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Optimization and Characterization of Moringa-Enriched Cassava Starch Coatings for Strawberry Preservation

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ABSTRACT

Strawberries are non-climacteric fruits that are highly perishable and have a short shelf life. Preserving fruit with edible coatings has garnered significant attention because of their low cost and ease of preparation. This study determined the optimal formulation of an edible coating made from cassava starch and moringa leaf extract based on its effects on strawberry physicochemical properties, and then examined the characteristics of the optimal edible coating. Strawberries coated with different edible coating formulations were stored at 28°C for nine days, and physicochemical properties including weight loss, decay rate, total soluble solids, titratable acidity, and antioxidant activity were evaluated. The results showed that strawberries coated with the edible coating performed better than uncoated strawberries on day 9. Strawberries treated with T5 comprising 2% cassava starch, 0.5% CMC, 1% glycerol, 1.5% moringa leaf extract, and 95% distilled water exhibited the best results, with a weight loss of 27.52%, spoilage of 4.44%, total dissolved solids of 8.07%, total titratable acidity of 1.31%, and total antioxidant activity of 24.39 mg AAE/gFW. We characterised the T5 edible coating using FTIR, viscosity, and spreadability tests, compared with the treatment without moringa leaf extract (T2). FTIR revealed chemical interactions between cassava starch and moringa leaf extract in T5 and T2. The viscosity of T5 1628.67 cP is lower than that of T2 1817.33 cP. The spreading power of T5 2.13 g·cm/s is greater than that of T2 1.96 g·cm/s.

Contribution to Sustainable Development Goals (SDGs):

SDG 2: Zero Hunger
SDG 3: Good Health and Well-being
SDG 12: Responsible Consumption and Production
SDG 15: Life on Land

1. INTRODUCTION

1.1. Research Background

Strawberries (*Fragaria* sp.) fruits that are grown in many places and are very valuable for the economy and a high-value horticultural crop widely consumed for their distinctive flavor and abundant bioactive compounds, such as vitamin C, anthocyanins, flavonoids, phenolic acids, and dietary fiber, which act as antioxidants to help prevent various degenerative diseases.

They are enjoyed all over the world because of their special color, shape, smell, taste, and nice texture. Strawberries have many nutrients like minerals, vitamins, anthocyanins, flavonoids, and phenolic acids, which are good for the human body[1]. Strawberries are not climacteric fruits, which means they do not ripen much after being picked. Because of this, perishable produce. They can get damaged from being handled too much, lose moisture, become soft, and also develop mold or fungus[2]. Keeping strawberries at the wrong temperature after picking



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makes them lose weight faster, get damaged more easily, and soften more quickly [3].

One useful approach is using edible coatings. These thin, edible layers are made from materials that are safe to eat and good for the environment [4]. Edible coatings are commonly used to improve the quality and keep fruits fresh longer because they help protect the color, natural acids, sugars, and taste chemicals. These natural edible coatings help keep fruit fresh during storage and transportation by preventing rot.

Cassava starch is a complex carbohydrate that can serve as a base for edible coatings because it contains two main types of starch molecules: amylose and amylopectin. However, starch-based edible coatings by themselves are usually not good at stopping microbial growth or stopping oxidation because they do not have enough bioactive compounds. Moringa (*Moringa oleifera*) leaf extract is an excellent natural supplement. These leaves contain specific chemical compounds such as flavonoids, tannins, alkaloids, saponins, and phenolic compounds. These chemicals are very good at fighting harmful substances and killing bacteria [5]. Using cassava starch as the main material and Moringa leaf extract for its active compounds, the edible coating creates a layer that shields against oxygen and moisture. It also offers extra benefits, such as preventing microbial growth and reducing oxidation.

This approach can help reduce the physical and chemical changes in strawberries, like losing weight, changing color, losing vitamin C, and getting spoiled by microbes, which helps keep the fruit fresh for longer in a safe and natural way [6].

1.2. Literature Review

Strawberries are highly susceptible to postharvest damage due to their high moisture content ($\pm 90\%$), soft texture, thin skin, and high rates of respiration and transpiration. These characteristics make strawberries highly susceptible to water loss, tissue softening, flavor changes, nutrient degradation, and attacks by spoilage microorganisms particularly *Botrytis cinerea* resulting in a relatively short shelf life, even under low-temperature storage conditions.

Postharvest damage to strawberries not only reduces product quality and market value but also increases food loss within the horticultural supply chain. Recent data from the Food and Agriculture Organization of the United Nations indicate that, globally, 13.3% of food is lost between the postharvest stage and the retail level, with fruits and vegetables representing the commodity group with the highest loss rate approximately 25.4% in 2023 primarily due to their highly perishable nature during handling, storage, transportation, and distribution. Furthermore, overall food loss and waste account for approximately 8–10% of global greenhouse gas emissions, posing a significant challenge to achieving sustainable food systems.

