doses, there is an increase of weak links on grain boundaries caused both by diffusion of atmosphere oxygen to the grain boundaries and the reaction, improving the conducting properties of the intergranular layers. At high doses of gamma irradiation, the intensive degradation of the ceramic surface layer occurs, caused by interaction with air and subsequent changing of phase composition (Aksenova et al., 1995).

Sample Characterization

A D8 Advanced X-Ray Diffractometer (XRD) has been used to determine all samples' phase and structural parameters. Scanning electron microscopy (SEM) provides detailed information that aids in examining the samples' microstructure. This research used the SEM to gather information regarding external morphology (texture), crystalline structure, and grain orientation. The microstructural analysis was conducted using the Hitachi SU8600 Ultra-High-Resolution scanning electron microscope.

The four-point probing technique was utilized to ascertain electrical resistance, with silver paste as the medium for establishing electrical connections. The experimental arrangement comprised a Keithley 197 Multimeter and a Keithley 220 Current Source. A CTI Cryogenics closed-cycle refrigerator Model 22 and a Lake Shore Cryotronics Model 325 temperature controller were employed to assess electrical resistance with respect to temperature. The constant current used was between 1 mA and 100 mA.

AC susceptibility measurements were carried out to identify the temperature of susceptibility transition, denoted as $T_{\chi'}$. The AC susceptibility (represented as $\chi = \chi' + i\chi$ ") was deduced using a susceptometer with the model number REF-1808-ACS manufactured by Cryo Industry. The critical current density at the temperature corresponding to the peak

of χ " (designated as T_P) was computed using the formula $J_c(T_P) = H_a/(l_w)^{1/2}$ where *l* and *w* stand for the dimensions of the cross-section of the bar-shaped samples.

RESULTS AND DISCUSSION

X-Ray Diffraction

The XRD patterns in Figure 1 show that all the samples display an orthorhombic crystal structure. Post irradiation, slight variations became apparent in the diffraction angles. The patterns pre- and post-irradiation showed changes in peak locations and intensities. These findings demonstrate alterations in the lattice parameter and confirm a reduction in grain size after irradiation. The irradiated samples exhibit significant distortions in the crystal lattice, particularly noticeable in the Bi-O block, which acts as a charge reservoir. Supporting SEM micrographs offer a more distinct visual representation of the diminished grain size induced by irradiation. Collectively, these results signified that irradiation prompts structural modifications in the material, culminating in changes in peak positions, peak intensities, and grain size. By using the Miller indices formula for an orthorhombic crystal structure, $1/d^2 = h^2/a^2 + k^2/b^2 + l^2/c^2$, where h, k and l are numbers from lattice plane, and d is the distance of spacing value obtained from XRD data, the lattice parameters can be calculated. The lattice parameter is related to the atomic radius of the sample's composition (Wang et al., 2007). The investigation centers on the correlation between minor shifts in parameter values within irradiated samples and the structural distortions that result from the interaction between accelerated particles and the samples during irradiation.

The lattice parameters and volume for all samples, including non-irradiated and irradiated samples exposed to different types of radiation (electron, gamma, and neutron). The lattice parameters and unit cell volume are listed for each sample, which remains orthorhombic after irradiation (Table 1). The non-irradiated sample exhibited lattice parameters of a = 5.389 Å, b = 5.398 Å, and c = 37.643 Å, and volume 1095.03 Å³. Upon electron irradiation, slight changes were observed in the lattice parameters (a = 5.408 Å, b = 5.413 Å, c = 37.015 Å), leading to a reduced volume of 1083.56 Å³. Similarly, the neutron-irradiated sample showed minor alterations in lattice parameters (a = 5.327 Å, b =5.303 Å, c = 38.391 Å) with a volume of 1084.51 Å³. Interestingly, the gamma-irradiated sample shows more significant changes in lattice parameters (a= 5.823 Å, b = 5.271 Å, c= 38.629 Å), resulting in a larger volume of 1185.64 Å³ compared to both non-irradiated and electron-irradiated samples. The gamma-irradiated sample exhibits more pronounced changes in the lattice parameters compared to electron and neutron irradiation due to the distinct characteristics of gamma radiation. Gamma radiation, high-energy electromagnetic radiation, possesses greater penetration abilities, allowing it to interact deeply with the atoms within the crystal lattice. It led to a higher probability of inducing structural modifications and, therefore, more substantial effects on the material's lattice parameters.

Gamma radiation's higher energy and penetration capabilities facilitate more profound interactions with the material's crystal lattice, causing atomic displacements, defect formations, radiation-induced stress and phase transitions. The phase transition appears to result from a double-hit process: initially, an ion impact creates oxygen defects; subsequently, a second ion hitting the already damaged impact zone triggers a crystalline-to-crystalline phase transition. However, the X-ray diffraction (XRD) patterns show no evidence of such a phase transition in this research. The consistent peak positions across all samples indicate that the orthorhombic structure is retained despite different types of irradiations. Variations in peak intensities suggest changes in the crystalline phase formation within the orthorhombic phase, which may be attributed to factors such as phase purity, preferred orientation, or the degree of crystal planes rather than a transition to a new phase. In contrast, electron irradiation has noteworthy penetration depths and induced direct interactions with the atoms in the lattice, resulting in significant changes compared to non-irradiated samples.



Figure 1. XRD for BSCCO-2223 for non-irradiated and irradiated samples

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Sample	<i>T</i> _c /K	T_p/K	T_p reduction	Lattice Parameter			Volume
				a/Å	b/Å	c/Å	V/\AA^3
Non-irradiated	125	96	-	5.389	5.398	37.643	1095.03
Electron-irradiated	110	83	13.5 %	5.408	5.413	37.015	1083.56
Gamma-irradiated	88	80	16.7 %	5.823	5.271	38.629	1185.64
Neutron-irradiated	100	74	22.9 %	5.327	5.303	38.391	1084.51

Table 1 Critical temperature, T_c , peak temperature, T_p , and lattice parameters for all samples

In our study of the XRD patterns for BSCCO-2223, we compared the peaks with those identified by the previous researcher, Fallah-Arani et al. (2019). We discovered several unidentified peaks at specific angles in all samples, particularly those exposed to electron, gamma, and neutron irradiation. These unidentified peaks suggest the possible development of new secondary phases within the BSCCO-2223 structure.

Furthermore, the XRD patterns for non-irradiated, electron-irradiated, gamma-irradiated and neutron-irradiated samples show significant differences in peak intensities at various angles (2θ) due to the distinct effects of each irradiation type on the crystalline structure. Gamma-irradiated samples exhibit higher intensities for the 008 and 0012 planes, likely due to reorientation or redistribution of crystalline planes and induced defects. Neutron-irradiated samples show intense peaks at the 0012 and 1111 planes as neutron irradiation penetrates deeper, causing displacement damage and strain within the lattice. Both types of irradiations introduce defects, alter crystallite size, and induce strain, affecting peak intensities. Despite the visible changes in crystallite size, the crystallite structure can remain the same. Non-irradiated samples show baseline intensities, reflecting the original structure, while electron-irradiated samples exhibit moderate changes, indicating less penetration.

Electrical Resistance and AC Susceptibility

Figures 2(a)–(d) illustrate non-irradiated and irradiated samples' electrical resistance versus temperature profiles. Each graph is marked with the respective critical temperature (T_c). In the case of the non-irradiated bulk sample, T_c was 125 K. Interestingly, the irradiated samples exhibit a gradual reduction in T_c , with values of 110 K, 100 K, and 88 K for electron, neutron, and gamma irradiation, respectively. This decline in critical temperature is a noteworthy observation. The neutron-irradiated sample exhibits the most significant alterations in T_c compared to the electron-irradiated and gamma-irradiated samples, as shown in Table 1.

Figure 3 displays the AC susceptibility $(\chi = \chi' + i\chi'')$ measurements for both irradiated and non-irradiated samples. In these measurements, a noticeable shift or peak in the graph emerges precisely at the critical temperature, marking the transition from the ordinary state to the superconducting state. The graph comprises two distinct segments: the real part χ' , which signifies diamagnetic behavior, and the imaginary part χ ", illustrating the efficacy of the flux pinning centers and the interconnection among grains. The peak observed in χ " graph, is denoted as T_p . By examining the χ " graph, we can deduce AC losses by comparing the values of these two peaks. The higher temperature peak represents intrinsic losses and reveals the intragranular current density (J_c -intra). The applied magnetic field influences the positions of both loss peaks in χ ".

Our experimental setup utilized a low magnetic field, which prevented the $H_{\rm ac}$ (alternating field) from piercing the grains. Consequently, a higher temperature peak was absent. However, the magnetic field was sufficient to penetrate within the grains and reveal the intergranular loss peak ($T_{\rm p}$). By maintaining an applied magnetic field (5 Oe), the strength of flux pinning was assessed by analyzing the degree of shifting and the width of the intergranular loss peak.

The AC susceptibility measurements were crucial in understanding the samples' superconducting behavior. The values of χ' and χ'' were analyzed to determine various aspects, including transition temperatures, intrinsic and coupling losses, and the strength of flux pinning based on the shifting and width of the intergranular loss peak.



Figure 2. Electrical Resistance *vs* Temperature for (a) non-irradiated bulk sample. (b) Gamma-irradiated bulk sample. (c) Electron-irradiated bulk sample and (d) Neutron-irradiated bulk sample



Figure 3. AC susceptibility of Bi-2223 for (a) non-irradiated sample, (b) electron-irradiated sample, (c) gamma-irradiated sample, (d) neutron-irradiated sample

Table 1 displays the critical temperature (T_c) and peak temperature (T_p) values for Bi-2223 superconductor bulk samples exposed to different irradiation conditions. In the non-irradiated sample, T_c registers at 112 K, while T_p , marking the onset of irreversibility in superconducting behavior, appears at 96 K. The shift in T_c for electrical resistance and T_p for AC susceptibility measurements is primarily due to the concentration of defects created by the irradiation. At the same time, $T_{c-onset}$ and $T_{c-offset}$ represent different stages of the superconducting transition, with $T_{c-onset}$ indicating the initial formation of superconducting regions and $T_{c-offset}$ signifying the complete transition to the superconducting state. Electron irradiation reduces T_c to 110 K and significantly lowers T_p to 83 K, marking a 13.5% decrease compared to the non-irradiated sample, showing defect introduction disrupting superconducting behavior. Similarly, gamma irradiation decreases T_c (to 88 K) and T_p (to 80 K), resulting in a 16.7% reduction compared to the non-irradiated sample, indicating defect-induced impact on superconducting properties. Neutron irradiation lowers T_c to 100 K, with T_p dropping notably to 74 K, representing a 22.9% decrease compared to the non-irradiated sample, highlighting neutron irradiation's substantial disruption of superconducting behavior. The differences in the initial and complete superconducting transition temperatures (Tc-onset and Tc-offset) across the samples can be explained by the varying energy levels of the irradiation sources. Higher-energy irradiations, like neutron irradiation, create larger defects that disrupt the superconducting state more extensively. It leads to a broader range of superconducting transitions, affecting various material parts. In contrast, lower-energy irradiation, such as electron irradiation, generates smaller defects that cause more consistent superconducting transitions across the material. This variation in irradiation energy affects how defects are introduced, which influences both the beginning and the end of the superconducting transition, explaining the differences seen in $T_{c-onfiset}$.

The reduction in T_c and T_p observed after irradiation indicates that defects introduced by irradiation act as pinning centers for magnetic flux lines, which can enhance the material's ability to carry superconducting currents. This phenomenon is desirable in many practical applications requiring high critical currents and magnetic field tolerances. Therefore, while irradiation may lower the absolute critical temperature, it can simultaneously improve the material's performance under certain conditions, making it more suitable for practical use in specific applications.

Scanning Electron Microscopy (SEM) Micrographs

The samples' micrographs provide further insights into the underlying mechanisms (Figures 4 to 8). The observations indicate changes in both the grain size and the grain orientation.



Figure 4. The grain size of non-irradiated Bi-2223

The micrographs showed a non-uniform phase distribution on the samples' surface. Some areas exhibit a layered structure, characteristic of the crystal structure of the Bi-2223 system. The samples also display a porous nature with grain sizes between 1.35 μ m and 1.69 μ m.

The presence of plate-like grains, typical of Bi-based high-temperature superconductors, was observed in the samples. The lamellar structure, associated with high critical temperature superconductors, can be seen in many grains. However, following irradiation, the grain size slightly decreased, and porosity increased (Figures 5 to 8). The grains exhibited a random distribution, indicating anisotropic grain orientation and poor interconnection between the grains. The Hall-Petch relation also expressed the influence of the grain size on mechanical properties such as ductile-brittle transition and tensile and hardness of polycrystalline materials (Armstrong, 1970; Hansen, 2004). Additionally, as the particles crystallize and bond together, the cavities between the particle grains become more numerous because the sintering process involves the elimination of porosity and the densification of the material. As the particles bond, the material becomes more compact, reducing the overall volume and increasing the density. This reduction in volume can create additional space (black regions) between the particle grains, resulting in cavities or voids (Imaduddin et al., 2023).



Figure 5. Microstructure of non-irradiated Bi-2223. The black regions circled in red represent randomly distributed grains within the matrix structure, indicating a weaker linkage between the grains

In Figures 5 to 8, the black regions circled in red represent randomly distributed grains within the matrix structure, indicating a weaker linkage between the grains. It is expected that after irradiation, the Bi-2223 compound will exhibit a higher density of grain boundaries due to the increased concentration of defects caused by accelerated particles. As particles crystallize and bond during sintering, the material becomes denser as air pockets are removed and the particles are compacted. This densification reduces the overall volume

of the material, minimizing the spaces or voids between the particle grains. This reduction in volume can create extra space (appearing as black regions) between the grains, forming cavities or voids. Similar in size to coherence length, these defects act as pinning centers due to their distribution and link to local variations in critical temperature. This arrangement boosts the creation of effective pinning centers while slightly decreasing the average size of the Bi-2223 crystallites (Al-Khawaja, 2006). This enhanced the formation of effective pinning centers while slightly reducing the average size of the Bi-2223 crystallites.



Figure 6. Microstructure of electron-irradiated Bi-2223. The black regions circled in red represent randomly distributed grains within the matrix structure, indicating a weaker linkage between the grains



Figure 7. Microstructure of gamma-irradiated Bi-2223. The black regions circled in red represent randomly distributed grains within the matrix structure, indicating a weaker linkage between the grains



Figure 8. Microstructure of neutron-irradiated Bi-2223. The black regions circled in red represent randomly distributed grains within the matrix structure, indicating a weaker linkage between the grains

The micrographs showed that the non-irradiated samples have the densest layering structure. This robust layering signals a well-organized and densely packed distribution of grains within the non-irradiated sample. In contrast, the samples subjected to electron irradiation reveal a slightly less dense layering structure than the non-irradiated counterpart. It suggests that electron irradiation triggered minor alterations in the grain configuration, leading to a slight disarrangement in the dense layering, which is evident in the non-irradiated sample. On the other hand, the sample exposed to gamma irradiation exhibits a more significant reduction in the layered structure's density compared to both non-irradiated and electron-irradiated samples.

This finding suggests that gamma irradiation has a more potent effect on the layered structure, resulting in a larger degree of disruption and a less compact arrangement of grains. The sample exposed to neutron irradiation displays the least dense layered structure among all the samples. Neutron irradiation seems to exert the most pronounced impact on the layered microstructure, culminating in a more spread-out and less orderly grain arrangement. The Figures 5 to 8 distinctly illustrate a trend concerning the layering structure's density across the samples. The non-irradiated sample manifests the highest density, followed by the electron-irradiated, gamma-irradiated, and ultimately the neutron-irradiated sample.

CONCLUSION

This study reveals that electrons, gamma, and neutron irradiations reduce the critical temperature (T_c) and peak temperature (T_p) of Bi-2223 superconductors. Among these, neutron irradiation causes the most significant decrease in T_p by 22.9%, highlighting its

effectiveness in introducing microstructural defects. These defects serve as pinning centers, disrupting superconducting capabilities more than other irradiation types. Consequently, neutron irradiation is identified as the most impactful method for modifying Bi-2223's superconducting properties.

However, the choice of irradiation technique should be tailored to specific application needs, as neutron irradiation's aggressive effects might not always be desirable. Future research should optimize the balance between defect introduction and superconducting performance, particularly under high magnetic fields. Rigorous statistical analysis is essential to validate the irradiation effects and ensure that superconductor development is based on reliable data. This approach will help modify superconductor properties for specific applications, advancing the field of superconductivity.

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Synthesis and Assessment of Metal-Organic Frameworks (MOFs) Adsorbents for CO₂ Capture: A Comparative Work of the CO₂ Adsorption Capability of Mono- and Bimetal-based MOFs Adsorbents

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ABSTRACT

Adsorption utilising porous solid adsorbent has been considered a feasible option for conventional CO₂ absorption over the past few decades. As a preliminary investigation towards obtaining Metal-Organic Frameworks (MOFs) adsorbent for CO₂ capture, the CO₂ adsorption efficiency using mono- and bimetal-based MOFs was assessed in this study. Among the numerous MOFs, Mg-MOF-74 exhibits the best CO₂ uptake at low pressures because of its open metal sites. A strategy to incorporate Zn in Mg-based MOF as a co-metal node is required to enhance the CO₂ adsorption performance of solid adsorbent. Selecting Zn as a metal node in MOF synthesis allows for the creation of stable, versatile, and functional materials for CO₂ adsorption. Therefore, combining several metals in a structure to develop a new MOF with an improved gas uptake is quite a useful approach to further harness the immense potential of MOFs. This study aims to compare the performance of mono- and bimetallic-MOFs and select the most suitable adsorbent for CO_2 capture. The performance of CO_2 adsorption was conducted using three parameters: the effect of metal loading on MOFs, pressure (1-5 bar) and adsorbent dosage (0.2-0.5g). Based on the characterisation findings, the studies confirm the formation of Mg-MOF-74, Zn-MOF and 50wt.%Zn/50wt.%Mg-MOF. Overall, it was found that the bimetal adsorbent with 50 wt.%Zn/50wt.%Mg-MOF displayed the highest CO2 adsorption capacity (323 mg_{CO2}/g_{adsorbent})

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E-mail addresses: khonisah@umpsa.edu.my (Nor Khonisah Daud) nurulhudainsyirah98@gmail.com (Nurul Huda Insyirah Muhammad Najib) *Corresponding author when compared to the monometallic MOFs (Zn-MOF ($134mg_{CO2}/g_{adsorbent}$) and Mg-MOF-74) ($122 mg_{CO2}/g_{adsorbent}$) indicating a 50% increase in adsorption capacity over monometallic MOFs.

Keywords: Bimetal-based MOFs, CO₂ adsorption, metal-organic frameworks, mono-based MOFs, solid adsorbent

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INTRODUCTION

Solid adsorption has been identified as one of the most capable technologies for collecting or storing gas because of its low energy usage, importance to the environment and outstanding recyclability (Wang et al., 2016). The major driver in employing adsorption technology is to meticulously manufacture the appropriate permeable adsorbents. Of the under-studied adsorbents, comprising zeolites (Bao et al., 2011; Yang et al., 2013), porous carbons, Covalent-Organic Frameworks (COFs) (Li et al., 2015; Wang et al., 2014) and Hyper Cross-linking Polymers (HCPs) (Cui et al., 2017; Saha et al., 2017), Metal-Organic Frameworks (MOFs) are distinguished by their great surface area, modifiable pore size, and tuneable surface feature. With their nanoscopic pores and exceptionally superior surface areas, MOFs are outstanding substances for gas capture and storage. MOFs possess wellordered and characterised permeable configurations and amendable chemical functionality that can be altered based on our requirements. Using various metal clusters and organic ligands, or both can also enhance the CO₂ selectivity of MOFs. An attentive selection of organic ligands and multi-metal units known as Secondary Building Units (SBUs) permit the assembly of MOF with the required properties and structural classes (Xin et al., 2011). Taking into account the capacity and usefulness of the carboxylate group, which illuminates strong co-ordination links and generates abundant structural patterns, organic multi-carboxylate ligands in various shapes, sizes, and rigidity/flexibility have been utilised to develop MOFs with diverse dimensions and varied topologies (Sumida et al., 2012). MOFs have been extensively examined for their ability to store and separate H_2 , CH_4 , CO_2 , and hydrocarbons (Barea et al., 2014).

The combination of metal nodes in the framework of MOFs also enormously increases CO₂ adsorption by tuning and optimising the adsorptive properties and enhancing the electrostatic potential of the material. Of the known metal nodes, Mg and Zn are intensively investigated for CO₂ adsorption. It is mostly owing to the existence of open metal centres allowing themselves to be possible CO₂ adsorbents (Yu et al., 2012) and a thermally and chemically unchanging structure with extraordinary porosity (for example, huge volume of pores and surface area) which can be utilised as an appealing hosting material for pcomplexation adsorbents (Kim et al., 2018; Vo et al., 2019). Yazaydin et al. (2009) examined M-MOF-74 (M = Ni, Zn, Co, and Mg)'s capacity to adsorb CO_2 through simulation and experimental practices at 1 atm and 25°C and Mg-MOF-74 showed the highest adsorption rate of CO₂, with a maximum of 8 mmol·g⁻¹. According to Bao et al. (2011), Mg-MOF-74 has a CO₂ intake much higher than zeolite 13X, reaching 8.61 mmol·g⁻¹. According to Tapiador et al. (2022), Zn-URJC-8 is a novel Zn-based MOF material that exhibits promising results in CO₂ conversion in added-value products. According to Zou et al. (2016), Zn-MOF showed an excellent ability to adsorb tiny molecular gases (CH₄, C₂H₆, and C₃H₈) and a remarkable ability to separate CO₂/CH₄, C₂H₆/CH₄, and C₃H₈/CH₄. At

273 K under 1 atm, this adsorbent can adsorb CO_2 at a rate of 92.1 cm³.g⁻¹. Recent studies have concentrated on improving adsorbents and developing efficient processes to ensure profitable capture performance. Capturing and separating CO_2 from a large volume of flue gas is always costly and energy-intensive; consequently, more effective adsorbents need to be developed in relatively concentrated streams. The performance of adsorbents currently available for CO_2 capture technologies requires improvement in terms of adsorption capability, lifespan and multi-cycle sustainability. New high-efficiency adsorbents need to be developed to capture CO_2 in technologically efficient systems. Based on Mg-MOF-74 and Zn-MOF's excellent CO_2 adsorption capability, a bimetallic approach was proposed to enhance its CO_2 adsorption capability.

