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Life Cycle Assessment of Conventional Broiler Farm System in Malaysia and Carbon Footprint Mitigating Strategies

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ABSTRACT

The livestock industry is a significant anthropogenic source of greenhouse gas (GHG) emissions due to rapid development and intensified production systems. This study evaluated GHG emissions from a commercial broiler production system using a life cycle assessment (LCA) approach from cradle to farm-gate and assessed carbon footprint mitigation strategies for poultry litter (PL) management. Three scenarios were compared: selling PL (farmer's practice), composting, and conversion into biochar. The LCA model was developed in accordance with Intergovernmental Panel on Climate Change (IPCC) guidelines and aligned with national sustainability goals. From each production cycle, 63.97 tCO_2-eq were estimated per house, with the largest contributor from feed production, followed by energy expenditure. Carbon reduction was reported to be 25.79%, 13.21%, and 16.98% by selling PL, composting, and biochar conversion, respectively. In carbon *hotspot* analysis, feed processing and energy consumption were determined as the major contributors from the production. Although selling PL brought greater carbon mitigation, it shows the least sustainable waste management and environmental gains compared to compost and biochar. Future studies should assess the emissions from land-use change, composting, and biochar production to improve the accuracy of carbon footprint estimations. These findings provide a clearer guide to improve poultry waste management and encourage achievement of national net-zero emission goals.

Keywords: Broiler production, cradle-to-farm gate, GHG emissions, LCA, mitigations, Malaysia

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INTRODUCTION

Greenhouse gas (GHG) emissions and climate change have been a long-term global challenge. Malaysia's livestock sector accounts for approximately 4% of the total agricultural Gross Domestic Product (GDP) in 2024 (Ministry of Economy, 2025).

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The agrifood system was reported to contribute approximately one-third of global anthropogenic GHG emissions, dominated by the livestock sector (FAO, 2022). Attia et al. (2024) reported that almost 10% of the total livestock emissions stemmed from the poultry sector, and a continuous increasing trend was discovered in recent years by Hegarty et al. (2024). According to OECD (2025), Malaysia's poultry industry is rapidly growing, with a forecasted average annual growth rate of 1.5% for 8 years due to high demand for poultry products. Based on the 2019 List of myGAP Poultry Farms by the Department of Veterinary Services Malaysia (DVS), they listed over 400 chicken farm operations were registered, while actual numbers are expected to be higher due to the presence of unregistered smallholder farmers. Regardless of its importance, GHG emissions records from Malaysia's livestock industry, particularly from the poultry sector, remain scarce. The majority of existing sources relied on Tier 1 assessment, using default values from global datasets such as IPCC and EPA. Approximately one-third of methane (CH_4) and 65% of nitrous oxide (N_2O) from the livestock total emissions were derived from poultry farming, dominated by manure management (Zubir et al., 2022). This emphasises that more comprehensive and localised studies should be done for efficient mitigation strategies.

Life Cycle Assessment (LCA) is a systematic, formalised methodology used to evaluate the environmental impacts and resource management of a product or process throughout its life cycle (Malaysian Plastics Forum, 2018). Malaysia has been introducing LCA for years to promote green evolution in the Ninth Malaysia Plan 2006-2010 (2006), yet market adoption was only observed in recent years.

Compliant with international agreements such as the Kyoto Protocol (1997) and the Paris Agreement (2015), much research in Malaysia has emerged as LCA-based studies to estimate GHG emissions across various sectors. For instance, a study conducted on the certified sustainable practices of oil palm plantations have reported a more than 10% of carbon mitigation efficiency (Bok et al., 2022); in crop production, such as paddy, Nurfarhain Mohamed Rusli et al. (2023) identified emission hotspots were preponderance from early plantation (Scope 1 emissions).

Nevertheless, LCA adoption in Malaysia is still relatively low, as several obstacles were identified, such as insufficient funding, specialists, and promotional efforts (Hafizan et al., 2021). Furthermore, there is a knowledge gap among local industries, even with the internationally published standards (Rajendran et al., 2021). In fact, this led to a disconnect between Malaysian industries' operations and LCA, resulting in a shortage of reliable national data for better assessment accuracy.

High climate action commitment was demonstrated by Malaysia through various national policies. In 2023, the National Energy Transition Roadmap (NETR) was released, aiming to achieve net-zero emissions by 2050. One of the major incidents resulting in this action was due to a drastic increase in net emissions of more than 200% since 1990, reported by the National Climate Change Policy 2.0 (NRECC, 2022), which prompted greater public concerns about the climate change impacts on agrifood systems. In the updated Malaysia First Nationally Determined Contribution (NDC) submitted to UNFCC (2021), agriculture and waste sectors were restated to play one of the key roles in achieving 45% total carbon mitigation intensity by 2023. Additionally, in early 2013, the MYCarbon Programme involved 26 listed companies that participated in voluntary carbon reporting and reduced their carbon emissions, showing encouragement to the local industries.

Poultry litter (PL) acts as one of the major pollution sources in poultry farming, with high nutrient-mix content, specifically droppings, feathers, and feed waste (Maruthamuthu et al., 2024). It is a common poultry industry by-product, consisting of feed residues, bedding materials, feathers, and excreta. PL has been widely used for centuries as an organic fertiliser due to its high nutrient content and traditional utilisation through direct application to agricultural land. Several studies have demonstrated its positive impacts on soil fertility and nutrient improvement (Mirabello et al., 2025); still, the adverse effects of the traditional practices are worrisome.

In poultry production, the majority of GHG emissions stemmed from manure management, regardless of production or handling processes (Meda et al., 2011). Moore et al. (2025) reported a significant increase in GHG emissions from 4-week to 8-week age flocks, likely due to larger manure production as the birds grow. This could also be explained by its slow decomposition and lower enzymatic properties compared to composted biodegradable materials, resulting in accumulation of GHGs within the poultry houses. Exacerbating this issue, large quantities of PL generated daily in intensive poultry farming systems have not been managed in a proper manner, leading to negative consequences for the local community.

Proper waste management is crucial in minimising environmental impacts. Some promising approaches are through composting or transforming into biochar. Composting is a biological process involving the degradation of organic matter into a nutrient-rich product through the elevation of temperature within the system under natural aerobic conditions (Nurin et al., 2024). Through composting, almost 50% of poultry waste could be reduced, introducing lower space requirements for storage and disposal.

Composting is globally recognised for its contribution towards environmental benefits. It is known for its high potential in GHG mitigation, tackling climate change, and serving as a soil amendment, thereby improving crop yield and soil water-holding capacity (Nurin et al., 2025). Additionally, certain antibiotic-resistant genes have been shown to be eliminated under specific composting conditions (Xiong et al., 2025), further supporting composting as an effective and sustainable waste treatment option. In the poultry industry, composting is a particularly attractive method for waste management due to its simplicity and cost-effectiveness. Aerobic composting is among the most common techniques used to treat poultry manure (Ma et al., 2025). Composting is a process to produce stable organic matter (OM) by fostering microbial activities under controlled conditions, i.e. temperature, moisture, and oxygen level.

