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A Second Life for Agro-Industrial Residues: Edible Coating from Roselle Decoction Residues for Preserving Wax Apple Quality and Antioxidant Properties

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ABSTRACT

Postharvest deterioration and fungal infection significantly limit the shelf life of wax apples (*Syzygium samarangense*), while roselle decoction residues remain underutilised despite retaining bioactive compounds after processing. This study aimed to evaluate the efficacy of roselle decoction residues as functional ingredients in edible coatings for wax apple preservation. Fresh roselle calyx (RC) (F3), fresh decocted cordial residue (DCR) (F4), freeze-dried RC (F5), and freeze-dried DCR (F6) were incorporated into various coating formulations and applied to fruits stored for 15 days at ambient temperature. Roselle-based coatings significantly delayed fruit deterioration by preserving colour, firmness, and biochemical attributes (soluble solids, acidity, vitamin C, phenolics, and flavonoids) compared to controls. Water loss was reduced, and antioxidant capacity (DPPH) was better maintained in coated fruits. Among treatments, fresh RC (F3) exhibited the most consistent performance in preserving quality attributes, followed by F6, F4, and F5. Under wound-inoculation conditions, selected roselle-based coatings also delayed visible disease development caused by *Pestalotiopsis* sp. Overall, the findings demonstrate that roselle decoction residues can be valorised as natural antioxidant-rich coating agents, contributing to improved postharvest quality and supporting sustainable by-product utilisation.

Keywords: Antifungal effect, antioxidant activity, cordial by-products, edible coating, fruit preservation, postharvest quality, roselle residue, waste valorisation

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INTRODUCTION

The postharvest handling process faces several obstacles, and in developing regions, these are even more pronounced due to limited storage capabilities and inadequate handling procedures, which continue to result in loss of the food supply chain. In the Asia-Pacific region, postharvest losses are primarily the result of physiological breakdown, microbial infestations, and mechanical disruptions throughout the distribution and marketing processes. Moist, fresh, and highly perishable fruit is especially susceptible to deterioration and is quickly degraded under the conditions found at local markets in developing regions (Esua et al., 2017; Food and Agriculture Organisation [FAO], 2011; Roelle, 2014).

Of the numerous postharvest handling challenges, fungal infections are perhaps the most destructive and have the greatest economic impact on the producer. In the postharvest handling process, several environmental conditions, such as high temperature and low humidity, in conjunction with physical handling stress, significantly promote fruit deterioration and ultimately result in the complete loss of marketable shelf life (Mendy et al., 2019; Shama et al., 2024). When weighing the costs associated with postharvest interventions, especially for small-scale fruit producers, managing marketable shelf life remains critical. Edible coatings (Vilaplana et al., 2020) provide a viable, low-cost, and potentially effective means of helping to reduce shelf-life-dependent postharvest losses.

Wax apple (*Syzygium samarangense*) is a highly perishable tropical fruit. Mechanical damage, high vapour pressure deficit, and high moisture content lead to rapid moisture loss and microbial decay. In Malaysia and other tropical countries, wax apples are sold at ambient temperatures, which is conducive to rapid fungal infections and shortening of shelf life (Department of Agriculture [DOA], 2022; Fenta et al., 2023; Sridhar et al., 2021). This indicates the need for simple and effective preservation methods.

Edible coatings have gained traction for their ability to enhance the postharvest shelf life of fresh fruits. Coatings enhance the shelf life of fruits by decreasing the rate of water loss, regulating gaseous exchange, and slowing the rate of biochemical changes. Edible coatings create a semipermeable barrier to protect fruits and also provide a means to reduce the incidence of oxidative stress and microbial infection by incorporating natural antioxidants and antimicrobials into the coating. (Dhall, 2013; Karthi et al., 2023; Pashova, 2023; Romanazzi et al., 2017; Sharma et al., 2019). Due to their low cost and simple application, coatings are well-suited for tropical fruits.

Recently, the focus has shifted to the use of plant-based residues as functional components of coatings. Coatings that incorporate by-products of plant origin with phenolic compounds contribute to extending the postharvest life of fruits, waste valorisation, and sustainable food systems. Several researchers have demonstrated coatings with plant-based antimicrobial and antioxidant compounds, thereby reducing the need for chemical additives (Flores-Contreras et al., 2024). However, as of now, the use of plant-based materials for coatings has yet to be thoroughly researched.

Roselle (*Hibiscus sabdariffa* L.) is a commercial beverage ingredient that produces high amounts of decoction (a method of boiling) waste that is usually thrown away. Studies have shown that even after heating, waste can still have high amounts of bioactive compounds like phenols, flavonoids, and some organic acids. The extracts from the wastes of roselle have shown *in vitro* antioxidant and antifungal properties (Yusoff et al., 2024), showing that they have potential use in postharvest preservation. However, there is little knowledge of how roselle decoction waste as part of an edible coating on fresh fruit, impacts the fruit's retaining quality and inhibits disease during storage.

This is the background on which the present study is based on, to explore the use of edible coatings made from waste of roselle decoctions and to quantify, for the first time, control of quality attributes (physiochemical), antioxidant, and disease of the wax apples during storage at ambient temperature. The study also attempts to capture the potential of using waste of roselle, with the understanding that incorporating fresh and freeze-dried roselle waste would be more practical, to create non-futuristic value-added coatings.