In bimetallic MOFs, two inorganic metallic nodes integrate two monometal MOFs. Bimetal MOFs significantly outperform their respective monometallic MOFs (Xie et al., 2020; Zhu et al., 2016) by using one-pot syntheses to produce them, which involve mixing various metals with appropriate ligands and linkers or by implementing postsynthetic changes by dipping a monometal MOF into a concentrated solution of a diverse (but compatible) metallic ion. These bi-metal MOFs have synergic effects and enhanced properties over their monumental counterparts, such as better adsorptive selectivity, selective catalysation and structural stability. Whereas Mg-MOF-74 bimetal is used extensively in thermocatalysis (Gao et al., 2021; Zurrer et al., 2021), its use in CO₂ adsorption is limited. Zhang et al. (2022) reported on mercury removal using bimetallic iron-copper-based Metal-Organic Frameworks (Fe-Cu-MOFs). The analysis of adsorption kinetics indicates that Fe-Cu-MOFs have a mercury equilibrium adsorption capability of 12.27 mg.g⁻¹. Kaur et al. (2016) presented the findings of the formulation of Co-Zn–ZIF-8 bimetal adsorbents. The incorporation of Co²⁺ resulted in a 33% increase in pore volume and a 40% increase in surface area through their work. Co-Zn-ZIF-8 bimetal adsorbents also exhibited increased CO₂ adsorption under environmental conditions. These findings confirmed the advantages of synthesising bi-Metal Organic Frameworks for the development of MOF applications. Ling et al. (2022) stated that MgxCu_{1-x}-MOF-74's CO₂ adsorption capability was exceptional when prepared at 398 K and for 24 hours in the dimethyl-formamide (DMF)-EtOH-MeOH mixture's solvents. The CO_2 sorption of $Mg_{0.4}Cu_{0.6}$ -MOF-74 increased the most when exposed to an Xe lamp for 24 hours, reaching 3.52 mmol.g⁻¹. It surpassed that of Mg- and Cu-MOF-74 by 1.18 and 2.09 times, respectively. The interaction between Mg and Cu metals resulted in a stronger photostability of Mg_xCu_{1-x}-MOF-74 for CO₂ uptake and a wider range of photocatalytic applications. The "bimetal" approach has significant potential for usage in MOFs and provides an achievable adsorbent design method with outstanding CO₂ adsorption capability.

Within this context, this work presents the findings of a comparative study of the CO_2 adsorption efficiency of mono- and bimetal-based MOF adsorbents in the post-

combustion process to understand the CO_2 adsorption performance of MOFs when employed as solid adsorbents for the purpose of capturing CO_2 . The results documented in this study could help optimise the CO_2 adsorption capability of MOF for CO_2 capture.

METHODOLOGY

Materials

The selected adsorbents were synthesised using magnesium nitrate hexahydrate Mg $(NO_3)_2 \cdot 6H_2O$, 2,5-dihydroxyterephthalic acid, Dimethylformamide (DMF), ethanol, methanol, Zn $(NO_3)_2 \cdot 6H_2O$, CO₂ and deionised water. The chemicals were procured from Capital Eng. Resource Sdn Bhd was used directly in the experiments without additional purification.

Formulation of Adsorbents

Formulation of Mg-MOF-74, Zn-MOF and Mg/Zn-MOF

The Mg-MOF-74 adsorbent was produced employing the impregnation approach by dissolving 2,5-dihydroxyterephthalic acid into 12 mL of ethanol at an ambient condition. Subsequently, 0.795 g of magnesium nitrate hexahydrate in 12 mL of water was added into the synthesised mixture to develop Mg-MOF-74, followed by continuously stirring and drying to 120°C overnight. The powder was calculated in a furnace at 200°C for 1 hour. This method was repeated by changing 0.795 g of Zn (NO₃)₂·6H₂O to 12 mL of water as the metal group for MOF.

In the case of bimetallic adsorbent, the specific amounts of magnesium nitrate hexahydrate and Zn $(NO_3)_2 \cdot 6H_2O$ (15–85 wt.% of metal ions in MOF) were dissolved in a beaker containing 12 mL of deionised water. Then, 2,5-dihydroxyterephthalic acid in 12 mL of ethanol was mixed into this aqueous mixture and was stirred constantly on the hot plate until the mixture mixed well. After impregnation, the samples were dried at 120°C for 12 hours before being calcined at 200°C for one hour in a muffle furnace.

Structural Characterisations

Information on powdered XRD from different adsorbents was gathered by Geigerflex (Rigaku, Inc) diffractometer employing Cu K α radiation (0.154 nm) with scanning between 5.00 and 40.00 (2h) (variables: voltage (45 kV), current (35 mA), step size (0.020), and 1.2 min⁻¹). SEM pictures were acquired by means of a Hitachi S-2600 N scanning electron microscopy. The EDX analyses were done using the same instrument and parameter as the SEM at two different locations using the images obtained from SEM analyses. A Bruker Vector 22 FTIR spectrometer was employed to collect FTIR spectra within the frequency limit of 4000-500 cm⁻¹. N₂ adsorption/desorption isotherms were achieved at 77 K on a

Coulter CX-300 adsorption device. The specimen was degassed at 105°C for 24 hours by means of a high vacuum line before N₂ adsorption. The BET surface area was defined in the P/P_0 limit from 0.02 to 0.25 since the pores were occupied at extremely low relative pressure.

Gas Sorption Measurements

As shown in Figure 1, a cylindrical metal vessel was used as a device to perform the gas sorption process. This device was connected to the flow lines of CO_2 and N_2 tanks. Before the adsorption process started, N_2 gas was flowing to purge out all the impure components in the device. After the purging, the CO_2 valve was opened and led to fill in the device. The concentration of pure CO_2 gas was collected first without adsorbents in the device to attain the concentration of pure CO_2 . Before setting the operating temperature and pressure, the device was loaded with the required amount of adsorbent. After the adsorbent was loaded into the device, CO_2 flowed and achieved the required pressure, and the CO_2 adsorption process took place.



Figure 1. A schematic diagram of the CO2 adsorption test set-up

The exit gas was collected using a gas sampling bag to determine the total CO_2 adsorbed onto the adsorbent during a specific time interval, and the concentration was identified using Agilent 6890 FID gas chromatography. The amount of CO_2 sorbed over a given timespan was determined using Equation 1:

$$q_t = \frac{(C_o - C_t)V}{m}$$
[1]

where q_t , *C*, *V* and *m* are the quantity of CO₂ sorbed per dosage of adsorbent (mg.g⁻¹), CO₂ concentration, volume of the device (L) and dosage of the adsorbent (g), respectively.

The subscripts o and t indicate the conditions at the initial and CO₂ concentrations at interval time.

Effect of Pressure

 CO_2 adsorption was run at 0.2 g of adsorbent amount, ambient temperature, and 50 wt.% Mg/50 wt.% Zn-MOF of metal loadings to study the influence of adsorption pressure (1–5 bar).

Effect of Amount of Adsorbent

The study examined the effect of the amount of adsorbent on CO_2 uptake by varying the amount used (0.2, 0.3, 0.4 and 0.5 g) while maintaining pressure, temperature, and metal loading on MOF constant at 5 bar, ambient temperature and 50 wt.% Mg/50 wt.% Zn-MOF, respectively. The CO_2 adsorption was run in the reactor and analysed periodically.

Effect of Metal Ions Loading on MOF Adsorbent

The CO₂ adsorption process involved studying the impact of metal ion loading on the MOF. Different metal ion loadings (15–85 wt.%) for Mg and Zn were added along with CO₂ gas. The experiment's parameters were maintained at the optimum level of adsorbent dosage and pressure.

RESULTS AND DISCUSSION

Characterisation of the Prepared Adsorbents

Crystallographic Structure and Chemical Composition Analysis

Apart from the particles' specific surface area, the crystallinity of particles plays a role in CO₂ adsorption. Understanding the crystallinity of a material through crystallographic structure analysis provides valuable insights into its structural properties, which in turn affect its adsorption behaviour (Lee et al., 2012). Figure 2 indicates that the diffraction profile of Mg-MOF-74 was well aligned with the work described in the previous study (Campbell & Tokay, 2017). The blue line showed characteristic peaks at 15.60° (101) and 20.30° (202), confirming the formation of Mg-MOF-74. The existence of these distinctive bands, together with the presence of magnesium nitrate hydrate in the adsorbent, indicate that Mg-MOF-74 has been successfully formulated. The XRD pattern agreed with the Powder Diffraction Files (PDFs) (Reference No. 00-001-0349). Additionally, the crystalline structure of Mg-MOF-74 is confirmed by the sharp bands in this pattern. Crystalline structure tends to be more stable thermally and chemically, which can be advantageous in adsorption processes that involve harsh conditions. This crystalline material might have specific, high-energy sites that can strongly bind adsorbates (Lee et al., 2012). The main peaks of the diffraction scheme for Zn-MOF (orange line) were obtained at 2 θ values of around 11.05° (022), 13.58° (001), 16.70° (013), 19.10° (111), 25.40° (002), 28.90° (100) and 30.40° (044) that correspond to simulated XRD patterns, proving that the structure complies with the studies that have been reported (Bagheri et al., 2018; Li, 2021). Based on Figure 2, high-intensity peaks were indicating the crystallinity of Zn-MOF. The phase identification of the sample shows zinc nitrate hydroxide was identified as the main phase in Zn-MOF (PDF reference No. 04-014-0671).

The XRD patterns of 50 wt.% Mg/50 wt.% Zn-MOF (grey line) were well in line with those of Mg- or Zn-MOF. 50 wt.% Mg/50 wt.% Zn-MOF exhibited significant diffraction bands at $2\theta = 13.30^{\circ}$ (100), 20.55° (202), 21.90° (100), 25.52° (012), 27.60° (002), 33.10° (101) and 36.60° (012), which match those of the reported MOF-74 (Kahr et al., 2013; Tan et al., 2014). The phase identification of the sample 50 wt.% Mg/50 wt.% Zn-MOF shows a combination of more than one phase, with main phases of magnesium nitrate hydrate (PDF reference No. 00-001-0349) and zinc nitrate hydroxide (PDF reference No. 04-014-0671) developing from the co-ordination reaction of Mg, Zn, and DMF (Li et al., 2021). The replacement of Mg by Zn has no impact on the crystalline structure of Mg-MOF-74 or Zn-MOF, and 50 wt.% Mg/50 wt.% Zn-MOF is successfully synthesised.



Figure 2. XRD patterns of Mg-MOF-74, Zn-MOF and 50 wt.% Zn/50 wt.% Mg-MOF

Surface Functional Group Analysis

This analysis was carried out to discover the surface functional groups of single and bimetallic adsorbents, as shown in Figure 3 and Table 1. All vibrations can be separated into two distinct zones based on the MOF's co-ordination characteristics (Abooali et al.,

2020; Romero-Muñiz et al., 2020). The characteristic vibrations over the 700 cm⁻¹ zone are organic ligands, and regions under 700 cm⁻¹ have their place primarily in the metallic centres of Mg and Zn (Abooali et al., 2020)-the findings of Mg-MOF-74 (blue line), Zn-MOF (orange line) and 50 wt.% Mg/50 wt.% Zn-MOF (grey line) show a significant peak at 3369.19, 3233.49, 3483.57, 3346.10 and 3241.15 cm⁻¹ which are attributable to the hydroxyl group of H-bonded OH broad stretching. Moreover, the absorption bands at 2411.19, 2364.30, 2360.82, 2193.70, 2123.58, 2191.64, 2161.60, 2113.03, 2081.92, 2007.90, 1994.76, 1988.95, 1944.88, 1963.16, 1779.05, 1647.56, 1646.90, 1624.93, 1577.57 and 1550.32 cm⁻¹ appeared in the Mg-MOF-74, Zn-MOF and bimetal 50 wt.% Mg/50 wt.% Zn-MOF were ascribed to the vibration modes in the nitrile bond C≡N, O-H stretching vibrations caused by the intermolecular hydrogen bond of polymer compounds such as alcohols, phenols and carboxylic acid as well as aromatic C=C in-plane deformations peaks. A nitrile functional group $C \equiv N$ is derived from DMF solvent (Heravi et al., 2018). A number of sharp and clear absorption bands were detected at 1491.85, 1375.52, 1341.25, 1311.79, 1051.71, 1038.78, 1024.28, 1011.22, 819.05, 818.58, 804.31, 803.29 and 730.07 cm^{-1} , that were assigned to v(-C=O), v(-COO-), and v(C-H) of benzene rings (Abooali et al., 2020; Gao et al., 2021). Carboxylic functional groups found in adsorbents contribute to the 'breathing effect' as an outcome of the intra-framework interaction, which improves the CO₂ adsorption capability of the adsorbent (Serre et al., 2007). The characteristic peaks at 580 and 373 cm⁻¹ could be referred to as the metal cations, Mg^{2+} and Zn^{2+} in the Mg-MOF-74, Zn-MOF and 50 wt.% Mg/50 wt.% Zn-MOF (Wang et al., 2021). All adsorbents



Figure 3. Surface functional group patterns of Mg-MOF-74, Zn-MOF and 50 wt.% Zn/50 wt.% Mg-MOF

obtained exhibit the aforementioned characteristic peaks (Figure 3) (Li et al., 2021), which proves that Mg-MOF-74, Zn-MOF and 50 wt.% Mg/50 wt.% Zn-MOF crystals were successfully synthesised.

Wavenumber (cm-1)			
Mg-MOF-74	Zn-MOF	50 wt.% Mg/50 wt.% Zn-MOF	Functional Group
3369.19	3233.49	3483.57	Hydroxyl (O-H)
		3346.10	
2360.82	2364.30	3241.15	Carboxylic Acid (O-H), C≡N, C=C
2191.64	2193.70	2411.19	
2161.60	2123.58	2360.48	
2081.92	1988.95	2113.03	
2007.90	1936.16	1994.76	
1944.88	1624.93	1779.05	
1647.56	1550.32	1646.90	
1577.57			
1491.85	1311.79	1341.25	v(-C=O), v(-COO-), and v(C-H)
1375.52	1024.28	1051.71	
1038.78	803.29	1011.22	
819.05		818.58	
		804.31	
		730.07	
580.00		580.00	Mg-O
	373.00	373.00	Zn-O

Table 1 Wavenumber of Mg-MOF-74, Zn-MOF and 50 wt.% Mg/50 wt.% Zn-MOF adsorbents

Surface Morphology Analysis

The morphology of single and bimetallic 50 wt.% Mg/50 wt.% Zn-MOF were analysed through a Scanning Electron Microscope (SEM) analyser at different magnifications, as displayed in Figure 4. As indicated by Figure 4, there is a notable contrast in the surface morphology of the adsorbents. Irregular and favourably porous networks full of pores, flaws, and cracks are seen in the Mg-MOF-74 images (Figures 4(a) and (b)). The produced Mg-MOF-74 has a few voids attributed to the devolatilisation of inorganic materials primarily attached to the adsorbent wall. The images displayed in Figures 4(c) and (d) reveal Zn-MOF with a rough surface and some agglomerations. Figures 4(e) and (f) clearly demonstrate that 50 wt.% Mg/50 wt.% Zn-MOF's morphology has a similarity to those of the reference adsorbents but with an extra coral reef-like structure after the Zn²⁺ ions were introduced into the Mg-MOF-74. Therefore, the morphology of MOFs was significantly influenced by the presence of Zn²⁺ in the reaction solution, which is similar to that in a previous report by Yang et al. (2014).



Figure 4. SEM pictures for (a) Mg-MOF-74 (Magnification = 600x), (b) Mg-MOF-74 (Magnification = 2000x), (c) Zn-MOF (Magnification = 2000x), (d) Zn-MOF (Magnification = 1000x), (e) 50 wt.% Zn/50 wt.% Mg-MOF (Magnification = 1000x), and (f) 50 wt.% Zn/50 wt.% Mg-MOF (Magnification = 2000x)

Elemental Composition Analysis

The dissemination of the major components in the mono- and bi-metal 50 wt.% Mg/50 wt.% Zn-MOF was investigated by performing elemental composition analysis employing

an energy-dispersive X-ray analyser (EDX), and the results are shown in Table 2. The findings propose that the major components in the single (Zn-MOF and Mg-MOF-74) and bimetallic 50 wt.% Mg/50 wt.% Zn-MOF adsorbents, including Mg, Zn, C, and O, are uniformly distributed on the exterior of the solid materials. These well-distributed components offer significant active spots for CO_2 adsorption.

Elements	Mass (%)					
	Mg-MOF-74	Zn-MOF	50 wt.% Zn/50 wt.% Mg-MOF			
0	69.13	41.73	59.37			
Mg	15.26	-	7.64			
С	15.60	11.77	4.4			
Zn	-	46.50	28.59			

Table 2 Chemical Composition of Zn-MOF, Mg-MOF-74, and 50 wt.% Mg/50 wt.% Zn-MOF

Surface Area Analysis

The N₂ adsorption-desorption multipoint was used to evaluate the N₂ physisorption isotherms of the synthesised adsorbents at 77 K. The findings are depicted in Figure 5. According to the IUPAC class, the isotherms of all adsorbents are in category IV and have an H3 hysteresis loop that shows the occurrence of mesoporosity within all prepared adsorbents. Table 3 presents the samples' surface area, pore volume, and average pore size. CO₂ loading onto adsorbents is mediated through physical adsorption, which largely determines its adsorption by characteristics such as specific surface area and crystallinity (Lee et al., 2012). Comparatively, 50 wt.% Mg/50 wt.% Zn-MOF has a larger specific surface area than other adsorbents. This may be due to more mesopore structures and smaller crystal sizes in this material. The large surface area facilitates CO₂ uptake. In Table 3, the surface area is 50 wt.% Mg/50 wt.% Zn-MOF was approximately 3.13% bigger than that of Zn-MOF and 0.86% bigger than that of Mg-MOF-74. Zn-MOF had the minimum surface area and mesopore volume. This finding is consistent with the previous reports by Ling et al. (2022), Li et al. (2021) and Sun et al. (2019). The increase in specific surface area of 50 wt.% Mg/50 wt.% Zn-MOF can be attributed to the slight difference in cation radius and co-ordination modes between Mg and Zn cations. When constructing infinite structural units, bimetallic structures increase porosity and surface area. Present results are consistent with those expected because heavier transition metal substitution increases surface area (Villajos et al., 2015). Considering the double atomic mass of Zn with respect to Mg, the increase of surface area by bimetallic co-ordination in MOFs should be higher in terms of molar equivalent. It is thought that more vacancies might be created in the framework when a second metal ion was introduced, which includes lattice distortion

and locally unbalanced co-ordination, consequently resulting in higher porosity or higher lamellar charge (Vuong et al., 2013).

Notably, many MOF-74 have been reported with BET surface areas of more than 700 m^2/g , with the highest surface area reported for MOF-74 approaching 1900 m^2/g . While the surface areas of these prepared adsorbents fall short of the highest values achieved for MOF-74, this suggests that the comparatively low surface areas measured to date for prepared adsorbents are not an inherent limitation of their molecular nature. Following solvent exchange during the preparation of MOF materials, activation protocols that circumvent material decomposition and ensure complete removal of solvent guests are critical. Because the open metal sites in MOFs are of paramount importance for CO₂ adsorption, it is critical to completely free the metal sites of bound solvent during activation. If these methods are not performed properly, activation can cause structural collapse, thereby diminishing porosity and reducing material surface area (Deegan et al., 2021). In this study, the BET surface areas for all prepared adsorbents appear quite low; this might be due to the employment of temperature during the activation process ($\sim 200^{\circ}$ C), below the optimum temperature for DMF removal. Valenzano et al. (2011) showed via IR and EXAFS that dehydration of the Zr-cluster begins upon activation at 250°C and was completed at 300°C. The IR data indicated that the material was free of DMF by 250°C, indicating that this was the optimal activation temperature for solvent removal without changing the material structure. Indeed, this produces a high surface area of 1187 m²/g.

Figure 5 shows the isotherm linear plot for CO₂ adsorption and desorption of different prepared adsorbent samples. According to the IUPAC classification (Kahr et al., 2013), pores are classified into mesopores with pore diameters in the range of 2 to 50 nm. Table 3 reveals that all adsorbents have pores ranging in size from 2.6 to 6.5 nm. In addition,



Figure 5. N2 adsorption/desorption isotherms for Zn-MOF, Mg-MOF-74 and 50 wt% Zn/50 wt% Mg-MOF

as expected, the smaller pore size of 50 wt.% Mg/50 wt.% Zn-MOF relative to parental adsorbents is apparent.

Table 3

Textural parameters for Zn-MOF, Mg-MOF-74 and 50 wt.% Zn/50 wt.% Mg-MOF attained from the N_2 adsorption isotherm at 77 K

Sample	BET surface area (m2g-1)	Pore size (Å)	Pore volume (cm3g-1)
50 wt.% Zn/50 wt.% Mg-MOF	16.1695	26.6103	0.010757
Mg-MOF-74	8.7069	65.5707	0.014273
Zn-MOF	3.9186	38.5605	0.003778

CO₂ Adsorption

Influence of Different Metal Loading on MOF

The ability of single and bimetallic MOFs to adsorb CO_2 was assessed through the CO_2 adsorption analysis approach. The quantity of adsorbed CO₂ was determined per analysis, and the CO₂ adsorption value was employed to assess the performance of various adsorbents. Figure 6 illustrates the CO₂ adsorption capabilities of bi-metal MOF and pristine MOF. Since these adsorbents can be prepared fairly easily, and the metals studied to ensure that the characteristic properties of the MOF are preserved, like crystalline structure, thermal stability, and comparatively high surface area, it is therefore vital to investigate the ability of these materials to adsorb CO_2 . As can be seen in Figure 6, it is notable that the Zn-MOF and Mg-MOF-74 are capable of obtaining CO₂ at 134.55 and 122.08 mg/g, respectively, but bimetallic MOF has significantly higher adsorption capacities. In this present study, an Mg-MOF-74 acts as a parent structure and exhibits excellent CO₂ adsorption under ambient temperature and mild pressure conditions. However, adding another metal ion, such as Zn²⁺, as the bimetallic strategy is feasible for adsorbent design to achieve remarkable CO₂ adsorption capacity in the future. In principle, it is thought that mixed-metal MOFs can offer several advantages over monometallic MOFs by providing complexity and introducing functionality derived from the different metal ions in the MOF structure, and it is predicted that the adsorption performance of bimetal MOFs will be beyond that achieved by homometallic MOFs (Abednatanzi et al., 2019; Masoomi et al., 2019). In this study, the impregnation method was employed to synthesise the adsorbents where MOFs were constructed with two main components: the metal inorganic clusters and the organic linkers, where the linkers acting as "struts" connect the "joints" of metal ions (Abednatanzi et al., 2019). Usually, organic linkers are the processing targets to design functional MOFs to boost adsorption performance; for example, adopting large organic linkers enables larger pore size of MOFs to facilitate adsorption diffusion (Vuong et al., 2013), and decorating organic linkers with targeted groups [-NH₂ (Howarth et al., 2015), -OH (Luo et al., 2015)] offers more effective sites to increase adsorption capacity or improve adsorption selectivity.