However, several studies have reported that composting can also have negative environmental impacts, primarily due to the emission of major GHGs such as CH_4, CO_2, and N_2O, which are associated with various bacterial genera during anaerobic phases of the process (Cui et al., 2025). Gu et al. (2024) reported an increasing trend of CH_4 and carbon dioxide (CO_2) emissions during the anaerobic phase of composting due to methanogenic microbial activity. In contrast, N_2O concentrations tend to rise during the intermediate phase as a result of incomplete oxidation of ammonia, as illustrated in Figure 1. An overall reduction in sustainability practices might be observed from the accumulation of GHGs throughout these stages.

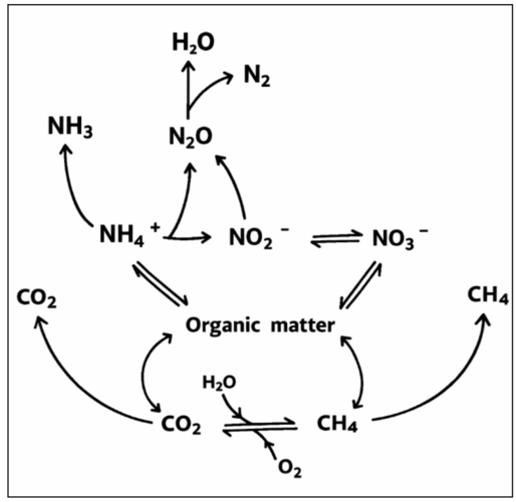

Figure 1. Production of GHG (i.e. CH_4, CO_2, and N_2O) during composting [Cui et al., 2025]

As an alternative to composting, biochar has recently gained significant attention due to its economic and environmental advantages. Biochar is a stable carbonaceous compound with the capability to improve soil health and carbon mitigation, a compliant solution for the circular economy in agriculture (Weng & Cowie, 2025). On top of it, biochar could enhance plant adaptation to climate change challenges, improving their resilience towards environmental stress, particularly during elevated temperature scenarios. It helps regulate interspecific relationships and improve crop production even under unfavourable medium conditions (Laungani et al., 2025). These extraordinary properties establish biochar as a rising star in promoting carbon mitigation and play an important role in building a sustainable future.

In response to the demand for national data and sustainable agricultural practices, this study aims to quantify total GHG emissions produced from commercial broiler production in Malaysia from cradle to farm gate and identify the emission *hotspots*. Furthermore, the study evaluates the net carbon footprint produced from three different manure treatments: 1) selling PL as raw waste, 2) composting, and 3) converting it into biochar. This research represents a crucial milestone in improving environmental assessment capabilities within Malaysia's broiler sector. By incorporating local data and applying advanced LCA methodologies, the study supports national climate goals and promotes more sustainable livestock production practices.

MATERIALS AND METHODS

Broiler Production Description

This study was conducted in an intensified commercial broiler farm located at Kulai, Johor, Malaysia. Three closed-house poultry houses were used for assessment. A minimum of 20,000 Ross 308 broiler chickens were raised per house to maximise the production profit. As the farm practices animal welfare standards, chicks were initially grown at a stocking density of 0.1 sqft/bird, and gradually increased to a minimum of 0.8 sqft/bird at the market age.

Day-old-chicks (DOC) from the breeder farm were transported to the broiler farm for growth within 24 hours after hatching. Through feather sexing in the hatchery, the chicks were packed separately according to their sex and transported to the broiler farm, where they generally have a proportion of 60% female and 40% male chicks.

The broiler growing process takes approximately 42 days, and an additional 20 days for thorough cleaning and disinfection, and preparing for the next cycle intake. The whole production process takes an average of 62 days to complete. From DOCs to an age of 21 days, the chicks were fed with starter feed and were gradually replaced by grower feed at the age of 21 till market weight, ranging from 2 to 2.5 kilograms, which aligns with the data provided by the Department of Veterinary Science Malaysia (DVS). Both types of feed were supplied by FFM Grains and Mills Sdn Bhd, located in Johor Bahru, Malaysia. Supplementation, i.e., probiotics and plant extract products, was used to treat the chickens to enhance their immunity and control disease outbreaks. The supplements used were supplied by a biotechnology company located in Johor Bahru.

Sawdust, with an important function as a bedding material, was transported to the farm at least two days before the DOCs' arrival. Insecticides were constantly bought to the farm for cleaning and disinfection purposes, regardless of the presence or absence of chickens.

Life Cycle Impact Assessment (LCIA)

The study focused on global warming potential (GWP_{100}) resulting from GHG emissions. According to the Climate Change Sixth Assessment Report IPCC (2023), the GWP_{100} values were listed in Table 1. CO_2 is the reference for estimating GWP_{100}: it remains the value "1" regardless of time period. CH_4, as one of the major ozone destructive gases, contributes approximately 29 to 30 GWP_{100}, followed by N_2O with 273 times higher heat absorption and remaining in the earth, denoting significant global warming effects (U.S. EPA, 2025).

Table 1
100-year Global Warming Potential (GWP_{100}) of CO_2, CH_4 emitted from combustion of fossil fuel and non-fossil fuel sources, and N_2O

Components	[1]GWP_{100}
CO_2	1
CH_4- fossil	27.9
CH_4- non-fossil	29.8
N_2O	273

Note. [1]Climate Change Sixth Assessment Report IPCC (2023)

Poultry Greenhouse Accounting Framework (Po-GAF) V1.45, originated from Primary Industries Climate Challenges Centre (PICCC), was modified to align with the farm's conditions. In this study, CO_2, CH_4, and N_2O were primarily estimated using the formulae provided in the PICCC model in Equation 1. The CH_4 EF was estimated using Equation 10.23 in Chapter 10: Emissions from Livestock and Manure Management (IPCC, 2019).

$$EF_M = B_0 \times 0.67 \times MCF \times AWMS \qquad [1]$$

where B_0 is the maximum producing capacity with the reference value provided in Table 10.16A, 0.67 is the conversion factor, MCF is the CH_4 conversion factor listed in Table 10.17, and AWMS is the animal waste management system fraction. As the farm practices fully sell PL, the AWMS is 100%.

Data obtained from Equation 1 was then used in CH_4 production (Equation 2) whereas N_2O production from manure management was estimated using Equation 3.

$$CH_4 = N \times VS \times AWMS \times EF_M \qquad [2]$$

$$N_2O = N \times NE \times AWMS \times EF_{N2O} \times \frac{44}{28} \qquad [3]$$

where N is the flock population, VS is the volatile solids excretion per bird (kg VS/bird), NE is the N excretion (kg N/bird), EF_{N2O} is the nitrous oxide EF listed in Table 10.21, and $\frac{44}{28}$ is the conversion factor.