Therefore, effective, safe, and environmentally friendly post-harvest processing technologies are needed to maintain strawberry quality while reducing harvest losses. One rapidly developing technology is the use of edible protective coatings that is, edible coatings.

Edible coatings can slow down respiration and transpiration rates, reduce weight loss, preserve fruit texture and color, inhibit oxidation, and suppress the growth of spoilage microorganisms, thereby extending the strawberry's shelf life.

Developing cassava starch based edible coatings enriched with moringa leaf extract (*Moringa oleifera*) offers a promising

alternative, as it combines the film-forming properties of starch with the antioxidant and antimicrobial activities of phenolic compounds and flavonoids found in moringa leaves. This approach not only has the potential to enhance strawberry quality and shelf life but also supports efforts to reduce postharvest food loss and achieve more sustainable food systems, aligning with the Sustainable Development Goals (SDGs) specifically Goal 12 regarding responsible consumption and production.

1.2.1. Strawberries Preservation

Strawberries (*Fragaria* sp.) are non climacteric fruits with high water content, a soft texture, and a relatively fast respiration rate, making them highly susceptible to postharvest damage. Microbial activity, water loss, oxidation of bioactive compounds, and mechanical damage during distribution and storage generally cause this damage. A high respiration rate accelerates the senescence process, which is characterized by color changes, softening of texture, and a decrease in nutrient content, such as vitamin C and phenolic compounds. These conditions result in a very limited shelf life for strawberries, making effective preservation technology necessary to maintain their quality [7].

Strawberry preservation aims to slow the physiological and microbiological processes that cause spoilage. In general, preservation methods include physical, chemical, and biological approaches, such as low-temperature storage, chemical treatments, radiation, and biopolymer-based technologies. The main principles of preservation are to inhibit respiration, reduce water loss, and suppress microbial growth. Modern technology is also moving toward environmentally friendly, safe methods, such as edible coatings and active packaging, which can maintain fruit quality without leaving harmful residues.

1.2.2. Edible Coating

Edible coatings are thin layers made from food materials applied to the outside of a product. They can be used instead of, or alongside, the natural wax that already covers some foods. These coatings protect the product by blocking moisture, oxygen, and other substances that could affect its quality.

These coatings are usually made from natural materials and polysaccharides. They form a layer on the fruit's surface, which changes the air inside the fruit and helps keep moisture from escaping. This slows down the ripening process and reduces how much weight the fruit loses [8]. Their use has been shown to work well in keeping the taste and nutrition of fruits intact [9].



Figure 1. Cassava Starch and Moringa Leaves as Raw Materials for Edible Coatings

Cassava starch is a complex carbohydrate that can be used as a base for edible coatings. It has two main parts, amylose and amylopectin, which can turn into a gel when heated during a process called gelatinization. Moringa leaves from the Moringa oleifera plant are the most commonly used part of the plant

because they have a very high level of nutrients and contain active compounds that are important for health and in food preparation. Moringa leaves are called the miracle leaf because they contain many vitamins, including A, C, and E, along with minerals such as calcium, potassium, and iron. They also contain compounds such as flavonoids, polyphenols, tannins, and phenolic acids. These compounds in Moringa leaves give them strong abilities to fight harmful substances, stop bacterial growth, reduce inflammation, and tackle fungi [10].

1.3. Research Objective

This study aimed to identify the optimal formulation of a cassava starch-based edible coating containing Moringa oleifera leaf extract based on its effects on the physicochemical properties and storage quality of strawberries. The optimal coating was subsequently characterized in terms of viscosity, spreadability, and FTIR functional groups.

2. MATERIALS AND METHODS

2.1. Material

This study was conducted in January 2026 in Padang, Indonesia. The materials used in this study were cassava starch from Padang, moringa leaves from Padang, strawberries from Alahan Panjang, glycerol, aluminum foil, Whatman filter paper, oxalic acid (Merck), NaOH (Merck), phenolphthalein (Merck), FeCl₃·6H₂O (Merck), glycerol (Intraco), and distilled water.

2.2 Methods

2.1.1 Preparation of Cassava Starch

Clean, peel, and wash the cassava, then blend it with distilled water in a 1:2 ratio. The resulting mixture is strained through a cheesecloth. The filtrate is then allowed to stand for 12 hours. Once sediment forms, discard the supernatant and wash the starch sediment again with clean water. Repeat the washing and sedimentation process 2–3 times to produce purer starch. The final starch sediment is then dried in a food dehydrator at 45°C. Once dry, the starch clumps are crushed and blended to obtain fine cassava starch, which is then stored in a sealed container [11].

2.1.2 Preparation of Moringa Leaf Extract

Moringa leaves are washed with clean water to remove dust or contaminants. They are then dried in a food dehydrator at 45°C for 12 hours to reduce moisture content, making it easier to extract bioactive compounds. Once dry, the moringa leaves are ground into a fine powder using a grinder to increase their surface area.