Figure 6. Influence of metal loading on MOFs. Initial conditions: pressure = 5 bar, adsorbent dosage = 0.3 g, initial concentration of CO₂ = 637 ppm and ambient temperature

Almost all bimetallic MOFs with different percentages of metal loading exhibit a greater adsorption capacity than single MOFs. Adsorption capacity soars in the direction Mg-MOF-74 < Zn-MOF< 85 wt.% Mg/15 wt.% Zn-MOF < 85 wt.% Zn/15 wt.% Mg-MOF<50 wt.% Zn/50 wt.% Mg-MOF, reaching, accordingly, 122.08 mg/g, 134.55 mg/g, 242.14 mg/g, 260.85 mg/g and 323.21 mg/g. 50 wt.% Zn/50 wt.% Mg-MOF shows an increased CO₂ adsorption capacity over all MOFs prepared in this study. This phenomenon could be attributed to the surface area and the pore volume of the adsorbent since the specific surface area is 50 wt.% Zn/50 wt.% Mg-MOF (16.1695 m²/g) is larger than that of Mg-MOF-74 and Zn-MOF (8.7069 m²/g and 3.9186 m²/g, respectively). Mesoporosity is a characteristic of single and bimetallic MOFs that may be indicative of successful adsorbent formation. Mesoporous materials are also believed to support CO₂ adsorption because the bimetal (Zn and Mg) that were mixed to MOF was not clogging the pores of pristine MOF itself, thereby enhancing the quantity of porosity in the bimetallic MOF. The adsorption capacity of a single MOF (Zn-MOF or Mg-MOF-74) is relatively high, whereas as the metal substance rises to 50 wt.% and over 85 wt.%, the adsorptive capability of the MOF drops substantially. This tendency, in turn, may be described by the amount of metal loading too much, which lowers adsorbent porosity by plugging some of the MOF's pores. The availability of adsorption sites decreases, which affects the potential for CO₂ sorption. According to the reported literature (Liu et al., 2019; Ren et al., 2020; Szczesniak et al., 2018; Wu et al., 2010), CO₂ adsorption may initially occur on open Zn or Mg cations and MOF cage windows, subsequently through further adsorption induced by van der Waals forces. The electrostatic interaction between Zn or Mg cations and CO₂ quadrupole is more significant than the van der Waals interaction. The addition of metals
in MOF, such as Zn or Mg, that contain oxygen-functional groups has been supported by mesopores structures particularly favourable for diffusion and mass transfer, probably because of the co-ordination linkages between the oxygen functional groups and Mg or Zn in the MOF structure.

Furthermore, the findings show that the metals used and their added quantity are significant in the MOF. For instance, 50 wt.% Zn/50 wt.% Mg-MOF has a higher adsorption capacity than Mg-MOF-74 and Zn-MOF, and the addition of metals and loading leads to a substantial rise in capacity relative to pristine MOF. Taking into account both the Mg and Zn content in MOF (ranging from 15 to 50 wt.%) and the CO_2 adsorption capability of pristine MOF, it might be inferred that the CO₂ uptake of bimetallic MOF is improved. Moreover, the Zn content influenced the CO₂ adsorption capacity of bimetal-based MOF. With the decrease in the Zn content, the CO_2 uptake of bimetal-based MOF decreased, which was attributed to the CO₂ adsorption heat of Zn ions being larger than that of Mg ions in a mild-pressure region. Because of the synergistic effect between Zn and Mg, the CO₂ adsorption of bimetallic-based MOF was enhanced considerably. These findings are in good agreement with the results obtained when Co and Zn coexist in the MOF-74 structure (Botas et al., 2011). So, a synergetic effect between Mg and Zn metal cations and the pore size reduction may contribute to CO₂ molecules retention with higher energies in this material. This fact can be explained as a result of Coulombic interaction forces related to the proximity of CO_2 to the adsorbent and the reduced pore diameter in this material (Zhou et al., 2008). So, the presence of a certain amount of Zn in Mg-MOF-74 material enhances the CO₂ adsorption capacity and energy interaction strength onto this framework, rather than having pure zinc or magnesium clusters, possibly as a consequence of the electronic environment that attracts slightly stronger CO₂ molecules as well as the differences in textural properties among isostructural materials or even to the presence of defects in the crystal structure that restrict the access to some of the pores (Sillar & Sauer, 2012). Adding bimetallic is vital, but it is crucial to keep in mind that the quantity of added metal is significant. The greater its content, the lower the porosity and adsorption capability of the CO₂.

In general, one can conclude that sorbents are the most promising at 50 wt.% Zn/50 wt.% Mg-MOF, which shows the highest CO_2 adsorption capacity.

Impact of Operating Pressure

Pressure plays a crucial role in the performance of the solid adsorbent in practical applications; hence, the effect of pressure was examined and depicted in Figure 7.

Various operating pressures were used to determine the amount of CO_2 adsorbed during 75 minutes of adsorption time, and the findings exhibit that it increases from 195.63 mg/g to 438.91 mg/g from 1 bar to 5 bar operating pressure. The rise in CO_2 uptake is attributed

to increased gas particles hitting the adsorbent surface, caused by the rising pressure. The openings are filled with CO₂ molecules as a result of higher pressure. The remarkable enhancement in CO₂ adsorption capability observed can be attributed to the synergetic effect of high P: high pressure effectively modifies the pore size and shape via changing the linker orientation and creating new adsorption sites within MOF. More significantly, several studies have shown that application of high external pressure can effectively tune CO₂ storage capability in MOFs (Choi et al., 2019; Hu et al., 2013, 2015; Jiang et al., 2018; Kontos et al., 2020). External pressure can change the MOF framework topology, alter pore size and shape, enhance host-guest interactions between framework and adsorbed CO₂, and even create new adsorption sites, increasing CO2 adsorptive capability. High mechanical pressure changes the effective pore size and shape as well as the linker orientation to open the "gate", facilitating the CO₂ adsorption. The change in the linker orientation also makes the channels connecting the cages accessible to CO₂ as additional adsorption sites at high pressure. The substantial difference in adsorptive capacity improvement under different pressures is intriguing and can be closely attributed to the framework structure under different pressures. Previous work by Moggach et al. (2009) showed that high external pressure could increase the effective pore size of MOFs by changing the linker orientation, which is the so-called "gate opening" effect.



Figure 7. Influence of pressure on CO_2 uptake. Initial condition: adsorbent dosage = 0.4 g adsorbent, initial concentration of $CO_2 = 637$ ppm, metal loading = 50 wt.% Zn/50 wt.% Mg-MOF and ambient temperature

However, at room temperature, the solidification of CO_2 occurs at a pressure above 0.6 GPa (Giordano et al., 2006). This phase change of CO_2 severely limits further insertion of CO_2 into the cavities of MOFs at higher pressures since solid CO_2 is immobile and not

diffusible. This problem can be remediated if a mixture of solid CO_2 and MOFs is heated to a temperature at which solid CO_2 existing outside MOFs is mobilised so that a significantly larger number of CO_2 molecules may be pressed into the framework of MOFs by pressure. Consequently, the CO_2 vibrations appeared at higher frequencies. A possible reason is that the framework might have been partially damaged by exposing the MOFs to harsher conditions, resulting in a slightly reduced porosity for adsorption.

It can be concluded that the increase in working pressure affects the formulated adsorbent's CO₂ adsorption, contrasting the findings of CO₂ adsorption by employing various working pressures (Figure 7). In addition, the capability of samples to adsorb CO₂ is highly subject to factors such as surface area, pore size and pore volume. The form of the isotherm shows the resulting 50 wt.% Zn/50 wt.% Mg-MOF is a mesoporous structure with the greatest surface area (16.1965 m²/g) (Table 3). The presence of more active sites is increased due to increased surface area and pressure, directing towards greater adsorption of CO₂. Furthermore, the surface area significantly influences CO₂ adsorption uptake (Chen et al., 2017). It is apparent that other aspects are impacting CO₂ uptake.

Effect of Dosage of Adsorbent

Figure 8 exhibits the effect of changing the dosages of 50 wt.% Zn/50 wt.% Mg-MOF from 0.2 to 0.5 g on CO₂ adsorption process. Based on the findings presented in Figure 8, 0.3 g should be the optimum dosage for CO₂ uptake as it has the utmost CO₂ adsorption capacity at 740.90 mg/g. Expanding the dosage up to 0.5 g reduced the adsorption capacity by 54



Figure 8. Influence of adsorbent dosage on the CO₂ adsorption process. Initial condition: initial pressure = 5 bar, initial concentration of $CO_2 = 637$ ppm, metal loading = 50 wt. % Zn/50 wt. % Mg-MOF and ambient temperature

% (338.54 mg/g). Thus, 0.3 g would be the best dosage of prepared bimetallic adsorbent as it has the highest adsorption capacity within 75 minutes of adsorption time.

Based on the findings illustrated in Figure 8, radical transformations are not observed when raising the dosage of the adsorbent. As adsorbents increase, the ability to adsorb CO_2 decreases while all other variables remain constant, as shown in Figure 8. It could be because the quantity of active sites is greater with smaller adsorbent doses. Increasing the adsorbent dose leads to the accumulation of particulate matter. As a result, the presence of adsorption sites may decrease due to reduced CO₂ adsorption capacity (Dien, 2019). It is in line with the conclusions made by Niyousha et al. (2020) and Nsami et al. (2013). The pore-clogging effect becomes more noticeable as the adsorbent dosage increases. The CO₂ uptake was decreased by the pore-blockage effect and poor diffusion caused by the higher adsorbent dose, which is because of the active phase layer of the adsorbent (Fatima et al., 2022). Smaller doses result in greater contact between the functional groups of the adsorbent and CO₂, and the support substantially influences physisorption. CO₂ particles have a higher affinity for anions (-OH and -COOH) of adsorbents (Torrisi et al., 2010). Due to the larger number of [OH] or [COOH]⁻ anion present, the highest surface coverage was achieved with a lower load. The surface area deteriorated with a greater adsorbent dose, and the adsorbent's influence on physisorption was also insignificant. Thus, the CO_2 uptake was observed to be less effective at higher adsorbent dosages. The best performance was achieved with 0.3 g of adsorbent dosage for 50 wt.% Zn/50 wt.% Mg-MOF.

CONCLUSION

This study prepared single and bimetallic-based Metal-Organic Frameworks (MOFs) containing Zn and Mg using the impregnation method. The properties of the respective MOFs characterise the prepared MOFs. For instance, its crystalline configuration is well-maintained, the characteristic crystalline phase is recognisable, and the characteristics show the existence of bimetal (varies in surface area). 50 wt.% Zn-50 wt.% Mg-MOF adsorbent is the most favourable for CO₂ uptake. In our study, the addition of bimetal to pristine MOF (Zn-MOF or Mg-MOF-74) enhances the adsorbed CO₂ amount by 59%–62% obtained in this study. Overall, comparing the single and bimetallic MOFs, it can be summarised that bimetallic MOFs can be regarded as the most promising, as 50 wt.% Zn-50 wt.% Mg-MOF shows higher CO₂ uptake capability relative to pristine MOFs. Moreover, the proportion of bimetal used in MOF, working pressure, and adsorbent quantity all have a significant impact on the CO₂ uptake of the solid adsorbent.

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Rice Extent and Cropping Patterns in Terengganu Malaysia Based on Sentinel-2 Data on Google Earth Engine

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ABSTRACT

Rice is a vital staple food in Malaysia, with consumption of 2.7 million MT in 2016, forecasted to rise to 3.5 million MT by 2026. To address food security, the Malaysian government targets a 70% self-sufficiency level (SSL) in rice production, requiring precise spatiotemporal information on rice cultivation. Remote sensing has been widely used to map rice extent in Malaysia, particularly in granary areas (facilitated by irrigation system), the main production zones. However, studies on non-granary areas (without irrigation systems) remain limited. This study addresses this gap by employing the Phenology-Expert Based Unsupervised Classification Method (PEB-UC) with Sentinel-2 time series data on the Google Earth Engine platform to map rice extent and cropping patterns at the sub-district level across Terengganu State, Malaysia, covering both granary and non-

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p5844@pps.umt.edu.my (Fatchurrachman) norhidayah.soh@umt.edu.my (Norhidayah Che Soh) ramisah@umt.edu.my (Ramisah Mohd Shah) p5277@pps.umt.edu.my (Frisa Irawan Ginting) sunnyg@umt.edu.my (Sunny Goh Eng Giap) nazirsiham@remotesensing.gov.my (Muhammad Nazir Siham) rudiyanto@umt.edu.my (Rudiyanto) * Corresponding author granary areas. The results revealed scattered rice parcels totalling 8,184 ha, with 4,377 ha in the IADA KETARA granary area (Besut District) and 3,807 ha in non-granary areas. The maps showed a relative discrepancy of -29.15% with agricultural statistics but demonstrated a strong correlation at the district level ($R^2 = 0.99$; RMSE = 632 ha). Validation of PEB-UC achieved an overall accuracy of 0.979 and a kappa coefficient of 0.957, outperforming Random Forest (RF) and Support Vector Machine (SVM) models. The PEB-UC rice map displayed denser, clearer separability between rice and non-rice compared to supervised models, as shown in

ISSN: 0128-7680 e-ISSN: 2231-8526 the comparison map at https://rudiyanto.users.earthengine.app/view/riceterengganu. This study provides valuable insights into rice cultivation in Terengganu State and supports efforts to enhance food security.

Keywords: Cropping pattern, Google earth engine, harvested area, paddy rice map, phenology, Sentinel-2

INTRODUCTION

Rice serves as a primary dietary component across Southeast Asia (SEA), including Malaysia. In 2016, the consumption of rice in Malaysia amounted to 80 kilograms per capita, totalling 2.7 million metric tons of rice consumed. The annual consumption of rice in Malaysia is on the rise and is forecasted to reach 3.5 million MT by 2026 (Omar et al., 2019). In response to the national food security issue, the Malaysian government, through the *Rancangan Malaysia Ke-12* (12th Malaysia Plan), has set a goal of attaining a self-sufficiency level (SSL) of 75% for domestic rice production, equivalent to 3 million metric tons by 2025 (Ministry of Economy Malaysia, 2023).

Malaysia's rice production management is divided into two categories: rice production managed by rice granary agencies (i.e., completed by irrigation system) and rice production outside the agencies (i.e., without irrigation system). Rice granary agencies dominate Malaysia's domestic rice production, constituting approximately 70% of the total supply (Omar et al., 2019).

Terengganu is one of the rice-producing regions in Malaysia. Although it is not the main rice producer in Malaysia, Terengganu has one of the granary areas with the highest yield, IADA KETARA, reaching up to 5.4 tons per hectare. Additionally, Terengganu contributes to national rice production through granary and non-granary areas (Department of Agriculture Peninsular Malaysia, 2021).

In order to achieve the SSL rice target, it is essential to gain precise and current information regarding the geographical distribution and quantity of rice cultivation areas. In the last decades, remote sensing technology has emerged as an efficient tool to provide spatiotemporal information for crop monitoring, including rice. Remote sensing offers a cost-effective method for monitoring crops at regional and national scales, as it facilitates the rapid retrieval of spatially distributed information over large areas. In contrast to field surveys, which are often time-consuming, lack geographical details and are also costly (Omia et al., 2023; Wang et al., 2024).

Rice has highly dynamic changes in growth stages to differentiate rice from other crops and land covers, in which time series imagery data are required (Ni et al., 2021; Rudiyanto et al., 2019). Moreover, the characteristics of rice fields in SEA typically consist of small blocks, averaging less than 1 ha, necessitating high-resolution imagery data (Fatchurrachman et al., 2022; Setiyono et al., 2018). Sentinel-2A and 2B satellites

constellation, which are equipped with multispectral instruments (MSI), offer imagery data covering a range of visible, near-infrared (NIR) and short-wave infrared (SWIR) wavelengths and have high-resolution ranging from 10-60 m (depending on the selected band) (Griffiths et al., 2019; Jiang et al., 2023). These satellite imagery data also have a monthly revisit time of 5-6 times. These features of Sentinel-2 imagery data make it particularly suitable for mapping rice. Multiple studies have demonstrated the successful utilisation of Sentinel-2 imagery for mapping rice fields across diverse regions, including Bangladesh (Tiwari et al., 2024), China (Feng et al., 2023), Egypt (Ali et al., 2021), India (Raju et al., 2022), Indonesia (Rudiyanto et al., 2019), and Pakistan (Rauf et al., 2022).

Data-driven mapping algorithms, such as machine learning and deep learning, have become increasingly popular in rice mapping (Liu et al., 2022; Ramadhani et al., 2020). Despite their excellent performance, extensive ground data samples are needed to train the algorithm (Padarian et al., 2020; Thorp & Drajat, 2021; Zhao et al., 2021). Another limitation of the supervised classification is the difficulty of transferring the model due to regional or temporal differences (Qiu et al., 2024).

On the other hand, unlike the supervised methods, unsupervised methods can eliminate the need for extensive ground training samples. In particular, the k-means unsupervised method has the ability to generalise clusters from data patterns and group time series data into unique spectral responses related to rice phenology and other land uses (Ni et al., 2021; Rudiyanto et al., 2019). Thus, these advantages of the phenology unsupervised method can be used to identify rice with varying cropping calendars in Southeast Asia (Han et al., 2022).

Current studies by Han et al. (2021), Fatchurrachman et al. (2022), and Han et al. (2022) have mapped rice extent across Peninsular Malaysia using remote sensing technology. However, these maps did not provide detailed information on rice's location and planting schedule in non-granary areas. Despite non-granary areas accounting for approximately 25% of the total rice field area in Peninsular Malaysia (Department of Agriculture Peninsular Malaysia, 2021), their contribution cannot be overlooked in addressing food security issues.

Considering the existing research gap, this study's objective was to map the extent of rice cultivation and its cropping pattern in Terengganu State, Malaysia, which covers granary and non-granary areas at the sub-district level. It was accomplished through the utilisation of Sentinel-2 temporal data and phenology-expert-based unsupervised classification (PEB-UC) within the Google Earth Engine (GEE) platform. The outcomes of this study will offer crucial information on the extent of rice cultivation and its cropping schedule in Terengganu State at the Sub-district level, which can aid in addressing food security concerns.

STUDY AREA AND RICE CULTIVATION PRACTICES

Terengganu is one of the states in Malaysia located on the northeastern coast of Peninsular Malaysia (3.87°N–5.85°N and 102.37°E–103.69°E; Figure 1). Terengganu comprises seven Districts: Besut, Dungun, Kemaman, Kuala Terengganu (Kuala Nerus), Marang, Setiu, and Hulu Terengganu. Similar to other states in Peninsular Malaysia, Terengganu undergoes two monsoon seasons: the northeast monsoon (NEM), occurring from November to March, and the southwest monsoon (SWM), which lasts from May to September. Additionally, there are two short transitional periods, spanning from April to May and October to November. The NEM brings heavy rains to this region. The annual mean air temperature ranges between 26° and 28°C (Suratman et al., 2015).

The rice fields in the study area are categorised as irrigated and non-irrigated. The rice intensity in the study area is mostly a double rice cropping pattern. Planting seasons are categorised into the main season, featuring wet paddy rice cultivation from September to March, and the off-season rice crop from April to September. Locally referred to as "tanaman musim utama" and "tanaman luar musim", respectively. The off-season denotes a period marked by the lack of precipitation in the region (Hashim et al., 2022).

Terengganu has one active rice granary area: the Integrated Agriculture Development Area (IADA) Kawasan Pembangunan Pertanian Terengganu Utara (KETARA). IADA



Figure 1. The study location comprises 7 Districts in Terengganu State, Malaysia. Rice extent based on this study is shown in red

KETARA is one of Malaysia's top rice producers, with yields surpassing 5.0 to 5.4 MT/ ha (Omar et al., 2019).

DATA COLLECTION

Sentinel-2 Temporal Imagery Data

The Sentinel-2 (S2) satellite constellation consists of two satellites, namely Sentinel-2A and Sentinel-2B. These satellites were launched by the European Space Agency (ESA) on 23 June 2015 (S2A) and 7 March 2017 (S2B), respectively. S2 satellites are equipped with a multispectral instrument (MSI) that acquires images with a swath width of 290 km and a spatial resolution ranging from 10-60 m (depending on the selected band). The S2 mission has a ten-day revisit time at the equator when utilising a single satellite and five days when the entire constellation is operational. (Xiao et al., 2021).

The Sentinel-2 Level-2A (Surface Reflectance, SR/ Bottom of Atmosphere (BOA)) images were not utilised in this study due to the presence of numerous artefacts and often being overcorrected, as noted by Brinkhoff et al. (2022) and Fatchurrachman et al. (2022). A recent study by Pascual-venter et al. (2024) suggests that TOA radiance has slightly better accuracy than BOA (SR) radiance. Pascual-venteo et al. (2024) also indicate that utilising TOA radiance can eliminate the need for complex atmospheric correction when retrieving vegetation traits, streamlining the process and potentially improving accuracy. Therefore, Sentinel-2 Level-1C (Top-of-Atmosphere Reflectance, TOA) images were chosen for this study.

Prior research has also documented the successful utilisation of Sentinel-2 Level-1C data for mapping paddy extent, such as in China (Ni et al., 2021; Shen et al., 2023) and Malaysia (Fatchurrachman et al., 2022). S2 L1C refers to Top-of-Atmosphere (TOA) reflectance image data that have been subject to radiometric and geometric corrections. These corrections encompass ortho-rectification and spatial registration on a global reference system, ensuring sub-pixel accuracy (European Space Agency, 2015; Google Developers, 2022).