In Malaysia, electricity is provided by Tenaga Nasional Berhad (TNB). The total electricity consumption per house was quantified, and emissions were assessed using country-specific EF reported in NRECC (2022) Table B-1. For emissions from stationary fuel such as fuel tanks, and for mobility such as transportation, the EFs were obtained from Table A-2 and Table 13-e, respectively, from the same source as the electricity EF.

Emissions associated with feed production were estimated by aggregating the raw feed materials based on their respective countries of origin, utilising emission intensity values derived from established literature. The emission intensities for each material are presented in Table 2. Due to confidentiality constraints imposed by the feed mill, the proportional composition of individual raw materials was not disclosed.

LCA Goal and Scope

This study's LCA goal and scope were essential to clarify according to the ISO 14040/14044 standard. The objective of this LCA study was to quantify the total GHG emissions and mitigation efficiency from the broiler farm from cradle to farm gate.

Table 2
Starter and grower raw materials GHG emission intensity

Material	Origin Country	[1]Emission intensity (t CO_2-eq/t material)	Reference
Corn	Argentina	0.20	Arrieta et al. (2018)
Soybean Meal	Argentina	0.41	Parajuli et al. (2022)
Corn Gluten Meal	USA	0.98	Taylor et al. (2023)
Crude Palm Oil	Malaysia	1.17	Kulim (Malaysia) Berhad (2020)

Note. [1]Greenhouse gas emission intensity

Scope and Boundary

The system boundary comprises the cradle-to-farm gate, which includes the production inputs from DOC intake until the adult chicken was harvested. The assessment was consolidated from both starter and grower emissions, and results were expressed in one-kilogram finishing chicken and presented in kilograms of CO_2 equivalent per kilogram of live-weight (kg LW/ kgCO_2-eq) of GHG emissions.

For better calculation of the GHG emissions, following the Corporate Standard (2004), the LCA was segregated into three scopes, i.e. Scope 1 (on-farm emissions/ direct emissions), Scope 2 (purchased electricity), and Scope 3 (upstream activities). The boundary of this LCA study was illustrated in Figure 2.

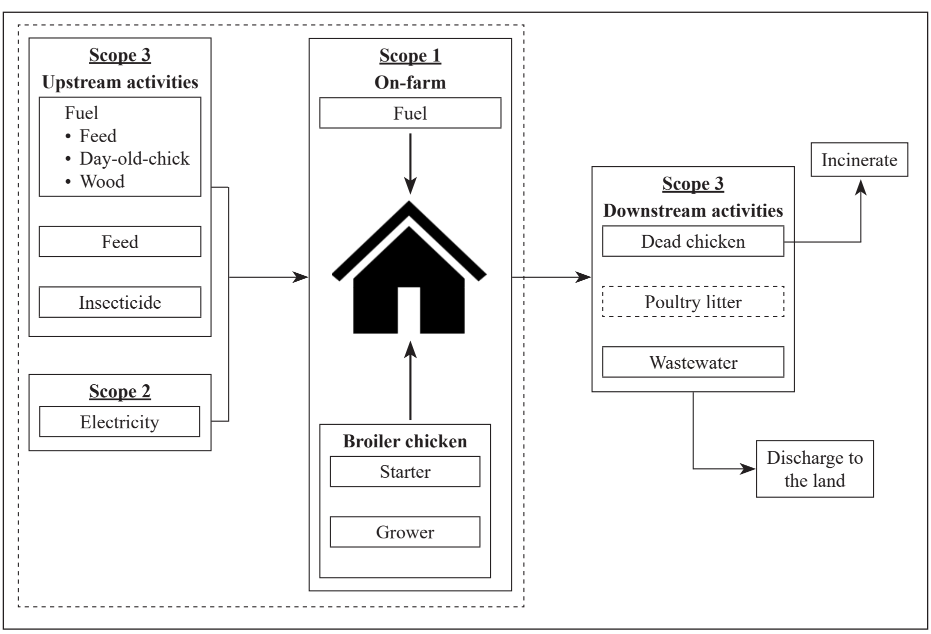

Figure 2. System boundary with activities quantified in this assessment. Subjects fall in dashes lines were in the boundary of assessment

In Scope 1, the emissions resulted from on-farm activities, specifically from manure management and fuel utilisation. Scope 2 emissions encompass electricity usage, whereas Scope 3 involves both upstream and downstream activities. For upstream activities, it involves fuel consumption for transporting DOC, feed, and wood shavings into the farm. As wood shavings and DOC were only transported into the farm once (before the cycle started), the fuel consumption was calculated as one trip; feed was transported into the farm for two times per week, and thus, the total fuel consumption was assessed based on the total frequency transported into the farm. Emissions during feed production also fell under Scope 3 as it is produced for farm use. Downstream activities involve several processes such as PL handling and other by-products handling; however, only PL management has fallen into this assessment due to limitations of data for other co-products produced.

DATA INVENTORY

The study comprises both primary and secondary data inventory for more accurate GHG emissions estimation. For a better understanding of the process flow, the operational sequence was illustrated in Figure 3.

Primary Data Inventory and Sample Collection

As defined in the Benedictine University Library (2025), primary data refers to the information that is directly collected by the researcher through methods such as surveys, interviews, or experiments. The purpose is specifically gathered for addressing and understanding the study hypothesis.

The primary data for this study were obtained mainly through on-field sample collection and laboratory analysis. PL samples were collected bi-weekly starting from DOC intake (Week 1) until harvested (Week 5), i.e., Week 1, Week 3, and Week 5. These sampling periods represent different growth stages of the broiler chickens, including early growth, intermediate growth, and finishing stages. Changes in birds' age and feed types resulted in different nutrient excretion, which influences GHG production. Therefore, collecting samples at these intervals provides a more representative estimation of total GHG emissions.

Grab samples were collected randomly from five to ten spots in each broiler house and mixed thoroughly to obtain a representative composite sample. From each house, six composite samples were collected. After the cleaning process at Week 8, three grab PL samples were collected from each house, which were obtained from the mixture of five to ten arbitrary points. All solid samples were immediately stored in an ice box before being transferred to an Acson R134a freezer (-18 °C) for further analysis. Total solids (TS) and volatile solids (VS) content were analysed following the procedures outlined by MacLeod et al. (2013), employing the methodologies recommended in the *Second Edition of Recommended Methods of Manure Analysis* (Wilson et al., 2022). Each sample was analysed in triplicate to determine the average values.