2.1.3 Preparation of Edible Coatings

The edible coating was made using cassava starch with added moringa leaf extract. As shown in Table 1, the formulation consists of cassava starch, glycerol, CMC, and moringa leaf extract. The starch was heated for 5 minutes at 65°C under continuous magnetic stirring; CMC and glycerol were then added while the mixture was still heating. The resulting edible coating was then cooled to room temperature 28°C.

Table 1. Composition of the edible coating

Treatment	Starch (g)	Glycerol (%)	CMC (%)	Moringa Leaf Extract (mL)	Total Volume (mL)
T1	0	0	0	0	100
T2	2,0	1,0	0,5	0	100
T3	2,0	1,0	0,5	0,5	100
T4	2,0	1,0	0,5	1,0	100
T5	2,0	1,0	0,5	1,5	100
T6	2,0	1,0	0,5	2,0	100

The edible coatings prepared according to Table 1 were applied to strawberries selected for uniform ripeness, shape, and size. After being washed and air-dried, the strawberries were dipped into each edible coating solution for 30 seconds, and the coated strawberries were stored at room temperature 28°C ± 2°C to simulate the typical ambient postharvest handling and marketing conditions commonly encountered in traditional markets in tropical regions of Indonesia, where refrigeration facilities are often unavailable. Although commercial strawberries are generally stored under refrigerated conditions (2–5°C), evaluating coating performance under ambient conditions provides practical information for local supply chains. Physicochemical analyses were carried out from day 0 to day 9 following coating. Once the optimal composition was determined, the coating was characterized based on viscosity, spreading ability, and FT-IR.

2.1.4 Physicochemical Analysis of Strawberries

2.1.4.1 Weight Loss

Strawberries from each treatment were weighed using a Shimadzu analytical balance on the first day and at the end of each storage interval (days 0 through 9). The difference between the initial and final fruit weights after 9 days of storage was considered the total weight loss.

$$\text{Weight Loss (\%)} = \frac{W_0 - W_t}{W_0} \times 100\% \quad (1)$$

2.1.4.2 Decay Rate

The level of decay was evaluated by visually observing physical symptoms on the fruit surface using the following scale:

- 0 = no signs of decay
- 1 = 1–10% decay
- 2 = 11–25% decay
- 3 = 26–40% decay
- 4 = 40–50% decay
- 5 = 50% decay

$$\text{Decay rate (\%)} = 100 \times \frac{A \times B}{C \times D} \quad (2)$$

2.1.4.3 Total Soluble Solids

Crushed the strawberries with a mortar and pestle. Then, place the crushed fruit pulp on the glass prism of the B-One Plus refractometer, and record the measured total dissolved solids content in the sample. The results are expressed in °Brix [12].

2.1.4.4 Titratable Acidity

Two grams of strawberries were weighed and diluted in 20 mL of distilled water to obtain a strawberry extract. Stir the mixture, then filter it using Whatman filter paper. Take 10 mL of the strawberry extract sample and add 3 drops of phenolphthalein indicator. Then titrate with NaOH 0,1 N until the solution turns pink. All measurements were performed three times[13].

2.1.4.5 Total Antioxidant Content

Total antioxidant content was determined using the modified phenanthroline method (MPM). The first step involved standardizing the spectrophotometric measurements. Distilled water served as the blank, and a standard calibration curve was constructed using ascorbic acid at concentrations of 0, 5, 10, 15, 20, and 25 ppm.

Two grams of strawberries were weighed and diluted in 20 mL of distilled water to obtain a strawberry extract. Subsequently, 1 mL of the extract was transferred into a small bottle, followed by the addition of 1 mL of distilled water, 1 mL of 0.1% $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, and 1 mL of 0.1% 1,10-ortho-phenanthroline. The resulting solution was incubated for 20 min, and its absorbance was measured at 510 nm using a Shimadzu UV-Vis spectrophotometer. All measurements were performed in triplicate, and the total antioxidant content was expressed as mg AAE/g FW.

2.1.5 Characterization of the Optimal Edible Coating

2.1.5.1 Viscosity

Viscosity was measured using a B-one plus viscometer. A 100 mL sample was added, the instrument was set to 60 rpm, and the temperature was set to room temperature (28°C). During the measurement, spindle No. 2 was used, and the solution was allowed to rotate for 1 minute until a stable reading was obtained[14].

2.1.5.2 Spreadability

One milliliter of edible coating was applied onto the surface of a flat glass plate with a diameter of 10 cm. The solution droplet was covered with a second flat glass plate, and a 100 g weight was placed on top of the upper glass plate for 5 min. After the specified time, the weight was gradually removed, and the upper glass plate was lifted. The spread of the coating solution was then measured in both the vertical and horizontal directions using a vernier caliper. Finally, the spread rate was calculated and expressed in g/cm/s[15].

$$S = \frac{M \times D}{T} \quad (3)$$

2.1.5.3 FTIR

One milliliter of edible coating solution was applied on the sample holder of the ATR-FTIR instrument (Shimadzu FTIR Trace-100), and the IR spectrum was analyzed over a wavenumber range of 250–4000 cm^{-1} .