MATERIALS AND METHODS

Plant Material

The Terengganu variety roselle calyxes (UMKL-1) were purchased from Aslah Hibiscus, Aslah Supply, and Services located in Batu Pahat, Johor, Malaysia (4.2105° N, 101.9758° E). The wax apples were obtained from Ladang Konsep Loceng Merah, Felda Lubuk Merbau, Kuala Nerang, Kedah (06°16' N, 100°37' E). Both samples were brought to the Postharvest Technology Laboratory, Faculty of Food Science and Agrotechnology, Universiti Malaysia Terengganu (5.3117° N, 103.1324° E). The selection of fruits was done in conformity with the commercial maturity index 3 and size L standards, as per the Malaysian Standard (2015) for the grading of wax apples. The outlined standards reflect and ensure uniformity of the experimental units to the uniform physiological maturity and commercial harvest stage.

Sample Preparation

The edible coatings were made using roselle calyces, which were extracted via the decoction method prior to extraction. Extraction was done via cold maceration, and then ethanol was removed using a rotary evaporator (Buchi R-300EL). Ethanol was chosen as the extraction solvent because it is considered a better solvent for the recovery of phenolic compounds, flavonoids, and other bioactive constituents of plant sources. After the rotary evaporator, the ethanol extraction was removed under pressure until it was dry prior to the extract being added to the aqueous coating formulations. Hence, the coatings were water-based and did not have any extraction solvent.

To minimise variability due to the presence of natural phytochemicals, all the roselle materials were sourced from a single supply and were all subjected to the same extraction parameters, such as solvent ratio, extraction time, and concentration. These same controlled parameters were consistently applied to preserve the relative phenolics and anthocyanins compositions prior to the formation of the edible coatings.

The experimental treatments consisted of uncoated wax apples (F1), a chitosan-based coating (F2), and roselle-based coatings formulated with 3% (w/v) fresh RC (F3), 3% (w/v) fresh DCR (F4), 3% (w/v) freeze-dried RC (F5), and 3% (w/v) freeze-dried DCR (F6). Chitosan was used as a positive control due to its extensive research as an edible coating material in postharvest studies, particularly for its film-forming, antimicrobial, and gas barrier properties, which serve as a recognised scientific benchmark for assessing innovative bioactive coatings. The 3% (w/v) concentration for all roselle-based formulations was determined from previous *in vitro* screening as the most effective in promoting stability of the formulation and inhibiting fungal growth. Higher concentrations did not induce a proportional increase in antifungal activity and negatively impacted the viscosity and uniformity of the coating, whereas lower concentrations caused a decrease in antifungal activity.

The chitosan coating (F2) was prepared using 1% (w/v) chitosan dissolved in 1% (v/v) acetic acid, followed by the addition of glycerol (20%, w/w) as a plasticizer and Tween 80 (1%, w/w) as an emulsifying agent, according to No et al. (2006) and Han et al. (2014). Roselle-based coatings (F3–F6) were prepared in aqueous solutions containing glycerol (20%, w/w) and Tween 80 (1%, w/w), without the addition of acetic acid, to avoid additional acidification that could confound the contribution of roselle-derived organic acids and bioactive compounds. Glycerol and Tween 80 concentrations were kept constant across all roselle-based formulations to standardize coating plasticity and dispersion properties.

The wax apples were washed under running tap water and air-dried on the paper towel for 2 h. The fruits were then surface-sterilized in 70 % ethanol, rinsed with sterile distilled water, and air-dried in a laminar flow at ambient temperature for 30 min. After that, the fruits were dipped in their corresponding coating solution for 30 seconds and allowed to air dry, where the coating solution was allowed to drain off. The purpose was to establish uniform coating applications across all treatments and replicates; therefore, coating application times, solution concentrations, and drain times were all standardised in controlled laboratory conditions. Coated fruits were then placed on a mesh rack and dried at room temperature. Once the coated fruits were dry, they were wounded on the equatorial surface using a sterile needle for fungal inoculation. Mycelial agar plugs obtained from 7-day old cultures of *Pestalotiopsis* sp. were carefully placed onto the wounding sites. The inoculated fruits were then kept at 25 ± 2 ºC for 15 days for analysis. The 25 ± 2 °C temperature was set to mimic first-tier customer-retail conditions, interleaving the projection of how wax apples would be displayed and sold at room temperature (not maintained in a refrigerated condition) within the local distribution chains. This approach allows evaluation of coating performance against real-world commercial handling conditions.

Colour

Wax apple was measured by Konica Minolta Chroma-Meter using CIE L*, a* and b* system. Colour was measured at three equatorials opposite sides for each wax apple surface and expressed in lightness (L*), a* value, b* value, hue angle (h°), and chroma (C*) (Nur Amirah, 2015).

Weight Loss

Weight loss was determined by measuring the reduction in fruit weight during storage and expressed as a percentage. The initial weight of each wax apple was recorded before being stored. The final weight was measured at 0, 3, 6, 9, 12, and 15 days of storage using a weighing balance (Model B303-5, Mettler Toledo, Japan).

Firmness

Three puncture tests were made per fruit surrounding the inoculated fungi by using a puncture probe set of P2 over a metal plate. The firmness was determined by using an electronic pressure tester (Model TA-XTPlus Texture Analyser), with pre-test speed: 1.0 mm/sec, test speed: 0.05 mm/sec, and post-test speed: 1.0 mm/sec, and distance of penetration: 0.7 mm. The data were expressed in Newton (N).

Soluble Solid Concentration (SSC)

One gram of the sample was homogenised using a handheld juice extractor (blender), and the juice was filtered through muslin cloth to remove suspended solids. A few drops of the extracted sample were then applied to the refractometer prism. To ensure more accurate readings, the data were recorded three times for each experimental unit using an infrared digital refractometer (Atago-Palette PR 101, Atago Co. Ltd., Itabashi-Ku, Tokyo, Japan) (Association of Official Analytical Chemists [AOAC], n.d.).

