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Article

Application of Cassava Starch-Based Edible Coating Enriched with Moringa Leaf Flour in Citrus Fruit Storage

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ABSTRACT

Various approaches have been developed to address the issue of fruit deterioration during storage, including packaging technology. Among these, the use of edible coatings has gained increasing attention. The method of this study was a laboratory experimental research with a completely randomized design with two replications. This study aimed to evaluate the effectiveness of a cassava starch-based edible coating enriched with moringa leaf flour in preserving the quality and extending the shelf life of citrus fruits during storage at room temperature. The experiment was carried out in three stages: (1) preparation of edible coatings with varying concentrations of moringa leaf flour (0%, 1%, 2%, and 3%), (2) application of the coatings to citrus fruits, and (3) observation of fruit quality over a 21-day storage period. The parameters assessed included weight loss, moisture content, firmness, and sensory attributes such as color, aroma, texture, and flavor. A Completely Randomized Design (CRD) was employed with two replications. The results indicated that the edible coating treatments effectively reduced the rate of physical quality degradation in citrus fruits. In particular, the treatment with 3% moringa leaf flour (F3) resulted in the lowest weight loss and the highest firmness by day 14. Additionally, the peel color of fruits in the F3 treatment remained more stable compared to the control. This study concludes that, although no significant differences were observed in moisture content among the treatments, the application of the edible coating was effective in better preserving the sensory quality of the fruits.

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1. INTRODUCTION

Citrus fruits are among the most popular and widely consumed fruits across the globe, prized not only for their sweet and tangy flavor but also for their high nutritional content, particularly vitamin C, dietary fiber, and a wide range of bioactive compounds such as flavonoids and antioxidants (Saini et al., 2022). These attributes make citrus a key component of a healthy diet, contributing to its strong consumer demand in both fresh and processed forms. Despite their popularity, maintaining the postharvest quality of citrus fruits remains a significant challenge. One of the primary limitations is their relatively short shelf life, which restricts their marketability and contributes to substantial postharvest losses, especially in regions lacking adequate storage and transportation infrastructure (Hanif & Ashari, 2021).

The deterioration in quality during storage is largely attributed to a series of physiological and biochemical changes that begin immediately after harvest. These include respiration and transpiration, which lead to moisture loss and weight reduction, as well as the activity of microorganisms that cause spoilage. Over time, these processes result in softening of the fruit's texture, changes in color, degradation of nutritional content, and the development of off-flavors, all of which negatively affect consumer acceptability (Hidayat et al., 2018; Nofriati & Asni, 2015). Moreover, environmental factors such as temperature and relative humidity can accelerate the senescence process, making effective postharvest handling and preservation strategies critical to extending shelf life and ensuring citrus fruit quality throughout the supply chain (Cui, 2024; Mesejo et al., 2024).

Moringa oleifera has great potential to support sustainable agriculture due to its ability to grow in poor soils and withstand drought. It is also well-suited for intercropping systems, enhancing agricultural biodiversity, and reducing reliance on a single crop (BRMP, 2025). Various approaches have been developed to address the issue of fruit deterioration during storage, including packaging technology. Among these, the use of edible coatings has gained increasing attention. Susilowati et al. (2017) demonstrated that edible coatings act as physical barriers that reduce moisture loss and oxidative damage. Moulia et al. (2019) highlighted that the application of edible materials via dipping or spraying can significantly prolong the shelf life of fruits. Cassava starch is a natural polymer that can be utilized as a base material for the formulation of edible coatings (Tarihoran et al., 2023). Ifmalinda et al. (2019); Yudiyanti & Matsjeh (2020) also found cassava starch to be a suitable base for edible film formation due to its film-forming properties.

Moringa orifeira could grow in poor soils and withstand drought. Its suitability for intercropping systems also promotes biodiversity. In addition, the significant export growth of Moringa leaves from Indonesia, reaching 4,350 tons and USD 13.75 million in early 2024, highlights both global demand and local availability of this functional plant (BRMP, 2025). Numerous studies have explored the diverse applications of *Moringa oleifera*, particularly its leaves, which are recognized for their potential as functional ingredients in food systems. In the context of edible coatings, moringa leaves have garnered significant interest due to their rich content of phytochemicals, vitamins, and secondary metabolites, which offer both nutritional and protective benefits. Compounds such as flavonoids, saponins, reducing sugars, and alkaloids present in moringa contribute to its antioxidant, antimicrobial, and preservative properties (Hodas et al., 2021; Srivastava et al., 2023), making it suitable for enhancing the shelf life and safety of perishable products. Furthermore, the presence of bioactive anticancer compounds, such as isothiocyanates and glucosinolates, underscores moringa's potential not only in improving food quality but also in delivering health-promoting effects. These characteristics make *Moringa oleifera* a promising natural component in the development of bioactive edible coatings for postharvest preservation.