2.1.6 statistical analysis

The research data were statistically analyzed using one-way analysis of variance (ANOVA), followed by Duncans Multiple Range Test using SPSS (Statistical Package for the Social Sciences).

3. RESULT AND DISCUSSION

This Results and Discussion section presents the results of an edible coating based on cassava starch enriched with moringa leaf extract applied to strawberries. The evaluation was conducted through an analysis of the fruit's physicochemical properties during storage to assess the coatings effectiveness in preserving fruit quality. In addition, the edible coating formulation with the optimal composition was further characterized through viscosity and spreadability tests, as well as functional group analysis using FT-IR.

3.1. Physicochemical Test Results

3.1.1 Visual Changes in Strawberries

Visual changes in the fruit are associated with color changes and senescence, which affect consumer appeal. Visual observations of color changes and shelf life were conducted during storage at room temperature Figure 2.

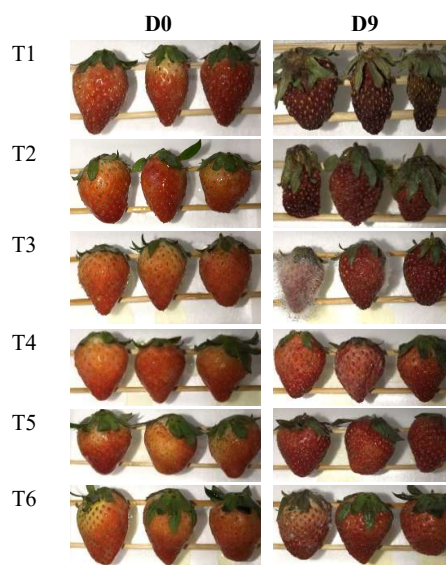


Figure 2. Visual appearance of strawberries storage life (Day 0 and Day 9) under different coating treatments.

Based on Figure 2, on day 0, all strawberries looked nearly identical. They were all bright red, had intact surfaces, and showed no visible damage or mold. After nine days of storage, each treated group declined in visual quality, though the rate of decline varied among the groups.

Treatments T1, T2, T3, T4, and T6 declined more rapidly in quality than Treatment T5. In T1 and T2, the fruit darkened, shrivelled, and the calyx dried, indicating that the fruit was losing water and still respiring. Treatment T3 showed the most severe quality deterioration, with greyish-white mould appearing on one fruit, indicating high microbial activity during storage. Treatments T4 and T6 also experienced fruit shrinkage, a loss of fresh appearance on the surface, and a less vibrant color.

In contrast, the T5 treatment kept the strawberries looking fresh and attractive through day 9. The berries retained their bright red color and appeared smoother. No mold was visible, and the rate of wilting was lower than in the other treatments. These findings indicate that the edible coating applied in the T5

treatment is more effective at inhibiting product deterioration during storage.

This is consistent with the study by Sarker et al. (2022), which showed that starch-based edible coatings can form a protective layer that inhibits gas and water vapor exchange, thereby slowing down the respiration and transpiration processes in fruit. However, their effectiveness increases significantly when combined with natural active compounds. This supports the findings of this study, in which treatment T5 (with moringa leaf extract) was more effective than treatments without extract or with suboptimal concentrations[16].

Furthermore, a study by Zahra et al. (2024) reported that edible coatings containing plant extracts can suppress microbial growth and maintain strawberry quality for up to 12 days during cold storage[17].

3.1.2 Fruit Weight Loss

The results shown in Figure 3 indicate that the use of a cassava starch-based edible coating containing moringa leaf extract significantly reduced weight loss in strawberries during storage. In all treatments, strawberry weight loss increased over time, but the rate varied among treatments.

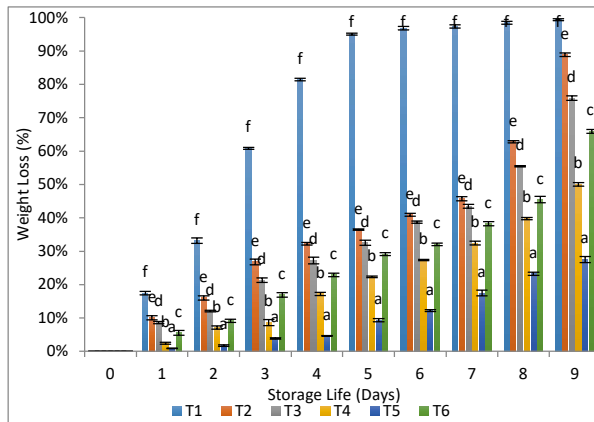


Figure 3. The Effect of Moringa Leaf Extract Composition as a Coating Agent and Storage Life on Weight Loss in Strawberries

The control fruit T1 experienced the greatest weight loss, losing 99.30% of its initial weight by day 9. Without a protective coating, water in the fruit tissue evaporates more easily, and gas loss occurs more rapidly. This is consistent with reports that, due to the absence of a barrier to water vapor and gas diffusion, uncoated fruit has a higher rate of weight loss compared to coated fruit. In contrast, treatment T5 (2% starch + 1% glycerol + 0.5% CMC + 1.5% moringa leaf extract) showed a smaller weight loss, with a weight loss of 27.52% on day 9, compared to other treatments such as T4 at 50.03% and T6 at 65.85%, T3 at 75.83%, and T2 at 88.81%.

