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Preservation of dragon fruit coated with cactus gel, passion fruit extract and silver nanoparticles

Abstract – The objective of this work was to develop a composite coating based on cactus gel (CG), passion fruit epicarp extract (PPFEE), and green-synthesized silver nanoparticles (AgNPs), as well as to systematically evaluate the bioactive composition, synthesis and structural characterization of nanoparticles, antioxidant and antibacterial activities, and effectiveness in extending the postharvest life of dragon fruit. The combined formulation of 40% CG solution with PPFEE/AgNPs-80 (0.67% PPFEE) exhibited the best performance, prolonging the shelf life of the dragon fruit up to 17 days at 25°C and 48 days at 10°C. Compared with uncoated controls, this coating significantly reduced weight loss, delayed changes in total soluble solids, and preserved visual quality. The results show that CG formed a physical barrier, while PPFEE/AgNPs exhibit strong antioxidant and antibacterial activities. The combined effect of these components results in superior postharvest preservation efficacy.

Index terms: *Selenicereus undatus*, edible coating, passion fruit epicarp, postharvest preservation.

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Conservação de pitaya revestida com gel de cacto, extrato de maracujá e nanopartículas de prata

Resumo – O objetivo deste trabalho foi desenvolver um revestimento composto à base de gel de cacto (CG), extrato do epicarpo do maracujá (PPFEE) e nanopartículas de prata (AgNPs), bem como avaliar sistematicamente sua composição bioativa, síntese e caracterização das nanopartículas, atividades antioxidantes e antibacterianas, além de eficácia no prolongamento da vida pós-colheita da pitaya. A formulação combinada de 40% CG com PPFEE/AgNPs-80 (0,67% de PPFEE) apresentou o melhor desempenho no prolongamento da vida útil da pitaya armazenada por até 17 dias a 25°C e 48 dias a 10°C. Em comparação com os controles não revestidos em condições ambiente, o revestimento reduziu significativamente a perda de peso, retardou alterações nos sólidos solúveis totais e preservou a qualidade visual. Os resultados demonstram que o CG pode formar uma barreira física, enquanto o PPFEE/AgNPs exibe fortes atividades antioxidantes e antibacterianas. O efeito combinado desses componentes resulta em aumento da eficácia de conservação.

Termos para indexação: *Selenicereus undatus*, revestimento comestível, epicarpo do maracujá, conservação pós-colheita.

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Introduction

Dragon fruit [*Selenicereus undatus* (Haw.) D.R.Hunt], commonly known as pitaya, is a tropical fruit characterized by an attractive appearance, a pleasant flavor, and a high content of vitamins, antioxidant phytochemicals, and flavonoids, such as betalains present in the red-pulp varieties. However, the fruit is highly perishable under ambient conditions, and consequently its weight, soluble solids and visual appearance commonly degrade within approximately 10–14 days. This rapid deterioration limits its shelf life, marketability and export potential (Chen et al., 2024; Latif et al., 2025).

To mitigate postharvest losses, a range of strategies, particularly edible coatings enriched with bioactive compounds has gained increasing attention due to their effectiveness and environmental friendliness (Ferreira et al., 2025). Driven by consumer preference for "clean label" products and environmental concerns, edible coatings and films made from natural biopolymers have gained traction as sustainable alternatives. These coatings form semipermeable barriers that reduce transpiration and gas exchange while simultaneously acting as carriers for antioxidants and antimicrobials (Dhall, 2013; Kavi et al., 2024; Li et al., 2025).

Among natural coatings, cactus gel (CG) from *Opuntia* spp., which contains polysaccharide compounds, vitamin C, betalains, and phenolic compounds, can function effectively as a physical barrier while simultaneously serving as an antioxidant and antimicrobial agent (El -Mostafa et al., 2014). Consequently, this biopolymer serves as a protective layer that preserves fruit quality through both physical and phytochemical mechanisms.