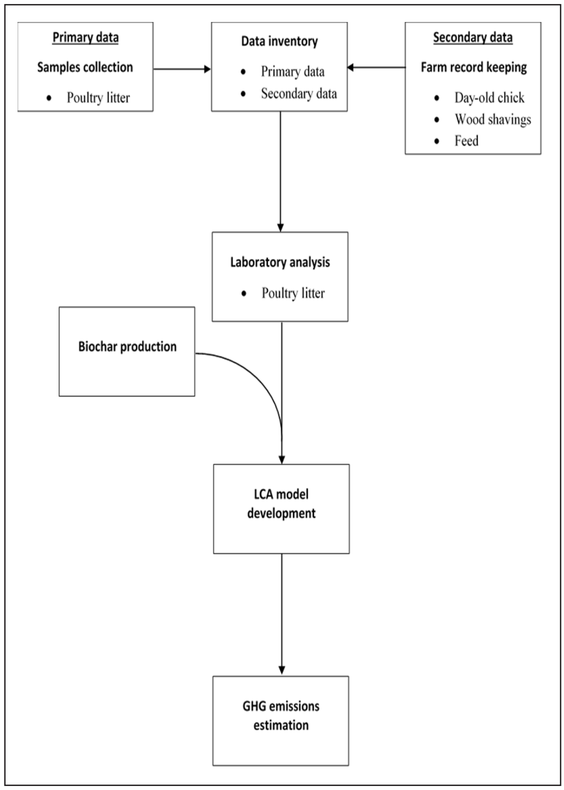

Figure 3. Process flow of the LCA

As the farm does not practice wastewater treatment, the impacts and downstream emissions from the discharge activity were excluded in this assessment.

Secondary Data Inventory

Secondary data refers to historical data generated by the organisation or institutions as part of their routine record-keeping. This data is later retrieved and utilised from various existing datasets for research or analysis purposes (Wagh, 2025). The data collected were flock population each house, total feed consumption, daily body weight, total insecticides purchased, total electricity consumption, and the total broilers marketed and coproducts produced at the farm gate. The feed composition was shown in Table 3, encompassing the farm's feed management, i.e. starter and grower feed.

Table 3
Feed nutrient compositions of starter and grower

Composition	Starter	Grower
Dry Matter (g/kg)	885	886
Crude Protein (g/kg)	198	211
Crude Fat (g/kg)	47	82
Crude Fibre (g/kg)	23	22
Ash (g/kg)	52	48
Nitrogen-free Extractives (g/kg)	566	524
Gross Energy (kcal/kg)	3835	4066

The data were de-identified and compiled in consolidated form to protect the confidentiality of proprietary corporate information.

Handling of Co-products

Finished broiler chickens are the primary products from the farm, while PL, bird carcasses, and wastewater generated during cleaning processes are considered as secondary outputs. The predominant method for managing PL involved selling it to local crop production enterprises. Emissions resulting from land application of PL were excluded from the assessment, as they fell outside the defined system boundaries. Bird carcasses generated during the production cycle were disposed of through incineration; however, the associated emissions were not evaluated due to a lack of reliable data. Wastewater produced during cleaning activities was discharged into the soil, and its environmental impacts were not included in this assessment.

Mitigation

After each production cycle, the farm practised selling PL as fertilisers to other crop production, which is one of the main co-product handling methods. However, due to potential adverse effects of PL on soil properties, including pH change, organic matter content, concentration of micro- and macronutrients, eluviation, and crop yield (Silva et al., 2025), alternative mitigation strategies have to be developed. Also, mass antibiotic usage in poultry farming has raised environmental and public health concerns. Lopes et al. (2024) have discovered multi-antibiotic bacterial strains in PL, and they exhibit great potential in horizontal gene transfer of antimicrobial resistance genes, especially in agricultural soil, consequently posing both environmental and human health risks. In intensive monoculture cropping systems and similar livestock populations, the environmental persistence and adaptation of pathogenic microorganisms potentially increase the reinfection of existing host populations (Wesley et al., 2000). This created concerns not only on the GHGs emissions, also to the public health. To improve the mitigation system, the study proposed composting and converting PL into biochar. Both mitigation methods were calculated for their total carbon sequestration.

Poultry Litter

The total amount of PL generated during the cycle in this study was recorded and assessed. Modelling the actual situation of the farm management, all the PL was sold to other crop production as fertilisers. No litter was recycled for the next production cycle.

Composting

Composting is a biological process that converts biomass into nutrient-rich organic matter through several successive stages. The process begins with the degradation of organic materials by mesophilic microorganisms (mesophilic phase), followed by the thermophilic phase, during which microbial activity intensifies, and heat is released as a by-product of decomposition. Finally, the curing phase occurs, characterised by the stabilisation and maturation of the remaining organic matter (Lim et al., 2019).

To estimate the total mitigation potential of composting in this study, it was assumed that all PL were composted, with animal waste management allocated entirely (100%) to composting. As the study does not have primary data obtained from the PL compost from the farm, reference values were retrieved from Naumova et al. (2024) and Tiquia & Tam (2000), where the characteristics of PL samples were more similar to this study (Table 4).

Biochar Production

Biochar is a stable, carbon-rich material derived from biomass sources such as wood chips, manure, and agricultural residues and is primarily used for carbon sequestration (USDA, 2025).

Biochar could be produced mainly through a few crucial steps, including organic matter collection, drying, grinding, and sieving before thermal processing, which would be carried out under minimal or absence of oxygen, named pyrolysis or carbonisation processes. For improving adsorption capacity, post-treatment is often done to enhance char's surface area. Optimal production generally occurs at temperatures above 200 °C (Xiang et al., 2020). Pyrolysis refers to the thermal decomposition of biomass into a carbonaceous product under limited or no oxygen conditions, usually at temperatures below 900 °C. The resulting biochar possesses a porous structure that enhances water-holding capacity, nutrient retention, pH modification, and cation exchange capacity (Zakaria et al., 2023).