The selection of Moringa leaf flour in edible coating formulation is based on its well-documented antioxidant and antimicrobial properties, which play a crucial role in preserving fruit quality. Dhayanti et al. (2013) reported antimicrobial activity of Moringa extract against Escherichia coli, while Dima et al. (2016) observed inhibitory effects on both E. coli and Staphylococcus aureus. Additionally, (Satriyani, 2021) highlighted the presence of flavonoids and β-carotene in Moringa leaves as potent antioxidants. Supporting this, Susanty et al. (2019) reported a strong antioxidant capacity of Moringa extract with an IC_{50} value of 4.289 ppm. These findings support the use of Moringa leaf flour in extending the shelf life of fresh produce such as citrus fruits. This research is significant as the application of an edible coating formulated with cassava starch and moringa leaves has the potential to enhance the resistance of citrus fruits to decay and oxidative deterioration, while also preserving their nutritional quality and freshness during storage (Picauly & Tetelepta, 2020; Satriyani, 2021).

While many studies have explored the use of starch-based edible coatings and natural antimicrobials separately, limited research has been conducted on the combined application of cassava starch and moringa leaf flour specifically for citrus fruits. This research seeks to address that gap by formulating and evaluating an edible coating based on cassava starch enriched with moringa leaf flour. The objective of this study is to assess the effectiveness of this formulation in preserving the moisture content, reducing weight loss, maintaining firmness, and improving the sensory quality of citrus fruits during storage.

2. MATERIALS AND METHODS

2.1. *Tools and materials*

The materials used in this study were cassava starch (Cikurubuk Market, Tasikmalaya, Indonesia), moringa leaf flour (West Jakarta, Indonesia), Brastagi orange (Cikurubuk Market, Tasikmalaya, Indonesia), distilled water, and glycerol. The tools used in this study were a hotplate stirrer (Barnstead Thermolyne Magnetic Stirrer with heating, type Cimarec, model SP131320-33 USA), a magnetic stirrer, an analytical balance (Kern als 220-4, Kern & Sohn GmbH D-72336 Balingen, Germany), an oven (Memmert UN55, Germany), a portable penetrometer, a desiccator, and other glassware.

2.2. *Methods*

This study was conducted in three stages. The first stage involved the preparation of cassava starch-based edible coatings with the addition of moringa leaf flour (MLF) at four different concentrations: 0% (F0), 1% (F1), 2% (F2), and 3% (F3). In the second stage, the edible coatings were applied to citrus fruit, which were then stored at room temperature. The third stage involved evaluating the weight loss, moisture content, and firmness of the citrus fruits on days 0, 7, 14, and 21. Additionally, untreated citrus fruits without an edible coating were included as a control group during the third stage of the study.

2.3. *The preparation of edible coating based on cassava starch with the addition of moringa leaf flour*

Four grams of cassava starch were dissolved in 100 mL of distilled water while stirring using a hot plate equipped with a magnetic stirrer. Glycerin was added at a concentration of 1.2 mL, followed by the addition of MLF at concentrations of 0%, 1%, 2%, and 3% (w/w based on starch). The mixture was then heated to 75C with continuous stirring at 300 rpm. After heating, the solution was cooled to 50^{o}C before being applied to the citrus fruits (Moulia, 2018).

2.4. *Application of edible coating on citrus fruit*

The test was conducted using citrus fruits coated with the best edible coating formulation. The citrus fruits were dipped into the coating solution for 30 seconds, then allowed to dry before being stored at room temperature (27–30^{o}C) for further observation (Moulia, 2018).

2.5. *Analysis of the quality of orange fruit during storage at room temperature*

In this study, observations were conducted on both the control group and citrus fruits treated with edible coating on days 0, 7, 14, and 21. The measured parameters included weight loss, moisture content, and firmness of the fruit using a penetrometer, as well as sensory evaluations of the color, aroma, flavor, and texture of the fruit (Santoso et al., 2004).