Moreover, fruit processing byproducts are an underutilized source of potent bioactive compounds (Shinga et al., 2025). For instance, the epicarp of purple passion fruit (*Passiflora edulis* Sims), can be a promising natural preservative and value-added ingredient for edible coatings. Targeted LC-QTOF/ESI-MS profiling of this epicarp revealed dozens of polyphenolic constituents (Siniawska & Wojdyło, 2023), while simpler colorimetric assays have demonstrated substantial phenolic/flavonoid levels and antioxidant activity (Ngibad et al., 2023).

Concurrently, green-synthesized silver nanoparticles (AgNPs), produced using plant extracts as reducing or capping agents, have emerged as effective antimicrobial and antioxidant additives for food-contact films and coatings (Dhaka et al., 2023; Lieu et al., 2024). When incorporated into fruit coatings, these nanoparticles significantly reduce microbial spoilage and help retain quality (Bizymis et al., 2023; Gemail et al., 2023). Feng et al. (2024) reported that incorporating biochar-based AgNPs into a chitosan-polyvinyl alcohol increased the film's antibacterial activity and reduced the weight loss rate of blueberries during storage. Similarly, Mouzahim et al. (2023) demonstrated that chitosan films loaded with AgNPs exhibited superior antioxidant and antibacterial properties compared with those without AgNPs. Therefore, the addition of AgNPs into a preservation mixture can provide combined effects with other components, thereby enhancing the freshness of postharvest fruits.

Nevertheless, despite these advantages, potential safety concerns regarding the application of nanomaterials in food-contact materials persist. For example, freely dispersed AgNPs may migrate from polymer matrices into food products, potentially leading to unintended ingestion. Moreover, studies suggest that AgNPs can disrupt cell membranes and generate reactive oxygen species, which can induce DNA damage or cellular oxidative stress. There are also concerns about the possible accumulation of silver in human tissues following long-term exposure. Furthermore, although AgNPs are effective against resistant microbial strains, debates continue regarding whether widespread environmental release could contribute to the development of additional microbial resistance (Jangid et al., 2025).

Although edible coatings, plant-derived extracts, and AgNPs have individually demonstrated potential for extending the shelf life of fruits, their combined application has not yet been systematically evaluated for dragon fruit under ambient storage conditions. In this study, CG was selected as the primary film-forming matrix because it is a polysaccharide-rich natural hydrocolloid capable of forming flexible, semipermeable coatings. Furthermore, it is abundantly available from *Opuntia* species cultivated in many arid and semi-arid regions, where large quantities of cladodes are produced annually. To complement this matrix, the epicarp extract from purple passion fruit was incorporated as a source of bioactive phytochemicals, while green-synthesized AgNPs were introduced to enhance antimicrobial functionality.

The objective of this work was to develop a composite coating based on CG, passion fruit epicarp extract (PPFEE), and AgNPs, as well as to systematically evaluate the bioactive composition, synthesis and structural characterization of nanoparticles, antioxidant and antibacterial activities, and effectiveness in extending the postharvest life of dragon fruit.

Materials and Methods

For the preparation of CG and PPFEE, fresh, intact cactus leaves (*Opuntia cochenillifera* (L.) Mill.) were harvested in Khanh Hoa Province, Vietnam, washed, and peeled to remove the outer layer. The remaining material was cut into small pieces, blended in an 819B industrial blender (Promix, China) at 20,000 rpm for 10–15 min, and sieved through a 200 mesh sieve to obtain the pure cactus gel (Shinga et al., 2025).

The purple passion fruit epicarp was dried in an oven, and ground into a fine powder. A 3 g portion of this powder was transferred into a 100 mL Erlenmeyer flask (Stellar Scientific, Baltimore, MD, USA). Extraction was performed by adding 60 mL of 70% (v/v) ethanol, followed by ultrasonication in a LBS1 ultrasonic bath (Falc Instruments, Treviglio, Italy) at 50°C for 45 min (Borah et al., 2025). The extract was then separated via vacuum filtration using a Büchner funnel equipped with a 125 mm filter paper (Sigma-Aldrich, Saint Louis MO, USA) connected to a DOA-P504-BN diaphragm vacuum pump (Gast Manufacturing, Inc., Benton Harbor, MI, USA). The resulting filtrate had a volume of approximately 20.5 mL, corresponding to a yield of 6.83 mL per gram of dried material.