Titratable Acidity (TA)

The samples (2 g) were homogenised with 40 mL of distilled water using a handheld juice extractor (blender). Aliquots of 5 mL of the extracted juice were filtered and titrated with 0.1 N sodium hydroxide (NaOH), using phenolphthalein as an indicator. A pH meter was used to monitor changes in the samples' pH. The titration was stopped when the pH meter indicated a value of 8.1. The volume of titrant used and any colour changes were recorded and expressed as a percentage of malic acid. The TA was calculated as a percentage of malic acid according to Ranggana (1986).

SSC/TA ratio

The SSC/TA ratio was calculated by dividing the SSC by the TA values, with the results expressed as a percentage (%).

pH Value

The sample (2 g) was homogenised with 40 mL of distilled water using a juice extractor (handheld blender). The aliquots from extracted juice were determined by a glass-electrode pH meter using buffers of pH 4.0 and 7.0 for calibration (Nur Amirah, 2015).

Vitamin C

Vitamin C was determined according to the method of Nur Amirah (2015) and Esua et al. (2017). The 2 g of wax apple were extracted with 10 mL of metaphosphoric-acetic acid solution. The homogenate was then centrifuged at 3000 rpm for 15 minutes. A 500 µL aliquot of the supernatant was mixed with 200 µL of 3% metaphosphoric acid, 1400 mL of distilled water, and 200 µL of diluted Folin reagent (Folin distilled water, 1:5 v/v). The absorbance of the supernatant was measured at 760 nm using a UV-VIS Spectrophotometer (UV-1800, Shimadzu). The vitamin C content was expressed as mg AAE/100 g fresh weight (FW) based on a calibration curve of authentic L-ascorbic acid (0 µg/mL to 140 µg/mL; y=0.0066x+0.0509; r2= 0.998)

Total Phenolic Content (TPC)

The TPC was determined by the Folin-Ciocalteau method, adapted from Swain and Hillis (1959) and Thaipong et al. (2006). A total of 150 µL of sample extract, 2400 µL of pure water, and 150 µL of 0.25 N Folin-Ciocalteau reagent were combined in a cuvette and mixed thoroughly using a vortex. The mixture was allowed to react for 3 minutes. Then, 300 µL of a 1 N sodium carbonate (Na_2CO_3) solution was added to each cuvette and mixed well. The solution was incubated in the dark for 2 h at room temperature (25 °C). The absorbance was measured at 725 nm by UV-Vis spectrophotometer (UV-1800, Shimadzu) and expressed as gallic acid equivalents (GAE), mg GAE/g extract, using gallic acid (0 µg/mL to 40 µg/mL; y=0.0273x+0.0816; r2= 0.9904) as the standard.

Total Flavonoid Content (TFC)

The TFC was determined using a modified version of the method described by Dewanto et al. (2002) and Abu Bakar et al. (2009). A 500 µL sample extract was mixed with 2250 µL of distilled water in test tubes. After 6 min, 150 µL of a 5% sodium nitrite ($NaNO_2$) solution was added, followed by 300 µL of a 10% aluminum chloride ($AlCl_3 \cdot 6H_2O$) solution, which was allowed to react for 5 min. Then, 1000 µL of 1 M NaOH was added, and the mixture was thoroughly vortexed. The absorbance was measured at 510 nm using a UV-Vis spectrophotometer (UV-1800, Shimadzu), and the results were expressed as quercetin equivalents (QE), mg QE/g extract. A quercetin standard solution ranging from 0 µg/mL to 125 µg/mL (y=0.0009x+0.0682; $r2$= 0.9996) was employed for calibration purposes.

DPPH Radical Scavenging Assay

The radical-scavenging ability of wax apple extract was evaluated to determine antioxidant activity as described by Esua et al. (2017). Initially, 500 µL of the lipophilic extract supernatant was combined with 500 µL of 0.1 mM DPPH reagent, vortexed, and placed in the dark to incubate for 30 min at room temperature. Using a UV-Vis spectrophotometer (UV-1800, Shimadzu) with methanol as a blank, the absorbance of the sample was measured at 517 nm.

Experimental Design and Statistical Analysis

The experimental design was a complete randomised design (CRD) factorial with six coating formulations (F1 to F6) and six storage durations (0, 3, 6, 9, 12, and 15 days). Each treatment combination had five replicates; the experimental unit was one individual fruit. Two-way analysis of variance (ANOVA) was used to evaluate the effects of fruit coating, duration of storage, and their interaction. Mean separation was done using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. All data analysis was carried out in SAS Studio 3.81 (SAS, 2024).

RESULTS AND DISCUSSION

The interaction effects between coating formulation and storage duration (CF × SD) for colour, weight loss, and firmness suggest that storage duration effects change based on what formulation is applied. Edible coatings applied during storage have a significant effect on the colour attributes of wax apples. Key chromatic parameters (L*, a*, b*, h°, and C*) changed the most, indicating a shift in postharvest brightness, saturation, and hue (Figure 1) parameters. During storage, a redder hue in wax apples was attributed to a reduction in h° and L, and a decline in b, accompanied by an increase in a. Coated formulations performed differently in colour retention. Among coated formulations, F3 and F6 were the most colour characteristic preservers, having maintained a redder (a), better hue (h°) stability, and colour saturation (C*). For F3, this improvement in stability was accompanied by a brightness and visual vibrancy improvement. For F6, improvement in stability was