2.6. *Weight loss analysis*

The weight loss measurement of citrus fruits is performed by comparing the difference in weight before and after storage. Weight loss during the storage period can be calculated using the following Equation 1 (Tarihoran et al., 2023).

$$weight\ loss = \frac{initial\ weight - final\ weight}{initial\ weight} \times 100\% \tag{1}$$

2.7. *Moisture content analysis*

The moisture content of the sample was determined by using the oven-drying method. Initially, the crucible and lid were dried in an oven at 105^{o}C for 30 minutes. The crucible and lid were then placed in a desiccator to cool for at least 30 minutes and weighed. Approximately 2 g of sample was weighed and placed in a pre-dried crucible, then dried in the oven at 105^{o}C for 24 hours. After the drying process, the crucible with the sample was transferred into a desiccator for cooling purposes before the weight was measured. The percentage of moisture content was determined according to Equations 2 and 3.

$$percentage\ of\ dry\ matter = \frac{weight\ of\ dry\ sample\ (g)}{weight\ of\ original\ sample\ (g)} \times 100\% \tag{2}$$

$$percentage\ of\ moisture\ content = 100\% - percentage\ of\ dry\ matter \quad (3)$$

2.8. Fruit hardness analysis

The hardness of citrus fruit was tested using a portable penetrometer. Before the measurement, the zero and peak hold buttons on the device were set to ensure the accuracy of the reading. Next, the citrus fruit was pierced perpendicularly using the penetrometer probe until the device showed the maximum penetration strength value. Measurements were made at two to three points on the surface of the fruit, and the results were expressed in kg/cm^2 as the fruit hardness value.

2.9. Sensory evaluation of citrus

Observation of sensory parameters was conducted descriptively to assess the attributes of skin color, aroma, texture, and flavor of orange fruit during storage at room temperature. The assessment was carried out visually and organoleptically on days 0, 7, and 14 by five semi-trained panelists. The color attribute was observed visually against changes in the color of the fruit skin. Aroma was assessed based on the intensity and characteristics of the orange aroma that was smelled immediately after the skin was opened. Texture was observed through hand touch and light finger pressure to assess the level of hardness or softness of the fruit. Meanwhile, flavor was assessed directly after tasting the fruit flesh, by paying attention to the characteristics of sweetness, sourness, bitterness, and freshness. All assessments were conducted in a room with natural lighting and controlled room temperature, and the results were recorded in the form of qualitative descriptions for each treatment and observation day.

2.10. Experimental Design and Analysis

The experimental design used in this study was a Completely Randomized Design with the addition of MLF (0%, 1%, 2%, and 3% (w/w)) with two replications. Data analysis was performed using SPSS 22 software using analysis of variance (ANOVA). The results of significant differences were further examined with Tukey's test at a significance level of α = 5%.

3. RESULT AND DISCUSSION

3.1. Fruit Hardness

Fruit hardness is a key quality attribute that significantly influences the shelf life of most fresh fruits. It is affected by various factors such as harvest maturity, storage temperature, and relative humidity (Alhassan et al., 2015). Among these, moisture loss is considered a major contributor to the deterioration of firmness during storage. The application of edible coatings has been shown to effectively help preserve the hardness of coated fruits compared to uncoated ones. The hardness of the orange fruit decreased progressively during storage (Table 1). On that table explained the numbers followed by the superscript letter (a,b,c), which are different in the treatment, indicating significantly different ($P<0.05$) and orange with edible coating added by moringa leaf flour (MLF) at four different concentrations: 0% (F0), 1% (F1), 2% (F2), and 3% (F3). However, on days 14 and 21, citrus fruits coated with edible coatings containing *Moringa oleifera* leaf flour (MLF) maintained significantly higher hardness compared to those without MLF and the control. The control fruits exhibited the fastest softening, reaching only 0.81 kg/cm^2 by day 21.

Tabel 1. Orange Fruit Hardness (kg/cm^2) During Storage

Treatment	Day 0	Day 7	Day 14	Day 21
F0	8.73 ± 0.50^a	8.12 ± 0.50^{ab}	5.39 ± 0.38^a	3.01 ± 0.50^b
F1	10.73 ± 0.70^b	9.87 ± 1.47^b	8.12 ± 0.10^b	6.94 ± 0.71^c
F2	8.40 ± 0.53^a	7.80 ± 0.53^{ab}	7.42 ± 0.30^b	6.94 ± 0.30^c
F3	8.40 ± 0.53^a	7.97 ± 0.15^{ab}	7.42 ± 0.14^b	7.05 ± 0.03^c
Control (without coating)	8.53 ± 0.76^a	6.75 ± 0.69^a	5.36 ± 0.30^a	0.81 ± 0.12^a