Silver nanoparticles were synthesized using a plant-extract-mediated method adapted from Logeswari et al. (2015). Specifically, 150 mL of PPFEE was combined with 50 mL of 0.1 mol L^{-1} $AgNO_3$ solution in a sterile glass beaker, resulting in a final $AgNO_3$ concentration of 0.025 mol L^{-1} and a pH of approximately 6.5. The reaction mixture was subjected to ultrasonic treatment at amplitudes of 40%, 60%, and 80% using a Q500 Sonicator (Qsonica, Newtown, CT, USA) at 90°C for 1 hour to facilitate nanoparticle formation. The resulting suspension was centrifuged at 7,000 rpm for 10 min, and the precipitate was dried at 60°C to collect the solid AgNPs, henceforth denoted as AgNPs-x, where x presents the amplitude levels. The formation of AgNPs was determined using the V-730 UV-Visible spectrophotometer (JASCO, Tokyo, Japan), D8 X-ray diffractometer (Bruker, Billerica, MA, USA), and the JEM-1400 FLASH transmission electron microscopy (JEOL, Tokyo, Japan).For the determination of the antioxidant activity measured by the DPPH free radical scavenging assay, a 0.15 mMol L^{-1} DPPH solution was prepared by dissolving 0.03 g of 2,2-diphenyl-1-picrylhydrazyl (Sigma-Aldrich, Saint Louis MO, USA) in 500 mL of methanol. For the analysis, 0.1 mL of either CG, PPFEE, or AgNPs-x was mixed with 3.9 mL of the DPPH solution, vortexed, and incubated in the dark for 30 min. The absorbance was measured at 517 nm using a UV–Vis spectrophotometer (Do et al., 2014). The control consisted of 0.1 mL methanol mixed with 3.9 mL DPPH solution, and then processed in the same way. All experiments were conducted in triplicates. The inhibition of DPPH radicals percentage was calculated using the following equation:

$$\text{DPPH scavenging activity (\%)} = \frac{\text{ACT} - \text{ASP}}{\text{ACT}} \times 100$$

where ACT is the optical absorption of the control sample, and ASP is the optical absorption of the extract sample.

The antibacterial activity was assessed following the well-diffusion method of Wiegand et al. (2008) with minor modifications. Mueller-Hinton agar was prepared according to the manufacturer's instructions, sterilized in an autoclave, and then 25 mL of the agar were poured into 90 mm petri dishes to obtain a 4 mm layer. These plates were used immediately in the subsequent step. *Escherichia coli* and *Staphylococcus aureus* were chosen as representative bacterial species. A 10 µL sample of bacterial suspension ($1–2\times10^6$ CFU mL^{-1}) was evenly spread over the agar surface and air-dried for 10 min. Wells measuring 6 mm in diameter were aseptically created at 2.5–3.5 cm intervals and 2.0–2.5 cm from the plate edge. Test samples, including 100 µL of either AgNPs-x, CG, or PPFEE, along with distilled water as a negative control, were applied directly into the wells. The plates were incubated at 37±0.5°C for 24 hours, after which the inhibition zone diameters were measured in millimetres.

To prepare the 40% (v/v) CG solution, 1,200 mL of pure CG was diluted with 1,800 mL of distilled water

and stirred at 800 rpm for 30 min. Similarly, the 0.67% (v/v) PPFEE solution was prepared by adding 20 mL of PPFEE to 2,980 mL of distilled water and stirred at 800 rpm for 30 min. To prepare the coating solution designated as Mix, containing 40% CG + 0.67% PPFEE solution, 20 mL of PPFEE and 1,200 mL of CG were combined with 1,780 mL of distilled water and stirred at 800 rpm for 30 min.

