

Evaluation of Lipid-Based Coatings on Postharvest Quality of Tomatoes during Ambient Storage

Ung Hua Ting^{1,2*}, Chia Shing Hwong¹, Lee Fung Ching¹, Kee Chuong Ting³, Mohd Zahid Abidin^{1,2}, Abdul Fattah Ab Razak^{1,2} and Mohd Syafiq Abdullah^{1,2}

¹Food Technology Department, School of Engineering and Technology, University of Technology Sarawak, No. 1, Jalan Universiti, 96000 Sibul, Sarawak, Malaysia

²Centre for Research of Innovation and Sustainable Development, School of Engineering and Technology, University of Technology Sarawak, No. 1, Jalan Universiti, 96000 Sibul, Sarawak, Malaysia

³Mechanical Engineering Department, School of Engineering and Technology, University of Technology Sarawak, No. 1, Jalan Universiti, 96000 Sibul, Sarawak, Malaysia

ARTICLE HISTORY

Received: 16 November 2025

Accepted: 15 January 2026

Online: 31 March 2026

KEYWORDS

physicochemical properties,
microscopy,
edible coating,
tomato preservation

* CORRESPONDING AUTHOR

Ung Hua Ting

Food Technology Department, School of Engineering and Technology, University of Technology Sarawak, No. 1, Jalan Universiti, 96000 Sibul, Sarawak, Malaysia

Email: thua@uts.edu.my

ABSTRACT

Tomatoes (*Solanum lycopersicum*) are susceptible to postharvest losses due to metabolic processes, physical injuries, and microbial spoilage. Edible coatings are a promising strategy to extend the shelf life of fresh fruits, including tomatoes, by providing a protective layer that controls the transfer of gases, moisture, aromas and volatile substances during storage. Thus, this study evaluated the effectiveness of lipid-based composite edible coatings in maintaining the postharvest quality of tomatoes stored at ambient conditions (24–26 °C, 65–75 % RH). Three coating emulsions were formulated in this study: F1 = coconut oil-lemongrass essential oil (CL), F2 = beeswax-coconut oil-lemongrass essential oil (BCL), and F3 = carboxymethylcellulose (CMC)-coconut oil-lemongrass essential oil (CCL). These coatings were applied to tomatoes at the turning stage and compared with uncoated samples over a 24-day period. Quality parameters, including weight loss, visual appearance, firmness, total soluble solids (TSS), and surface morphology, were evaluated at the end of the experiment. All coatings minimised moisture loss compared to the control, with F2 (BCL) showing the greatest reduction. Nonetheless, F3 (CCL) outperformed other coatings in preserving tomato firmness (525.07 ± 103.09 g) and TSS (4.50 ± 0.50 °Brix), indicating enhanced control of the respiration and ripening. Microscopic analysis further revealed that F3 (CCL) formed a smooth, homogenous coating layer, with improved barrier features and no adverse sensory effects. Conversely, F2 (BCL) exhibited uneven coating distribution due to beeswax crystallisation, causing undesirable surface deposits and decreased firmness retention. These findings highlighted the potential of lipid-polysaccharide composite, particularly with CMC inclusion, to prolong the postharvest shelf life of tomatoes by reducing weight loss and retaining firmness and TSS content. Component compatibility is also crucial for structural integrity, functional properties, and consumer acceptability in edible coating applications.

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1. INTRODUCTION

Tomatoes (*Solanum lycopersicum*) are widely acknowledged for the nutritional and health benefits, playing a crucial role in a balanced diet and the prevention of chronic illnesses (Collins et al., 2022). This climacteric fruit is vulnerable to postharvest losses due to physiological changes, such as ripening metabolism, physical damage and microbial deterioration, leading to a reduced shelf life and significant postharvest losses. Sawicka (2020) characterised the loss of horticultural products as physical changes caused by spoilage, pest infestation, and weight reduction. In developing nations, the losses of fresh produce can reach up to 50% (Khalid et al., 2022). Approximately 40% postharvest

losses of fruits and vegetables have been reported in

Malaysia, occurring in orchards, at the wholesalers and retailers (Abu Bakar et al., 2020). These losses pose significant economic challenges for growers and suppliers, in addition to affecting local food security and safety. Therefore, national policies have been established to boost agricultural production and apply effective postharvest techniques for supply and quality protection (National Agrofood Policy 2021-2030 (NAP 2.0)).