This study is consistent with the findings of Kubheka et al. (2020) and Ngubane et al. (2024a), who reported that edible coatings incorporated with *Moringa oleifera* leaf extract were effective in reducing weight loss and maintaining the firmness of avocados. Their research demonstrated that various moringa-based treatments successfully inhibited moisture loss and texture degradation, thus extending shelf life and preserving the overall quality of the fruit during storage. The prolonged storage of citrus fruits promotes the breakdown of carbohydrate components into simpler compounds, leading to a progressive softening of the texture of the fruit (Manurung et al., 2024). Concurrently, cassava starch exhibits excellent film-forming properties, enabling it to cover the fruit's surface and retain internal moisture effectively. This directly impacts the texture and firmness of the fruit, which tends to be preserved for a longer period compared to untreated fruit. The addition of moringa leaf extract can enhance the mechanical strength and reduce the water vapor transmission rate (WVTR) of the edible film (Amini & Larasati, 2022). The findings suggest that applying an edible coating is effective in maintaining the structural integrity of citrus fruits during postharvest storage. The coating significantly delayed the reduction in fruit firmness, suggesting its potential role in mitigating textural degradation over time. Functioning as a semi-permeable barrier, the edible coating modulates gas exchange and moisture loss by reducing respiration and transpiration rates, thereby contributing to the maintenance of the texture, hardness, or structural integrity of citrus fruit (Saputra et al., 2019).

3.2. Weight Loss

Weight loss serves as a critical indicator of fruit quality deterioration, often associated with dehydration, increased respiration, and loss of freshness during postharvest storage. In this study, the weight loss of orange fruits increased progressively during storage (Table 2). These results are in line with the findings of Hidayat et al. (2018), who reported that weight loss in orange fruits increases with prolonged storage duration. This increase is primarily attributed to the gradual loss of water through transpiration and respiration, resulting in fruit shrinkage and a corresponding reduction in weight over time. As shown in Table 2, the results of this study indicate that citrus fruits coated with edible coatings containing 3% moringa leaf flour (MLF) experienced the lowest weight loss during storage. This suggests that increasing the concentration of MLF in the edible coating formulation can effectively reduce the rate of moisture loss in citrus fruits. In contrast, the uncoated citrus fruits exhibited the highest percentage of weight loss, highlighting the protective effect of the moringa-based edible coating in preserving fruit quality. These findings are consistent with the work of Tesfay et al. (2017), who observed a decrease in weight loss in avocados treated with edible coatings combined with moringa leaf or seed extracts. Similar results were also reported by (Kubheka et al., 2020; Ngubane et al., 2024b), where edible coatings incorporated with moringa leaf effectively reduced avocado weight loss throughout the storage period.

Tabel 2. Pembagian data untuk Training dan Testing

Treatment	**Day 7**	**Day 14**	**Day 21**
F0	17.67 ± 3.51^{a}	27.33 ± 5.51^{ab}	36.00 ± 4.58^{a}
F1	18.00 ± 7.55^{a}	29.33 ± 3.06^{b}	44.33 ± 11.85^{a}
F2	16.33 ± 13.20^{a}	31.33 ± 4.51^{b}	32.33 ± 11.24^{a}
F3	10.00 ± 3.00^{a}	17.67 ± 2.08^{a}	26.33 ± 1.53^{a}
Control	21.33 ± 2.52^{a}	34.33 ± 2.08^{b}	40.67 ± 3.21^{a}

The F3 treatment exhibited the lowest percentage of weight loss, followed sequentially by F2, F1, F4, and the control. Thus, it can be observed that higher concentrations of MLF incorporated into the coating formulation are effective in reducing weight loss in citrus fruits. Both the treatment type and storage duration significantly influence postharvest quality attributes. The observed weight loss is primarily associated with transpiration, characterized by the continuous diffusion of water vapor through the fruit surface, which accelerates during storage and leads to a reduction in overall fruit mass (Amini & Larasati, 2022).