A one-way ANOVA analysis and Duncan's post hoc test revealed significant differences ($p \leq 0.05$) among the treatments, particularly between T5 and T1. This indicates that applying coatings T1 through T6 affected the percentage of fruit weight loss differently over 9 days of storage.

The results show that treatment T5 significantly reduced weight loss in strawberries compared with the other treatments, indicating the effectiveness of edible coatings in inhibiting water loss during storage. These findings are consistent with a study by

Khodaei et al. (2021), which reported that the use of edible coatings based on CMC and other polysaccharides significantly reduced weight loss and damage levels in strawberries compared to the control[18].

Furthermore, recent research supports the effectiveness of the T5 treatment, which contains plant extracts, by showing that adding bioactive compounds to edible coatings can enhance barrier properties and antimicrobial activity. A study published in the journal *Scientia Horticulturae* (2024) showed that pectin-based coatings enriched with bioactive extracts significantly reduced weight loss in strawberries during storage[19].

3.1.3 Rate of Decay

Based on the results shown in Figure 4, the use of a starch-based edible coating enriched with moringa leaf extract had a significant effect ($P < 0.05$) on the percentage of strawberry spoilage during storage. Overall, all treatments showed increased strawberry spoilage as storage time increased, but at varying rates.

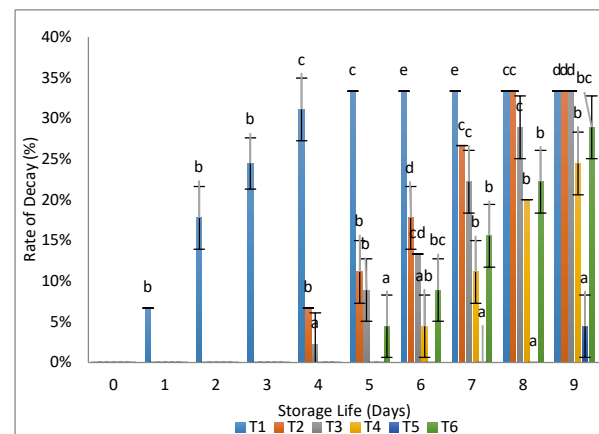


Figure 4. The Effect of Moringa Leaf Extract Composition as a Coating Agent and Storage Life on Strawberry Decay

The fastest decay rate occurred in the T1 control fruit, beginning on the 3rd day and increasing dramatically to 33.33%. In contrast, treatment T5 inhibited decay, with a decay rate of 4.44% on the 9th day of storage. This is because the absence of a protective coating allows microbial activity and physiological processes such as respiration and transpiration to continue. Fruits without an edible coating tend to decay more quickly due to high water loss and increased microbial activity.

These results are consistent with the study by Liguori et al. (2021), which reported that the use of biopolymer-based edible coatings can reduce microbial infection rates and slow fruit decay during storage[20]. Compared with those studies, treatment T5 in this study showed comparable effectiveness even under room-temperature storage conditions, where the spoilage rate was still suppressed through the 9th day. This indicates that the combination of cassava starch and moringa leaf extract holds strong potential as an effective and practical natural edible coating material for extending the shelf life of strawberries.

3.1.4 Total Soluble Solids

Based on the results shown in Figure 5, the cassava starch based edible coating enriched with moringa leaf extract had a significant effect ($P < 0.05$) on the total soluble solids content of strawberries

during storage. It can be seen that the total dissolved solids content in each treatment increased during storage and decreased after ripening.

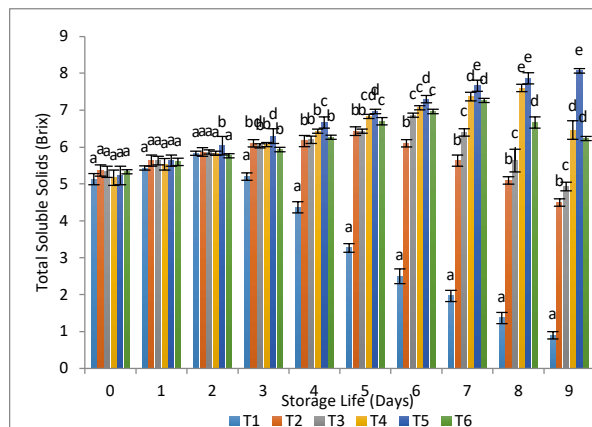


Figure 5. The Effect of Moringa Leaf Extract Composition as a Coating Agent and Storage Life on the Total Soluble Solids in Strawberries

The lowest total soluble solids value was observed in treatment T1 without coating, at 5.8°Brix on day 2. Furthermore, the coated fruits were able to maintain their total dissolved solids content at 6.4°Brix on day 5 for treatment T2, 6.9°Brix on day 6 for treatment T3, 7.3°Brix on day 7 for treatment T6, and 7.6°Brix on day 8 for treatment T4. Treatment T5 performed best in maintaining total soluble solids through day 9 at 8.1°Brix. Treatment T5 was able to maintain a more stable increase in TDS through day 9, indicating that the edible coating effectively slows down fruit respiration and metabolism[21].