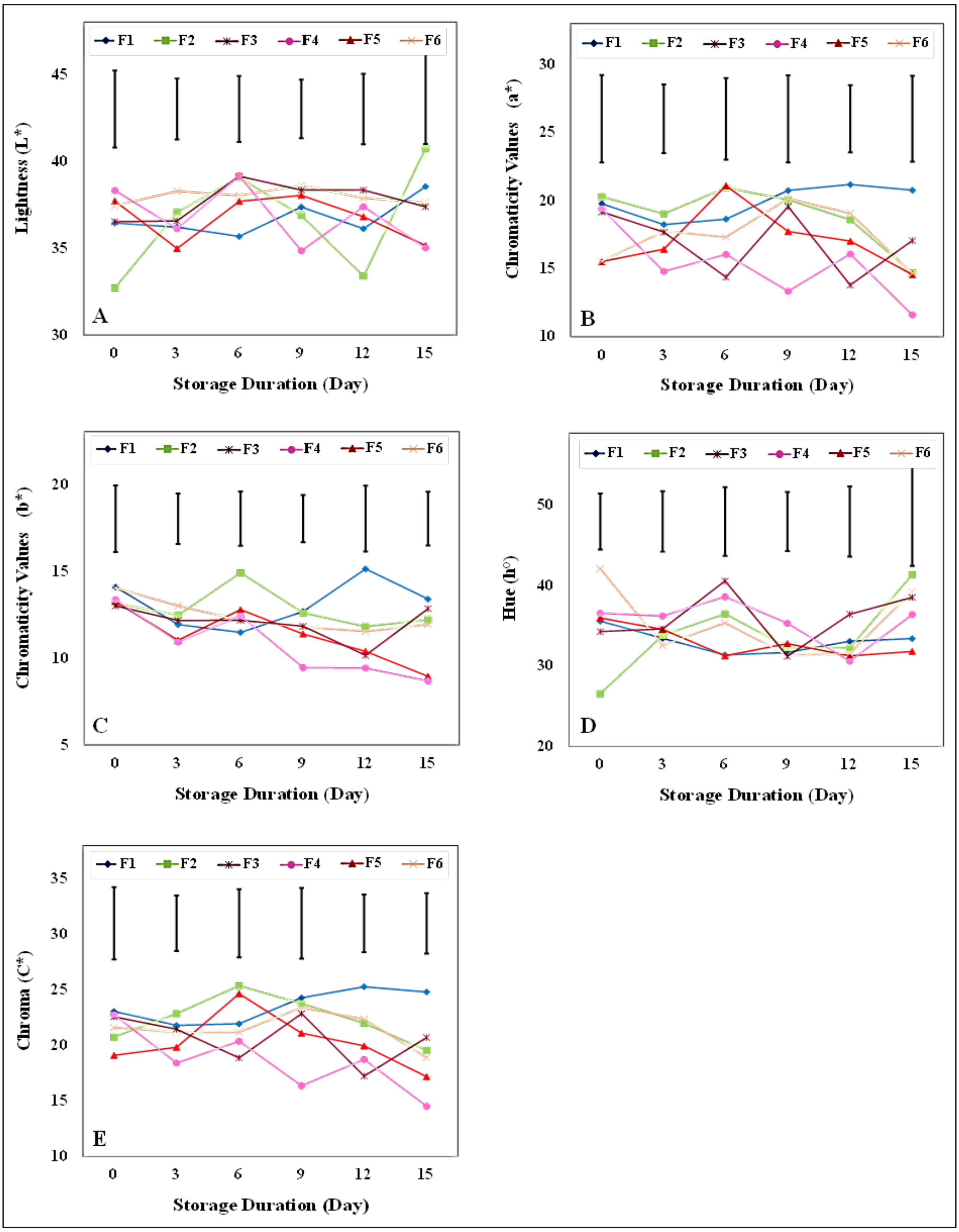


Figure 1. Effect of coating formulations on *the* colour of wax apples during 15 days of storage. A. lightness, B. chromaticity value a*, C. chromaticity value b*, D. hue angle, and E. chroma values. *The vertical* bar represents *the* HSD value at 5% significant level

accompanied by better retention of the natural red hue of the fruit. For F4, stability was the worst, showing inconsistent colour retention. F4 experienced greater fluctuation of b* and C*, resulting in the least colour retention stability.

The enhanced colour retention in F3 and F6 can be explained by the presence of anthocyanins and polyphenols in the extract of roselle decoction residue. Natural anthocyanins are pigments that are water-soluble and capable of producing a wide range of colours from red to purple due to their ability to stabilise colour in response to structural changes that occur due to changes in pH (Wallace & Giusti, 2019). The presence of anthocyanins in edible coatings can protect coated fruit from colour degradation caused by oxidative or enzymatic activities, especially if the coating is protected by a physical barrier (Varasteh et al., 2012). The polyphenols in the roselle residue may also assist through antioxidant interactions that lessen the oxidative degradation of the pigments (Jung et al., 2022; Oren-Shamir, 2009). However, the present study did not quantitatively measure any enzymatic activities such as polyphenol oxidase (PPO).

As expected, the control (F1) exhibited the highest weight loss, followed by F2, F6, F5, F4, and F3 (Figure 2A) due to its high moisture content and delicate skin (Gunny et al., 2024; Kader, 2002). These factors make wax apples particularly susceptible to dehydration and mechanical damage. However, the roselle-based coatings significantly reduced this water loss compared to the control, which experienced nearly double the weight loss. This indicates that the coatings provided an effective semipermeable barrier to water vapour diffusion. Similar to weight loss, F3 and F4 stood out from all other formulations in preserving the firmness (Figure 2B). In other words, these two formulations were effective at preventing both weight loss and texture degradation. Meanwhile, the control (F1) exhibited the lowest firmness across all formulations throughout the 15-day storage period.