Four bands from the S2 L1C TOA dataset were employed for computing the Normalised Difference Vegetation Index (NDVI) and Modified Normalised Difference Water Index (MNDWI). Band 4 (red) and 8 (near-infrared, NIR) were employed for computing NDVI, while band 3 (green) and band 11 (short-wave infrared 1 or SWIR1) were used to calculate MNDWI. The S2 TOA images possess a spatial resolution of 10 meters. S2 TOA temporal data were collected from January 2022 to October 2023, covering the study area's main and off seasons. A total of 3,900 scenes of S2-TOA temporal data were obtained from the Google Earth Engine (GEE) catalogue. GEE, a cloud-based platform for geospatial analysis (Gorelick et al., 2017), facilitated tasks such as data access, image pre-processing, vegetation index computation, area mapping, and calculations.

ESA WorldCover 10 m v100 2020

The ESA WorldCover 10m v100 was used to exclude non-cropland areas by masking out the cropland area (class value 40). Spurious data from other land cover types that could impact classification results were reduced, focusing on the cropland areas. The ESA WorldCover 10 m v 100 2020 dataset was generated based on the combination of Sentinel-1 and 2 temporal data as part of the ESA WorldCover project, which is a component of the 5th Earth Observation Envelope Programme (EOEP-5) by the European Space Agency. The product is a global land cover map for the year 2020 with a resolution of 10 meters, based on data from Sentinel-1 and Sentinel-2 satellites. The product contains 11 classes of land cover that include tree cover, shrubland, grassland, cropland, built-up, bare or sparse vegetation, snow and ice, permanent water bodies, herbaceous wetland, mangroves, moss and lichen (Google Developers, 2021; Zanaga et al., 2021).

Google Street View Images

Google Street View images accessed from Google Maps were utilised to verify the presence of rice fields in the classified area. Although the images were not acquired in 2022, they can still be used as indicators for the presence of rice fields in the classified area. Points of verification are accessible on the Google Earth Engine (GEE) platform (https://code. earthengine.google.com/7cb17f0460c4d9a00cc00787a28ec8a0).

Administrative Boundary

The administrative boundaries at both the State and District levels were acquired from the Global Administrative Unit Layers (GAUL) dataset provided by the Food and Agriculture Organization of the United Nations (FAO UN). The boundary data were accessed through the GEE catalogue using the command ee.FeatureCollection("FAO/GAUL/2015/level2").

Agricultural Statistics and Existing Rice Map

This study compared results using the Malaysia Paddy Production Survey (PPS) report published in 2021. The report collected estimates of yield, planted area and production for each season using probability sampling methods and objective measurements. These data were generated at the District, State and granary area levels (Department of Agriculture Peninsular Malaysia, 2021). The paddy parcel and harvested areas were compared with this study's estimates and presented in hectares (ha).

An existing rice map, NESEA-Rice10, was also compared with the results of this study (Table 1). NESEA-Rice 10 is a project that provides paddy rice maps for Northeast and Southeast Asia. It utilises a rule-based method combining temporal data of Sentinel-1 and MODIS satellite data to overcome the mixed-pixel challenge arising from coarse spatial

No	Districts	R	ice parcel area	Relative discrepancy	Relative discrepancy	
		This study (ha)	NESEA- Rice10 (ha)	Statistic (ha)	(a) and (b)	(a) and (c)
		(a)	(b)	(c)	(%)	(%)
1	Besut	6,148	6,145	7,370	0.05	-16.58
2	Dungun	33	721	44	-95.42	-25.00
3	Hulu Terengganu	164	348	300	-52.87	-45.33
4	Kemaman	49	737	93	-93.35	-47.31
5	Kuala Terengganu	683	577	1,387	18.37	-50.76
6	Marang	208	455	792	-54.29	-73.74
7	Setiu	899	2,287	1,565	-60.69	-42.56
	Total	8,184	11,270	11,551	-27.38	-29.15

Table 1

Rice parcel area comparison between this study data, NESEA-Rice10 and statistic and its relative discrepancy

resolution. The dataset is publicly available at https://doi.org/10.5281/zenodo.5645344 (Han et al., 2021) and can be accessed for further analysis and decision-making.

METHODOLOGY

Figure 2 illustrates the workflow of the methodology employed in this study. The methodology framework employed in this study is referred to as the framework of phenology-expert-based unsupervised classification method (PEB-UC), which involves combining the k-means unsupervised method with expertise in rice phenology curves from Sentinel-2 data.

Data Pre-processing

Sentinel-2 TOA temporal data spanning from January 2022 to October 2023 were employed; These data were compiled and processed into the Monthly Maximum Value Composite (MaxVC) of NDVI and MNDWI. NDVI spectral was used to differentiate rice from other land covers and identify growth stages (Fatchurrachman et al., 2022; Ni et al., 2021). Meanwhile, MNDWI was used to detect the presence of standing water during the tillage and planting stage. In addition, although wet surfaces and built-ups have similar reflectance, MNDWI is capable of improving the differentiation between those two objects (Mansaray et al., 2019; Talema & Hailu, 2020). NDVI was calculated using Equation 1, employing band 4 (red) and band 8 (near-infrared). Meanwhile, MNDWI was calculated using Equation 2, employing band 3 (green) and band 11 (short-wave infrared 1 or SWIR1):

$$NDVI = \frac{band \ 8 \ (NIR) - band \ 4 \ (Red)}{band \ 8 \ (NIR) + band \ 4 \ (Red)}$$
[1]



Figure 2. Workflow of the methodology in this study

$$MNDWI = \frac{band \ 3 \ (Green) - band \ 11 \ (SWIR1)}{band \ 3 \ (Green) + band \ 11 \ (SWIR1)}$$
[2]

Phenological studies using Sentinel-2 are limited by data gaps arising due to cloud cover, a prevalent issue with optical sensors (Misra et al., 2020). Additionally, optical Sentinel-2 data can be influenced by various factors, including changes in illumination and viewing conditions within and across images, fluctuations in atmospheric constituents such as water vapour and aerosol concentrations, as well as the presence of cloud cover (Holben, 1986). This study minimises these effects using maximum value composites (MaxVC) of the NDVI calculated from Sentinel-2 TOA temporal data from January 2022 to October 2023. MaxVC of the NDVI has proven effective in prior studies utilising MODIS, SPOT, and Sentinel-2 data (de Bie et al., 2012; Fatchurrachman et al., 2022; Gumma et al., 2014).

A compilation of 22 months of MaxVC NDVI and MNDWI datasets from January 2022 to October 2023 was stacked into a single image. First, we excluded non-cropland areas using the ESA WorldCover 10m v100 cropland band to reduce computational time, This procedure extracted rice fields from the classified cropland area and herbaceous area.

Concentrating on the cropland and herbaceous areas eliminated spurious data from other land cover area types that could impact classification results; it also significantly reduced computational cost and time.

Phenology-expert Based Unsupervised Classification Method (PEB-UC)

The pre-processed images served as inputs for the K-Means clustering model, implemented using the ee.Clusterer.wekaKMeans function within the GEE. This model employed a random-point sampling technique to establish centroids and produce clusters. Subsequently, these clusters were used to visually distinguish rice field and non-rice field areas based on characteristic spectral profiles derived from a monthly composite of NDVI and MNDWI temporal data.

Figure 3 illustrates the temporal evolution of the NDVI and MNDWI cluster profiles for four land covers: water bodies, built-up areas, trees and rice fields. Rice fields demonstrate a distinct temporal cluster profile characterised by seasonal fluctuations in NDVI values, while signals for other land covers remain relatively stable.

In detail, rice fields are flooded with water during the tillage and planting stage (T). Figure 3 depicts rice fields exhibiting a local minimum NDVI value during this period, while the MNDWI value reaches a maximum peak (F) (similar spectral of a water body or wet surface). Subsequently, as rice grows and canopy closure occurs in the vegetative (V) and reproductive (R) stages, increasing chlorophyll signals coincide with a significant decrease in soil signals (Ni et al., 2021). Consequently, NDVI value rapidly increased during this period, peaking at the end of the reproductive period. In contrast, the MNDWI value decreased until the maturity period (M) as the water content decreased.

A rapid decrease in chlorophyll content marks the maturity (M) period as the carotenoid content increases (Ni et al., 2021). This distinctive drop in NDVI values indicates the maturity of the rice plant, typically occurring in the last month of the rice growth cycle. Finally, NDVI values decreased due to biomass loss, signalling the harvest and fallow stages.

The representative cluster profiles of NDVI and MNDWI were visually identified, separating rice and non-rice field areas. We employed this method in our previous studies (Fatchurrachman et al., 2022; Rudiyanto et al., 2019) and successfully generated highly accurate maps of rice field extent.

Supervised Classification Model

In addition, we also performed supervised classification methods using random forest (RF) and support vector machine (SVM) to map rice parcel extent (growing area) in GEE. RF is an ensemble learning method that addresses the limitations of single decision trees by integrating many trees through a process called bootstrap aggregating (bagging) (Breiman, 2001). Meanwhile, SVM utilises a hyperplane to divide the support vectors and distinctly



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Figure 3. Temporal evolution of monthly composite NDVI and MNDWI cluster profile for four land-cover classes: water body, built-up, tree and rice field; T = tillage and planting, V = vegetative, R = reproductive, M = maturity, F = Flooding, OS = off-season, MS = main season

classify the data points (Maxwell et al., 2018). RF and SVM have built-in parameters that can be tuned to enhance their prediction performance. Based on trial and error, the number of tree parameters in the RF model was set to 30, while the SVM model used a radial basis function (RBF) kernel type with a gamma parameter of 0.5 and a cost of 10.

For training and validation of the models, 247 points (126 rice and 121 non-rice class) were visually labelled based on the very high-resolution image (VHRI) base map (i.e., satellite layer) in GEE and the Street View images in Google Maps. The observed data were randomly split into training and validation groups with a ratio of 8:2. For comparison, the same validation sample data were also used to check the validation accuracy of the PEB-UC classification results.

Accuracy Assessment

The agreement between the statistics of rice extent areas and the results obtained in this study was assessed using the coefficient of determination (R^2), as shown in Equation 3; the root mean square error (RMSE), as shown in Equation 4; and the percentage of relative discrepancy (%RD), as shown in Equation 5.

$$R^{2} = 1 - \frac{\sum_{i=1}^{n} (y_{e-i} - y_{s-i})^{2}}{\sum_{i=1}^{n} (y_{s-i} - \mu)^{2}}$$
[3]

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_{e-i} - y_{s-i})^2}{n}}$$
[4]

% RD =
$$\frac{(y_{e-i} - y_{s-i})}{y_{s-i}} \times 100$$
 [5]

Where y_e is the estimated rice extent from this study, and y_s is the rice extent from either statistical data or existing rice map of NESEA-Rice 10, subscript-_i represents District, and n is the total Districts in Terengganu. Furthermore, the accuracy of the produced rice parcel extent maps from PEB-UC, RF and SVM models was also evaluated using overall accuracy and kappa coefficient through a contingency matrix for both the training and validation datasets.

RESULTS AND DISCUSSION

The PEB-UC proposed in this study is straightforward and resulted in rice parcel extent and rice cropping intensity through visual observation of the phenology of the spectral profile of Sentinel-2 time series data. Thus, we discussed the PEB-UC extensively in this study. Subsequently, we evaluated the comparison results between the PEB-UC and the two supervised methods (RF and SVM).

Distribution of Rice Extent and Cropping Schedule

Based on the labelled rice clusters extracted from the PEB-UC, rice extent or growing area across Terengganu was identified as shown in Figure 1 (https://rudiyanto.users.earthengine. app/view/riceterengganu). These rice extent areas were then calculated and presented at the district level. According to our findings, rice fields in Terengganu are dispersed across all districts. The total area of rice fields in Terengganu amounts to 8,184 hectares, with 53% (4,377 ha) situated within the IADA KETARA granary area exclusively in Besut District and the remaining 47% (3,807 ha) in non-granary areas distributed throughout the entire region. Figure 4 illustrates the distribution of the total rice fields (8,184 ha), where a significant portion of 75.12% (6,148 ha) of Terengganu's rice area is concentrated in Besut District, followed by Setiu 10.98% (899 ha), Kuala Terengganu (including Kuala Nerus)

8.35% (683 ha), Marang 2.54% (208 ha), Hulu Terengganu 2% (164 ha), and Kemaman 0.60% (49 ha), with Dungun having the smallest area at 0.40%, equivalent to 33 hectares.

Figure 5 showcases rice fields in Besut District, primarily situated along the northern Terengganu border with Kelantan State. The NDVI spectral profile indicates double cropping seasons, with rice planted in January and July. Most rice fields, constituting 71% of Besut's parcels, are within the IADA KETARA granary area, while 29% are in non-granary regions.

Only 24.9% of rice fields are situated beyond Besut District, with Dungun District featuring a singular planting area in Sungai Melung Sub-district (Supplementary Figure 1). Notably, based on the NDVI spectral profile, rice cultivation in this region occurs once



Figure 4. Percentage of Rice Field Extent at District level of Terengganu State, Malaysia



Figure 5. Rice extent at Besut District (red colour). The green colour line is the boundary area of IADA KETARA. © Google Street View image coordinate 102.50696604601183, 5.670731115164914

a year, specifically in April (2021) and February (2022). Moving on to Hulu Terengganu, rice cultivation spans across four sub-districts: Tok Lawit, Matang (Supplementary Figure 2a), Gaung, and Kemat (Supplementary Figure 2b), with planting occurring twice annually, in February and July. Similarly, Kemaman's rice cultivation is distributed across two subdistricts, Pasir Semut (Supplementary Figure 3a) and Dadong (Supplementary Figure 3b), both following a double cropping season with plantings in February and June, as depicted in the NDVI spectral profile, while fluctuations or sudden drops suggest the presence of clouds.

In Kuala Terengganu, encompassing Kuala Nerus, rice fields are dispersed across eleven sub-districts: Darat Batu Rakit, Tok Kulit, Padang Maras, Maras, Medan Cengal, Bukit Cempaka, Teluk Merbau, Bukit Wan (Supplementary Figure 4a), Tualang, Wakaf Mempelam, Gong Kemunting, and Alur Parit (Supplementary Figure 4b). Kuala Terengganu adopts a double cropping schedule, with rice planted in March and October. In Marang, rice cultivation is segmented across four sub-districts: Lubuk Pandan, Jerong Tuan, Bukit Kulim, and Bukit Jelulong (Supplementary Figure 5), adhering to a single cropping system with rice planted either in November or December. Lastly, in Setiu District, rice cultivation predominantly concentrates in the Permaisuri area, notably across four sub-districts: Gong Kubu, Kederang, Bukit Kemudu, and Buruk (Supplementary Figure 6a), alongside Alur Serdang Sub-district (Supplementary Figure 6b). Setiu operates on a double cropping system, with rice planted in January and September.

In summary, five districts—Besut, Hulu Terengganu, Kemaman, Kuala Terengganu, and Setiu—feature double cropping seasons in one year. Meanwhile, Dungun and Marang Districts adhere to a single cropping season within the same timeframe.

Comparison of Classification Results with Statistical Data and Existing Map Product

Table 1 compares the extent of rice parcel area in seven districts of Terengganu as determined by this study (2022), NESEA-Rice10 (2019), and agricultural statistics from 2021. The total area estimated for rice fields in this study is 8,184 hectares, compared to 11,270 hectares reported by NESEA-Rice10 and 11,551 hectares according to agricultural statistics in 2021. The map generated in this study shows a relative discrepancy of -29.15% from the agricultural statistics, whereas the discrepancy from NESEA-Rice10 is -27.38%. This discrepancy, particularly evident in the NESEA-Rice10 dataset, is attributed to the inclusion of non-rice areas being misclassified as rice fields, a phenomenon often referred to as the "salt and pepper effect." Due to the lack of spatial data, further investigation into this statistical disparity was not feasible.

Figures 6a and 6b show scatter plots of the agreement between the rice extent calculated from this study, agricultural statistics data, and the agreement between the NESEA-Rice10 estimates for 2019 (Han et al., 2021) and agricultural statistics data, respectively. This

study's estimated rice field extent had a higher correlation with agricultural statistics with a coefficient of determination $R^2 = 0.99$ and an RMSE of 632 ha (Figure 6). Meanwhile, the correlation of the NESEA-Rice10 map with agricultural statistic data was $R^2 = 0.93$ and RMSE of 732 ha (Figure 6b). By comparison, this study has a better agreement than the NESEA-Rice10 map product to the statistical data.

Table 2 lists the rice harvested area across seven districts of Terengganu generated from this study compared with agricultural statistics from 2021. Based on the results, the study data and the statistics indicate that the harvested area during the main seasons is larger than during the off-season. The number of seasons identified in this study data aligns well



Figure 6. Comparison between rice area estimates derived from (a) this study and statistical data (District level) and (b) NESEA-Rice10 data and statistical data (District level)

No	Districts -		This Study	7	Statistic		
110		Harvested Area (ha)		Number of	Harvested Area (ha)		Number of
		Off Season	Main Season	Season per year	Off Season	Main Season	Season per year
1	Besut	6,148	6,148	2	7,095	7,095	2
2	Dungun	0	33	1	0	33	1
3	Hulu Terengganu	164	164	2	120	193	2
4	Kemaman	49	49	2	58	58	2
5	Kuala Terengganu	683	683	2	377	1,167	2
6	Marang	0	208	1	0	509	1
7	Setiu	899	899	2	1,448	1,448	2
	Total	7,943	8,184		9,098	10,503	

The harvested rice area and number of seasons are compared using this study's data and statistics

Table 2

with the 2021 statistics. Overall, the study data underestimate the harvested areas during both off-season and main seasons compared to the statistical data from 2021.

Comparison between PEB-UC and Supervised Classification

Accuracy of Classification Models

The accuracy assessment between the PEB-UC, RF, and SVM classification models is listed in Supplementary Table 1. The PEB-UC classification result was validated using the same validation sample points as the supervised models. The overall accuracy for the validation of PEB-UC was 0.979, with a kappa coefficient of 0.957, which is higher compared to both RF (overall accuracy = 0.875 and kappa = 0.743) and SVM (overall accuracy = 0.937 and kappa = 0.870). PEB-UC outperformed both supervised methods because the two supervised methods showed relatively high overfitting, as indicated by a training overall accuracy of 1 and a kappa coefficient of 1 (Supplementary Table 1).

Comparison of Rice Parcel Area and Quality of Rice Map

Comparison of rice parcel areas between PEB-UC, RF, SVM, and statistics, along with their relative discrepancies, are presented in Supplementary Table 2. PEB-UC estimated 8,184 ha, RF 8,428 ha, and SVM 7,966 ha. Compared to 2021 agricultural statistics (11,551 hectares), the relative discrepancies were -29.15% for PEB-UC, -27.04% for RF, and -31.04% for SVM. The PEB-UC rice map also shows more dense and clear separability

between rice and non-rice (roads, irrigation channels, built-up areas, and other vegetation covers) compared to both supervised models, as shown in the comparison map available at https://rudiyanto.users.earthengine.app/view/ riceterengganu.

Uncertainty Source

The current study has successfully produced a highly accurate map of rice extent. Nonetheless, it is essential to acknowledge certain potential limitations. Common errors occur at the boundary zones between rice and non-rice fields. The mixed pixel effect at these boundary zones contributed to this discrepancy, as illustrated in Figure 7. This effect, documented in previous rice mapping studies, remains a



Figure 7. Example of error in rice field classification: The red colour shows an area classified as a rice field, while the RGB colour is the non-rice areas in Besut District (102.45713 E, 5.74593 N)

significant source of spatial uncertainty (Clauss et al., 2016; M Wang et al., 2022; Mo Wang et al., 2022). Commission errors, where non-rice areas are misclassified as rice fields, were primarily attributed to unwell-managed rice blocks being detected as rice.

CONCLUSION

The Phenology-Expert Based Unsupervised Classification Method (PEB-UC), using Sentinel-2 time series imagery data on the Google Earth Engine platform, has successfully generated a high-resolution (10 m) map of rice extent across Terengganu, Malaysia. This approach also offers cropping calendars based on monthly NDVI spectral profiles. The study reveals that the total rice extent in Terengganu is 8,184 hectares, with 53% situated in the IADA KETARA granary area and the remaining portion spread across nongranary areas. At the district level, the estimated rice field extent correlates strongly with agricultural statistics ($R^2 = 0.99$, RMSE = 632 ha), and the number of cropping seasons per year in this study aligns well with the statistics. The overall accuracy for the validation of PEB-UC was 0.979, with a kappa coefficient of 0.957, which outperformed both RF and SVM models. The PEB-UC rice map also shows more dense and clear separability between rice and non-rice compared to both supervised models. These insights into the spatial and temporal patterns of rice cultivation in Terengganu are valuable for policy formulation by the Department of Agriculture (DOA) Malaysia. Additionally, these spatial data complement agricultural statistical data, frequently presented as tabulated numerical data only.