These results are consistent with a study by Zahra et al. (2024) in the International Journal of Biological Macromolecules, which reported that a plant extract-enriched polysaccharide-based edible coating was able to maintain the °Brix levels of strawberries during storage by suppressing respiration and preserving cell integrity. In that study, the coating treatment showed higher TDS values than the control through the end of the storage period, similar to the results for the T5 treatment in this study[17].

3.1.5 Titratable Acidity

Based on the results shown in Figure 6, the cassava starch-based edible coating supplemented with moringa leaf extract had a significant effect ($P < 0.05$) on the total titratable acidity of strawberries during storage. Total titratable acidity in each treatment decreased during storage and increased once the decay process began.

The test results showed that treatment T1 had a total titratable acid value of 9.21% on day 9, the sharp increase in total titratable acid in treatment T1 through day 9 indicates the accumulation of organic acids due to tissue damage and microbial activity. In contrast, treatment T5 maintained a lower and more stable TAT through day 9 (1.31%), followed by T4 (2.91%), T3 (3.93%), T6 (4.01%), and T2 (4.56%). This indicates that the edible coating effectively inhibits the rate of respiration and maintains the fruits metabolic balance[22]. This indicates that the coating on T5 effectively slows respiration and substrate degradation, thereby

reducing the accumulation of organic acids. This mechanism is related to the edible coatings ability to form a semipermeable layer that controls gas exchange (O_2 and CO_2) and reduces the enzymatic activity involved in acid metabolism.

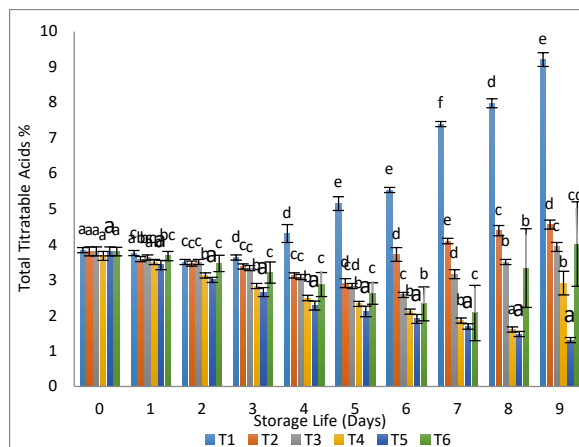


Figure 6. The Effect of Moringa Leaf Extract Composition as a Coating Agent and Storage Life on the Total Titratable Acids in Strawberries

These results are consistent with the study by Liguori et al. (2021), which also showed that the use of edible coatings on strawberries can preserve the fruit's chemical quality, including by reducing fluctuations in acidity levels during cold storage. In that study, coated fruit exhibited more stable TTA changes compared to the control group, which reinforces the findings of this study that coating treatments particularly T5 play a crucial role in maintaining acidity stability[20].

3.1.6 Total Antioxidant Content

Based on the results shown in Figure 7, the total antioxidant content of strawberries increases until the fruit begins to rot, after which it decreases. Based on the one-way ANOVA test, a significant P-value ($P < 0.05$) indicates significant differences among the treatments. Duncan's multiple range test followed, showing that on day 9, treatments T1 and T5 differed significantly.

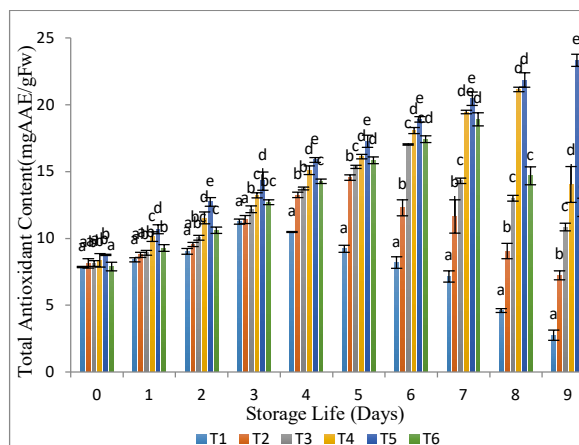


Figure 7. The Effect of Moringa Leaf Extract Composition as a Coating Agent and Storage Duration on the Total Antioxidant Content in Strawberries