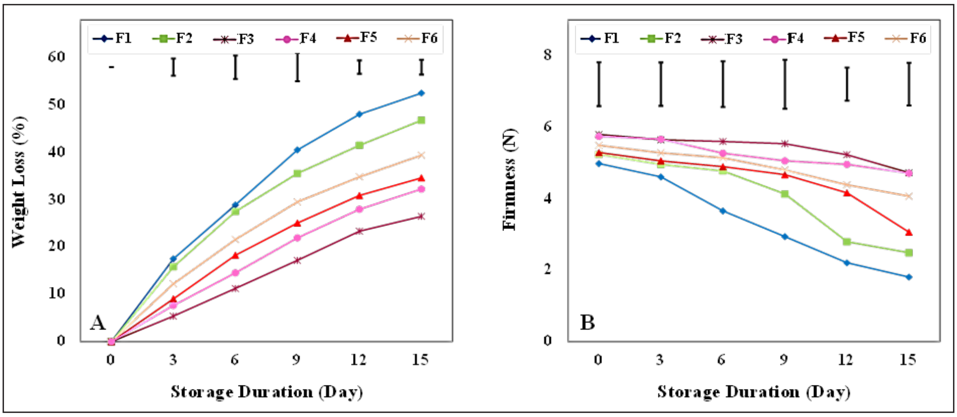


Figure 2. Effect of coating formulation on A. weight loss, and B. firmness of wax apples during 15 days of storage. *The vertical* bar represents *the* HSD value at 5% significant level

The softening of fruit during storage is closely linked to water loss and enzymatic degradation of cell wall components such as pectin, cellulose, and hemicellulose. In non-climacteric fruits like wax apples, ethylene production is inherently low, and there is no respiration spike postharvest (Shu et al., 2011). However, structural degradation still voccurs through the activity of enzymes such as polygalacturonase, pectin methyl esterase, and cellulase, which break down the middle lamella and weaken cell adhesion (Amit et al., 2017; Serrano & Valero, 2010).

The roselle-based coatings likely contributed to firmness retention through multiple mechanisms. First, the coatings serve as a semipermeable barrier that reduces moisture loss and may influence gas exchange, which is commonly associated with delayed softening in coated fruits. However, respiration rate was not directly measured in the present study. Second, polyphenols and organic acids in the roselle extract may contribute to the oxidative stability of cell wall components, although enzyme activity related to softening was not quantified. Third, the coating-forming components, particularly polysaccharides and mucilage (Sinha et al., 2022; Shinga & Fawole, 2023; Wang et al., 2020) from roselle residues, may provide an additional protective barrier to the fruit surface and minimise mechanical impact, thereby assisting in the retention of structural integrity of the fruit during storage.

Table 1 shows the effect of coating formulation on the development of fruit rot in wax apples over storage. Initially, the fruits appeared to be in good condition, exhibiting a glossy finish after being coated with the most effective roselle calyx residue extract from the *in vitro* bioassay. However, from day 12 onward, a noticeable decline in fruit quality and the onset of rot were observed in formulations containing roselle calyx residues, whereas other coatings began to show spoilage even earlier. The edible coatings certainly delayed the wax apples from fungal rot, but in the end, the coatings had little to no protective effect, signifying the need for the development of novel formulations in order to achieve better wax apple storage results.

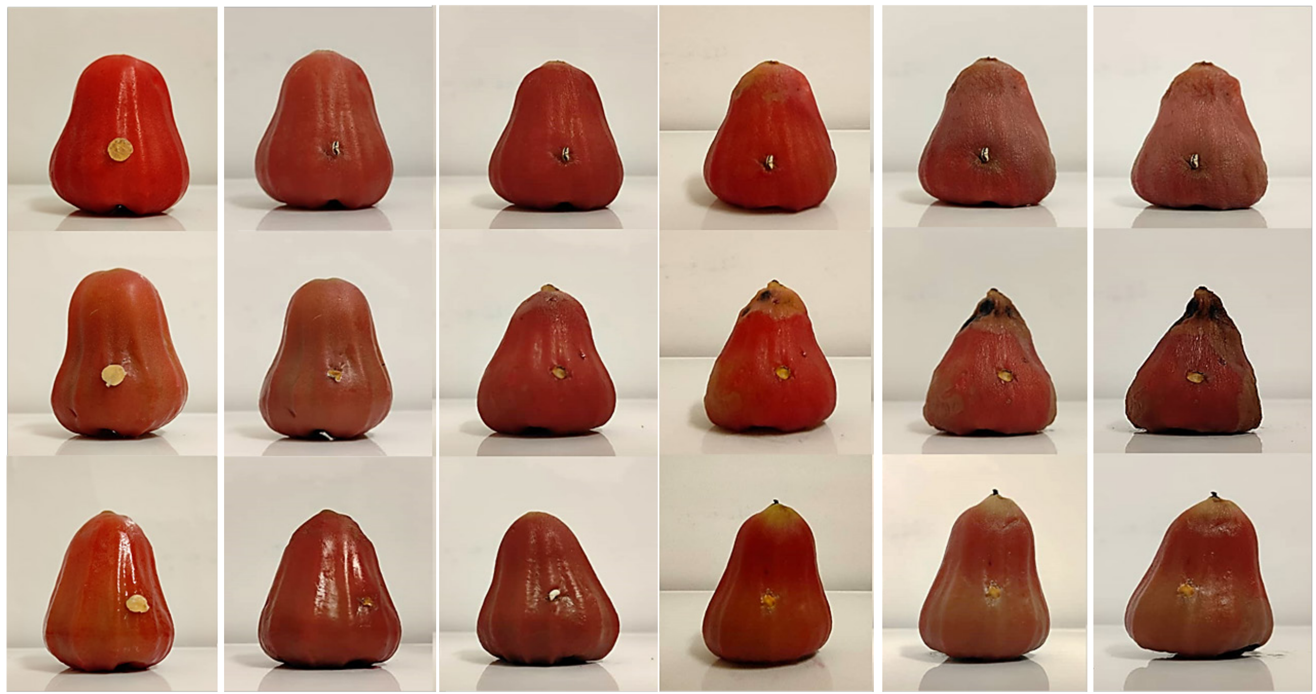
In the present study, the results demonstrated a significant interaction effect between coating formulation and storage duration (CF × SD) on SSC, TA, SSC/TA ratio, and pH values ($p \leq 0.001$). This indicates that the impact of storage duration on these quality attributes varied depending on the coating formulation, emphasising the role of edible coatings in modulating postharvest biochemical changes in wax apples.