To prepare the 40% CG + 0.67% PPFEE/AgNPs-40 solution (Mix-40), 100 mg of the synthesized AgNPs-40 was added to 20 mL of PPFEE to obtain the PPFEE/AgNPs-40 suspension, which was then mixed with 2,980 mL of 40% CG. Similarly, Mix-60 and Mix-80, were prepared by replacing PPFEE/AgNPs-40 suspension with PPFEE/AgNPs-60 and PPFEE/AgNPs-80, respectively. The composition of the preservation formulations is summarized in Table 1. Dragon fruits were harvested in Binh Thuan Province (10°56'N, 108°06'E), where the typical growing conditions include temperatures of 28–30°C, and relative humidity ranging from 77 to 80%. After harvesting, the fruits were immersed in the respective coating formulations for 3 min, and then taken out for air-drying. Fruits used as the control sample were washed with distilled water only. The treated fruits were individually packaged in bags and stored in cardboard boxes, with each box containing three bags. These boxes were stored under controlled conditions of 25±2°C and 60±4% relative humidity.

Quality attributes including total soluble solid (TSS) content, weight loss, and color were assessed after 5, 10, 13, 15, 17, and 19 days of storage. TSS was measured in °Brix using a PAL-BX ACID Pocket Brix-Acidity Meter (ATAGO CO., LTD, Tokyo, Japan). The weight loss rate was quantified by recording the dragon fruits weight before and after the storage period, and subsequently calculating the loss according to the following equation:

$$WLR(\%) = \left(\frac{FWBS - FWAS}{FWBS} \right) \times 100$$

where WLR is weight loss rate, FWBS is fruit weight measured in g before storage, and FWAS is fruit weight measured in g after storage.

Fruit color was measured in terms of ΔL, Δa, Δb, and ΔE values using an LS170 45/0 Colorimeter (Shenzhen Linshang Technology Co. Ltd., Guangdong, China) before storage and after 5, 10, 13, and 15 days of storage. Additionally, fruit appearance was documented using photographs taken with an iPhone 11 digital camera (Apple, Cupertino, CA, USA). All experiments were conducted using a completely randomized design with three replicates per treatment. Data processing was performed using Microsoft Excel 2016 and statistical evaluations were subjected to analysis of variance (ANOVA) followed by Tukey's post hoc test via JASP software version 0.19.1.0 (JASP Team, 2024).

Table 1. Composition of the different composite coating materials[1].

Formulation	Materials			
	CG (mL)	PPFEE (mL)	AgNPs (mg)	Water (mL)
40% CG	1,200	-	-	1,800
0.67% PPFEE	-	20	-	2,980
Mix	1,200	20	-	1,780
Mix-40	1,200	20	100	1,780
Mix-60	1,200	20	100	1,780
Mix-80	1,200	20	100	1,780

[1]CG, cactus gel; PPFEE, purple passion fruit epicarp extract; AgNPs, green-synthesized silver nanoparticles.

Results and Discussion

For the UV-Vis and XRD analysis of the biosynthesized silver nanoparticles, the PPFEE lacks a distinct surface plasmon resonance (SPR) band in the visible region, whereas all AgNPs-x samples display a new absorption feature in the ~400–550 nm range, which is diagnostic of the SPR of dispersed silver nanoparticles synthesized via plant metabolites (Figure 1 A). This spectral profile is fully consistent with recent reports on green AgNPs, where the spectrum typically reveals an SPR maximum ranging from 400 to 450 nm depending on the particle size, dielectric environment, and capping by phytochemicals (Fahim et al., 2024; Chughtai et al., 2025). Across the three synthesis conditions, the relative intensity and line shape of the SPR band differentiate the samples. The AgNPs-40 sample shows the lowest intensity, indicating a lower particle yield or wider size distribution, whereas the SPR peak of AgNPs-60 exhibits an increased intensity and a