3.3. Water Content

The water content decreased slightly during storage, as observed in all treatments and controls (Table 3). The results of statistical analysis showed that the difference in water content between all treatments and controls was not significant ($p > 0.05$) during the storage period. The addition of moringa leaf powder appears to play a significant role in enhancing the microstructural integrity of the edible film matrix, resulting in a more compact and cohesive structure that effectively reduces water vapor permeability. This structural improvement likely contributes to the film's enhanced barrier properties, particularly in minimizing moisture loss during storage. The present findings align with previous studies on cassava onggok starch-based edible films, which demonstrated that increasing the concentration of moringa leaf extract correlates with a progressive decline in the water vapor transmission rate (WVTR), thereby improving the film's ability to retain internal moisture (Amini & Larasati, 2022). Similarly, Mohamad et al. (2023) reported that incorporating purified flavonoids from *Moringa oleifera* into chitosan-based films significantly reduced WVTR and improved structural compactness. However, unlike most studies that used moringa leaf extract, this study utilized moringa leaf powder directly, offering a simpler and more affordable alternative. The insoluble fiber in the powder may help reinforce the film structure and enhance moisture retention. Although this study did not measure the moisture content of Moringa leaf powder itself, proximate data from other research indicate that dried Moringa leaf powder typically has low moisture levels (approximately 6.9%) and a high fiber content (Masitlha et al., 2024).

Tabel 3. Water Content Data of Orange Fruit

Treatment	Day 0	Day 7	Day 14	Day 21
F0	86.61 ± 0.22^a	85.80 ± 1.17^a	84.53 ± 0.69^a	$84{,}14 \pm 1{,}20^a$
F1	88.42 ± 3.28^a	86.86 ± 0.57^a	83.44 ± 1.12^a	$84{,}00 \pm 2{,}36^a$
F2	87.57 ± 1.13^a	85.60 ± 1.04^a	84.11 ± 1.53^a	$84{,}33 \pm 1{,}47^a$
F3	87.74 ± 1.54^a	87.16 ± 1.53^a	81.96 ± 3.29^a	$83{,}44 \pm 1{,}11^a$
Control	87.57 ± 0.56^a	85.93 ± 1.59^a	84.43 ± 0.96^a	$80{,}85 \pm 0{,}79^a$

3.4. *Results of Sensory Observations of Color, Aroma, Texture and Flavor of Citrus fruits on Days 0, 7 and 14*

Observations on the color, aroma, texture, and flavor of citrus fruits were conducted throughout the storage period. Among the four sensory parameters evaluated, noticeable changes were observed in the color of the fruit peel. With prolonged storage, the peel of citrus fruits that were not coated with the edible film containing moringa leaf flour tended to develop a blackish discoloration (Figure 1).

Gambar 1. Visual changes in orange peel in each treatment during storage at room temperature

Tabel 4. Color Observation Results

Treatment	Day 0	Day 7	Day 14
F0	greenish orange	greenish orange	greenish orange
F1	orange	Orange	orange
F2	greenish orange	greenish orange	greenish orange
F3	orange	Orange	orange
Control	greenish yellow	greenish yellow	Greenish yellow, black circles

The color of the citrus fruit peel naturally degrades over time due to physiological processes, including respiration, pigment oxidation, and enzymatic activity (e.g., polyphenol oxidase), which are triggered by exposure to oxygen and fluctuations in temperature during storage (Table 4). These processes accelerate the color change of the fruit peel to a dull or brownish hue, indicating decreased fruit freshness. The application of a cassava starch-based edible coating has been shown to slow down color changes on citrus fruit peel effectively. The edible coating formed from cassava starch acts as a barrier that hinders the exchange of gases, such as O_2 and CO_2, which directly slows down the respiration process and pigment oxidation on the fruit surface. As a result, the natural pigments, such as carotenoids and flavonoids, in the citrus peel remain stable, allowing the fruit peel color to stay bright for a longer period (Masoom et al., 2024). A similar result was reported by Ngubane et al. (2024a), who found that applying a carboxymethyl cellulose (CMC)-based edible coating containing *Moringa oleifera* extract helped maintain color stability and visual quality of Hass avocados during cold storage. This supports the role of Moringa-enriched edible coatings in delaying surface discoloration of fresh produce.

An edible coating formulated with moringa leaf flour acts as a protective barrier, minimizing moisture loss and limiting exposure to oxygen and other environmental factors that can accelerate fruit deterioration. This dual-action mechanical protection, combined with antioxidant activity, enhances the overall effectiveness of the coating in preserving the quality of orange fruits. As a result, fruits coated with moringa-enriched edible films retain their color and freshness for longer periods, even under extended storage conditions. These findings suggest that moringa leaf powder can be utilized as a natural active ingredient in edible coatings, offering a sustainable and safe alternative to synthetic preservatives while contributing to the extension of shelf life and the maintenance of postharvest quality in orange fruits (Masoom et al., 2024).