In this study, after the collection of PL at Week 8 of production, 20 g of PL samples were used to convert into biochar, referring to the methods conducted by Chin et al. (2024). Biochar was first pre-dried in a Memmert Universal Lab Oven at 60 °C for 12 hours. After drying, the samples were ground and crushed into 0.20 mm particle sizes and further dried in an oven at 105 °C for 24 hours to minimise the water content before pyrolysis. Following their method, the samples were pyrolysed at 420 °C for 30 minutes in an ELF 11/14B Chamber Furnace to maximise the organic carbon recovery from PL. The dry weight was determined by heating it at 105 °C for 24 hours (Nkomo et al., 2021). Biochar yield was calculated as a percentage, as shown in Equation 4.

$$\text{Biochar yield} = \frac{\text{Biochar produced, g}}{\text{Biomass pyrolysed, g}} \times 100\% \qquad [4]$$

Table 4
Poultry litter (PL), compost, and biochar composition obtained from primary data, except for composting, which used reference values

	DM	Moisture	Ash	Carbon	Organic Carbon	Yield
				%		
PL	71.596	28.404	89.935	41.1	-	-
*Compost	75.5	24.5	10.65	20.45	9.425	-
Biochar	99.971	0.029	-	44.86	33.73	61.885

Note. (*) indicated data obtained from other sources, i.e. Naumova et al. (2024) and Tiquia & Tam (2000); DM, dry matter content on dry basis; Yield, total yield after treatment

Carbon Sequestration

Equation 5 shows the method for carbon sequestration assessment using PL and compost, while Equation 6 is for biochar, where $\frac{44}{12}$ is the conversion factor to convert the carbon reservoir in the biomass into CO2, Ydm is the biochar yield in dry mass, and C-stock is the carbon stock, adapted from Li et al. (2021) and Suhardono et al. (2024). The results were accounted in t CO2-eq.

$$CO_2 \text{ sequestration} = \text{Carbon-stock (t)} \times \frac{44}{12} \quad [5]$$

$$CO_2 \text{ sequestration}_{\text{-Biochar}} = \text{Carbon-stock (t)} \times Y_{dm} \times \frac{44}{12} \quad [6]$$

C-stock is defined as the reservoir or ecosystem which has the ability to hold or release carbon, such as soil (Newell-Price et al., 2023). To determine the C-stock in PL, compost, and biochar, they are calculated using Equation 7 (Muthmainnah et al., 2021) and Equation 8 (Goslee et al., 2015), respectively. Total carbon content (C%) was quantified using a Carbon Nitrogen Sulphur (CNS) elemental analyser, following *628 Series: Elemental Analysis* by Combustion (2016).

$$\text{C-stock}_{\text{-PL/Composting}} \text{ (t)} = \text{Dry mass of sample (t)} \times \text{C\%} \quad [7]$$

$$\text{C-stock}_{\text{-Biochar}} \text{ (t)} = \text{Dry mass of feedstock (t)} \times \text{C\%} \quad [8]$$

Emissions from biochar production were excluded from the assessment due to insufficient data.

Exception

Emissions resulting from the disposal of bird carcasses were excluded from this study due to nondisclosure by the farm. Furthermore, carbon emissions associated with wood shavings, insecticide use, and dietary supplementation during broiler production were omitted owing to insufficient data availability. Additionally, emissions during biochar production were excluded from the study due to insufficient data. Lastly, land-use change (LUC) was considered outside the defined system boundaries of the LCA.

Data Analysis

A one-way Analysis of Variance (ANOVA) was performed to evaluate significant differences in TS and VS of PL across different weeks. All statistical analyses were conducted at a 95% confidence level. Tukey's post-hoc test was applied for multiple mean comparisons.

RESULTS AND DISCUSSION

Broiler Performance

Based on the performance data presented in Table 5, the average body weight observed was lower at hatch (Day 0), but it was consistently higher than the values reported in the Ross 308 Performance Handbook (Aviagen, 2022) from Days 7-14. However, a slower growth in body weight was observed after Day 14. This discrepancy may be attributed to the findings of Cowieson and Parsons (2024), who reported that reduced feed intake in smaller chicks leads to diminished growth performance. This observation is consistent with the present study, where the reduction in feed intake observed at Day 14 may have contributed to the subsequent decline in body weight gain.

Table 5
Broiler performance from day-old chick to market weight

Age (day)	ABW (g/bird)	Cumulative Feed Intake (g/bird)	ABWG (g/bird)	FCR
0	38.67	-	-	-
7	266.83	167.31	228.17	0.73
14	611.00	502.08	572.33	0.88
21	980.67	1039.38	942.00	1.10
28	1503.33	1732.61	1464.67	1.18
35	2050.00	2686.43	2011.33	1.34
Market	2540.00	3397.84	2501.33	1.36

Note. ABW, average body weight; ABWG, average body weight gain with Day 0 as the baseline body weight; FCR, cumulative feed conversion ratio

On Day 0, the average body weight of the chicks was considerably lower than the reference value reported in *Ross 308 Performance Handbook* (44 g). However, the average body weight exceeded the recommended standard at Weeks 1 and 2, despite a similar and lower cumulative feed intake, respectively. At Day 7, cumulative feed intake was slightly higher than the standard (166 g/bird), which might be due to lower starter feed nutrient density (Lamot et al., 2019) or a compensatory feed consumption behaviour as described by Morais et al. (2017). Post-hatch chicks may exhibit increased feed consumption to compensate for insufficient nutrient intake and support rapid development of bone and muscles.

The lower FCR values from Day 7 (0.73) to 14 (0.88) were likely influenced by the averaging of data from the three poultry houses, which consisted of a mixed population of small chicks (≤37 g) and medium-sized chicks (>37 g), resulted in slightly higher calculated average body weight while maintaining relatively lower feed intake, resulting in an artificially improved FCR during the early growth development. After Day 21, the introduction of grower feed may have enhanced the growth performance of small-sized chicks, allowing them to undergo compensatory growth and achieve similar body weight and feed intake as the medium-sized chickens. Consequently, the FCR values increased and followed the more expected trend as the flock progressed through the later growth stages.

Nevertheless, the growth performance after Day 14 gradually declined along with reduced feed intake. Although Khulel et al. (2020) reported that smaller chicks could negatively affect body weight gain and feed intake, this factor is unlikely to be the sole contributor in the present study, as the flock demonstrated exceptional body weight gain during the first two weeks of production. Poor flock uniformity was expected to be one of the contributors to this phenomenon, especially starting from harvesting, which leaves smaller or stunted-growth birds behind the catch. As catching operations act as stressors to the birds, inducing fear, agitation, and abnormal behaviour (Wolff et al., 2019), feed intake and growth rate could be disrupted, eventually reducing body weight gain.

Emissions by Scopes

As illustrated in Figure 4, Scope 3 emissions constituted the largest proportion of total GHG emissions (37.18 tCO_2-eq) associated with conventional broiler production from cradle to farm gate, followed by Scope 1 (15.01 tCO_2-eq) and Scope 2 emissions (11.78 tCO_2-eq). Scope 3 emissions primarily stemmed from upstream processes, including feed production, insecticide, and fuel consumption for the transportation of materials to the farm.