narrower band, implying a higher concentration of well-dispersed particles with a tighter size distribution. For AgNPs-80, the spectrum exhibits a slight redshift and band broadening suggesting incipient aggregation. These mechanistic assignments match recent optical analyses of biosynthesized AgNPs (González & Noguez, 2007; Maduraimuthu et al., 2023; Mafhala et al., 2024). The presence of AgNPs in the samples was confirmed by their XRD patterns. As shown in Figure 1 B, the XRD patterns of the AgNPs-x samples showed characteristic diffraction peaks of 111, 200, 220, and 311 at 20=38.2º, 44.3º, 64.5º, and 77.6º, respectively, showing the formation of AgNPs (Vanaja & Annadurai, 2013). Moreover, the crystal sizes of AgNPs were estimated from the XRD data using the Debye-Scherrer equation. Specifically, the AgNPs-40, AgNPs-60, and AgNPs-80 displayed crystal sizes of 15.9, 16.1, and 10.3 nm respectively. An increase in ultrasonic power resulted in the overall decrease in AgNPs crystal size, which is consistent with the UV–Vis results. Furthermore, transmission electron microscopy analysis was performed to elucidate the morphology and particle size distribution of the synthesized AgNPs. Figures 1 C to 1 E reveal that all samples exhibit a uniform spherical morphology, with average particle size ranging from 40 to 50 nm. These results further confirm the correlation between ultrasonic power and particle size of AgNPs, and