Significant differences in SSC were observed across all storage days (Figure 3A). Throughout the storage durations, SSC exhibited an increasing trend, ranging from 5.00% on day 0, and rising up to 22.64% on day 15. During the early storage days, F3 showed a lower level of sweetness than that reported in F4 and F6. This indicates that the application of roselle-based coatings, especially formulations F3 and F5, effectively delayed the increase in SSC by limiting sugar metabolism and moisture loss. This effect, together with

Table 1

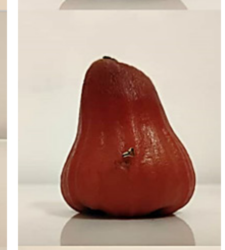
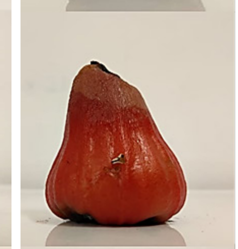
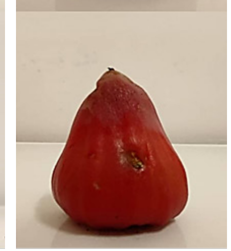
Effect of coating formulation on fruit rot of wax apples through storage duration

CF	Day 0	Day 3	Day 6	Day 9	Day 12	Day 15
F1						
F2						
F3						



Note. CF: coating formulation, F1: negative control, F2: positive control, F3: fresh RC. RC: Roselle calyx

Table 1 (*continued*)
Effect of coating formulation on fruit rot of wax apples through storage duration

CF	Day 0	Day 3	Day 6	Day 9	Day 12	Day 15
F4						
F5						
F6						

Note. CF: coating formulation, F4: fresh DCR, F5: freeze-dried RC, F6: freeze-dried DCR. RC: roselle calyx. DCR: decocted cordial residue

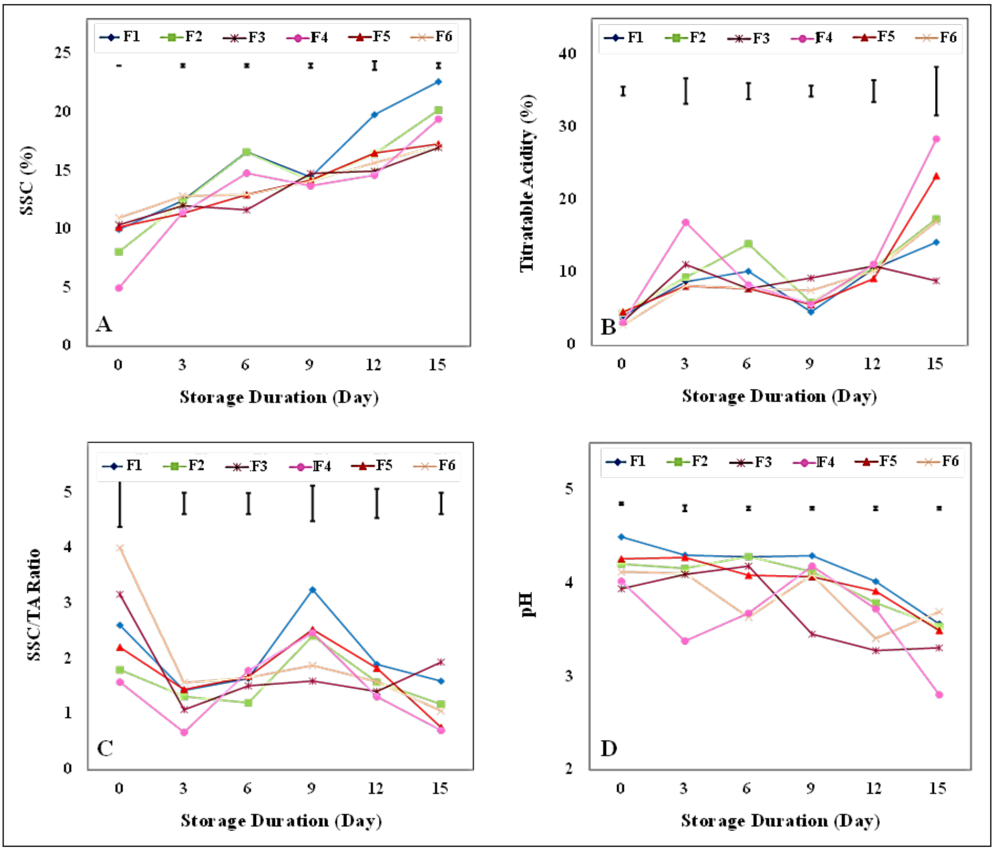


Figure 3. Effect of coating formulation on chemical quality of wax apples during 15 days of storage. A. soluble solid concentration (SSC), B. titratable acidity (TA), C. SSC/TA ratio, and D. pH. The vertical bar represents the HSD value at 5% significant level

their performance in preserving firmness, suggests their utility in extending postharvest quality and shelf life of wax apples by maintaining biochemical stability across multiple parameters. These findings are supported by similar studies in other fruits (Das et al., 2013; Gu et al., 2024; Sharma et al., 2019; Siti Fairuz, 2022).