Modified atmosphere packaging (MAP) and controlled atmosphere storage (CAP) are common techniques used to delay the ripening of fresh fruits by creating an environment with higher carbon dioxide and lower oxygen levels than the normal atmospheric conditions. Nevertheless,

studies have highlighted the risks of MAP leaks, thus compromising the controlled atmosphere and the postharvest quality assurance of fruits (Kumar et al., 2020). Alternatively, edible coatings can also prolong the postharvest shelf life of fresh produce by establishing a protective barrier against moisture loss and gas exchange. Similar to MAP and CAP, edible coatings alter the internal atmosphere on the fruit surface, slowing respiration rates, enzymatic browning, emission of volatile compounds during ripening, and microbial spoilage (Reddy & Singh, 2020). This technique also visually enhances fruits by giving the product a glossy appearance.

Traditionally, chemical preservatives, pesticides, and fungicides are used to preserve fruit freshness, but numerous studies have highlighted the drawbacks of these chemicals, including health and environmental hazards (Rai & Singh, 2022). The rising demand for safe and environmentally friendly options has led to more research on biopolymer-based coatings as alternatives to synthetic options, such as polyethylene wax and carbowax (Reddy & Singh, 2020). Biopolymers such as lipids (plant-derived oils and waxes) and polysaccharides (gums, cellulose) have emerged as promising edible coating ingredients due to the antimicrobial and good barrier properties. These additional properties have become a trend in edible coating formulation, including the incorporation of antioxidants and antimicrobial agents derived from essential oils or nanoparticles into biopolymers to enhance the functional role of the coatings (Ceylan & Özdamar Ünlü, 2023; Kawhena et al., 2021; Yuan et al., 2023).

Coconut oil is rich in medium-chain fatty acids such as lauric, myristic, palmitic, and capric acids (Deen & Jayawardana, 2021). The conversion of high lauric acid into monolaurin also imparts robust antibacterial, antiviral, and antifungal attributes of coconut oil (da Silva et al., 2023). As an edible coating, this plant-based oil has been reported to create a hydrophobic layer on the fruit surface that significantly reduced moisture loss and maintained the firmness of lemons in storage (Nasrin et al., 2020, 2023). Beeswax, a natural lipid produced by honeybees, is another edible coating that enhances the barrier characteristics of coated produce, prolonging storage life by resisting moisture and gas transmission. Studies have shown that lipid-based coatings made from coconut oil and beeswax improved the water vapour barrier properties of coated fruits, such as limes (Alahakoon & Sarananda, 2024) and lemons (Nasrin et al., 2023), compared to those that were uncoated. Nonetheless, the use of lipid-based edible coatings should be limited, as the inclusion of 5% w/v coconut oil and beeswax in the coating mixture adversely impacted the sensory characteristics of the coated samples, resulting in the formation of white, opaque

residues on the fruit surface (Ting et al., 2025).

Lemongrass essential oil contains active compounds such as limonene, ocimene and valencene, making this ingredient a potential edible coating. de Oliveira et al., (2020) applied the lemongrass essential oil at a low concentration, in combination with a different type of base carrier to create an edible coating. The inclusion at low concentration minimises the sensory impact attributed to the strong aroma of lemongrass, and ensures a controlled release of active compounds while preventing toxicity (Hasan et al., 2022). Previous studies have reported that coatings infused with lemongrass essential oil effectively maintained the quality of various fruits, including pineapple (Azarakhsh et al., 2014), bell pepper (Ali et al., 2015), and pomegranate (Kawhena et al., 2021). This essential oil also demonstrated antimicrobial properties against Gram-positive and Gram-negative bacteria, fungi, and yeasts (Kawhena et al., 2021; Naik et al., 2010; Yousuf et al., 2018). Despite the abundance of literature on lipid-based coatings, few have investigated the potential of essential oils in preserving horticultural crops.

Polysaccharides such as cellulose are one of the most abundant natural polymers. While unmodified cellulose is limited by insolubility in water and a tightly packed crystalline structure, carboxymethylcellulose (CMC) provides superior solubility and film-forming properties as a cellulose-derivative (Aguilar González et al., 2024). The combination of 1% w/v CMC with *Lactobacillus plantarum* effectively inhibited yeast and mould growth while preserving ascorbic acid and phenolic compounds in fresh strawberries (Khodaei & Hamidi-Esfahani, 2019).

Lipid-based edible coatings are desirable in the market for the outstanding moisture barrier offered by the hydrophobicity property, but excessive application leads to anaerobic respiration in fruits (Pham et al., 2023; Ting et al., 2023a). Meanwhile, coatings made from polysaccharides effectively restrict gas exchange but provide limited protection against moisture loss (Aguilar González et al., 2024). As different coatings demonstrated strengths and weaknesses, researchers have begun exploring the potential of combining various substances in composite edible coatings, instead of relying solely on a single material to improve overall effectiveness. These composite emulsions may include similar or different biopolymers, such as polysaccharide-polysaccharide, protein-protein, polysaccharide-protein, or lipid-lipid mixtures (Armghan Khalid et al., 2022).