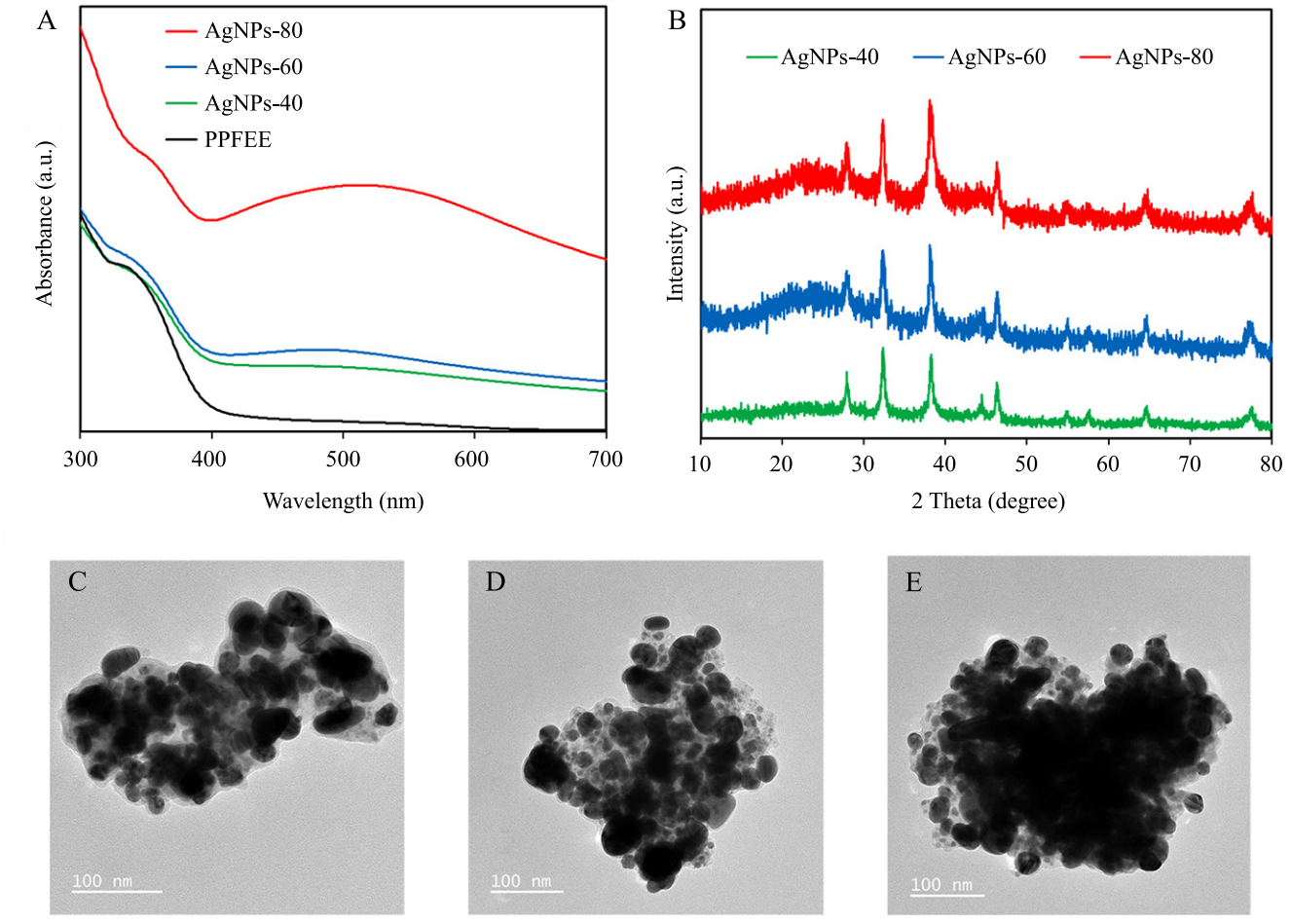

Figure 1. Characteristics of green-synthesized silver nanoparticles (AgNPs): UV-Vis spectra comparing with purple passion fruit epicarp extract (PPFEE) (A); X-ray diffraction patterns (B); transmission electron microscopy images of AgNPs-40; AgNPs-60; and AgNPs-80 (C, D, and E).

suggest that higher ultrasonic power could accelerate the reduction of Ag^+ ions to Ag^0, thereby promoting the formation of more nucleation sites and consequently a smaller particle size.

The matrix of purple passion fruit epicarp plays a decisive role in both reducing of Ag^+ and stabilizing the nascent particles. The epicarp is rich in polyphenols and anthocyanins, such as cyanidin-3-glucoside, which serve to donate electrons for Ag^+ reduction, while simultaneously capping particle surfaces via phenolic and anthocyanin functional groups. Such capping elevates colloidal stability, modulates the local refractive index around the particles, thereby fine-tuning the SPR wavelength and bandwidth observed in Figure 1. Current byproduct-focused and metabolomics studies on purple passion fruit pericarp substantiate this phytochemical profile and its impact on nanoparticles optical signatures (Weyya et al., 2024; Chen et al., 2025). For the leaves and epicarp of passion fruit, recent studies place AgNP SPR near the 420–480 nm wavelength range, with shifts and bandwidth changes linked to synthesis conditions, thereby mirroring the trend observed across the three amplitude levels (Preetha et al., 2025).

Regarding the antioxidant and antibacterial activities, all examined extracts exhibited measurable free radical scavenging activity, with statistically significant differences ($p<0.05$) among treatments (Table 2). The cactus gel alone showed a DPPH scavenging capacity of 17.23%. This value confirms that the limited phytochemical content of the cactus gel contributes to its low antioxidant performance, in agreement with previous studies on *Opuntia* spp. (Jiménez-Aguilar et al., 2015; De Wit et al., 2019). In contrast, the PPFEE showed an antioxidant activity of 41.31%. According to Ngibad et al. (2023), passion fruit peel extracts frequently showed high antioxidant potential, with DPPH inhibition ranging from 20% to over 80% depending on extraction conditions.