Throughout the broiler farm production, the farm emitted a total of 25.03 tCO_2-eq GHG solely from the feed production, comprising 67% of the Scope 3 emissions, followed by 33% of emissions from fuel, and 0.3% from insecticide. This suggests that the majority of emissions within the broiler production system originate not from on-farm activities but rather from external upstream sources. Indeed, the cost of broiler production in Malaysia is mainly through the production inputs, mainly from feed cost (Abdurofi et al., 2017). Following Scope 1 emissions, it is attributed entirely to on-site manure management,

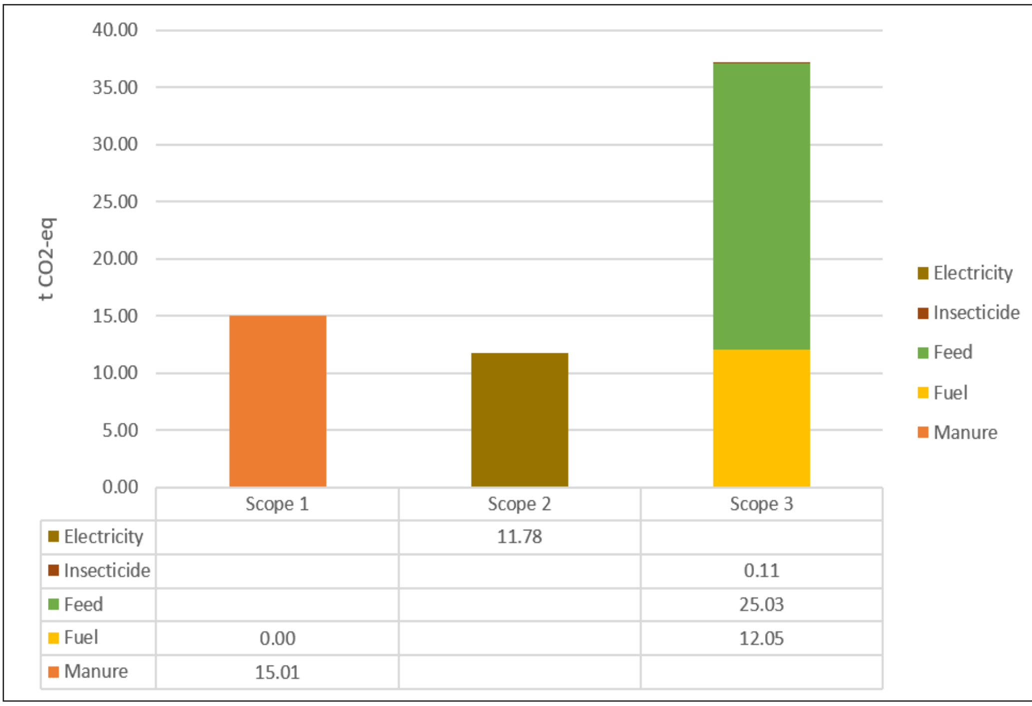

Figure 4. Total GHG emissions in the conventional broiler production farm from cradle-to-farm gate according to Scope 1, 2, and 3, with total emissions of 63.97 tCO_2-eq/house/cycle

reflecting the minimal contribution of fuel use to the farm's direct emissions, as the majority of the daily tasks were performed by hand. Though Scope 2 emissions consist solely of electricity consumption, its result is comparable to that of Scope 1, bringing attention to the environmental impacts from electricity generation.

Hotspot Analysis

Following scope-based emissions (Figure 4), Figure 5 illustrates a more in-depth evaluation of the carbon footprint incorporated with production activities. According to Figure 5, feed purchased indicated the main contributor to GHG emissions in conventional broiler production from cradle-to-farm gate, with an approximate 39% of total emissions. While manure management acted as the second contributor with 24% of total emissions, electricity and off-farm fuel consumption represented similar amounts of carbon footprints, 18% and 19%, respectively. As the farm does not practice wastewater treatment, emissions produced from the disposal were indeterminate.

In fact, fuel consumption and insecticide usage in Scope 1 and 3, respectively, were found to have negligible outcome to the overall emissions. This could be explained by low consumption of fuel usage during the brooding period, which has often been reported

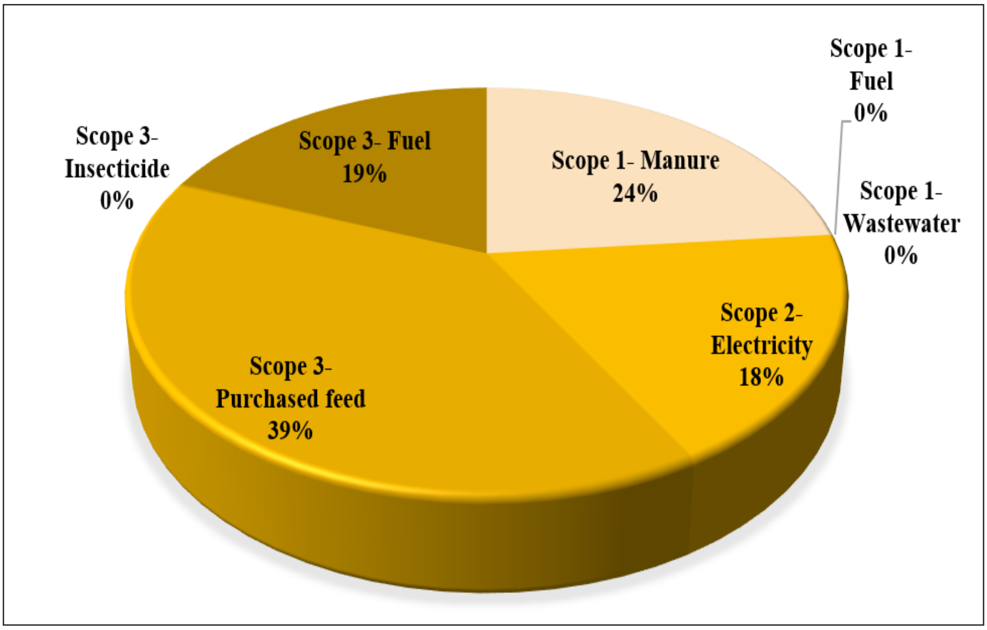

Figure 5. GHG hotspot analysis in the conventional broiler production farm from cradle-to-farm gate with a total emission of 63.97 tCO_2-eq/house/cycle

to play a key role in on-farm emissions (MacLeod et al., 2013). The analysis indirectly outlined the low dependency of the farm on fossil fuels, primarily due to the implementation of automated closed-house systems, which rely heavily on electricity for daily operations. Low emissions stemming from pesticide usage likewise indicated limited application of anthropogenic inputs, suggesting more sustainable farming practices.

Nevertheless, energy utilisation (fuel and electricity) represented a significant amount, with a total of 37% of overall emissions, which went beyond manure management, yet remained lower than feed production. This finding further highlights the profound impact of feed production on GHG production in the broiler production chain, aligning with the study by Ogino et al. (2021). By the same token, Zisis et al. (2023) concluded the main source of carbon emissions in broiler production arose from feed and LUC. Results from this study are consistent with their findings, with the highest emissions *hotspots* were associated with purchased feed. Additionally, energy used for PL and carcass disposal was identified as a key contributor to overall GHG emissions during production.