In the present study, TA increased significantly throughout the 15-day storage period, except on day 12 (Figure 3B); meanwhile, pH values exhibited an inverse relationship with acidity, where lower pH values corresponded to higher acidity in wax apples (Figure 3D). Overall, a gradual decrease in pH was observed across all formulations, resulting in increased acidity throughout the storage period. Typically, organic acids such as citric and malic acid are consumed during ripening through respiration, leading to decreased TA and increased pH (Dávila-Aviña et al., 2011). However, in this study, TA increased while pH decreased, particularly in coated fruits. In non-climacteric fruits, organic acids are typically consumed during respiration, resulting in stable or declining titratable acidity over storage. The deviation observed here is likely associated with the acidic nature of the roselle decoction residue extract. Roselle contains organic acids such as hibiscus acid, citric acid, and malic acid (Al-Wandawi, 2015; Izquierdo-Vega et al., 2020; Nur Amirah, 2015), which may have contributed to the measured acidity through surface interaction or limited diffusion into fruit tissue. However, migration was not directly quantified in this study. Additionally, the semipermeable coating may have reduced respiratory metabolism, thereby slowing endogenous acid utilisation. Collectively, these factors may explain the increase in TA observed in roselle-coated fruits.

As SSC increases and TA decreases over time, the SSC/TA ratio tends to rise, resulting in a sweeter taste. However, in the present study, the inverse was observed (Figure 3C). The decline in SSC/TA observed in coated fruits, especially F3 and F4, is likely attributed to the infusion of organic acids from the roselle extract into the fruit matrix, leading to a general decline in SSC/TA ratios over time. This change has significant impacts on the sensory qualities of fruits. As roselle is rich in hibiscus acid, malic acid, and citric acid (Al-Wandawi, 2015; Izquierdo-Vega et al., 2020), which can increase TA and decrease the relative contribution of SSC to the sweetness of the taste. This explains why even coated fruits with moderate SSC levels may taste very sour and lose their sweetness.

The interaction effect between coating formulation and storage duration was significant for vitamin C content, TPC, TFC, and DPPH radical scavenging activity ($p \leq 0.001$).

The presence of vitamin C, a highly sensitive compound, is easily exposed to oxidative degradation. It is especially susceptible to conditions involving high temperatures, the presence of oxygen, and alkaline, as well as metal ion conditions (Lee & Kader, 2000). However, in acidic conditions, its presence is considerably more stable as lower pH conditions slow the rate of oxidation. Considering this, coating formulations based on roselle may have enhanced the retention of vitamin C by creating a microenvironment that is slightly acidic around the surface of the fruit. The roselle calyx extracts contain some organic acids, which may help in lowering the pH and provide an antioxidant effect.

Of all the coating formulations, F6 demonstrated the highest efficacy in preserving vitamin C content throughout the storage duration, followed closely by F5 and F4 (Figure 4A). These findings signify the promising nature of the prospective coatings derived from roselle in shielding sensitive nutrients, including vitamin C, due to their combination of antioxidant components, acidic, and protective layers. With the consideration of SSC, TA, and pH, F6 and F5 are suggested to assist in the possible multiple layers of protective coatings and to extend the overall quality of postharvest wax apples. This was consistent with findings by Ali et al. (2010), in which it was shown that coated papayas had a much slower rate of vitamin C synthesis and degradation compared to the controls. Tigist et al. (2013) and Dávila-Aviña et al. (2014) also demonstrated that the coated tomatoes had slower increases and eventual declines in vitamin C content during the storage period, which further confirms the nutrient retention in coated produce.

Among all coating formulations, F3 was found to retain more TPC than the control and was better able to retain phenolics over the storage period (Figure 4B). It should be noted that the Folin–Ciocalteu assay measures total reducing capacity and may respond to non-phenolic reducing substances such as sugars and ascorbic acid; therefore, TPC values are interpreted as comparative indicators rather than absolute phenolic quantification. All applied formulations, as well, experienced TPC reductions by day 3, which is in accordance with the process of oxidative stress and metabolic senescence. Although the roselle coatings still experienced TPC losses, they experienced the slowest losses. The TPC losses in phenolic evidence structures were likely due to oxidations, which are enzymes common during storage and ripening.

Such findings are consistent with earlier studies indicating a naturally occurring reduction of phenolic compounds during postharvest storage as a result of oxidative metabolism and stress from pathogens (Nur Atirah, 2023; Siti Fairuz, 2022). Furthermore, phenomena such as depletion of phenolic compounds and post-infection fungal accelerated infections (Lattanzio et al., 2006). The phenolic compounds are significantly consumed at the sites of infection when exposed to pathogens, which results in a significant decline in TPC over time.