Considering the unique advantages of coconut oil, lemongrass essential oil, beeswax, and CMC, incorporating these ingredients into edible coating formulations presents a promising approach to improve the postharvest quality of tomatoes. While earlier studies have examined edible

coatings using coconut oil, beeswax, and lemongrass oil on fruits such as guava, lemon, and pomegranate, there is a lack of comparative research on the combined effect on tomatoes, particularly lipid–lipid and lipid–polysaccharide emulsions during ambient storage. Thus, this study aims to evaluate the potential of these formulations in maintaining tomato postharvest quality during ambient storage, focusing on parameters such as moisture loss, firmness, total soluble solids (TSS) retention, and microbial growth.

2. MATERIALS AND METHODS

2.1. Sample selection and coating ingredients

Tomatoes with a maturity index of 3 were acquired from Coucou Agrotech Co., a local retailer in Pulau Li Hua, Sibul, Sarawak. The fruits were consistent in weight (20–50 g), with 10% to 30% of the surface showing a noticeable shift in colour from green to tannish-yellow. An inspection was carried out to ensure all tomatoes were free of any physical and microbiological damage. Cold-extracted extra virgin coconut oil (MH Food, Philippines), steam-distillation extracted lemongrass essential oil (Thelement, Sri Lanka), and CMC (R&M Chemicals, Malaysia) were purchased to formulate the coating emulsion, with Tween 80 (Sigma-Aldrich, France) as the surfactant.

2.2. Preparation of fruit samples

The tomatoes were rinsed with tap water to eliminate any leftover soil and air-dried at ambient conditions (24–26 °C, 65–75% RH) (Hajar et al., 2024). Subsequently, the fruits were labelled before undergoing the coating treatment. Equipment and materials that came into contact with the tomatoes were thoroughly cleaned and disinfected with 75% ethanol to prevent any potential microbial contamination. Ethanol was the disinfectant of choice, as this option is safer than chemical disinfectants that might leave harmful residues.

2.3. Coating formulations and application

In this study, three types of lipid-based composite coating emulsions were developed using different ingredient combinations and preparation methods. Formula 1 (F1) was produced by mixing 28 g of coconut oil and 0.8 g of lemongrass essential oil (CL) in a 35:1 ratio. Formula 2 (F2) was prepared by melting beeswax in a water bath at 62–64 °C (Nasrin et al., 2023) before adding coconut oil and lemongrass essential oil (BCL) at a ratio of 35:35:1. In formula 3 (F3), CMC, coconut oil and lemongrass essential oil (CCL) were used in a ratio of 7:70:2. The CMC powder was first dissolved in distilled water and then combined with coconut oil and lemongrass essential oil. All formulations were enhanced with 0.1% w/v Tween 80 as a surfactant before undergoing high-speed homogenisation to achieve emulsion stability. The

formulation ratios were selected based on findings from preliminary trials and previous studies (de Oliveira et al., 2020; Khodaei & Hamidi-Esfahani, 2019; Ting et al., 2025).

The coating techniques were performed as described by earlier studies, with modifications (Nur Hanani et al., 2023; Ting et al., 2023b). Tomatoes were randomly selected and immersed in different coating emulsions for 15 s at ambient conditions. Each treatment was carried out in triplicate to ensure statistical reliability (Zhang et al., 2024). Following the coating process, the fruits were air-dried for 1 h (Sumonsiri et al., 2022) before being placed on sterilised stainless-steel trays. The samples were stored at ambient conditions (24–26 °C, 65–75% RH) for 24 days. Uncoated fruits served as the control group in this study.

2.4. Physicochemical parameters

In line with the methods employed by earlier studies (Huang et al., 2021; A. Kumar & Saini, 2021), physicochemical parameters were evaluated through a non-destructive technique (weight loss, visual inspection), beginning on day 1 and at regular intervals thereafter. At the end of the experiment, destructive evaluations (firmness, TSS, and surface microscopy) were conducted on the samples. The data were analysed by comparing mean values and standard deviation (SD) between groups.

2.4.1 Weight loss

The weight of three fruit samples from each treatment was recorded, and the percentage of weight loss in comparison to the initial weight on day 0 was calculated using Equation 1 (Huang et al., 2021).

$$\text{Weight loss (\%)} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100 \quad (1)$$

2.4.2 Visual inspection

The visual quality of tomatoes was tracked via photographic images, focusing on decay incidence (black/brown spots, fungal development). Changes in colour, shape, and size were also observed as signs of ripening or ageing (Rosman et al., 2022).