Overall Emissions and Mitigation

Table 6 represents the emission intensities for broiler production based on a cradle-to-farm gate assessment, covering three PL management options: selling untreated PL, composting, and biochar production. The baseline carbon footprint was calculated at 1.54 kg CO_2-eq/

kg LW/cycle. Among the options evaluated, selling PL showed the largest reduction in emissions, decreasing the footprint by 29.87% (0.46 kg CO_2-eq/kg LW). Biochar production followed by a reduction of 20.13% (0.31 kg CO_2-eq/kg LW), while composting resulted in a smaller decrease of 15.58% (0.24 kg CO_2-eq/kg LW).

Table 6
Summary of net greenhouse gas emissions with different mitigation methods from cradle-to-farm gate resulting from the broiler production farm

Subject	*Emission Intensity (kg CO_2-eq/kg live weight)	Total Carbon Reduction (%)
Total (without mitigation)	1.54	-
After selling poultry litter	1.08	29.87
After composting	1.30	15.58
After conversion to biochar	1.23	20.13

Note. (*) Emission intensity indicates total carbon emissions

However, the apparent benefit of selling PL needs to be interpreted carefully. The reduction is largely due to emissions being shifted across farm boundaries rather than actually reduced. In other words, untreated litter is simply transferred elsewhere, which lowers the farm-level footprint but does not solve the underlying environmental issue. This raises concerns from a sustainability perspective.

Raw PL contains high levels of N and phosphorus (P), which have high mobility in soil that is prone to leaching, water pollution, and air quality problems (Gržinić et al., 2023). The natural decomposition of untreated litter could generate CH_4, ammonia, and other volatile compounds, worsening environmental impacts. Since PL consists of animal droppings, feathers, and residual feed materials, it contains abundant nutrients, including N, P, carbon (C), and oxygen-containing compounds, which serve as substrates for microbial decomposition and subsequently contribute to greenhouse gas (GHG) emissions.

Compared to selling untreated litter, composting or conversion into biochar seems to be a more promising mitigation strategy. Composting is a method for converting biologically degradable substances into nutrient-rich soil amendments. During composting, moisture loss occurs through evaporation and degradation of water-holding organic matter in PL, resulting in a reduction of PL volume while improving the carbon-to-nitrogen ratio (C:N) of the final product (Tiquia & Tam, 2002). Furthermore, high C:N enhances nitrogen uptake efficiency and reduces nitrogen leaching, thereby improving nutrient retention and environmental sustainability (Holub et al., 2020). Through compost, nutrient restoration to the soil can be achieved by reducing the formation and release of carbon- and nitrogen-based volatile compounds into the atmosphere, thereby reducing total GHG emissions.

Nevertheless, nutrient leaching and detrimental gas emissions, including GHGs, remain major concerns associated with the composting process, as deviation of raw material properties, including balanced C:N, oxygen supply, and pH, could lead to undermine quality and reduce agroeconomic aspects (Weindorf et al., 2011).

As an alternative measure, biochar production through the pyrolytic conversion of PL provides waste reduction and long-term carbon sequestration benefits. Biochar, as a stable carbonaceous compound, has a high ability to adsorb organic carbon and prevent oxidation to form volatile CO_2. During pyrolysis, nitrogen- and oxygen-containing compounds in PL are rapidly decomposed, resulting in the formation of a highly stable carbonaceous structure (Yang et al., 2024) with a lower degradation rate compared to untreated PL.

The natural porosity structure of biochar acts as a natural habitat for microbes, hyphae, flora and fauna, with other advantages such as improving soil aeration, water retention, and binders for heavy metals and nutrients, efficiently immobilising pollutants and improving crop productivity (Biswal & Balasubramanian, 2025). Furthermore, it promotes the growth and activity of methanotrophic bacteria, which enhance CH_4 oxidation, while also providing an adsorption platform for inorganic nitrogen, thereby reducing the production of N_2O (Amirahmadi et al., 2025). In addition, lower CO_2 emissions have been observed when organic waste is co-applied with biochar, as biochar has the ability to reduce the carbon degradation rate and enhance carbon stabilisation (Palansooriya et al., 2025), acting as a powerful carbon sink strategy. On top of these characteristics, biochar therefore represents a comprehensive and sustainable waste management pathway that integrates climate benefits with farming enhancement.

Despite these benefits, potential environmental concerns may arise during biochar production, particularly due to the emission of smoke and syngas generated during the pyrolysis process. Therefore, a trade-off assessment of greenhouse gas (GHG) emissions should be conducted in future studies to determine the net GHG impact of each mitigation approach.

Interestingly, the overall difference in total carbon mitigation between composting and biochar conversion was minimal, approximately 5%, corresponding to less than 0.1 kg CO_2-eq/kg LW. This indicates that both methods offer comparable emission reductions within the current LCA boundary. To improve the accuracy of these estimates, future studies should consider expanding the LCA system boundaries to include energy consumption, process emissions, and transportation activities associated with each treatment method. Such comprehensive review would allow a more accurate assessment of net GHG mitigation potential and identify the true environmental trade-offs among different PL management strategies.

Total Solids and Volatile Solids

Table 7 represents the weekly TS and VS content in PL, from day-old chicks to market age. Both TS and VS reached their peak concentrations at week 3 of the birds' age, scoring 63.05% and 97.51%, respectively. The elevation of volatile compounds in excreta could be explained by dietary adaptation, shifting from starter to grower feed, which affected the gut microbial activities and nutrient absorptions, and consequently affected the excreta compositions. Despite this, TS concentrations did not vary significantly across different ages ($p = 0.30$), whereas VS concentrations showed statistically significant differences throughout the production cycle ($p < 0.05$).

Table 7
Weekly total solids (TS) and volatile solids (VS) mean values of the poultry litter (PL)

Composition	Mean	P-value	*Przybulinski et al. (2023)*	P-value	*Marchioro et al. (2018)*	P-value
TS (%)	61.41		62.91	0.40	76.0	0.15
Week 1	60.13	0.30				
Week 3	63.05					
Week 5	61.05					
VS (% of TS)	94.62		91.36	<0.05	64.0	<0.001
Week 1	95.28^{a}	<0.05				
Week 3	97.51^{a}					
Week 5	91.08^{b}					

Note. Means within a column followed by different letters (a-b) are significantly different ($P<0.05$)

However, when compared to other findings presented by Przybulinski et al. (2023) and Marchioro et al. (2018), VS values assessed from this study showed significant higher amount, while TS showed insignificant differences. High VS concentrations may be attributed to a higher proportion of biodegradable organic matter, such as wood shavings, in the manure. This composition likely contributed to increased VS emissions during the degradation process (Li et al., 2019).