The roselle decoction residue extract contains bioactive polyphenols and flavonoids, which are largely responsible for the antioxidant and antimicrobial activity of the edible coatings. When the coating is applied to the fruit, it creates a semipermeable layer that is expected to inhibit the diffusion of gases, particularly oxygen, which in turn may be able to slow down the oxidative degradation processes and preserve the phenolic compounds during storage. The organic acids of roselle may result in an increase in active acidity of the coating, which will reduce the activity of the enzyme responsible for browning. However, it should be noted that in this study, the PPO activity was not measured. Therefore, any assumptions made regarding the value of the suppression of the enzyme are purely speculative and require further validation of the enzyme. The coating's protective microenvironment played a significant role in maintaining TPC.

Furthermore, TFC retention in coated wax apples was significantly influenced by the relationship between storage duration and the specific coating applied (Figure 4C). With regard to the formulation used, F5 and F3 were the most promising as they demonstrated a moderate and consistent performance during the different storage periods. It is likely that the incorporation of the roselle extract altered the flavonoid biosynthetic pathway by activating the respective enzymes and providing oxidative protective walls against degradation. Furthermore, these observations reiterate the need for the development of edible coatings that preserve and refine active coatings to control and enhance the biochemically active pathways of the coated fruits. This would potentially increase the functionality and nutritional value of the fruits after they have been harvested.

The observed increase in DPPH activity during storage may also reflect the fruit's biochemical defence response to postharvest stress, including pathogen exposure and oxidative conditions (Figure 4D). This phenomenon has been reported in other fruits like tomatoes and grapes, where increased antioxidant activity was linked to endogenous responses to microbial threats (Siti Fairuz, 2022; Wang et al., 2015). The application of roselle extract may have contributed to antioxidant enhancement through direct deposition of phenolic and flavonoid compounds onto the fruit surface. In addition, postharvest stress and pathogen exposure are known to influence endogenous antioxidant responses in fruits. However, the present study did not directly measure enzyme activity or gene expression associated with phenolic biosynthesis pathways. Therefore, the relative contribution of coating-derived antioxidants and fruit-induced biosynthesis cannot be definitively separated

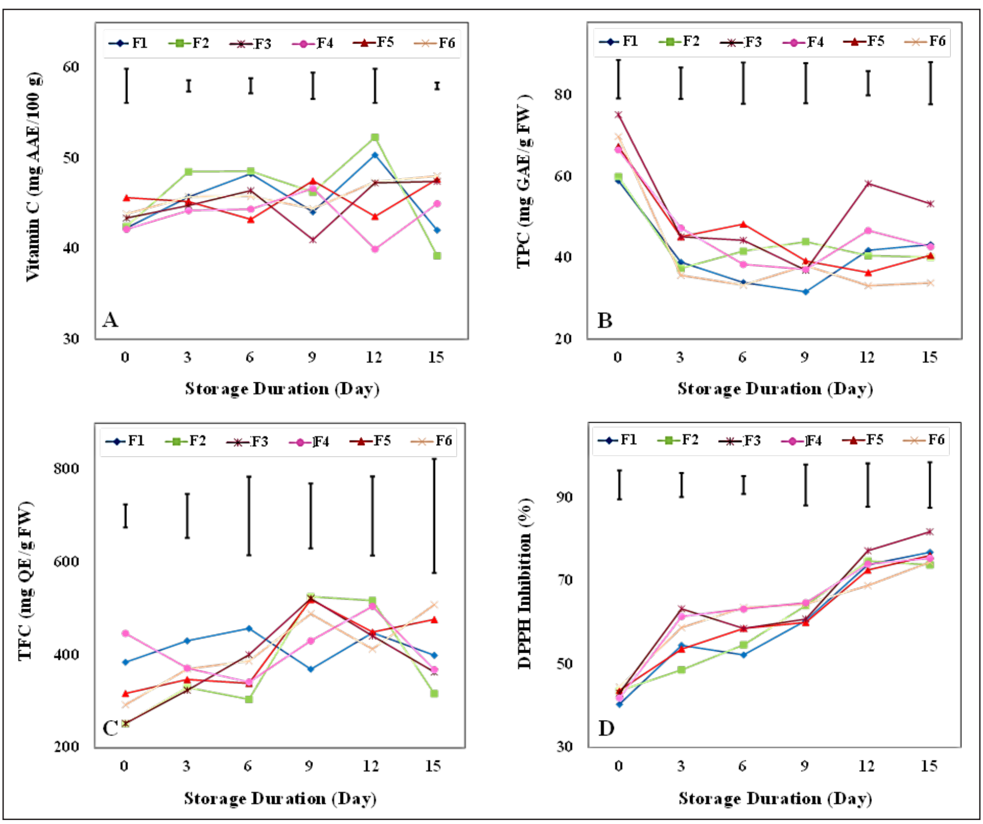


Figure 4. Effect of coating formulation on antioxidant activities of wax apples during 15 days of storage. A. vitamin C, B. total phenolic content, C. total flavonoid content, and D. DPPH inhibition. The vertical bar represents the HSD value at 5% significant levelV

within the scope of this study and requires further investigation. The elevated TPC and TFC observed in F3 and F5 are consistent with the enhanced DPPH activity in these treatments.

CONCLUSION

This study demonstrated that roselle decoction residue-based edible coatings improved the postharvest quality of wax apples during 15 days of ambient storage. Roselle-based coatings significantly enhanced colour retention, reduced weight loss, maintained firmness, and preserved key biochemical attributes, including titratable acidity, vitamin C, total phenolic content, total flavonoid content, and antioxidant activity, compared to uncoated controls. Among the formulations, fresh RC (F3) showed the most consistent performance across multiple quality parameters, followed by F6 and F4. Under wound-inoculation conditions, selected coatings also slowed down the growth of the *Pestalotiopsis* sp. These studies show that roselle decoction residues can be valorised as functional ingredients in edible coating systems for improving postharvest stability of wax apples.

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