2.4.3 Firmness

Fruit firmness was assessed using a texture profile analyser (TA.XTplus, Stable Micro Systems Ltd, England) fitted with a 2 mm diameter probe (P/2), in accordance with the method described by Moreira et al. (2022). The probe penetrated 5 mm into the fruit pulp at a rate of 1.5 mm/s. Three measurements were taken randomly from the equatorial region of each fruit, and the average force was recorded in grams (g).

2.4.4 Total soluble solids

The TSS in tomatoes were measured using a portable refractometer (Atago, Japan). Juice was extracted from the tomatoes using a fruit juicer (Panasonic, Malaysia). A drop of juice from each sample was applied to the refractometer prism and covered. The results were expressed in °Brix units. Each sample was measured for TSS individually (Ting et al., 2025).

2.4.5 Surface microscopy

Surface features of coated and uncoated (control) tomatoes were examined using a digital microscope (Hirox KH-8700, Shibata Co., Ltd, Japan). A specific area of the tomato skin was meticulously cut out from each sample using a sterile scalpel. The excised sections were observed under a digital microscope, and images were taken to evaluate surface characteristics (Futami et al., 2021), including texture, smoothness, and structural differences attributed to coating application. All observations were performed under uniform lighting and environmental conditions to maintain comparability among samples.

2.5. Statistical analysis

Statistical analysis was conducted for each quantitative physicochemical parameter using GraphPad Prism version 10 (GraphPad Software Inc., San Diego, California, United States). All measurements were taken in triplicate, and the results were reported as mean \pm SD. Normality was evaluated before performing statistical comparisons. Depending on the data distribution, comparisons between two groups were carried out using either Student's t-test, for normally distributed data or the Mann–Whitney U test, for non-normal data (Ting et al., 2025).

3. RESULT AND DISCUSSION

3.1. Effect of coating treatments on weight loss during storage

Weight loss associated with moisture loss over 24 days in storage at ambient conditions was assessed to evaluate the efficacy of various coatings. Figure 1 demonstrates that all coating formulations (F1, F2, and F3) significantly diminished the weight loss of tomatoes compared to the uncoated control at the end of the experiment. Thus, all edible coatings in this study were effective in minimising moisture loss to improve tomato shelf life.

While in storage, the control group consistently exhibited the greatest percentage of weight loss, reaching approximately 8% by day 24. In contrast, the coated samples demonstrated considerably lower weight loss, particularly in the later storage stages of storage. Notably, the effects of F1

were more prominent during the first few days, possibly due to delamination caused by repeated handling during weighing. Meanwhile, the satisfactory performance of F3 was potentially due to the presence of beeswax and CMC that enhanced the film-forming properties for better adhesion on the tomato surface. The CMC, in particular, is a hydrophilic polymer that creates a semipermeable film, lowering respiration and transpiration rates. Similar results were observed when CMC was used in combination with different essential oils as edible coating emulsions for kiwi (Iqbal et al., 2024).

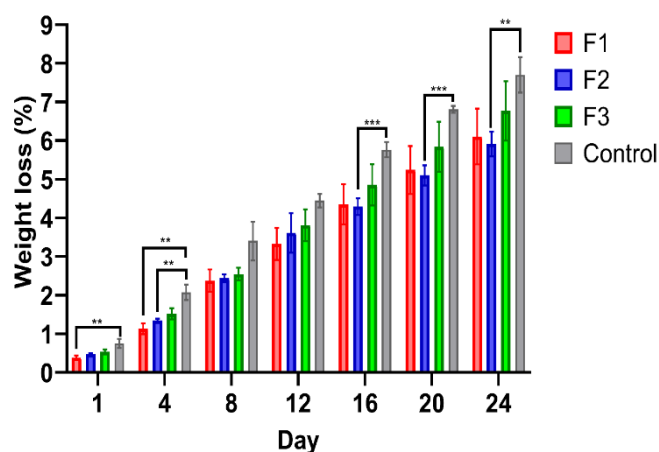


Figure 1: Weight loss (%) of tomatoes coated with different formulations over 24 days in ambient storage. Treatments include F1 (CL: coconut oil and lemongrass essential oil), F2 (BCL: beeswax, coconut oil and lemongrass essential oil), F3 (CCL: carboxymethylcellulose, coconut oil and lemongrass essential oil) and control (uncoated). Values are expressed as mean \pm SD (n = 3). Asterisks (*) indicate statistically significant differences between treatments at the same time point (**p < 0.01 and ***p < 0.001).