The T1 control treatment, antioxidant levels were relatively lower and declined sharply from 9.37 mgAAE/gFw on day 3 to 2.79 mgAAE/gFw on day 9, indicating accelerated degradation of bioactive compounds due to oxidation and tissue damage. In contrast, treatment T5 showed the highest and most stable increase in antioxidant activity through day 9, reaching 24.39 mgAAE/gFw, indicating that the edible coating protects bioactive compounds from oxidative degradation. This was followed by T4 (14.64 mgAAE/gFw), T6 (12.84 mgAAE/gFw), T3 (13.55 mgAAE/gFw), and T2 (9.41 mgAAE/gFw). This indicates that the T5 coating formulation is highly effective at protecting bioactive compounds from oxidative degradation. This mechanism is related to the edible coating's ability to act as a barrier against oxygen, thereby suppressing oxidative reactions, as well as the presence of active compounds from plant extracts such as moringa leaves that contribute as additional antioxidants[23].

These results are consistent with a study by Shafique et al. (2023) in the International Journal of Food Properties, which reported that using moringa leaf extract in an edible coating can increase the antioxidant capacity and extend the shelf life of strawberries. This effect is attributed to the high content of phenolic compounds in moringa leaves, which act as natural antioxidants[24]. These findings are highly relevant to the present study, particularly since treatment T5 contains similar bioactive components and shows higher antioxidant values than the other treatments.

3.2. Characterization of the Optimal Edible Coating

3.2.1 Viscosity

Based on the viscosity measurements in Table 2, treatment T2 (starch + CMC + glycerol) showed a higher viscosity value compared to treatment T5 (starch + CMC + glycerol + moringa leaf extract). The average viscosity of T2 was 1817.33 cP, while the average viscosity of T5 was 1628.67 cP.

Table 2. Viscosity Results for Edible Coating Solutions T2 and T5

Treatment	Speed (RPM)	Spindle	Viscosity(cP)
T2	60	2	1817,33 ± 4,2
T5	60	2	1628,67 ± 64

The decrease in T5 viscosity after adding moringa leaf extract indicates that bioactive compounds in the extract affect the structure and intermolecular interactions within the edible coating solution. Moringa leaf extract is known to contain various secondary metabolites, such as phenolic compounds, flavonoids, proteins, and minerals, which can interact with the polysaccharide matrix starch and CMC. These interactions can disrupt the formation of the gel network that typically forms from hydrogen bonds between starch and CMC chains, thereby causing a decrease in the solution's viscosity[25].

According to the literature, viscosity plays a crucial role in film formation, coating thickness, and barrier properties. According to a recent study by Li et al. (2024), the viscosity of the coating solution is closely related to interactions among biopolymer components (proteins, polysaccharides), which

determine the film's network structure and its ability to protect food products. Solutions with high viscosity tend to form a denser network, resulting in a thicker and stronger film, however, they may be less flexible and uneven[26]. This is consistent with the research data, in which T5 (which has a lower viscosity than T2, but not too low) produced the best performance.

3.2.2 Spreadability

Based on the results in Table 3, treatment T5 showed a higher diffusion rate than T2. The average diffusion rate for T2 was 1.96 g·cm/s, while for T5 it increased to 2.13 g·cm/s. The increase in spreadability is related to the decrease in viscosity observed in treatment T5. In principle, spreadability is inversely proportional to viscosity, the lower the viscosity of a solution, the easier it flows and spreads across a surface. This is evident in previous results, where the addition of moringa leaf extract caused viscosity to decrease, thereby increasing molecular mobility in the solution and making the solution spread more easily[27].

Table 3. Spreadability test results for edible coating solutions T2 and T5

Treatment	Mass (g)	Time (s)	Dispersion Rate (g.cm/s)
T2	100	300	1,96 ± 0,01
T5	100	300	2,13 ± 0,02

According to the literature, higher viscosity increases flow resistance, making it harder for the solution to spread. Conversely, lower viscosity allows the fluid to flow faster and spread more widely across the material's surface. Thus, the higher spreadability value observed in T5 indicates that the coating solution has better flow properties, enabling it to form a more uniform layer on the surface of the strawberries. This is particularly important in edible coating applications because a homogeneous layer enhances protection against water loss and gas exchange.

These results are consistent with the study by Santosh et al. (2024), which also confirms that rheological properties such as viscosity significantly influence a coatings ability to spread and form a continuous layer, excessively high viscosity hinders the flow and distribution of the solution on the material's surface[28]. This supports the study's finding that T2 (high viscosity) has lower spreadability than T5.

3.2.3 FT-IR Functional Groups

Based on the analysis of the fruits physicochemical properties, it was found that T5 is the most effective coating for maintaining fruit quality during storage. Therefore, T5, composed of 2% starch + 0.5% CMC + 1% glycerol + 1.5% moringa leaf extract, was selected as the sample for FT-IR analysis and compared to T2, which consisted only of 2% starch + 0.5% CMC + 1% glycerol. Based on the results in Figure 8, a comparison of the T2 and T5 spectra reveals shifts, changes in spectral intensity, and the appearance of a new peak in the wavenumber range of 2100–2300 cm⁻¹, indicating that the addition of moringa leaf extract to the cassava starch-based food layer has caused a chemical interaction.