Tabel 5. Aroma Observation Result

Treatment	Day 0	Day 7	Day 14
F0	orange scent	orange scent	the aroma is not too strong
F1	orange scent	the citrus scent is not too strong	the aroma is not too strong
F2	orange scent	the citrus scent is not too strong	the aroma is not too strong
F3	orange scent	the citrus scent is not too strong	the aroma is not too strong
Control	orange scent	the citrus scent is not too strong	Bad smell

At day 0, all samples exhibited a fresh citrus scent. However, aroma intensity declined during storage. By day 14, the control developed a distincly unpleasant odor, while coated fruits (F1-F3) retained an acceptable citrus aroma (Table 5). This incidates that the cassava starch-based edible coating with Morinaga leaf powder helped limit microbial and oxidative degradation of volatiles. Ngubane et al. (2024a) observed similar results in avocado fruits, where Moringa-based coatings helped maintain aroma quality by reducing oxidative spoilage. Likewise, Govender & Siwela (2020) found that up to 5% *Moringa oleifera* leaf powder preserved acceptable aroma in bread products, while higher levels reduced sensory appeal.

Tabel 6. Texture Observation Result

Treatment	Day 0	Day 7	Day 14
F0	a bit hard	mushy	mushy
F1	a bit hard	a bit hard	mushy
F2	a bit hard	a bit soft	a bit soft
F3	a bit hard	a bit hard	a bit soft
Control	a bit hard	mushy	mushy

Samples F1-F3, particularly F2, maintained a desirable texture up to day 14, while the control and F0 became mushy by day7 (Table 6). The inclusion of Moringa leaf powder likely densified the edible film matrix, helping seal moisture and gases. This barrier mechanism slows down respiration and enzymatic softening, thus postponing the breakdown of fruit tissue structure (Kubheka et al., 2020). Ngubane et al. (2024a) observed similar effect in avocados coated with Moringa-based films, which retained firmness through reduced moisture loss and delayed senescence. Govender & Siwela (2020) also found that moderate levels of Moringa powder in bread maintained textural integrity, while excessive levels reduced softness and palatability.

Tabel 7. Pembagian data untuk Training dan Testing

Treatment	**Day 0**	**Day 7**	**Day 14**
F0	sweet, slightly sour	sweet, slightly sour	sweet, slightly sour
F1	a little sweet	a little sweet	a little sweet
F2	sweet a bit bitter	Sweet	sweet and sour
F3	sour slightly bitter	Sour	sour
Control	a bit sour	sour	sour

During storage, flavor profiles diverged among treatments. While F1 and F2 maintained a balanced sweet to sour taste, the control and F3 developed a more sour or slightly bitter flavor by day 14. Moderate inclusion of Moringa leaf powder, as applied in F2, seems to help maintain flavor stability in this context. In contrast, higher concentrations (F3) may impart slight bitterness due to the inherent phytochemical compounds of Moringa (Kubheka et al., 2020). This physiological effect may arise because the coating slows down microbial and enzymatic spoilage processes such as fermentation and breakdown of sugars, thus delaying the onset of off-flavors and preserving taste qualities longer (Ngubane et al., 2024b).

4. CONCLUSION

The findings of this study indicate that the application of cassava starch-based edible coatings enriched with Moringa leaf flour effectively preserved the quality of citrus fruits during room-temperature storage. The treatment with 3% Moringa leaf flour (F3) showed the best performance in maintaining fruit hardness (7.05 kg/cm^2 at day 21), minimizing weight loss (only 26.33% at day 21), and preserving peel color, as the fruits remained bright orange with minimal discoloration. Although the differences in moisture content were not statistically significant across treatments, F3 maintained better internal moisture and structural integrity. Sensory evaluations also revealed that F3 retained acceptable aroma and texture longer than the control, though F2 offered a better overall flavor profile with a balanced sweet-sour taste. Thus, F3 is the most effective in maintaining firmness, visual appearance, and structural preservation, while F2 provides superior flavor retention. These results highlight the potential of Moringa-enriched edible coatings as a sustainable solution for extending shelf life and preserving the postharvest quality of citrus fruits. Future studies should investigate its impact on key nutritional components such as vitamin C and antioxidant stability to provide a more comprehensive understanding of its efficacy in preserving both physical and nutritional quality during storage.

5. DEKLARASI

Author Contributions

All authors contributed equally as major contributors to this paper. All authors read and approved the final paper.

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Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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