In order to minimise the effects during waste treatment, TS and VS values are crucial indicators (Peces et al., 2014). A higher VS content indicates a greater proportion of biodegradable organic matter, which enhances the biological treatment potential and contributes to effective waste minimisation. High VS content is often associated with higher GHG emissions potential, as the abundant biodegradable organic matter can be readily decomposed and converted into various gaseous products under both aerobic and anaerobic conditions. Nevertheless, the findings of the current study demonstrate a higher proportion of degradable compounds compared to those reported in previous studies.

Table 8
Total solids (TS) and volatile solids (VS) mean values of the poultry litter (PL) [wood shavings-based PL] when comparing with Collins et al. (2023) [straw-based PL], Wedwitschka et al. (2020) [mixture of chicken manure from different sources], and Mohd Johari et al. (2020) [fresh poultry manure]

Composition	TS (%)	P-value	VS (% of TS)	P-value
Mean	61.41		94.62	
Collins et al. (2023)	84.9	<0.001	84.3	<0.001
Wedwitschka et al. (2020)	78.3	<0.001	69.5	<0.001
Mohd Johari et al. (2020)	23.79	<0.001	77.0	<0.001

For better evaluation of different housing systems on the GHG production potential, straw-based PL (Collins et al., 2023), mixtures of chicken manure with other sources (Wedwitschka et al., 2020), and fresh poultry manure (Mohd Johari et al., 2020) production systems were summarised in Table 8. The results revealed highly significant differences in both TS and VS values relative to those obtained in this study.

Fresh poultry manure exhibited the lowest TS value (23.79%), followed by chicken manure from different sources (78.3%). Low TS content was attributed to high moisture content, which could range from 53-78% (Khodadadi et al., 2024), leaving a low proportion of dried residues and organic materials after treatment. Thus, resulting in decreased TS concentration.

Based on these results, the water-holding capacity of different bedding materials can be ranked as follows: straw-based PL > mixture of poultry manure with other sources > wood shavings PL > fresh poultry manure. Furthermore, the total moisture content is influenced by storage method and duration, with a significant decrease observed during the first two days of storage, and after 28 days, particularly under freeze-drying conditions (Pan et al., 2009).

In the setup of Wedwitschka et al. (2020), chicken manures were mixed from various sources, including bedding materials, storage periods, and housing methods. Although these mixtures were expected to contain higher levels of biodegradable organic matter, resulting in higher VS, the results instead showed the lowest VS values compared to individual housing systems (69.5% on a TS basis), suggesting low-degradable organic matter compositions compared to fresh poultry manure and PL. Therefore, the mixture demonstrated the lowest potential for VS production, which is a key parameter in evaluating biogas potential and energy recovery through anaerobic digestion (Wang et al., 2023).

Total solids (TS) represent the total dry matter content, consisting of both degradable and non-degradable components. According to Le Riche et al. (2017), a high TS content may promote crust formation, which can alter aerobic and anaerobic conditions that influence GHG production, including CO_2, N_2O, and CH_4. Furthermore, high VS content indicates the presence of greater amounts of biodegradable organic matter, including nitrogen-containing compounds, which can be transformed into GHGs through microbial processes. Therefore, lower TS and VS contents are generally preferred in mitigation approaches to reduce the potential formation and emission of GHGs.

Based on these findings, the potential of various feedstock substrates for biogas or power generation can be ranked as follows: wood shavings-based PL > straw-based PL > fresh poultry manure > mixture of poultry manure with other sources. This ranking reflects the availability of biodegradable organic matter represented by VS content. For waste management strategies aiming to minimise GHG emissions, the preferred sequence should follow the same descending order, as substrates with higher biogas potential allow greater conversion of organic matter into energy while reducing the amount of degradable material remaining for uncontrolled decomposition and subsequent GHG emissions.

Nevertheless, statistical comparisons of significant differences among these studies could not be conducted due to insufficient primary data.

IMPLICATIONS OF THE STUDY

The study acts as a milestone for the poultry industry in Malaysia to develop nation-based data, reducing full dependency on the global default value, which is often reported to have some deviations in the accuracy of local results.

In addition, the results of the data allow the broiler company to achieve an Environmental, Social, and Governance (ESG) certificate, improving its competitiveness and sustainable footprint.

LIMITATION AND RECOMMENDATION FOR FUTURE RESEARCH

As the study focuses on the direct and upstream emissions, impacts produced from land-use change and manure management were excluded. Carbon emissions produced during manure management such as anaerobic digestion and composting should be evaluated in future studies to minimise environmental impacts. A more comprehensive LCA, quantifying the net carbon footprint, should be done, including the emissions during biochar production to review the effectiveness in carbon reduction.

Another potential mitigation approach is through feed modification, evident from this study in highest influence in GHG emissions throughout the production. For instance, reduction of N content in PL could significantly reduce N_2O formation. Total methanogens in gastrointestinal tracts or excreta could presumably be quantified as one of the indicators in assessing emissions potential. Compared to the high installation cost for technologies, nutrition modifications act as a more financially friendly strategy and could potentially be implemented worldwide.

Moreover, housing systems could also influence carbon emissions. Implementations such as slatted floors, cages, or free-range production vary in terms of manure management, exposure, and flock performance, which lead to different emission profiles. Assessing these alternative systems is recommended to guide environmentally sustainable housing practices.

In upcoming research, total volatile fatty acids (VFAs), including butyric and acetic acids, could be integrated into poultry manure analysis, due to their high volatile properties and CH_4 production, which negatively impact the environment (Yin et al., 2022). Also, it could serve as an indicator of microbial activities, assist in minimising GHG emissions, and prediction for biogas potential.

Lastly, environmental pollution potential and bio-reactant capacity could be assessed by quantifying N, CO_2, and CH_4 concentrations in poultry manure, with varying mixtures and moisture contents. These parameters not only reflect the potential for anaerobic digestion and biogas production but also provide insight into possible local environmental pollution during storage (Higgins et al., 2021).

CONCLUSION

In summary, the conventional broiler production system assessed in this study generated a cumulative total of 63.97 tCO_2-eq/house per production cycle. The largest share of emissions (39%) originated from feed procurement (excluding LUC), followed by energy consumption (37%) and manure management (24%). Scope 3 emissions accounted for the highest proportion of the carbon footprint, followed by on-farm emissions under Scope 1. In the absence of mitigation measures, total emissions per house per cycle were estimated at 1.54 kg CO_2-eq/ kg LW of bird. Although the sale of PL offers the highest potential emission reduction (-29.87%), its associated negative environmental impacts make it a less favourable option. Alternatively, converting PL into compost or biochar presents a more sustainable mitigation strategy, reducing total emissions to 1.30 kg CO_2-eq/ kg LW and 1.23 kg CO_2-eq/ kg LW, respectively.

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