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APPENDIX



Supplementary Figure 1. Rice extent at Dungun District. Rice location coordinates 103.10482603697415, 4.799146193703962



Supplementary Figure 2. Rice extent at Hulu Terengganu District: (a) Tok Lawit and Matang Sub-district, (b) Gaung and Kemat Sub-district. © Google Street View image coordinate: (a) 102.89854868916677, 5.15998499939375; (b) 102.98815719945003, 5.074533627188336



Supplementary Figure 3. Rice extent at Kemaman District: (a) Pasir Semut Sub-district; (b) Dadong Subdistrict, © Google Street View image coordinate: (a) 103.34212221711789; 4.223077206270977 (b) 103.23149627791656, 4.282389429361505



Supplementary Figure 4. Rice extent at Kuala Terengganu District: (a) Darat Batu Rakit, Tok Kulit, Padang Maras, Maras, Medan Cengal, Bukit Cempaka, Teluk Merbau, Bukit Wan Sub-districts; (b) Tualang, Wakaf Mempelam, Gong Kemunting, and Alur Parit Sub-districts, © Google Street View image coordinate (a) 103.04158359086921, 5.41650121980068 (b) 103.15765153308007, 5.289039091455927



Supplementary Figure 5. Rice extent at Marang District. © Google Street View image coordinate 103.1121499235461, 5.146720931152082



Supplementary Figure 6. Rice extent at Setiu District; (a) Gong Kubu, Kederang, Bukit Kemudu, and Buruk Sub-district, (b) Alur Serdang Sub-district, © Google Street View image coordinate (a) 102.75026252196312, 5.536907633129734 (b) 102.67003608683842, 5.63992921464419

Mathad	Trai	ining	Validation		
Wiethou	Overall Accuracy	Kappa Coefficient	Overall Accuracy	Kappa Coefficient	
PEB-UC	-	-	0.979	0.957	
RF	1.000	1.000	0.875	0.743	
SVM	1.000	1.000	0.937	0.870	

Supplementary Table 1 Accuracy comparison of classification models: PEB-UC, RF and SVM

Supplementary Table 2

Rice parcel area comparison between this study data (PEB-UC), RF, SVM and statistics and its relative discrepancy

Rice Parcel Area by (ha)				Relative discrepancy			
PEB-UC	RF	SVM	Statistic	(a) and (d)	(b) and (d)	(c) and (d)	
(a)	(b)	(c)	(d)	(%)	(%)	(%)	
8,184	8,428	7,966	11,551	-29.15	-27.04	-31.04	


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The Impact of Air Pressure on Performance, Combustion Behavior, and Emissions of An Air-assisted Port Fuel Injection HCCI Engine

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ABSTRACT

Low-temperature combustion is achieved through homogeneous charge compression ignition (HCCI), which lowers the emission of nitrogen oxides (NOx) associated with diesel engines. HCCI combustion faces various obstacles, including combustion phasing, high hydrocarbon (HC) emissions, a limited operation range, and homogeneous mixture preparation. This research aims to compare the influence of air pressure in an air-assisted injector on performance, combustion behavior, and emissions. The experiment was conducted at an intake temperature of 50°C, speed of 2100 RPM and air pressures of 3,4 and 5 bar. Intake air was heated in an intake pipe heater, and an air regulator regulated the air pressure. An air assist pressure of 5 bar resulted in the highest brake thermal efficiency, ranging from 20.5% to 23.3%. For brake-specific fuel consumption, an air pressure 3 bar produced higher values ranging from 410.8 g/kWh to 500.8 g/kWh. The in-cylinder pressure

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E-mail addresses: firdausdzulkafli@gmail.com (Mohd Firdaus Dzulkafli) ahziz@upm.edu.my (Abdul Aziz Hairuddin) memo.alprince41@gmail.com (Muntasser Abdulabbas Mossa Al Anbagi) * Corresponding author for 3,4 and 5 bar pressure exceeds 80 bar at 25% load. Air pressure of 4 bar recorded the lowest HC, ranging from 50 to 75 ppm. For NOx emission, 3 bar air pressure showed the lowest levels, ranging from 8 to 12 ppm across the tested loads. The highest carbon monoxide (CO) percentage was recorded at 5 bar air pressure at 20% load with a CO value of 0.53%. At 20% and 25% load, the combustion profile displayed a three-stage ignition process, indicating the occurrence of diffusive combustion.

Keywords: Air assisted, diesel, fuel injection, HCCI, internal combustion engine, port fuel injection

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INTRODUCTION

Internal combustion has been dominated by spark ignition (SI) and compression ignition technology (CI) technologies. In traditional SI engines, the spark plug ignites the homogeneous charge of fuel-air. In compression ignition (CI) engines, the combustion is facilitated by the high compression of the homogenous charge of fuel and air mixture inside the combustion cylinder. The depletion of fossil fuels and growing environmental concerns have prompted research to find alternative fuels for sustainable energy solutions. Experimental research on biodiesel by several researchers (Zheng & Cho, 2024; Engine, 2023; Khujamberdiev & Cho, 2023; Zheng & Cho, 2023; Khujamberdiev et al., 2023) shows that castor oil and swine oil can be mixed with diesel without the need for major engine modifications. Various combustion technologies have been developed to enhance internal combustion in both spark ignition and direct injection engines, with particular attention paid to improving the fuel and air mixture. More researchers are involved in the study of advanced combustion to improve engine efficiency and emissions in internal combustion. Premixed charge compression ignition (PCCI), reactivity-controlled compression ignition (RCCI) and homogeneous charge compression ignition (HCCI) are some of the advanced combustion modes based on the conventional CI and SI technologies. The PCCI combustion mode uses two fuels with different reactivity injected at the intake port and the cylinder. RCCI also uses a dual-fuel injection method, and the ignition timing is controlled by changing the ratio of these two fuels. Figure 1 shows the different combustion modes in internal combustion. One of the combustion technologies that has attracted significant interest is HCCI. HCCI combines spark ignition and compression advantages for better combustion performance. The air-fuel mixture is premixed and compressed at high pressure to auto-ignite the charge in the HCCI engine (Pandey et al., 2018).

Managing combustion phasing in HCCI combustion is challenging. In traditional SI engines, spark timing controls combustion, while in CI engines, the fuel injector controls the injection. In HCCI, the fuel and air mixture are homogenously premixed before combustion with auto-ignition depending on factors such as intake temperature, mixture



Figure 1. Combustion mode in internal combustion engine (Duan et al., 2021)

homogeneity, compression ratio, fuel properties and more. High unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions, cold start issues, and homogenous mixture preparation are some of the obstacles in HCCI (Yao et al., 2009).

The HCCI engine is associated with the low-temperature combustion (LTC) method. A higher degree of dilution minimizes combustion temperature and prolongs the ignition delay. This extended ignition delay reduces homogeneities in the reactant mixture and allows the fuel to evaporate, which in turn reduces the production of nitrogen oxides (NO_x) from locally hot zones and soot from locally fuel-rich zones (Kumar & Rehman, 2016).

Two mixing strategies can reduce the local fuel regions. The strategies for mixture preparation are either in-cylinder direct injection or external mixture, as shown in Figure 2.

Effective mixture preparation and avoiding wall wetting are critical for improving fuel economy, lowering hydrocarbon (HC) and particulate matter (PM) emissions, and preventing oil dilution. Fuels with low volatility, such as diesel, are challenging for HCCI combustion. Elevated intake air temperature or fuel atomizer is used for better fuel and air mixture formation. Port fuel injection (PFI) is one of the external mixture formation methods used to create a better homogenous mixture of fuel and air, improving combustion effectiveness. Ganesh and Nagarajan investigated HCCI combustion of diesel fuel using PFI with a fuel vaporizer. Experiments were performed both without EGR and with varying percentages of EGR. Low NOx and smoke emissions were obtained, with fuel consumption 12% higher than the standard diesel operation when the engine was operated with 30% EGR (Ganesh & Nagarajan, 2010). The performance comparison of diesel and biodiesel in HCCI mode was investigated by Singh et al. (2014) using the PFI strategy. It was discovered that combustion is more stable in biodiesel HCCI than diesel HCCI because of the lower heat release rate (RoHR) rate in biodiesel. Fuel adaptability is one of HCCI's benefits. Maurya and Agarwal (2014) examined the performance, combustion, and emission characteristics of an HCCI engine powered by ethanol and methanol and compared the results to baseline gasoline fuel. Experiments were performed on a modified HCCI engine operating at varying intake air temperatures and relative air fuel ratios using ethanol and methanol as fuels. Compared to ethanol and methanol, gasoline requires higher



Figure 2. Strategies for mixture preparation (Bendu & Murugan, 2014)

engine speeds and intake temperatures. Port injection pressure has a considerable impact on the performance and emissions of an HCCI engine (Gowthaman & Gobikrishnan, 2021) used fuel injection pressure of 2,3 and 4 bar to study fuel penetration and mixing quality in an HCCI engine. The HCCI engine operating at 3 bar exhibits superior brake thermal efficiency (BTE) values under all loading conditions and produces approximately 10% more power than a normal diesel engine. Increasing the air intake temperature also helps the auto-ignition of the HCCI combustion, as studied by Dhileepan et al. (2023), Teoh et al. (2021) and Parthasarathy et al. (2020).

Most researchers have used fuel vaporizers for low-volatility and high-viscosity fuels to facilitate mixture formation. One of the less common methods involves using air assistance for external formation. Early studies on air-assisted injection have focused on the spray and atomization characteristics of the injector (Wu et al., 2020; Kourmatzis et al., 2013; Fan et al., 2014; Das & Dent, 1994). Cathcart and Zavier (2000) studied the basic characterization of Orbital's pressure air-assisted, spray-guided combustion system, considering the effect of in-cylinder charge motion, injected gas composition and injection pressure. The studied combustion system has demonstrated the potential to operate more stratified with reduced fuel consumption and emissions at a nominal injection pressure of 6.5 bar gauge. Two-phase injectors in constant volume chambers and optical engines have been studied using laser diagnostic and computational fluid dynamic techniques by Boretti et al. (2007). The characteristics of air-assisted fuel injection in a constant volume space have also been explored by Wu et al. (2019). Kerosene was used under different gasoline direct injection (GDI) engine conditions. As the chamber pressure increased from 0.5 bar to 3.5 bar, the penetration decreased because of air and fuel interface differential pressure reduction and resistance to penetration.

Previous studies have concentrated on the direct injection performance and characteristics of air-assisted fuel injectors (Saikalis et al., 1993; Jin et al., 2004; Leach et al., 2005). The application of air-assisted injection has been extended to homogenous charge compression ignition-direct injection (HCCI-DI) combustion. A homogenous mixture of fuel and air is prepared upstream of the intake manifold, known as PFI. This method avoids the wall wetting on the cylinder walls. Air-assisted injection can replace the high-pressure PFI injection used by many researchers. Teoh et al. (2021) investigated the impact of premixed ratio and intake temperature on combustion behavior in a partial HCCI-DI diesel engine. Significant advancement in the start of combustion, along with higher HC and CO emissions, was observed along with the pressure rise when the premixed ratio was increased. An increase in intake temperature improved the HC emissions but contributed to higher CO and NOx being released.

This study aims to assess the influence of air assist pressure in a single-cylinder HCCI engine on its performance, combustion behavior, and emissions. Three different air pressure

settings, 3, 4 and 5 bar, are evaluated. The fuel and air are mixed via port fuel injection using a low-pressure pump and air compressor.

MATERIALS AND METHODS

Experimental Setup

A single-cylinder, four-stroke direct injection (DI) diesel engine was employed in this study. The technical specifications of the diesel engine are shown in Table 1. The engine was connected to an eddy current dynamometer, allowing the engine load to be varied. In this experiment, the load varied from 5% to 25%. Fuel consumption was recorded manually using a burette and a stopwatch. Brake power and torque were recorded using dynamometer software. The in-cylinder pressure was measured with an Optrand pressure sensor and recorded on a computer using customized software.

Figure 3 shows the setup of the diesel engine. The engine was fitted with an intake pipe with a coil heater. The intake manifold was equipped with a Type-K thermocouple sensor, while the exhaust temperature was measured using another Type-K thermocouple sensor. The air-to-fuel ratio was measured using a Bosch wideband Innovate Motorsport sensor, displayed through MTX-L digital air/fuel ratio gauge. The rotational speed was measured with a

Table 1		
Technical specification	of the	engine

Description	Specification
Make	Yanmar
Model	L48N
Туре	Diesel engine
Bore x Stroke	$70 \times 57 \text{ mm}$
Displacement	0.219 L
Rated Power	3600 rpm
Rated Speed	3.5kW
Fuel Injection timing	16.5° BTDC



Figure 3. Setup of the port fuel injection air-assisted HCCI

Hall sensor and fed to the dynamometer software. The intake manifold was fitted with a Synerjet Strata air assist injector, supplied using a compressor via an air pressure regulator. The injector properties are given in Table 2. Emissions were analyzed using the EMS 5002 Portable Gas analyzer. Figure 4 shows the experimental engine setup.

Diesel is supplied via direct injection at the beginning of the experiment. Once the engine is stable, the manual valve supplying fuel for the direct injection is closed, and fuel is supplied through PFI using an air assist injector in HCCI mode. The settings of the air assist injector were configured through Tuner Studio software (Figure 5). Figure 6 shows the air assist injector with fuel injector and rail. The air temperature intake was



Figure 4. Experimental setup of air-assisted HCCI engine



Figure 5. Tuner Studio software for the air assist injector



Figure 6. Air assist injector

controlled using Watlow series 988 temperature controllers. Air pressure varied at 3, 4 and 5 bar via the air pressure regulator. The intake temperature was set at 50°C, and the load

was adjusted to 5%,10%,15%,20% and 25% at 2100 rpm. Table 3 shows the parameter settings for the experiment. All recorded power, in-cylinder pressure, and emission readings were repeated three times for each air pressure setting to ensure consistency.

Fuel Properties

For this experiment, Petronas diesel Euro 5(B0) was used as the fuel. The diesel was obtained from Pandamaran Synergy Petroleum. The physical and thermal properties of diesel fuel were tested according to American Society for Testing and Materials (ASTM) standards, and the results are presented in Table 4.

Table 2Synerjet strata injector specification

Description	Specification
Maximum Pressure	850kPa
Static Air Flow	0.1-2.5 g/sec
Dynamic Air Flow	0.1-0.9 g/sec
Atomization	4 SMD-28 SMD(µm)
Operating voltage	8V-18V

Experimental parameter settings for HCCI

Description	Specification
Air assisted pressure	3, 4 and 5 bar
Load	5, 10, 15, 20 and 25%
Intake temperature	50°C
Speed	2100 rpm
Mode	PFI

Table 4
Properties of diesel

Properties	Method	Unit	Value
Density	ASTM D 4052-11	kg/L	0.8409
Kinematic Viscosity	ASTM D 445-14	mm ² /s	3.650
Heating Value	ASTM D 4737-10	MJ/kg	44.022
Cetane Number	ASTM D 4737-10	-	55

RESULTS AND DISCUSSION

Effect of Air Pressure on Engine Performance

Figure 7 shows brake power variation with increasing load. At a 5% load, the brake power for all air assist pressures showed no significant difference, varying from 0.63kW to 0.66kW. As the load increased, the brake power for 5 bar rose higher than that for 3 and 4 bar pressure. The brake power at 5 bar air assist pressure increases by 63.7%, with values ranging from 0.66kW to 1.82kW as the load increases from 5% to 25%. As load increases, brake power range is from 0.66kW to 1.67kW. An air pressure of 3 bars recorded the lowest brake power, ranging from 0.63kW to 1.59kW. At 25% load, brake power of 1.59kW, 1.67kW and 1.82 kW were recorded for air pressure of 3,4 and 5 bar, respectively.

BTE variations with varying air assist pressure are shown in Figure 8. An air assist pressure of 5 bar demonstrates a higher BTE compared to 3 and 4 bar air pressure, with BTE values ranging from 20.3% to 23.3% as load increases. Air assistance at 3 bar shows the lowest BTE across all load conditions compared with the other pressure, with values ranging from 16.3% to 19.7%. The 4-bar air assist pressure shows BTE values ranging from 16.5% to 20.5%. At 25% load, the air assist pressure of 5 bar shows an 18.3% improvement compared to 3 bar. The significant improvement in BTE percentage shows that higher pressure of air assistance substantially affects the performance of HCCI combustion. The atomization of diesel fuel was improved with the introduction of higher air-assisted pressure.

Figure 9 compares brake-specific fuel consumption (BSFC) for all air pressure settings. At a low load of 5%, the air pressure of 5 bar demonstrates the lowest BSFC of 398.9 g/ kWh compared with 3 and 4 bar air pressure, which shows values of 500.8 g/kWh and 494.5 g/kWh, respectively. As load increases, the BSFC for 5 bar air pressure shows a significant difference compared to the 3 and 4 bar, with values ranging from 398.9 g/kWh to

347.5 g/kWh. For 3 bar air pressure, BSFC varies from 500.8 g/kWh to 410.8 g/kWh. For 4 bar, the BSFC decreases from 494.5 g/kWh to 365.1 g/kWh as the load increases from 5% to 25%. Mixture preparation has a significant effect on fuel efficiency. For HCCI operation, proper mixing of air and fuel is necessary to form a homogeneous charge. Thus, 4 and 5-bar air pressure shows better BSFC as the fuel disintegrates into smaller droplets, enhancing air and fuel mixing.



Figure 8. Brake thermal efficiency variation with varying air-assisted pressure



Figure 7. Brake power variation with varying air assist pressure



Figure 9. Brake-specific fuel consumption with various air assist pressure

Effect of Air Pressure on Combustion Characteristics

The combustion behavior of an internal combustion can be observed through the incylinder pressure and heat release rate(HRR) profile. Canova et al. (2007) performed an experimental study on an HCCI engine with a fuel atomizer to observe the cylinder pressure and net heat release against the crank angle. One of the indicators of combustion behavior in HCCI combustion is HRR analysis, which is determined using the cylinder pressure data illustrated by Equation 1 (Ganesh & Nagarajan, 2010).

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} * P * \frac{dv}{d\theta} + \frac{1}{\gamma - 1} * v * \frac{dP}{d\theta}$$
[1]

The combustion process for HCCI diesel uses a two-stage heat release. A small percentage of the total energy (7%-10%) is released during the first stage of heat release, which is caused by low-temperature reactions (LTR), and a larger fraction is released during the second stage, which is caused by high-temperature reactions (Hasan & Rahman, 2016).

Figure 10 displays the in-cylinder pressure and HRR profile for a 5% load. The air pressure 3 bar recorded a maximum in-cylinder pressure of 60.9 bar, which is lower than the 4 and 5 bar air pressures. The 4 and 5 air pressures recorded maximum in-cylinder pressures of 62.8 bar and 63.1 bar, respectively. The pressure profile of 4 and 5 bars also indicates earlier combustion compared to the 3-bar air pressure. The HRR profiles for 4 and 5 bars are almost similar, showing no significant difference.

As the load increases to 10%, the in-cylinder pressure and HRR also increase compared to the 5% load, as illustrated in Figure 11. The maximum in-cylinder pressure recorded by the 3, 4 and 5 bar air pressure settings is 62.4 bar, 64.2 bar and 65.8 bar, respectively.



Figure 10. HRR profile and cylinder pressure at 5% load



Figure 11. HRR profile and cylinder pressure at 10% load

The HRR profile shows a similar pattern as the 5% load. The HRR profile for 5% and 10% load displays two-stage ignition with almost identical combustion timing.

From Figure 12, the maximum cylinder pressure increases to 67.2 bar, 70.3 bar and 69.7 bar for air pressures of 3, 4 and 5 bar, respectively, as the load increases to 15%. The HRR generally increases for all pressure settings as more fuel is required, resulting in a lower lambda λ value. An additional spike around the Top Dead Centre (TDC) indicates that early combustion occurred compared to the 5% and 10% load.

At 20% load, the combustion phase for all air pressure is almost similar, although the maximum cylinder pressure for 3 bar air pressure recorded at 75.2 bar is lower compared to 4 and 5 bar settings. Maximum cylinder pressure for 4 and 5 bars are 79.4 bar and 78.8 bar, respectively. The maximum HRR has increased beyond 4.0 J/°CA for 4 and 5-bar air pressure, as shown in Figure 13. The HRR profile exhibits a significant three-stage ignition, with the highest peak occurring after the combustion stage. It suggests that diffusive combustion is still taking place, indicating that the fuel and air may not have mixed properly during the first stage of ignition.

Figure 14 displays the in-cylinder pressure and HRR of the HCCI engine at its maximum load. The in-cylinder pressure values have exceeded 80 bar for all air pressure settings. The maximum cylinder pressures for 3, 4 and 5 bars are 88.0 bar, 89.1 bar and 87.5 bar, respectively. Higher pressures lead to a knocking problem, a significant problem in HCCI combustion. Operating at loads higher than 25% may cause substantial noise and vibration, potentially damaging the engine. The initial spike in the HRR rate also increases significantly, indicating that early combustion has occurred. In an HCCI engine, the volumetric ignition of full charge causes rapid HRR, which could result in knocking combustion (Chaudhari & Deshmukh, 2019).



Figure 12. HRR profile and cylinder pressure at 15% load



Figure 13. HRR profile and cylinder pressure at 20% load



Figure 14. HRR profile and cylinder pressure at 25%

Effect of Air Pressure on Emission

HCCI allows minimal nitrogen oxide and soot emissions. Introducing oxidation catalysts into the fuel can enable low carbon monoxide emissions and unburned hydrocarbons in HCCI engines. HCCI may be a viable alternative to diesel for achieving low urban and global pollution levels due to its cleaner emissions (Saxena & Bedoya, 2013). Figure 15 shows the emission of HC and NOx. The air pressure of 4 bar recorded the lowest HC emissions, ranging from 50 to 75 ppm, compared with 3 and 5 air pressure. For 3-bar air pressure, HC values ranged from 50 to 79 ppm, while the 5-bar air pressure recorded values ranging from 44 to 91 ppm. Higher HC levels are a consequence of incomplete combustion. 3 bar air pressure shows poor mixture formation, contributing to higher HC.

For NOx emission, an air pressure of 3 bar showed the lowest ppm ranging from 10 to 12 ppm throughout the tested load compared with 4 and 5 bar air pressures. The 4-bar air pressure recorded NOx values ranging from 11 to 17 ppm, while the 5-bar air pressure showed NOx emissions ranging from 15 to 21 ppm. NOx emissions are formed by the reaction between nitrogen and oxygen at high temperatures and pressures during the combustion process in an engine cylinder (Pandey et al., 2012). Based on the HRR profile, the 5-bar air assist generally exhibits higher peaks, which contribute to higher NOx emission.

The gas analyzer also recorded the emission of carbon dioxide (CO_2) and CO, and Figure 16 compares the different air pressures used. The fuel-air equivalence ratio determines CO emissions from internal combustion engines. As shown in Figure 16, CO emission, the 4-bar air pressure recorded the lowest CO emissions, ranging from 0.11% to 0.45%. The highest CO percentage was recorded by the 5-bar air pressure at 20% load with a value of 0.53%. The percentage range of CO for all air assist pressure is almost similar, as Gowthaman and Gobikrishnan (2021) reported. The highest emission of CO₂



Figure 15. Emission comparison for HC and NOx for various air pressures



Figure 16. Emission comparison for CO and CO2 for various air pressure

was recorded by 5 bar air assists with values ranging from 3% to 4.7%. The 4-bar air assist pressure showed CO₂ values ranging from 2.6% to 3.9%.