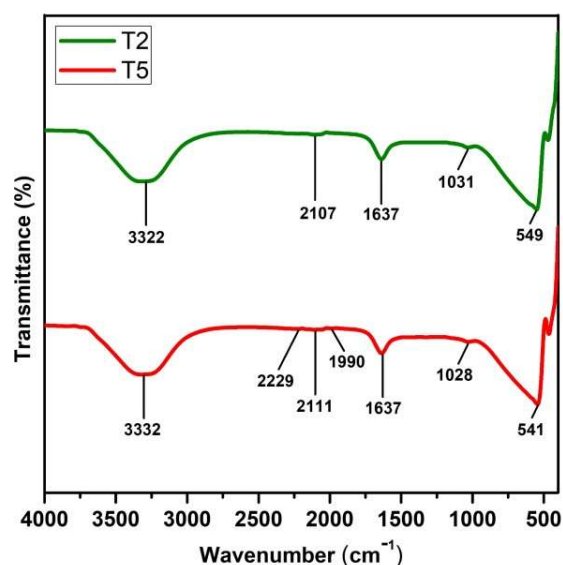


Figure 8. IR spectra of edible coatings T2 (starch + CMC + glycerol) and T5 (starch + CMC + glycerol + moringa leaf extract)

In both samples, a broad absorption band around 3322–3332 cm^{-1} indicates the presence of hydroxyl (O–H) groups, characteristic of starch and phenolic compounds. The slight shift and broadening of the peak in T5 (3332 cm^{-1}) compared to T2 (3322 cm^{-1}) indicate an increase in hydrogen bonding due to the presence of bioactive compounds in moringa leaves, such as polyphenols and flavonoids. This is consistent with research indicating that the addition of plant extracts can strengthen hydrogen bonds within the biopolymer matrix[29]. The weak absorption observed in the 2100–2300 cm^{-1} region may reflect instrumental artefacts, atmospheric CO_2 interference, or weak intermolecular interactions reported in similar starch-based biopolymer systems. Therefore, interpret this peak cautiously and do not consider it evidence of new functional group formation.

Research explains that absorption bands in this region in biopolymer materials often do not arise from alkyne groups, but instead from combination vibrations, vibration overtones, or interference from atmospheric gases during FT-IR measurements. In starch-based edible film systems, intermolecular interactions like hydrogen bonding between starch, plasticizers, and bioactive components can produce weak bands in this region without indicating the formation of new functional groups[28]. Additionally, CO_2 is known to have a characteristic absorption band around this area, so it often appears, especially if the FT-IR instrument's purging process is not optimal.

Furthermore, the peak at 1637 cm^{-1} observed in both samples is associated with carbonyl (C=O) vibration or bound water, which is common in starch-based systems. Peaks T2 at 1031 cm^{-1} and T5 at 1028 cm^{-1} indicate the presence of C–O and C–O–C vibrations originating from the polysaccharide structure in the starch. These small changes indicate that an ion exchange has occurred between the starch and the biologically active compounds in the moringa leaf extract, altering the structural form of the film layer[30].

Table 4. Comparison of the T2 and T5 values from this study with those found in the literature

Functional Groups	Compound Sources	Wave Numbers			References
		Theory	T2	T5	
O–H stretching	Pati, glycerol, CMC	3200-3400	3322	3332	Zhang et al., 2024
C≡C	Weak bonds resulting from polymer matrix interactions	2100-2300	2107	2111, 2229	Messaad et al., 2025
H–O–H bending/ C=O / C=C aromatic	Bound water in starch and CMC	1600-1650	1637	1637	Khan et al., 2023
C–O, C–O–C stretching	Glycosidic bonds between starch and CMC	1000-1150	1031	1028	Zhang et al., 2024
Vibration in the fingerprint area	Polysaccharide structure	500-600	549	541	Tao Hong et al., 2021

3.3. Limitation

This study did not evaluate the sensory acceptability of strawberries coated with moringa leaf extract. Because moringa has a characteristic green colour and herbal flavour, higher extract concentrations may influence consumer perceptions of appearance, aroma, and taste. Future studies should include sensory evaluation and consumer acceptance testing, along with refrigerated storage, to further validate the practical applicability of this edible coating.

4. CONCLUSION

Incorporating moringa leaf extract into cassava starch-based edible coatings improved the physicochemical quality and extended the shelf life of strawberries stored under ambient conditions. The optimized formulation exhibited superior barrier and antioxidant properties, indicating its potential as an environmentally friendly postharvest preservation technology. Future studies should evaluate sensory acceptance and coating performance under commercial cold-chain storage conditions.

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