While all coatings aided in weight loss (%) reduction, F2 (BCL) consistently recorded the lowest weight loss among all treated samples. This formulation was more effective than F1 (CL) and F3 (CCL) in reducing the rate of moisture loss, particularly after day 12. The remarkable water barrier ability of beeswax aided in reducing moisture loss in F2-treated tomatoes. In contrast, tomatoes of the 'Popvriend' variety coated with 5% beeswax alone were found to experience approximately 50% weight loss by day 16 during ambient storage (29 °C, 72–75 % RH) (Afedzi et al., 2022). This notable loss is likely attributed to unfavourable anaerobic respiration, which results in the formation of ethanol and acetaldehyde. This outcome led to fermentation, tissue damage, and the breakdown of cells, ultimately increasing moisture loss. Such weight loss reduction was not observed in other groups in the present study. In terms of reducing weight loss percentage, the lipid-lipid F2 (BCL) composite demonstrated superior performance compared to the lipid-lipid composite without beeswax, F1 (CL), and the lipid-polysaccharide combination, F3 (CCL).

3.2. Effect of coating treatments on microbial spoilage and visual decay

The uncoated tomatoes had a shelf life of approximately 20 days, which aligns with an earlier study (Salama et al., 2024). There are several common microorganisms associated with tomato spoilage. High moisture and low pH of the fruit supported the growth of fungi, such as *Aspergillus niger* and *Rhizopus stolonifera* (Aguda et al., 2021; Rai & Singh, 2022). Aguda et al. (2021) also identified bacteria, *Escherichia coli* and *Proteus mirabilis*, as the cause of tomato spoilage. In the present study, microbial growth on tomatoes was characterised by softening or mushiness, followed by rotting that was accompanied by off-odour and dark, sunken spots, particularly on the blossom end. Figure 2 illustrates the visual appearance of tomatoes treated with different coating formulations on day 1 and day 24 in storage during ambient conditions.

Tomatoes in the control group demonstrated deep red colouration in most areas, with sunken spots and possible fungal growth. Evidence of fluid leakage also suggested extensive ripening and decay in the absence of a protective coating. The proliferation of microorganisms within the uncoated tomatoes had compromised the fruits' cellular structure, leading to softening and the release of cloudy and foul-smelling fluids, even though the fruit exterior appeared unblemished. Such conditions are ideal for further microbial

growth, worsening spoilage. This internal deterioration indicated that the tomatoes were no longer safe for consumption. Eventually, the tomatoes will rupture as a result of internal pressure caused by fluid accumulation within the fruits.

White depositions appeared on the surface of tomatoes coated with F2, which contains beeswax. This outcome is likely caused by the heterogeneous nature of beeswax that has limited miscibility with coconut oil and lemongrass essential oil. The non-uniform dispersion of beeswax within the emulsion resulted in phase separation during the drying or storage processes, leading to the formation of visible waxy deposits on the fruit surface. These deposits may lead to uneven coating, potentially reducing the uniformity of the protective barrier and causing interference with gas exchange in a non-controlled manner. Consequently, the fruit respiration is affected, causing unfavourable odour and changes in colour and texture (Pham et al., 2023).

The white residues negatively affect the visual appearance of the tomatoes, leading consumers to perceive the fruits as less fresh or spoiled. Furthermore, consuming fresh and unpeeled tomatoes with white deposits on the surface results in an unpleasant waxy or greasy mouthfeel. Furthermore, the altered surface texture may raise concerns regarding product cleanliness or safety, thereby influencing consumer acceptance.