Moreover, the AgNPs-x samples enhanced antioxidant capacity, with DPPH scavenging activity increasing progressively from 63.79% for AgNPs-40 to 67.00% for AgNPs-60, and reaching 73.99% for AgNPs-80 (Table 2). This trend suggests that higher ultrasonic power correlates with improved radical scavenging ability, potentially due to a higher yield of Ag nanoparticles. Comparable findings have been reported for other plant systems, in which phytochemical-capped silver nanoparticles exhibited superior antioxidant activities relative to their corresponding crude extracts, due to combined effects between metallic nanoparticles and plant-derived phenolics (Kamaraj et al., 2020; Al hamza Hasoon et al., 2024). Neither the cactus gel nor the distilled water produced inhibition zones, while the purple passion fruit epicarp extract alone slightly inhibited the growth of *S. aureus* and *E. coli*. As expected, the biosynthesized AgNPs-x samples exhibited the strongest inhibitory effect against the tested bacteria. The inhibition zone diameters against *S. aureus* were 10.2, 22.4 and 28.1 mm for AgNPs-40, AgNPs-60, and AgNPs-80, respectively, whereas the values observed against *E. coli* were 7.5, 9.3, and 13.9 mm. This trend indicates that antibacterial activity arises from the silver nanoparticles formed in the epicarp matrix rather than from the individual components (Table 1). The stronger inhibition towards Gram-positive *S. aureus* and weaker towards Gram-negative *E. coli* are consistent with previous work on green-synthesized AgNPs (Arya et al., 2024; Rodrigues et al., 2024; Sati et al., 2025). Aguilar-Garay et al. (2024) reports that the thicker peptidoglycan layer and the absence of an outer lipopolysaccharide barrier in Gram-positive bacteria facilitate AgNP contact, Ag^+ ion release, and membrane disruption, whereas the outer membrane of Gram-negative bacteria partially hinders nanoparticle penetration. There were distinct differences in the TSS content among the treatments throughout the storage period (Figure 2 A). In the control sample, °Brix steadily declined until day 13, after which it showed a sharp reduction. This decline reflects the combined

Table 2. Antioxidant and antibacterial activities of cactus gel, purple passion fruit extract, and green-synthesized silver nanoparticles[1].

Samples[2]	DPPH scavenging activity (%)	Diameter (mm) of inhibition zone	
		Escherichia coli	*Staphylococcus aureus*
CG	17.23±0.54a	-	-
PPFEE	41.31±0.82b	6.5±0.2a	6.4±0.4a
AgNPs-40	63.79±0.31c	7.5±0.5b	10.2±0.7b
AgNPs-60	67.00±0.32d	9.3±0.7c	22.4±0.9c
AgNPs-80	73.99±0.24e	13.9±0.9d	28.1±1.1d

[1]Means followed by different letters, in the same columns, differ from each other by Tukey's test, at 5% probability. Values are expressed as mean±standard deviation (n = 3). [2]CG, cactus gel; PPFEE, purple passion fruit epicarp extract; AgNPs, green-synthesized silver nanoparticles.

effects of rapid respiration, sugar utilization, and tissue degradation, which are commonly observed in non-coated dragon fruit during ambient storage (Wu et al., 2023; Wang et al., 2024). Similar decreases in the soluble solids of uncoated dragon fruit at room temperature have been attributed to rapid metabolic activity, leading to sugar depletion and subsequent loss of sweetness (Chen et al., 2024). Comparable trends have also been documented in passion fruit, in which uncontrolled storage accelerates the compositional breakdown of sugars and soluble solids (Charan et al., 2017). In contrast, all fruits coated with CG, PPFEE, and Mix exhibited a slight increase in TSS values up to day 13, followed by a decline at day 15. This transient increase is likely attributable to the enzymatic hydrolysis of stored carbohydrates into simpler sugars, which is a common phenomenon during ripening (Nxumalo & Fawole, 2022). Similar mid-storage increases in TSS have been observed when edible coatings were applied to tropical fruits, such as dragon fruit coated with *Aloe vera* L. gel (Misir et al., 2014).