CONCLUSION

In general, all air pressure settings (3, 4 and 5 bar) can be used to run the combustion in HCCI mode. The load can be varied from 5% to 25% without any significant knocking during combustion. The engine performance, combustion behavior and emissions have been successfully analyzed. Based on the investigation, the following conclusions can be drawn:

- BTE increases as load increases for all air pressure settings. The 5-bar air pressure recorded the highest efficiency, ranging from 20.5% to 23.3%. In contrast, the 3-bar air pressure shows the lowest BTE compared to the 4 and 5-bar air pressure settings, recording values from 16.3% to 19.7%. Fuel is atomized better with 5 bar air pressure and mixed homogenously with air, leading to more efficient combustion.
- The BSFC decreases as load increases for all air pressure settings. The 5-bar air pressure demonstrates the lowest BSFC, ranging from 346 g/kWh to 399 g/kWh. The highest BSFC was recorded by the 3-bar air pressure setting, ranging from 411 g/kWh to 501 g/kWh.
- As load increases, in-cylinder pressure also rises for all three air pressure settings. At load 5% and 10%, all pressure settings exhibit two-stage ignitions, and at load 15%, 20% and 25%, a stage ignition is recorded. At 25%, the in-cylinder pressure exceeds 80 bar, which can contribute to knocking if more load is applied.
- Higher HC emissions were observed for the 3 and 5-bar air pressure settings. The
 4-bar air pressure recorded the lowest HC emission, ranging from 50 ppm to 75

ppm. The 3-bar air assist recorded the lowest value for NOx emission, ranging from 8 ppm to 12 ppm.

• The 5-bar air assist recorded the highest CO2 emissions, ranging from 3% to 4.7%, indicating high combustion efficiency. In contrast, the 4-bar air pressure exhibited the lowest carbon monoxide (CO) emissions compared to the 3-bar and 5-bar settings, with emissions ranging from 0.11% to 0.28%.

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Review Article

Integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) Concepts as an Adaptive Approach to Pollutant Loading Management in Asia: A Review

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ABSTRACT

Water scarcity and pollution are escalating challenges in Asia, impacting ecological systems and human livelihoods. This paper reviews the integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) in water management to address the dual issues of water quality and quantity. TMDL focuses on regulating the number of pollutants entering water bodies to meet quality standards, while EFA ensures that enough water is available to support aquatic ecosystems. Their independent application, however, often leads to gaps—TMDL can overlook ecological needs, while EFA may neglect pollution control. The integration of these two frameworks offers a more holistic solution, especially in water-stressed regions like Southeast Asia, where moderate water availability is exacerbated by urbanization, industrialization, and agricultural runoff. Case studies from Malaysia, Indonesia, and China reveal the limitations of applying TMDL

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fasihah.mohd.yusof@gmail.com (Fasihah Mohd Yusof) norrohaizah@upm.edu.my (Nor Rohaizah Jamil) syahida9505@gmail.com (Syahida Sapia'e) frankie@ukm.edu.my (Frankie Marcus Ata) khaliesah.malik@gmail.com (Nur Khaliesah Abdul Malik) * Corresponding author and EFA separately and underscore the necessity of addressing both ecological flow requirements and pollution limits. This paper identifies key pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), heavy metals, and total suspended solids (TSS), particularly in urban and semi-urban areas, and highlights the importance of tailoring strategies to the specific needs of different regions. By combining TMDL and EFA, policymakers can better manage pollutant loads, secure ecological health, and address Asia's pressing water management issues. This review emphasizes the need for adaptable, integrated water management strategies that account for seasonal fluctuations, competing water demands, and regional water availability and pollution differences.

Keywords: Environmental Flow Assessment (EFA), modeling, pollutant load, Total Maximum Daily Load (TMDL), water quality

INTRODUCTION

Economic development often takes priority over environmental protection, particularly in regions like Southeast Asia, where water resources are limited. Competition between industries, agriculture, and domestic users complicates pollution control. For instance, reducing water abstraction during high pollution periods is resisted due to economic costs, even though it would help maintain river flow for pollutant dilution (Monfared. et al., 2017). Weak infrastructure, poor regulatory enforcement, and fragmented governance further hinder effective water resource management (Lee et al., 2012).

The integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) is crucial for comprehensive water resource management, particularly in addressing the interconnected issues of water quality and quantity. TMDL is a regulatory tool that sets limits on the number of pollutants discharged into water bodies to meet water quality standards, primarily targeting human use, such as drinking water and agriculture (Kwon et al., 2023; US Environmental Protection Agency, 2007). It controls both the concentration of pollutants and the volume of discharge, often relying on reservoirs or dams to dilute pollutants while balancing competing water demands (Bello et al., 2024; Setiawan et al., 2018). In certain cases, high pollution levels necessitate the reduction of water abstraction by economic sectors like agriculture and domestic water supply to preserve sufficient river flow for pollutant dilution. However, this may incur significant costs (Monfared et al., 2017). Conversely, EFA ensures that rivers maintain sufficient flow to support ecological health, protecting aquatic species and ecosystem services, but it does not directly address pollutant load reduction (International River Foundation, 2007; King et al., 2019).

In Asia, TMDL and EFA are applied to address growing water management challenges, including pollution and water scarcity. However, the independent application of these frameworks reveals distinct advantages and limitations. TMDL effectively reduces pollutant loads but often overlooks ecological water needs, potentially leading to ecosystem degradation despite improved water quality (Lee et al., 2012). On the other hand, EFA guarantees ecological flow but may leave rivers vulnerable to pollution, as it does not directly tackle contaminant reduction (Liu et al., 2021). These gaps underscore the need for integration, particularly in regions like Southeast Asia, where moderate water availability is compounded by significant pollution (Sedighkia & Abdoli, 2024).

The integration of TMDL and EFA offers a holistic approach, addressing water quality and quantity needs. Both frameworks share common goals, such as regulating water discharge and maintaining flow, albeit for different purposes—TMDL for human and economic needs and EFA for ecological health. Integration ensures that pollutant load limits are set while maintaining environmental flows, balancing socio-economic demands with ecological sustainability (Godinho et al., 2014; Hall et al., 2014). This approach can solve critical issues like reconciling industrial, agricultural, and domestic water demands with the ecological needs of river systems. By combining the strengths of both frameworks, policymakers can ensure the sustainable management of water resources, particularly in water-stressed regions like Asia, where these challenges are becoming increasingly pressing (Theodoropoulos et al., 2018).

WATER QUALITY AND SCARCITY PROBLEMS IN ASIA

Water resource management in Asia faces diverse challenges, with specific regions suffering from water scarcity and pollution. In Central Asia's Aral Sea basin and northern China, severe water scarcity makes pollution control secondary, limiting the applicability of frameworks like TMDL and EFA, which focus on water quality and ecological flows (Satoh et al., 2017). In contrast, Southeast Asia has moderate water availability but struggles with industrial and urban pollution, making the integration of TMDL and EFA highly relevant (Dewata & Adri, 2018; Tang et al., 2020).

This paper focuses on managing pollutants in urban and semi-urban areas in Asia. Industrial, domestic, and agricultural activities significantly degrade water quality in these regions. Pollutants like biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and heavy metals are prevalent due to untreated wastewater and industrial discharges (Dewata & Adri, 2018; Tang et al., 2020). For instance, inadequate sewage treatment in Malaysia has led to high levels of BOD, ammoniacal nitrogen (NH₄-N), and suspended solids in rivers (DOE, 2020). Similarly, Indonesia's Cirarab River receives 80% of untreated wastewater from residential and industrial sources (Indriyani et al., 2020).

Heavy metals, ammonia, BOD, and COD are primary pollutants in Asian rivers. Rivers like the Yamuna in India and the Ganh Hao in Vietnam contain heavy metals exceeding safe limits for drinking water (Akhter et al., 2023; Muoi et al., 2022). Urbanization and industrialization intensify these challenges by increasing water demand and pollution loads (Outlook & Management, 2012). For example, in Indonesia, the TMDL for the Batang Kuranji River was used to estimate pollutant loads of BOD, COD, and TSS, setting targets to meet water quality standards for drinking purposes (Dewata & Adri, 2018).

In the Jiulong River watershed in China, effective non-point source nitrogen reduction strategies have been implemented to improve water quality for drinking and irrigation, focusing on management, mapping, and quantifying these sources (Yan et al., 2018). The increasing industrial and population development in Beijing has worsened pollution in the Beiyun River, where pollution limits are regularly exceeded due to rising sewage discharge (Zhang et al., 2015).

GAPS IN INDEPENDENT TMDL AND EFA APPLICATION

While TMDL originated in the US, many Asian countries have adopted similar frameworks with different terms. Indonesia uses PCC, while Vietnam applies RWEC (Bui & Pham, 2023; Setiawan et al., 2018). In China, RWEC is part of a broader Water Resources Carrying Capacity (WRCC) approach, integrating hydrology, ecology, and economics to assess a river's ability to support human activities and environmental health (Dou et al., 2015). These frameworks ensure that water quality targets are set based on pollutant sources and river conditions. However, these frameworks primarily focus on limiting pollutants without addressing the necessary ecological flows for ecosystem health. In Beijing's Beiyun River, China, while an integrated environmental decision support system (EDSS) for water pollution control is in progress, the water environment problems are complex. More data are needed to verify model calculations under different hydrological flow and pollution conditions and verify water quality simulations(Zhang et al., 2015).

In Korea, the TMDL system has been in place since 2004, with a focus on reducing BOD levels for rivers under low-flow conditions. The Ministry of Environment requires local governments to develop TMDLs for major rivers, and the National Institute of Environmental Research provides guidelines for this process (Kang et al., 2006; Lee et al., 2012). However, the allocation of target water quality somewhat unfairly has faced strong opposition from local governments, which has seriously threatened a plan to add more parameters to be covered in TMDL. On the other hand, efforts in India to maintain environmental flows are progressing but do not fully address pollution issues, as seen in India's Yamuna River, where untreated industrial discharges persist (Asim & Rao, 2021; Godinho et al., 2014).

EFA is progressively accepted in Malaysia within the Integrated River Basin Management (IRBM) framework, focusing on sustainable river management to preserve biodiversity and guide water resource management decisions, as highlighted by Abdullah (2017). The initiative involves various departments and institutes (Ariff et al., 2023), aiming to identify measures for reducing pollutants. However, implementing IRBM frameworks faces challenges as there are many overlapping laws and multiple agencies with fragmented responsibilities. Adopting loading-based standards, such as TMDL, remains a distant goal. Alternatively, the Water Quality Index (WQI) (Table 1), a concentration-based approach, is currently utilized to assess and monitor water quality (DOE, 2020). While it is useful for resource management, this approach is limited in effectively regulating industrial

discharges, as it does not account for cumulative pollutant loads, potentially leading to less stringent control over pollution sources. The selected applications of TMDLs across Asia are presented in Table 2.

DADAMETED	UNIT			CLASS		
FARAMETER	UNIT	Ι	II	III	IV	V
PH	_	> 7	6–7	5–6	< 5	> 5
DISSOLVED OXYGEN (DO)	mg/L	> 7	5-7	3–5	1-3	< 1
BIOCHEMICAL OXYGEN DEMAND (BOD)	mg/L	< 1	1–3	3–6	6–12	> 12
CHEMICAL OXYGEN DEMAND (COD)	mg/L	< 10	10–25	25–50	50-100	> 100
SUSPENDED SOLIDS (SS)	mg/L	< 25	25-50	50-150	150-300	> 300
AMMONIACAL NITROGEN (AN)	mg/L	< 0.1	0.1-0.3	0.3-0.9	0.9–2.7	> 2.7
WATER QUALITY INDEX (WQI)	_	< 92.7	76.5–92.7	51.9–76.5	31.0-51.9	> 31.0

Table 1Malaysian Water Quality Index (WQI) Classification (Department of Environment Malaysia, 2020)

Table 2TMDLs application in Asia

NO.	LOCATION	METHOD	REFERENCES
1	Yamuna River, Delhi, India	The QUAL2K assessment of organic matter breakdown in terms of BOD, DO, nitrification-denitrification, and phosphate reduction in the composite river water body.	Mangottiri et al., 2011
2	Hongqi River	The QUAL2K model was calibrated by adjusting the input pollution loads through trial and error until the water quality simulation results met the desired objectives	Zhang, 2012
3	Qiantang River Watershed, China	The conventional one-dimensional point discharge model and QUAL2K model were used to examine the BOD assimilative capacity to ensure the sustainable use of water resources.	Fang et al., 2014
4	Karun River Basin, Iran	QUAL2K was the water quality modeling framework employed. BOD and dissolved oxygen were the input parameters used in QUAL2K.	Marzouni et al., 2014
5	Beiyun River, China	Environmental Decision Support Systems (EDSS) development includes hydrological and pollutant load, hydrodynamic, water quality, environmental capacity, and load distribution model.	Zhang et al., 2015
6	Malacca River, Malaysia	TMDL is carried out by conducting water quality monitoring, developing a water quality model using Environmental Fluid Dynamic Codes (EFDC), and implementing a TMDL implementation plan.	Osmi et al., 2016
7	Lake Chini, Malaysia	TMDL was determined by bedload and suspended load sampling in both the dry and rainy months.	Dom et al., 2016

Table 2	(continue)
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NO.	LOCATION	METHOD	REFERENCES
8	Galing River, Kuantan, Pahang, Malaysia	A numerical model was created using the Environmental Fluid Dynamic Code (EFDC) to determine the optimal action for enhancing the water quality.	Lee et al., 2017
9	Luliao Reservoir Watershed, Taiwan	The EPA's SWMM identifies pollution hotspots and calculates total phosphorus loads. At the same time, the Vollenweider model evaluates water quality in reservoirs under different pollution scenarios, informing TMDL calculations based on target water quality concentrations.	Chen et al., 2016
10	Langat River, Malaysia	Using the application of QUAL2K, the water quality of Sungai Langat is assessed based on the low-flow dry period Q1007.	Abidin et al., 2018
11	Selangor River, Malaysia	The QUAL2K simulation model was used to determine river water quality using the Water Quality Index (WQI). The water quality variables DO, BOD, and NH ₃ -N were used for modeling.	Chowdhury et al., 2018
12	Dengsha River, China	The export coefficient approach was combined with the QUAL2K water quality model to calculate the loads of NH4-N and total phosphorus from various sources and investigate their individual contributions.	Xin et al., 2019
13	Yeongsan River basin, Korea	A fuzzy model for managing water quality was created to address the satisfaction level related to the cost of reducing pollution and improving river water quality.	Cho & Lee, 2020
14	Skudai River, Malaysia	This study utilized an integrated QUAL2K-GIS application to reduce NH3-N pollution discharge to improve Skudai River's water quality for use as a source of water supply.	Kamal et al., 2020
15	Belik River, Yogyakarta	BOD load reduction using the Water Quality Analysis Simulation Program (WASP) modeling.	Tofani & Hadi, 2020
16	Johor River Basin, Malaysia	The variations in the water quality metrics between base and storm flow events were studied to pinpoint the pollutant sources.	Mohamad et al., 2020
17	Duliujian River, Tianjin, China	Water quality standards are established based on the TMDL and the water's capacity in accordance with the water body's needs.	Liu et al., 2020
18	Tungabhadra River, India	To forecast the water quality in the contaminated areas of the river, use the QUAL2KW water quality model.	Ranjith et al., 2020
19	Tebrau River, Johor	This study used QUAL2K, the modernized version of QUAL2E, to simulate the impact of pollution from industrial areas on the Tebrau River Basin.	Kamal et al., 2020
20	Daejeon City	The study used two methods: the Load Conversion Method (LCM) adjusts discharge loads for rainfall changes, while the Multi-Regression Equation Method (MREM) predicts discharge loads directly.	Park et al., 2021
21	Jing-Mei Creek	The study used HEC-RAS and QUAL2K simulations to determine flow velocities and water depths for different river sections.	Fan et al., 2009

Table 2	(continue)
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NO.	LOCATION	METHOD	REFERENCES
22	South Korea	The CA-Markov model was used to simulate changes in LULC under the influence of the special countermeasure area (SCA) and TMDL.	Song, 2021
23	Citarum River, Indonesia	To assess pollutant load allocation using the river's TMDL. The pollutant load is BOD, and the model makes use of QUAL2KW.	Djuwita et al., 2021
24	Batu Pahat River, Malaysia	The study measured six parameters: DO, BOD, COD, NH3-N, TSS, and pH. It used them as input in the QUAL2K model to simulate water quality and explore different scenarios for reducing pollutant concentrations.	Adnan et al., 2022
25	Gua Musang, Kelantan, Malaysia	The impacts of mining on water quality during different flow conditions were modeled over time. HEC-RAS and QUAL2K were used for river and stream quality modeling.	Anees et al., 2022
26	Lam Takhong River, Thailand	A one-dimensional steady-flow systems river water quality model, QUAL2KW, was built and simulated to identify the sources of influence on the river's water quality.	Tran et al., 2022
27	Kedah River, Malaysia	Analyzed secondary data to assess TMDL for five water quality parameters, incorporating Risk Quotients analysis. Flow estimation was achieved using remote sensing using Bjerklie's model.	Ariff et al., 2023
28	South Korea Watersheds	The land-based diffused pollutant unit load values are utilized in the Natural Resources Conservation Service (NRCS) technique to compute the diffuse pollutant discharge loads in the TMDL standards.	Kwon et al., 2023
29	Jeneberang River, Indonesia	A geographical methodology and a numerical water quality model are used to calculate TMDL.	Kurniawan et al., 2023
30	Hai Phong City, Vietnam	Contaminants analyzed included BOD5, NH ₄ , NO ₃ , DO, and others. The pollutant load production in the water quality model helps forecast pollution trends. This study used MIKE11, a one-dimensional hydrodynamic model.	Hoang et al., 2023

MODELLING TOOLS

Modeling serves as a vital tool in watershed management, offering insights into water system behavior and predicting the effects of management strategies (Wang et al., 2014). Water quality modeling and hydraulic-hydrological models form the basis for determining water environment capacity and calculating pollutant load reductions (Zhao et al., 2012). In recent years, water quality modeling has emerged as a scientifically robust method for understanding the relationship between pollutant reduction and water quality enhancement (Wang & Lin, 2013). It has become a valuable tool for water quality management decision-making (Figure 1).



Figure 1. Linkages among watershed, transport, and water quality models (Camacho et al., 2019)

CHALLENGES AND WAYS FORWARD

Water management in a river basin is inherently complex, requiring the reconciliation of multiple, sometimes conflicting needs such as water use, flood control, and ecosystem protection. This challenge becomes more pronounced when considering the integration of Total Maximum Daily Load (TMDL) and Environmental Flow Assessment (EFA) for pollution control. This concept is crucial for addressing river and wetland pollution. However, it remains unclear worldwide, hindering risk assessment, policy formulation, and solutions (Liu et al., 2021). A crucial aspect of this integrated approach is the recognition that different stakeholders, including industries, agricultural users, domestic consumers, and environmental advocates, have diverse needs and priorities (Huang et al., 2023; Jiménez et al., 2020; Saddiga et al., 2022). The necessity of storing flood runoff and releasing it according to the needs of different water users must be balanced against instream ecosystem needs, which can often conflict with agricultural, industrial, ecosystem needs and domestic water demands (Kennen et al., 2018; Zhang et al., 2023). For instance, opposition from local governments to target water quality allocations complicates matters (Khalid et al., 2018; Lavorel et al., 2020; Lee et al., 2012; Sim et al., 2018), making achieving water quality objectives challenging, even when there is no discharge (Chen et al., 2014).

To succeed, adjustments to target water quality allocations are necessary, considering multiple stakeholders and water resources to ensure sustainability (Novotny, 2004). Each river basin may require tailored policies, reflecting varied priorities such as surface water or

groundwater usage (Wang et al., 2019). Several multi-criteria decision-making-model such as the Cobb-Douglas production function (Sun et al., 2023), can be applied to determine the most feasible solution that closely aligns with the subjectively chosen optimal values for each water target objective (Shang, 2008; Wang et al., 2024).

Moreover, the variability in hydrological conditions across seasons poses another challenge (Arthington et al., 2018; Kennen et al., 2018; Liu et al., 2005; Zhang et al., 2020). In regions like northern China, where flow rates fluctuate dramatically, relying on consistent discharge estimates for TMDL and EFA becomes problematic (Li et al., 2018; Li et al., 2010). Seasonal variations necessitate adaptive management strategies that can adjust pollutant load limits and flow requirements in response to changing environmental conditions (Firizqi & Widyastuti, 2020; Ge et al., 2018; Park et al., 2021; Todeschini et al., 2011; Wang & Lin, 2013). This adaptability is crucial for maintaining ecological integrity while meeting human water needs, particularly during low-flow periods when pollutant concentrations can rise significantly (Torrefranca et al., 2021).

Numerous laws have gaps and overlaps; many agencies and departments are also involved in dealing with fragmented sectoral functions (Saddiqa et al., 2022). There is invariably a lack of resources to enforce (Abdullah, 2017; Nurtazin et al., 2019). For instance, Malaysia and most Southeast Asian countries require shifting from concentration-based regulations to load-based pollutant limits, which would necessitate regulatory reforms and the introduction of TMDL frameworks to manage cumulative pollution loads effectively (Firizqi & Widyastuti, 2020). Furthermore, introducing legislation to protect minimum environmental flows is essential, alongside adaptive management strategies that adjust flow requirements based on seasonal and real-time water availability, securing ecosystem health while balancing human and industrial demands (Meynell et al., 2021; Zhang et al., 2020). Adopting an Integrated River Basin Management (IRBM) approach would facilitate collaboration and governance among stakeholders, ensuring that both water quality and quantity are managed holistically to meet the needs of industries, communities, and ecosystems (Burke & Do, 2021; Park et al., 2021; Syahputra et al., 2022).

Furthermore, enhancing data collection and sharing is critical for informed decisionmaking. Establishing geospatial databases and monitoring systems can provide valuable insights into water quality and flow dynamics, enabling more effective management strategies (Gorgoglione et al., 2020). It is particularly important in regions facing data scarcity, where unreliable information often hinders informed policymaking.

CONCLUSION

In conclusion, while integrating TMDL and EFA presents significant challenges in Asian river basin management, adopting a collaborative, data-driven, and flexible approach

can pave the way for more sustainable water resource management practices. A balanced approach that supports both human needs and ecological health can be achieved by addressing the complexities of stakeholder interests, regulatory frameworks, and climate variability.

More research is needed to develop standardized methodologies and guidelines for assessing pollutant loads and environmental flow requirements, considering the unique characteristics and challenges faced by Asian rivers. Additionally, the integration of advanced modeling tools, such as water quality modeling and hydraulic-hydrological models, can enhance the accuracy and effectiveness of TMDL and EFA assessments. These models can provide valuable insights into the behavior of water systems and help predict the impacts of different management strategies. Furthermore, collaboration among countries in the region is crucial to sharing knowledge, experiences, and best practices in implementing TMDL and EFA approaches, as water resources are often shared among multiple countries. By continuously improving and refining these approaches, Asia can better manage and mitigate the impacts of water pollution, ensuring the sustainable use and protection of freshwater resources for future generations.