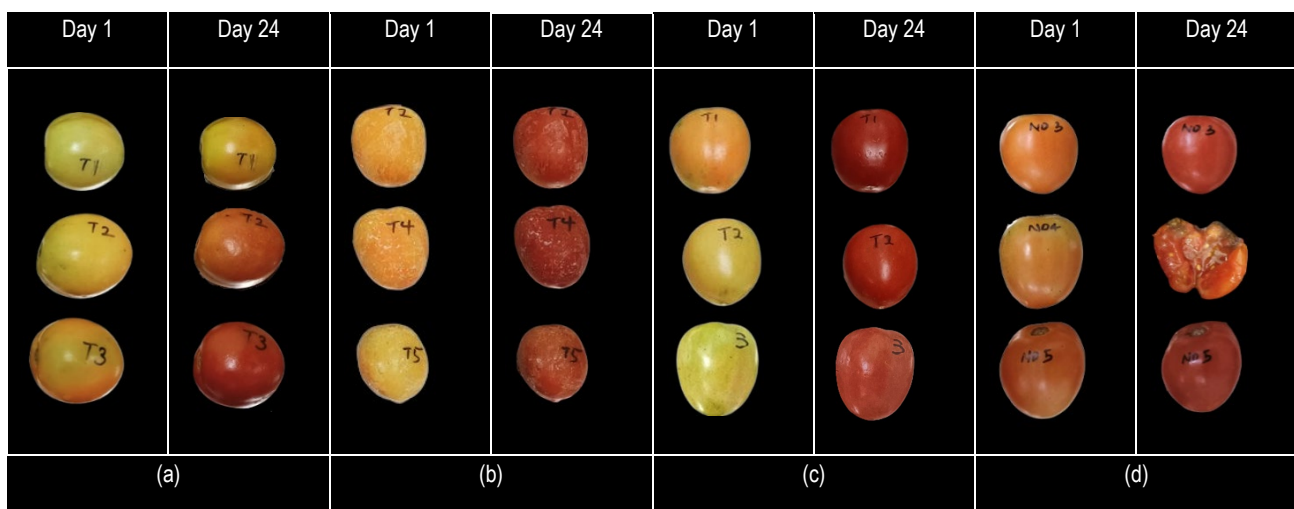


Figure 2: Visual appearance of tomatoes treated with different coating formulations on day 1 and day 24 of ambient storage. (a) F1 (CL – coconut oil and lemongrass essential oil), (b) F2 (BCL – beeswax, coconut oil and lemongrass essential oil), (c) F3 (CCL – carboxymethylcellulose, coconut oil and lemongrass essential oil) and (d) control (uncoated). Each formulation shows progressive ripening and degradation, with the control exhibiting severe spoilage by day 24.

None of the coated tomatoes were spoiled by day 24. Tomatoes coated with F3 were slightly more reddish than those in the F1 and F2 groups, but the fruits remained intact and free from visible microbial spoilage. This observation is associated with the inclusion of lemongrass essential oil and

coconut oil in the coating mixtures. Lemongrass essential oil is recognised for the potent antimicrobial properties, largely due to an abundance of citral that disrupts microbial cell membranes and inhibits the growth of spoilage-causing bacteria and fungi (Kawhena et al., 2021; Naik et al., 2010).

Likewise, coconut oil contains medium-chain fatty acids such as lauric acid, which demonstrated antimicrobial properties (Deen & Jayawardana, 2021; Nasrin et al., 2023). Combining these ingredients effectively reduced microbial growth on the tomato surface, thus prolonging shelf life and preserving the quality of the fruits.

3.3. Effect of coating treatments on firmness

Firmness is a crucial quality parameter in fruits, which reflects the structural integrity and freshness of tomatoes during storage. Fruits are known to lose firmness and soften due to prolonged storage. After 24 days of ambient storage, there was a significant difference ($p \leq 0.05$) in tomato firmness for all treated groups (see Table 1).

Table 1: Firmness of tomatoes coated with different formulations at day 24 during ambient storage

Treatment	Firmness (g)
Formula 1	444.47 ^{ab} ± 70.41
Formula 2	343.90 ^b ± 17.76
Formula 3	525.07 ^a ± 103.09
Control	410.86 ^a ± 28.82

Values are expressed as mean ± SD (n = 3). Mean values with ^{ab} different superscript letters are significantly different at $p \leq 0.05$.

Among the treatment groups, tomatoes treated with F3 (CCL) demonstrated significant and highest firmness (525.07 ± 103.09 g), compared to F2 (BCL) (343.90 ± 17.76 g). This finding implies that the addition of CMC was vital in preserving fruit firmness, likely due to the binding capacity to create a more consistent film-forming coating matrix that diminishes respiration rate by limiting gas exchange. A slower decline in firmness in F1- and F3-coated fruits compared to controls indicated that both coatings preserved structural integrity by limiting gas exchange (oxygen), which in turn delayed ripening and retained firmness. These results are consistent with earlier studies that demonstrated the efficacy of different composite coating emulsions in maintaining the fruit firmness in storage (Vieira et al., 2021; Yu et al., 2023).