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Short Communication

Comparison of Tensile Properties Data Analyzed Using ANOVA and MANOVA Methods: Case Study Data of PVA-Gambir Blend Film

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ABSTRACT

In our previous research, the Analysis of Variance (ANOVA) method was applied to analyze data on the tensile properties of pure PVA films and blend films mixing PVA (10%), BA (0.5%), and UG (1%). The results using ANOVA analysis are not significant for treatments in samples. This study compares data from Multivariate Analysis of Variance (MANOVA) and ANOVA methods. The accuracy level of both methods is $\alpha = 5\%$ (0.05). The result showed that the tensile properties of samples

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Keywords: ANOVA, MANOVA, multivariate analysis, PVA film, tensile properties

INTRODUCTION

Polyvinyl alcohol (PVA) is a synthetic polymer with good biodegradability in the natural environment (Alonso-Lopez et al., 2021; Hashim et al., 2021). This material can overcome the problem of natural environmental degradation due to its properties when disposed of in nature. However, PVA has limitations in terms of physical and chemical properties, so to overcome the limitations, the ratio of PVA (10%), BA (0.5%), and UG (1%) was chosen when developing polymer blend film because of the distinct properties each component brings and the desired characteristics of the final film. Previous research has shown that incorporating Gambir at certain concentrations improves the physical and chemical characteristics of polyvinyl alcohol (PVA), especially regarding its ability to block UV rays (Abral et al., 2022). The results show that Gambir has promising uses for food packaging. However, PVA/UG blends have some drawbacks. The limitations of these blend films for food packaging come from their highly hydrophilic (water-attracting) nature. It is recommended that substances that decrease the hydrophilic properties of the blend films be added to address these limitations. Research has shown that boric acid has the potential to reduce issues caused by the hydrophilic nature of these materials (Mahdi & Habeeb, 2023). As a result, composite film materials show improved physical and mechanical characteristics (Rahmadiawan et al., 2022).

Tensile properties describe the ability of materials to hold deformation force until they break. Tensile properties were primarily measured at the tensile test, in which the force was applied slowly at the tip of the sample while the other tip was fixed (Zheng et al., 2020).

This research has a range of applications across various industries, particularly where biodegradable, functional, and active packaging materials are needed, i.e., food or pharmaceutical packaging (Sunarsono et al., 2024). The novelty lies in the strategic use of PVA, boric acid, and Uncaria gambir to create biodegradable, mechanically robust films with sustained bioactive properties, thereby filling gaps left by earlier research.

Statistical methods, especially analysis of variance (ANOVA), have become effective analytical tools for examining significant differences between two or more data groups (Rahmadiawan et al., 2022). In the context of material tensile properties, ANOVA can be used to determine whether there are significant differences in tensile properties between different groups of materials.

The previous research was done on the same type of PVA with 1% Gambir added, using different treatment times (Rahmadiawan et al., 2022). It used ANOVA, which is a single dependent variable. Hence, this experiment used MANOVA, which extends ANOVA by allowing for the analysis of multiple dependent variables simultaneously while considering their potential interrelationships. MANOVA is a statistical method to identify the relationship between multiple dependent and one or more independent variables. Using MANOVA along with ANOVA can help determine if there are no significant differences between treatments and provide recommendations for more appropriate analyses to find treatment differences in the same sample in Khorasani et al. (2021) to find effective variables.
This research introduces a more effective alternative to ANOVA for statistically analyzing material testing data: MANOVA. It enables a more accurate and efficient evaluation of interaction effects between various materials compared to running separate ANOVA tests for each dependent variable (Huang, 2020). Additionally, MANOVA considers the correlations between the dependent variables, thereby providing more reliable results and reducing the risk of type I errors.

MATERIALS AND METHODS

Data

The data used in this study is secondary data, namely tensile properties data in previous studies (Rahmadiawan et al., 2022). The variables observed were tensile strength with additional treatment of Pure Polyvinyl Alcohol (PVA), Polyvinyl Alcohol/Boric Acid (PVA/BA), Polyvinyl Alcohol/Uncaria Gambir (PVA/UG), and Polyvinyl Alcohol Uncaria Gambir/Boric Acid (PVA/UG/BA). Samples were cut using a mold according to ASTM D638-14 type 5 tensile test standards, with five samples per variation/treatment. The thickness and width of the samples were measured using an optical microscope at 5 points. The samples were stored in a desiccator for ± 2 days until they reached RH = $50 \pm 5\%$.

Analysis Method

ANOVA was used in the PVA-Gambir-Boric Acid Blend Film's study to determine treatment differences. ANOVA was used to assign differences in sample treatment by adding components, namely PVA, PVA/BA, PVA/UG, and PVA/UG/BA, which obtained significant results at the α level (5% = 0.05). Based on Almonroeder (2022), ANOVA compares the average between three or more groups or treatments. The primary purpose of ANOVA is to specify whether there is a significant difference between the means of the groups on one type of response or outcome variable. Whereas in the research conducted by Rahmadiawan et al. (2022), four results will be known, namely tensile strength (MPa), tensile modulus (GPa), toughness (MJ/m³), and elongation at break (%). For this reason, this study will provide an alternative for determining differences in each treatment with four results or responses that MANOVA will see. MANOVA is a statistical method used to simultaneously compare the averages of two or more groups on two or more dependent variables. MANOVA will provide another alternative to evaluate whether there is a significant average difference between groups on all response or outcome variables simultaneously.

RESULTS AND DISCUSSION

The average difference in the sample with four treatments and four test results is made by determining the response or outcome variables and predictor variables that will be used

for the testing process to be carried out simultaneously. There are four response variables used, namely Mod Elastic (Y1), Tensile Strength (Y2), Break_Strain (Y3), and Toughness (Y4), as well as four predictor variables, namely PVA 10% (X1), PVA + BA (X2), PVA + G (X3), PVA+BA+G (X4). This research used PVA, BA, and UG to create polymer blend films due to the specific and complementary properties each material contributed to the film. It allows them to create multifunctional, eco-friendly films that meet various application requirements, especially in a critical mechanical performance field.

Table 2 contains the analysis results obtained using the MANOVA method to test the response variables and multiple predictors simultaneously through Statistical Software.

On the results of the multivariate test in Table 2, the sig. On each intercept and treatment test of 0.000 at a significance level of α (5% = 0.05). This means there are significant differences in each response and predictor variable simultaneously, and the results of the

test of between-subject effects in Table 3 support this.

The results are in Table 3, where the sig value is obtained. For all observed variables, the significance level α is (5% = 0.05). It means that the addition of X1, X2, X3, and X4 components significantly impacts Y1, Y2, Y3, and Y4. The interaction mechanism between PVA, boric acid, and Uncaria gambir involves crosslinking through hydrogen bonding. Boric acid crosslinks the PVA chains, creating a more stable and water-resistant film, while Uncaria gambir contributes bioactive properties through its polyphenolic compounds. The interactions between these materials create a wellintegrated polymer network with enhanced mechanical properties (Sciences, 2022).

Furthermore, a comparison was made between the results of previous studies using ANOVA and the results of tensile properties data testing using MANOVA conducted in this study, as seen in Figure 1 (Rahmadiawan et al., 2022).

Figure 1 shows a significant difference in the ANOVA and MANOVA test results. In

Table 2	
Multivariate	tests

Effect		Sig.
Intercept	Pillai's Trace	,000
	Wilks' Lambda	,000
	Hotelling's Trace	,000
	Roy's Largest Root	,000
Treatment	Pillai's Trace	,000
	Wilks' Lambda	,000
	Hotelling's Trace	,000
	Roy's Largest Root	,000

Table 3Tests of between-subjects effects

Source		Sig.
Corrected Model	Y1	,000
	Y2	,004
	Y3	,002
	Y4	,006
Intercept	Y1	,000
	Y2	,000
	Y3	,000
	Y4	,000
Treatment	Y1	,000
	Y2	,004
	Y3	,002
	Y4	,006

the ANOVA test, not all observed variables were significantly different. It can be seen from the sig value $< \alpha$ of (5% = 0.05). While testing using the MANOVA method, all observed variables significantly differ at α (5% = 0.05). This finding is in line with what was done in Khorasani et al. (2021) using the MANOVA method to find the effective variable on tensile properties.

Many material research studies use ANOVA to test the significance of treatments applied to the observation objects, where multiple tests are conducted simultaneously



Figure 1. Comparison between ANOVA and MANOVA

on the same sample (Abral et al., 2021). The results of this research provide a more effective alternative for performing statistical testing on material testing data other than ANOVA, namely, MANOVA.

CONCLUSION

We have compared tensile property data using ANOVA and MANOVA methods to the case study data of the blend film. Based on the comparative analysis performed, it has shown that the results using the ANOVA method were not significant for all treatments in the sample observed in the data tensile properties. The two methods' accuracy level is at the level of $\alpha = 5\%$ (0.05). Meanwhile, the MANOVA method shows that the tensile properties of the sample have a significant effect on the tensile properties of the data. Therefore, we recommend MANOVA for testing more than one or multivariate response variables.

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Comparative Analysis of Carbonized Hybrid Briquettes Produced from Cassava Peel and Sawdust for Cooking Application

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ABSTRACT

The increasing use of biomass residues in briquette forms is not just for disposal problems but provides alternatives to fossil fuel and fuelwood. This research concentrated on assessing the effectiveness of the briquettes when used for cooking. The briquettes were prepared from carbonized materials: 100% Cassava peels (CP), 100% Sawdust (SD) of *Gmelina arborea* and their hybrid (MIX₁ -75:25, MIX₂ -50:50, and MIX₃-25:75) with starch binder in percentage (5% and 10%) by weight at varying resident time of 10, 20, and 30 minutes. ANOVA was utilized to evaluate the significance at p<0.05. The produced briquettes were oven-dried and subjected to mechanical, boiling test, and fuel performance tests to evaluate their suitability as domestic fuel. The result shows that shatter index ranged between 46.81%–95.54%, compressive strength ranged from 0.12–0.26 N/mm². Briquette's thermal efficiency with good flame was within the range of 24.27%–55.55%. However, the average burning rate of all the briquette types was between 0.39 to 0.85 kg/hr, while the average specific fuel consumption ranged from 0.08 to 0.14 kg/l. The briquette took 15 minutes to boil water from

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E-mail addresses: adesolacharles@gmail.com (Charles Adesola Ajagbe) Z_faiz@upm.edu.my (Mohamad Faiz Zainuddin) latifahmanaf@upm.edu.my (Latifah Abd Manaf) rahim@upm.edu.my (Nik Nor Rahimah Nik Ab Rahim) gloriaanguruwa30@gmail.com (Gloria Titi Anguruwa) * Corresponding author 96.9°C to 97. 9°C. The comprehensive briquette test reveals that cassava peel exhibits the highest capacity for handling, while hybrid briquettes MIX1 and MIX3 demonstrate commendable fuel performance. It was noted that the binder ratio, type of biomass material, and residence time significantly impact the properties of the briquettes.

Keywords: Briquette, carbonization, characterization, compressive test, fuel efficiency

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INTRODUCTION

Sustainable and renewable energy is essential for humanity's well-being. Biomass energy constitutes approximately 15% of the energy consumption in the world. Biomass encompasses any organic material suitable for fuel, such as wood, charcoal, animal manure, plant matter, and agricultural waste (Ferguson, 2012). Fuels commonly used in households within developing nations are referred to as 'traditional,' including wood, animal dung, and agricultural residues. In Nigeria, fuelwood and charcoal alone contribute to around 73% of cooking energy, according to the International Energy Agency (IEA, 2019).

These fuelwood collection practices lead to major environmental issues, such as air pollution caused by greenhouse gas emissions, soil erosion, land degradation, and deforestation. Shaaban and Petinrin (2014) report that around 350,000 hectares of forest and natural vegetation are lost yearly, while afforestation efforts only cover 50,000 hectares annually. Deforestation has caused the depletion of 79% of Nigeria's old-growth forests between 1990 and 2005 (Mfon, 2014). Furthermore, Bolaji (2012) observed that burning agricultural residues, fuelwood, roots, and animal dung releases a great amount of carbon monoxide, particulate matter, and hydrocarbon into the atmosphere.

Many developing nations, including Nigeria, have abundant untapped renewable energy sources that apply to various uses (Orisaleye et al., 2018). Due to their rich renewable resources, developing countries can use different energy alternatives such as wind, solar, geothermal, biomass, and hydro (Sotannde et al., 2010). Supporting this idea, Piebalgs (2017) states that developing nations naturally have the means to utilize renewable energy by making the most of their natural resource abundance. According to FAO data from 2019, Nigeria is currently the world's foremost cassava producer, surpassing countries like Thailand (31 million tons), Brazil (21 million tons), and Ghana (18 million tons). Despite this significant production, only a fraction of the cassava tubers harvested in Nigeria are utilized for consumption, with the majority discarded, often littering roadsides. Regrettably, peels and other byproducts, like chaff, are often seen as nuisances rather than valuable resources.

In Nigeria, the absence of robust and enforceable legislation governing cassava waste management challenges peasants and smallholder farmers in grasping the interplay between cost-effective waste treatment and the added value of managing cassava waste. This discrepancy is commonly termed as a knowledge gap (FAO, 2020). Using wood-based industrial waste, such as sawdust from sawmills, to produce activated carbon stands out as one of the most ecologically advantageous methods for transforming low-value residues into high-value materials. Activated carbons demonstrate exceptional performance across various industrial applications, playing a pivotal role. Because of their large specific surface area, conductivity, and structural versatility, with adjustable porosity, activated carbon materials are useful in a diverse array of critical technologies. These encompass catalysis,

energy storage, energy conversion, sensors, environmental protection, and the synthesis of fine and bulk chemicals (Nahil & William, 2012).

The selection of raw materials for biomass briquettes is guided by the energy potential and availability of the chosen waste (Bot et al., 2022a). Millions of tons of waste generated from human activities, particularly agricultural activities related to food production, cause serious environmental pollution due to the challenges associated with their disposal (Ezenwa et al., 2019). Most of these agricultural wastes, produced during the cultivation and processing of crops, are often either dumped on farm sites or burned at disposal sites, posing environmental hazards such as global warming and soil degradation (Arachchige, 2021). Sawdust, a byproduct of wood processing, mainly consists of fibers and cellulose (Lubwama & Yiga, 2018). These wastes can be transformed into solid fuels through the briquetting process, which enhances their calorific value and produces high-grade solid briquettes that ensure a clean, smoke-free flame suitable for small-scale industrial and domestic applications (Bello & Onilude, 2020) and biomass briquettes promote economic development in underdeveloped nations while also conserving the environment (Bamisaye & Raphael, 2021). According to the conclusions of Bot et al. (2022b), households would gain from replacing fuelwood with briquettes. The most significant economic benefit comes from using briquettes instead of fuelwood. The plant (cassava) generating the residues selected for this study is as widespread around Oyo town (the sample collection location) as the other sources, and the waste is available in relatively large quantities. Sawdust is also readily available due to the numerous sawmills in the town.

Multiple researchers, including Waheed and Akogun (2020), Kpalo et al. (2021), Bamisaye and Raphael (2021), and Waheed et al. (2022) have explored the creation of briquettes using processed agricultural waste for energy generation. Their studies have highlighted the utility of these products for various applications. Incorporating a variety of biomass feedstocks into the briquette mixture, as proposed by Akogun et al. (2022) and Ajimotokan et al. (2019), Improves the thermal properties and physical attributes of the resulting briquettes by promoting better adhesion between the constituent particles. It is crucial to compress these processed agricultural wastes into briquettes to make them easier to manage and better suited for heating purposes, as Waheed and Akogun (2020) emphasized. Achieving optimal briquetting requires careful selection and configuration of processing variables. Navalta et al. (2020) noted that the compression strength, density, and energy potential of briquettes are significantly influenced by factors such as pressure, temperature, particle size, choice of binder, and the properties of the biomass material (carbonized or uncarbonized).

Research has shown that briquettes' combustion and mechanical characteristics are enhanced when waste is converted into biochar. Wu et al. (2018) characterized fuel briquettes produced from wood sawdust and cotton stalks using various thermochemical processes, such as hydrothermal carbonization, dry torrefaction, and pyrolysis, before briquetting. Their findings revealed that the method used to produce carbonized biomass significantly impacted the briquettes' performance, including calorific value, density, and compressive strength. Li et al. (2019) compared heat transfer efficiency and pollutant emissions between briquettes made from raw and charred biomass for household cooking. They found that briquettes from charred biomass enhanced thermal efficiency and emitted fewer pollutants.

This study aims to assess the performance of two biomasses in cooking applications as an alternative fuel source for domestic use. It investigated the physico-mechanical and combustion properties of the briquettes for use in domestic cooking. Additionally, it was hypothesized that due to their availability, a mixture of cassava peel (agricultural waste) and sawdust (forest waste) in different proportions would result in high-quality hybrid briquettes with good combustion behavior, influenced by adequate fuel properties to enhance cooking efficiency in Oyo State, Nigeria. Household cooking is a significant energy use in developing countries such as Nigeria. This need is typically met by the direct burning of wood and its byproducts. Wood energy, including firewood, wood char, sawdust, and wood chips, constitutes over 80% of Africa's energy supply for cooking and heating. The inappropriate use of wood fuel has a wide range of negative environmental and health consequences (WHO, 2011; Kpalo et al., 2020).

MATERIALS AND METHODS

Materials

Five-ton hydraulic jack briquetting machine, Hammer miller, Digital weighing balance, 2mm mesh screen, Universal strength-testing machine, Element analyzer, Muffle furnace, Bomb calorimeter, Digital Multi-Stem thermometer.

Samples Selection and Preparation

This study used Gmelina sawdust samples converted and collected at Idi igba, Oyo state, Nigeria. In contrast, cassava peels were collected from a waste dump site for garri and starch manufacturers at Ajegunle market, Oyo state, Nigeria. The cassava peel was rinsed, after which both peel and sawdust were spread out on a thick bag to prevent contamination and left to air-dry for 2 weeks to a 12% moisture content and then milled using a Hammer miller after which both samples were sieved using a 2 mm particle-size mesh screen for consistency.

Carbonization Procedures

The dried cassava peel and sawdust were charred at a temperature of 400°C for 3 hours to produce a high–carbon product char (Figure 1). Cassava peel and sawdust, which serve as a control, were mixed at different percentages (100:0, MIX_1 -75:25, MIX_2 -50:50, MIX_3 -25:75, and 0:100) for cassava peel and sawdust mixture, respectively (Table 1). It was carried out



Figure 1. Elaborate schematic illustrating the briquetting process employed in this investigation

in accordance with the work of Velusamy et al. 2023 for mixing the proportion of Senna auriculata and Ricinus communis, and Palanisamy et al., 2023 for Gloriosa superba waste and turmeric leaves waste.

Table 1		
Mixing proportion	of cassava peel	and sawdust

Samples	Mixing Proportion	
Cassava peel (CP)	100	0
MIX1	75	25
MIX2	50	50
MIX3	25	75
Sawdust (SD)	0	100

Binder Preparation

The binder used for this study was starch obtained from cassava. The starch binder

proportion varied into 5g and 10g. The starch was measured into bowls, and 100 ml of boiling water at 98°C was added to form a gelatin paste, following the methods of Velusamy et al. (2021a), Chungcharoen and Srisang (2020), and Aransiola et al. (2019). 100 ml of boiling water to prepare the starch paste because the sample quantity was 50 g. Each 50 g portion of cassava peel and sawdust was then vigorously mixed with the prepared binder at 5 g and 10 g levels, respectively (Figure 2). Starch was selected as the binding agent due to its easy availability in the study area (Palanisamy et al., 2023).



Figure 2. Pictorial representation of (a) Sieved materials, (b) Carbonized samples, (c) Starch binder

Production of Briquettes

The 5-ton hydraulic jack briquetting machine was used in manufacturing the briquettes. The machine has twelve cylindrical molds that are welded onto a single frame and have dimensions of 80 cm in height by 6.5 cm in diameter. The blend was manually inserted into the briquetting machine while a pressure of 2.4 MPa or 10 kg/cm² was applied for the mixed paste to compact and form a briquette. The briquette molds produce twelve briquettes per batch, which are expelled at different periods (10-, 20-, and 30-minute resident time) to determine the effects of setting the time on the briquette characteristics. Each production batch was replicated for CP, MIX₁, MIX₂, MIX₃, and SD three times. The produced briquettes were allowed to set for 3 days before oven drying. Each sample's weight,



Figure 3. Produced briquettes from sawdust and cassava peel materials

height, and diameter were duly noted after sun drying (Figure 3). Cassava starch was used due to its light quality and higher physical and mechanical attributes in accordance with the method described by Velusamy et al., 2021b.

Characterization

The mechanical properties (shattering index and compressive strength), physical properties (density), and calorific values were examined to evaluate if the briquettes were suitable for handling, transportation, and storage. The performance of the briquettes was assessed for cooking efficiency utilizing the outcomes from a water boiling experiment. These properties were tested days after the briquettes were produced and given time to dry. A straightforward random sample technique was employed to establish the characteristics of the briquettes utilized for sampling.

Physico-mechanical Characteristics

The physico-mechanical properties were determined to reflect the briquette's hardness, a significant factor in crafting new solutions for household energy sources.

Density. The compressed density of each briquette produced was determined after sun drying, using a ratio of measured mass to the volume of the briquettes. The mass of the produced briquettes (mb) was determined using a digital weighing balance. In contrast, the dimensions, including the briquettes' diameters (db) and height (hb), were measured using a Vernier caliper. The measured diameters and height were subsequently used to calculate the volumes (Vb) of the briquettes using Equation 1, while the corresponding densities (pb) were calculated using Equation 2 (Aliyu et al., 2021).

$$Vb = \pi \frac{db}{4} hb$$
 [1]

$$P_b = \frac{m_b}{v_b}$$
[2]

Shatter Index. The shattering index or durability index of the produced briquettes was measured according to the ASTM D440-86 (2002) method of drop shatter, developed for coal by Davies and Abolude (2013). The test was conducted after sun drying of the briquette samples. The weight of each sample was measured and placed in a polythene bag. The bag was dropped from a height of 2 m onto the concrete floor four times. After the dropping, the briquettes and their fractions were placed on top of a 35 cm square mesh screen and sieved. The mass of the remaining briquettes was measured, and the shatter index, expressed as the ratio of the weight of material retained on the screen (mbs) to the weight of briquettes before the dropping (mb), was determined using Equation 3 (Davies & Abolude, 2013).