The lowest firmness among all treatment groups was recorded by F2 (BCL), despite the inclusion of beeswax to create moisture-resistant barriers. This outcome can be attributed to the poor miscibility or heterogeneity in the beeswax-based emulsion, which could impact coating thickness and effectiveness in preserving tomato firmness. Figure 2 demonstrates that the F2 tomatoes had white, translucent deposits on the surfaces, which could have facilitated anaerobic respiration. This condition potentially led to damage in cellular tissues by degrading cell wall constituents, reducing firmness beyond uncoated samples

(Moreira et al., 2022; Sharma & Saini, 2021). In summary, the lipid-lipid composite coating emulsion that contains wax (F2) was unsuitable for preserving tomatoes. Conversely, the incorporation of a polysaccharide, such as CMC, into the lipid-based coating emulsion significantly improved firmness retention in tomatoes. The lipid-polysaccharide coating emulsion (F3) was the most effective in maintaining the firmness of tomatoes during ambient storage.

3.4. Effect of coating treatments on TSS

The TSS content (°Brix) reflects the sugar level and serves as an important indicator of sweetness and ripeness. Enzymes such as β-amylase, cellulase, hemicellulase, and pectinase break down complex carbohydrates into simpler sugars during the ripening process (Sharma & Saini, 2021). Evaluating TSS allows for the comparison of different coating treatments concerning fruit maturity and sugar accumulation. As shown in Table 2, the control group recorded the lowest TSS (2.67 ± 0.58 °Brix) in this study, caused by the rapid metabolic degradation and the breakdown of cellular structures that may have hindered sugar accumulation. Kawhena et al. (2021) stated that the rate of sugar consumption for respiration exceeded the rate of sugar synthesis in control samples.

Table 2: Total soluble solids (TSS) of tomatoes treated with different coating formulations on day 24 of ambient storage

Treatment	TSS (°Brix)
Formula 1	3.83 ^{ab} ± 0.29
Formula 2	3.33 ^{ac} ± 0.29
Formula 3	4.50 ^b ± 0.50
Control	2.67 ^c ± 0.58

Values are expressed as mean ± SD (n = 3). Mean values with ^{abc} different superscript letters are significantly different at $p \leq 0.05$.

The TSS values differed significantly between coated samples and the control, except F2, which recorded the lowest TSS content among all coated samples. The F2-treated tomatoes appeared to undergo accelerated respiration during the later stages of storage, possibly triggered by the application of waxy coating emulsion. The F1-treated tomatoes effectively maintained significantly higher TSS (3.83 ± 0.29 °Brix) compared to the control sample (2.67 ± 0.58 °Brix), demonstrating a more rapid decrease over time. This outcome was due to the suppression of ethylene production by the coating, which reduced the respiration rate and decelerated the consumption of metabolites, thereby minimising the TSS loss. Similar findings have been reported in other composite edible coating emulsions (Ceylan & Özdamar Ünlü, 2023; Kumar & Saini, 2021).

The F3 (CCL) was the most effective in maintaining the structural integrity and biochemical quality of tomatoes during ambient storage, without causing adverse sensory impact on the surface appearance. The synergistic effects of CMC and lipid components contributed to an optimal coating structure that balanced gas exchange, moisture retention, and ripening processes.

3.5. Effect of coating treatments on surface microscopy

The microscopic analysis of tomato surfaces was performed to assess the structural variations between coated and uncoated samples, and the effects of all coatings on the surface morphology of the fruits. Based on Figure 3, the uncoated tomatoes exhibited clear signs of spoilage by day 24, characterised by severe wrinkling, rupture, and a sagging appearance. The fruits surfaces were irregular, with a rough and uneven texture. For instance, the natural features of the tomato cuticle, such as microcracks, were more pronounced than those of coated samples. The lack of a film layer led to a drier, matte surface. These attributes indicated greater

exposure to environmental factors, which hastened dehydration, microbial growth, and senescence.

The microscopic image of F1-coated tomatoes was smoother, more uniform, and glossier than the F2-coated samples (beeswax deposits) and the control. This group exhibited fewer visible white deposits, suggesting better dispersion and compatibility of the lipid components than the F2 formulation. The compatibility of coating components enhanced F1 performance, which had a lower respiration rate, as indicated by higher firmness and TSS content compared to F2.

The F2-coated tomatoes featured noticeable pale yellowish and translucent spots scattered throughout the surface. These deposits were the result of crystallisation or incomplete dispersion of beeswax within the lipid matrix. The coating formed a non-uniform layer that impacted gas permeability and created anaerobic conditions during storage. These outcomes influenced the overall visual quality and coating efficacy, leading to poor firmness due to rapid senescence.

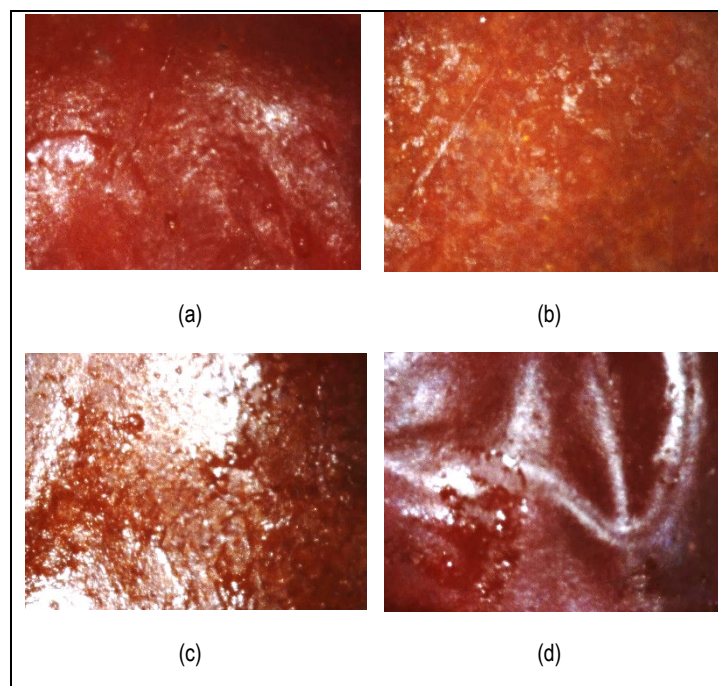


Figure 3: Microscopic surface morphology of tomatoes on day 24 after treatment with different coating formulations: (a) F1 (CL): Coconut oil and lemongrass essential oil, (b) F2 (BCL): Beeswax, coconut oil and lemongrass essential oil, (c) F3 (CCL): CMC, coconut oil, and lemongrass essential oil, and (d) Control (uncoated). Coated samples (F1, F2 and F3) exhibited intact surfaces compared to the control, which showed severe wrinkling and sunken dark red areas. The F1-coated tomatoes exhibited a smoother surface morphology than the F3-coated fruits, as only lipid biopolymers were used in F1. For F2, the tomato surfaces demonstrated white translucent patches that resulted from beeswax crystallisation or non-uniform dispersion within the lipid matrix. Meanwhile, the F3 coating, which combined lipid and polysaccharide components, resulted in a glossier appearance.

The surfaces of the F3-coated tomatoes were uniform and smooth with a glossy finish, indicating the formation of a continuous film across the epidermal layer of the fruits. The homogeneous colour and reflectivity suggest that the F3 coating effectively filled micro-irregularities on the fruits and adhered evenly on the surfaces. Meanwhile, the observed smoothness and glossiness were attributed to the film-forming capability of CMC combined with the hydrophobic nature of coconut oil and lemongrass essential oil. These components synergised to create a semi-permeable barrier, minimising moisture loss and gas exchange while offering antimicrobial protection. Furthermore, the incorporation of CMC facilitated the even distribution of lipid globules on the tomato surface. The continuous and even film formation of F3 indicated improved coating homogeneity than the lipid-lipid composites (F1), which contributed to a controlled ripening rate with better moisture retention, firmness, and TSS content during storage.

The differences between the coated and uncoated surfaces provided visual confirmation of the structural and functional role of edible coatings. Continuous film formation of F3 on the tomatoes highlighted the potential of this formulation as a protective barrier that mitigated physical and microbial deterioration. These findings also align with earlier studies that supported the efficacy of the polysaccharide, lipids, and essential oils combination in edible coatings to preserve fresh produce (Kumar & Saini, 2021; Murmu & Mishra, 2018; Nur Hanani et al., 2023).

4. CONCLUSION

This study demonstrated the efficacy of lipid-based composite edible coatings in preserving the postharvest quality of tomatoes, with the CMC-fortified formulation (F3) exhibiting the best performance in retaining firmness and TSS. The findings emphasised the importance of compatibility or miscibility of components used in developing functional composite as edible coating emulsions. Incompatibility issues, as observed with beeswax, could lead to phase separation and reduced effectiveness of the coating. Conversely, using a single biopolymer type (F1) could lead to delamination during prolonged storage and handling. Despite promising outcomes on tomato preservation during ambient storage, the findings are limited to specific coating concentrations and storage conditions. Future studies should explore the effects of different concentrations of the coating formulation, storage conditions, and preservation methods. In addition, studies can investigate the coating application on freshly cut tomatoes and assess the sensory appeal of the coated fruits to guarantee functional efficacy and consumer acceptance.

ACKNOWLEDGEMENT

This study was funded by the Centre for Research of Innovation and Sustainable Development (CRISD), University of Technology Sarawak (UTS) (Research ID: UTS/RESEARCH/3/2024/17).

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