Shatter index =
$$\frac{Mbs}{Mb} \times 100$$
 [3]

Compressive Strength. The briquette's axial compressive strength (N/mm²) was measured using a Universal Testing Machine with a digital control and display unit for test control and result display. The dimension of the sample was first measured and inputted into the system, and the briquette was placed directly under the plunger to be pressed. The machine applied the load to the briquette until failure occurred. The applied force was recorded and displayed until the maximum force corresponding to the failure was recorded. The compressive strength is then calculated using Equation 4 (Davies & Abolude, 2013).

$$Compressice strength = \frac{Maximum force applied}{Surface area of the briquette}$$
[4]

Determination of Fuel Performance in Cooking Application

The temperature at the boiling time was measured using an LCD digital Multi Stem Thermometer (Model ST9283B). The duration for igniting the briquettes and heating the water to 100°C was measured. Additionally, the thermal fuel efficiency (TFE), fuel burning rate (FBR), and specific fuel consumption (SFC) were assessed throughout the experiment.

Water Boiling Test. The outcome of a boiling water experiment was used to evaluate how well the briquettes performed in the cooking application. These characteristics were established days after the briquettes were created and given time to dry. The efficacy of the briquette for household cooking was evaluated through a water boiling assessment conducted in accordance with the Chinese Water Boiling Test Protocol 2008, as outlined by (Chen et al., 2016; Lubwama & Yiga, 2017); this was utilized for this study as it was found to be more practical in rural environments. A stopwatch was utilized to measure the

duration of the briquette's combustion. The timer was set but not initiated until the fire was started. The empty pot was placed on the scale and weighed, and 1L of water was poured into the pot. The weight of the pot with the water was taken and recorded in a field activity notebook. The thermometer was placed in the pot to take the water's starting temperature, and it was captured. Two hundred grams of briquettes were put into the conventional cook stove, and a fire starter was used to ignite them.

The pot, filled with water, was positioned on the stove just as the flames ignited. Subsequently, the timer was initiated, and the water temperature was measured every 3 minutes throughout the burning process. As the water in the pot reached the boiling point (100°C), the pot lid was removed. The time it took the water to boil and the boiling temperature was recorded. Additionally, all remaining fuel samples were left in the stove chamber and allowed to continue burning till they burned out. The pot weights with hot water and the extracted ash from the stove were taken and recorded. The test concludes once the water within the pot cools to 5°C below the boiling point. The data recorded during the burning of the briquette and the boiling of water was analyzed to assess how well the briquette performs when used for cooking.

Thermal Fuel Efficiency. This measures the ratio of useful energy water receives in the pot to the energy consumed during combustion. The energy imparted to the water in the pot serves dual purposes: heating the water and facilitating evaporation. The amount of evaporated water was determined by subtracting the initial water weight in the pot from the final weight after cooling. Total useful energy (TFE) can be computed using Equation 5, provided by Davies and Davies (2013).

$$TFE = \frac{M_W C_P (T_b - T_O) + M_C L}{M_F E_F}$$
[5]

Where, TFE = Thermal fuel efficiency; M_W = mass of water in the pot (kg/liter); C_P =specific heat of water (kJ/kg K); T_O = initial temperature of water (K); T_b = boiling temperature of the water (K); M_C mass of water evaporated (kg); L= latent heat of evaporation (kg); M_F = mass of fuel burnt (kg); E_F =calorific value of the fuel (kJ/kg).

Fuel-burning Rate. According to Desta et al., 2024, the burning rate is when a given mass of briquette fuel burns in the air. If it is low, it indicates that the briquette has a high energy density and is of high quality. The fuel burn rate was calculated using the above test arrangement described in the ignition time of the briquette's discussion. The weight of the briquette sample before and after burning was recorded. The time it took to burn the briquette was also recorded. It was done three times for each of the briquettes. Fuel-burning rates were estimated using Equation 6.

$$FBR = \frac{M_F}{T}$$
[6]

Where, FBR=Fuel Burning Rate; M_F = mass of fuel burnt (kg); T= Time taken to burn fuels (hr)

Specific Fuel Consumption. Specific fuel consumption refers to the quantity of solid fuel required to accomplish a specific task relative to the task's weight. It represents the relationship between the fuel mass (in kilograms) and the volume of water (in Liters) consumed. This computation follows Equation 7, outlined by Hakizimana and Kim (2016).

$$SFC = \frac{M_F}{M_W}$$
[7]

Where, SFC= Specific Fuel Consumption; $M_F = mass$ of fuel burnt (kg); $M_w = mass$ of water in the pot (liter)

Experimental Design

The chosen experimental setup employs a $2 \times 3 \times 5$ factorial design within a completely randomized design (CRD) framework with 3 replications, giving 90 samples in total. The following are the variables.

- 1. Material Type: 5 (CP, MIX₁, MIX₂, MIX₃ and SD)
- 2. Binder Level: 2 (5g and 10g)
- 3. Resident time: 3 (10, 20, 30 mins).

Statistical Analysis

Briquette samples were chosen through a simple random sampling technique within each of the five categories, and their characteristics were examined and duplicated three times. The data obtained from these tests underwent statistical analysis using the Statistical Package for Social Sciences. Analysis of Variance (ANOVA) was employed to identify noteworthy variations among the means of different briquette properties and their performance in a water boiling test. Throughout this study, all significant tests were conducted at a 95% confidence level (p < 0.05).

RESULTS AND DISCUSSION

Briquette Characterization (Mechanical Physical properties)

Density

The various p-values of physical and mechanical properties obtained from ANOVA and their interactions are presented in Table 2. The density of the produced briquettes was notably influenced by both the type of briquette and the interaction between briquette type and binder level, with statistical significance (p<0.05, while binder level, resident time, their interaction, and 3- factors interaction did not yield any noticeable impact on the briquettes. Table 3 displayed the follow-up test on the briquette type using the Duncan Multiple Range Test to show the extent of significance where the density of CP and SD show significant differences. In the meantime, Figure 4 presents the average impacts of factors on the density of briquette samples. Sawdust had the highest density of 627.79 kg/m³ at 5% binder level and at 30 mins resident time compared to 320.18 kg/m³ obtained at 5% binder level and at 10 mins resident time.

Table 2

P-values for density.	compressive strength	and shatter index of	of briquettes
i vantes joi actisity,	compressive strength	and sharter mater o	<i>j</i> or iquettes

Source of Variation	Degree of Freedom	Density (Kg/m³)	Shatter index (%)	Compressive strength (N/mm ²)
Briquette Type	4	0.036248*	0.000000*	0.000000*
Binder level	1	0.092818	0.964512	0.120707
Resident time	2	0.535503	0.067867	0.411608
Briquette Type*Binder level	4	0.242672	0.002109*	0.003678
Briquette Type*Resident time	8	0.850590	0.040970*	0.528162
Binder level*Resident time	2	0.210566	0.212416	0.190859
Briquette Type*Binder level*Resident time	8	0.808155	0.464415	0.935329
Error	60			
Total	89			

*Significant at p < 0.05)



Figure 4. Mean values of density of briquettes about binder level (%) and resident time (mins)

Akogun et al. (2020) recorded a higher result of briquettes made from fresh sawdust and torrefied cassava peels. and ranged between 870 kg/m³–1080 kg/m³. The 147 kg/m³ range to 1362 kg/m³ was recorded for waste-based briquettes, as Ossei-Bremang et al. (2024) reported. The highest density of sawdust briquette (627.79 kg/m³) was slightly lower than 660 kg/m³ obtained in palm kernel but higher than rice husk, sawdust, and corncob with 384.3kg/m³, 396.1 kg/m³ and 443.5kg/m³ respectively (Adu-Poku et al., 2022; Sunnu et al., 2021). This difference may be due to the porosity of the material type used for production. It has been suggested by Guo et al. (2020) and Chaisuwan et al. (2020) that briquettes made by a hydraulic piston press typically have a density of less than 1,000 kg/m³, commonly ranging from 300 to 600 kg/m³.

			-		
DADAMETEDS		BF	RIQUETTE TY	PE	
FAKAWLIEKS	СР	MIX ₁	MIX ₂	MIX ₃	SD
Density	424.01ª	431.19 ^{ab}	517.26 ^{bc}	440.65 ^{abc}	520.81 ^d
Shatter index	67.58623ª	91.30800 ^d	23.19186°	78.60582 ^b	73.20769 ^{ab}
Compressive strength	0.2592763°	0.176556ª	0.160172ª	0.157751ª	0.070444^{b}

Note. Means with the same letter(s) in the row are not significantly different (p < 0.05)

Duncan's multiple range test for density, shatter index, and compressive test of briquettes

Shatter Index

Table 3

Table 2 is the Anova of shatter index, which shows that the different briquette types along with 2-factor interactions of briquette type and binder level as well as briquette type and resident time shows markedly distinct at (p > 0.05). 2-factor interactions of binder level and resident time and 3-factor interactions did not notably impact the shatter index of the briquettes produced. Regarding the material type, binder level, and resident time, the highest shatter index of 95.54% was recorded in the MX₁ briquette at a 5% binder level and 30 minutes of resident time (Figure 5). Duncan's test, presented in Table 3, shows that the shatter index of MIX₁ and MIX₂ are significantly different from each other and other briquette materials.

The average shatter index obtained for MX_1 in this study is in line with the work of Tembe et al. (2014), who reported similar shatter index values ranging from 83.5% to 99.1% in their study. Meanwhile, CP, MX_3 , and SD are within the lower range of 63.76% to 75.47%, as reported by Aliyu (2021). These findings align closely with the top shatter indices Ajiboye et al. (2016) achieved for sawdust and charcoal briquettes, which were 98.21% and 98.17%, respectively. Sotannde et al., 2010 obtained an average value of 98.74 for briquettes made from charcoal briquettes. In their study, Adu-Poku et al. (2022) found that palm kernel shells and sawdust achieved average rates of 95.52% and 95.02%, while rice husk and corn cob yielded 93.75% and 94.34%, respectively. Additionally, in



Figure 5. Mean of shatter index of briquettes about binder level (%) and resident time (mins)

accordance with the Italian briquette standard, all demonstrated an impact resistance index surpassing or equaling 97.7%, consistent with the findings of Mitchual et al. (2013). This variance might stem from differences in binder composition and the carbonization process.

Compressive Strength (N/mm²)

Analysis of variance (ANOVA) shows that material type and 2-factor interaction of material type and binder level had a notable impact on the compressive strength of the briquette (p<0.05). Meanwhile, binder level, resident time, 2-factor interaction, and their 3-factor interaction did not exert any notable impact on the compressive strength of the briquettes (Table 2). The follow-up test using the Duncan Multiple Range Test in Table 3 indicates no significant variance in compressive strength among the hybrid briquettes.

The result in Figure 6 gave the highest compressive strength of the CP briquette, with a value of 0.29N/mm2 at a 10% binder level and within 10 minutes of resident time. The lowest compressive strength happens in the SD briquette, with a value of 0.04 N/mm² at a 5% binder level and within 10 minutes of resident time. Table 3 shows the follow-up test to observe the extent of significance of the briquette type.

The briquettes made from sawdust had finer particle sizes and were less porous due to stronger intermolecular bonds between the particles, which consequently increased the briquettes' strength. This study partially aligns with Blesa et al. (2003), who assert that an increase in residence time positively impacts the mechanical strength of briquettes. In

their study, Ezenwa *et al.* 2024 recorded a higher compressive strength of 8.31 N/mm² for breadfruit pulp. Blesa et al. (2003) state that the two primary characteristics necessary to produce a good briquette are compression (crushing) and water resistance. Gendek *et al.* (2018) stated that other factors influencing the strength of briquettes include particle size, material type, moisture content, and compaction parameters. Compressive strength enhances the durability of briquettes by decreasing their capacity to absorb moisture (Kers et al., 2010). According to Borowski and Hycnar (2013), tests conducted on commercial fuel briquettes determined that a compressive strength of at least 1.0 MPa is acceptable. The compaction pressure enhances the strength properties by improving the intermolecular bonding among the briquette particles (Ajimotokan *et al.*, 2019). This study's compressive strength was lower than values obtained from Oladeji and Oyetunji (2013) and Oyedemi (2012), which may have resulted from the carbonization of the material. This implies that pyrolyzing the material could affect the compressive strength of the briquette.



Figure 6. Mean of compressive strength of briquettes about binder level (%) and resident time (mins)

Fuel Performance in a Cooking Application

Boiling Water Test

This discussion presents and analyzes the results of the various parameters tested during the water boiling test. Traditional cookstoves were utilized because they reflect the cooking methods commonly used in most developing regions where fuel wood and charcoal are the primary energy sources. Boiling time is the duration it takes for the water in the pot to reach its boiling point. Readings of the values obtained from the boiling test were used to plot a graph showing temperature against time, as shown in Figures 7 to 11. In this study, 96°C was set as the water boiling point based on the time the boiling temperatures were attained during the test for each briquette. At inception (0 mins), the boiling water behavior of the CP briquette in Figure 7 shows a particular temperature pattern through a significant change in temperature after 6, 9, and 12 mins of boiling water. The result in Figures 8 to 10 shows that when hybrid briquettes (MX_1 , MX_2 , and MX_3) at 10% binder level were used to boil 1L of water, it showed an increase in temperature after 6 and 12 minutes. The graph in Figure 11 shows that boiling water with SD briquettes, regardless of binder level

and resident time, shows the same trend at intervals of time except at 12mins, where SD at 5% binder level became higher in temperature than SD at 10% binder level. The plotted graph indicates that short-term exposure to adverse weather conditions during storage and transport does not affect the briquette's performance, as Saha et al. (2014) observed. In a similar study, Lubwama and Yiga (2018) used a comparable number of briquettes made from rice and coffee husks to boil 1 liter of water. Onuegbu et al. (2011) highlighted that briquettes' burning rate and calorific value are critical factors in determining the time required to bring water to a boil.



Figure 8. 3D response surface of temperature, binder level, and resident time on water boiling test of hybrid MIX1 briquettes



Figure 7. 3D response surface of temperature, binder level, and resident time on water boiling test of Cassava peel briquettes



Figure 9. 3D response surface of temperature, binder level, and resident time on water boiling test of hybrid MIX2 briquettes

Carbonization of Hybrid Briquettes



Figure 10. 3D response surface of temperature, binder level, and resident time on water boiling test of Hybrid MIX3 briquettes



Figure 11. 3D response surface of temperature, binder level, and resident time on water boiling test of sawdust briquettes

Fuel Performance of the Briquettes

Thermal Fuel Efficiency (%)

Analysis of variance shows that material type, binder level, and 2-factor and 3-factor interactions significantly influenced the Briquettes' TFE, both at p<0.05, as shown in Table 4. Duncan's multiple range test in Table 5 shows that CP and MIX₂ are not significantly different. The results in Figure 12 indicated that the highest TFE of 55.55% was obtained in hybrid briquette MX₁ and MX₃ at 30 minutes of resident time and 5% and 10% binder level, respectively. The lowest TFE of 30.34% was obtained from CD at 10% binder level,

Table 4p-values for mechanical properties and fuel performance

Source of Variation	Df	Thermal Efficiency (%)	Fuel Burning Rate (kg/h)	Specific Fuel Consumption (kg/l)
Material Type	4	0.000000*	0.000000*	0.000000*
Binder level (%)	1	0.000000*	0.009224*	0.005886*
Time (Mins)	2	0.069406	0.000001*	0.000213*
Material*binder level	4	0.000000*	0.000000*	0.000000*
Material*Time	8	0.008342*	0.004191*	0.023171*
Binder level*Time	2	0.125103	0.325107	0.320393 ^{ns}
Material*binder level*Time	8	0.043889*	0.622135	0.072830 ^{ns}
Error	60			
Total	89			

Note. * = Significant at P < 0.05; ns = not significant at P < 0.05



Figure 12. Mean of thermal fuel efficiency of briquettes about binder level (%) and resident time (mins)

Table 5

Duncan's multiple range test of thermal fuel efficiency, fuel burning rates, and specific fuel consumption based on material type

DADAMETEDS	BRIQUETTE TYPE						
FAKAWETEKS	СР	MIX ₁	MIX ₂	MIX ₃	SD		
Thermal fuel efficiency (%)	32.57389ª	44.40389°	32.99722ª	55.38000 ^d	31.69556 ^b		
Fuel-burning rates (kg/h)	0.450000^{a}	0.588333°	0.437222ª	0.737778^{d}	0.495556 ^b		
Specific fuel consumption (kg/l)	0.100889ª	0.110000ª	0.105389 ^{ab}	0.124556 ^b	0.100500 ^b		

Note. Means with the same letter(s) in the row are not significantly different (p < 0.05)

10 minutes resident time, and SD at 5% binder level and 30 minutes resident time. It was observed that TFE tends to be higher where the ratio of CD and SD was higher.

Several factors, including the type and amount of biomass, the binder, and the cookstove, influence the Briquettes' TFE. The values obtained in this study are lower than those of Davies and Davies (2013). The efficiency of the briquettes was higher than the range obtained by Oyedemi (2012) at 15%–38%, which greatly depends on the amount of briquette burnt. The result of this study compared the fuel efficiency of groundnut shell briquette in the range of 14.47%–18.46% and for firewood, which was 10.31% (Oyelaran et al., 2015), as evidenced by the shorter time required for boiling one liter of water. This study also conforms well to Achebe *et al. (2018)* results for Gmelina arborea briquettes at 33.8% and 43.4% while performing lower than Bello et *al.* (2022) at 49.31%–57.80% using different binder types and ratios.

Fuel Burning Rates (kg/h)

Table 4 shows the analysis of variance, which shows that the material type, binder level, resident time, and their 2-factor interaction had a significant impact on the burning rate of the briquettes. Table 5 shows Duncan's multiple range test recorded based on briquette type; the fuel burning rates of CP and MIX₂ are not significantly different. On the other hand, a follow-up test based on resident time shows no significant difference between fuel burning rates at 10 and 20 mins. Figure 13 shows that FBR was highest with a value of 0.85kg/h in both MX₁ and MX₃ at 10% binder level and 20 mins resident time, while the lowest FBR of 0.39 kg/h was recorded in briquettes produced from CP, MX₂, and SD at binder level 5%, 5% and 10% within resident time at 20, 30 and 30mins respectively.

The tested briquettes burned brightly and steadily, and they produced red-hot char. Achebe *et al.* (2018) reported a burning rate of 0.055 and 0.214kg/min, which was lower than the results obtained for this study. Rudiyanto *et al.* (2023) also reported a burning rate for cassava peel between the range of 0.021 - 0.026g/s, which appears to be lower than the results of this study. Oyedemi (2012) reported a burn rate of 0.80 kg/hr for Gmelina arborea sawdust briquettes, which conformed with this study. These variations in values may have resulted from the production procedure of the individual briquettes. Firewood, on the other hand, has a burn rate of 1.166 kg/hr (Oyelaran *et al.*, 2015), indicating that the briquettes produced in this study are suitable substitutes for firewood. Navalta et al. (2020) observed that the type and composition of biomass used in briquette production affects its burning rate, along with its density, shape, and size.



Figure 13. Mean of fuel burning rate of briquettes about binder level (%) and resident time (mins)

Specific Fuel Consumption (kg/l)

Table 4 The ANOVA test revealed a significant impact of material type, binder level, resident time, and their two-factor interactions on the specific fuel consumption of the briquette samples. However, the 3-factors interaction was not significant (p < 0.05). Duncan's test based on material type shows that the specific fuel consumption of MIX₂ is significantly different from (CP and MIX₁) as well as (MIX₃ and SD). On the other hand, a follow-up test based on resident times shows no significant difference between specific fuel consumption at 10 and 20 mins. Figure 14 shows that the highest SFC (0.14 kg/l) of the briquettes was recorded among the hybrid briquettes MX₁ and MX₃ at 5% and 10% binder level and 20 mins resident time. The follow-up test for briquette type and resident time is presented in Tables 5 and 6, respectively.

The specific fuel consumption value in this study was within the range of 0.09-0.14 kg/l, which was lesser than Oyedemi (2012) for cassava peel briquette (0.4), wood (0.6), and charcoal (0.5, Stoves and Bello et al., (2022) at a fuel consumption rate of 0.575. As

Table 6

Duncan's multiple range test of fuel burning rates and specific fuel consumption based on resident time

DADAMETEDC	R	s)	
PARAMETERS -	10	20	30
Fuel-burning rates (kg/h)	0.572000ª	0.570667ª	0.482667 ^b
Specific fuel consumption (kg/l)	0.109533ª	0.111700ª	0.103567 ^b



Figure 14. Mean of specific fuel consumption of briquettes about binder level (%) and resident time (mins)

comparable to firewood, Oyelaran et al. (2015) reported a fuel consumption rate of 0.332, which appeared to be higher than the value in this study. Also, a very higher SFC was reported as Rice husk showed an SFC of 4.987 kg/l, sawdust recorded 4.59 kg/l, and corn cob measured 4.036 kg/l. and 2.559 kg/l for palm kernel shells Adu-Poku et al., (2022). This result implies that lesser quantities of briquettes would be needed while taking a longer period to cook. Also, this could be due to a rise in density of the briquettes, which might reduce their porosity, thereby limiting the rate of oxidant infiltration and the outflow of combustion products during burning (Adu-Poku et al., 2022).

CONCLUSION

This study concluded that hybrid briquette MX1 demonstrated the highest durability with a shatter index of 95.54% at a 5% binder level and 30 minutes of residence time. In comparison, cassava peel briquette had the strongest compressive strength (0.29 N/mm²) at a 10% binder level and 10 minutes of residence time. These briquettes possess adequate durability for handling, transportation, and storage. The fuel performance of hybrid briquettes MX1 and MX3 showed the highest thermal fuel efficiency (TFE) of 55.55% and a fuel burning rate (FBR) of 0.85 kg/h at specific binder levels and residence times. These briquettes also exhibited efficient cooking performance with easy ignition and minimal ash generation. Using cassava peel and sawdust in briquette production presents significant environmental and socio-economic benefits for rural communities in Oyo State and Nigeria by addressing waste management, energy deficits, and air pollution. Overall, the study affirms these briquettes' high quality and potential as a viable alternative to fuel wood.

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