The impact of these coatings on weight loss was further evaluated (Figure 2 B). The control fruits exhibited the highest losses, reaching 0.32, 1.52, and 3.10% after 5, 10, and 13 days of storage, respectively, before becoming completely deteriorated by day 15. In contrast, the coated fruits showed significantly reduced weight loss. At the final assessment on day 15, the CG, PPFEE, and Mix treatments recorded weight losses of 2.63, 2.21, and 2.46%, respectively, confirming their ability to extend the marketable shelf life relative to the uncoated control. The superior performance of the coatings can be attributed to their semipermeable nature, which restricts transpiration and gas exchange, thereby slowing metabolic activity and desiccation, (Lahrich et al., 2019). This behaviour suggests that the phenolic-rich extract not only reduces oxidative stress but it can also strengthen cellular integrity and delay tissue degradation while the CG primarily functions as a structural barrier (Li et al., 2025). This result is consistent with previous reports on extract-based coatings in passion fruit (Nxumalo & Fawole, 2022).

The visual appearance inspection and colour measurements further assessed the quality of the dragon fruits during storage under different treatments (Figure 3 A and B). The untreated control fruits exhibited severe dehydration, shrivelling, and skin collapse by day 13, which aligned with the changes observed in ΔL, Δa, Δb, and ΔE colour parameters. In contrast, fruits treated with PPFEE, CG and Mix exhibited reduced wrinkling and retained a relatively smooth skin. Notably, Mix-coated fruits showed a slower increase in the colour values, suggesting that the Mix coating effectively reduced the ripening rate. Finally, the maintenance of this morphological integrity is consistent with the low cumulative weight loss recorded previously.

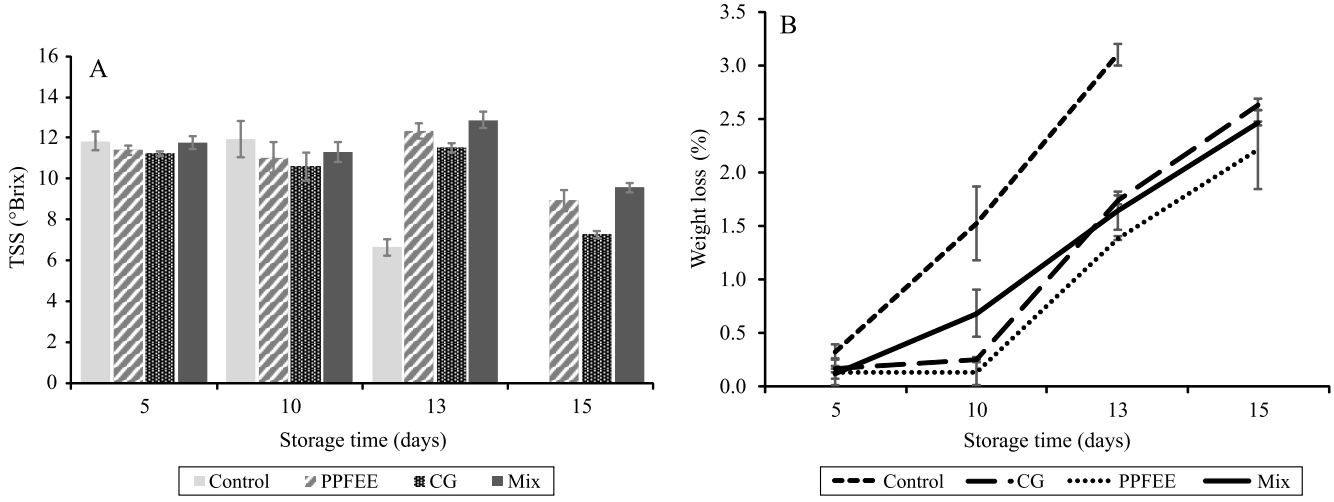

Figure 2. Total soluble solid (TSS) content (A), and weight loss (B) of dragon (*Selenicereus undatus*) fruits subjected to cactus gel (CG), purple passion fruit epicarp extract (PPFEE), mix, and control treatments during storage.

The incorporation of AgNPs into the coatings significantly influenced the physicochemical properties of dragon fruit during storage (Figure 4). The coating without AgNPs deteriorated completely by day 15, resulting in a sharp decline in TSS value (Figure 4 A). In contrast, samples coated with Mix-40 and Mix-60 maintained relatively stable TSS values up to day 15, while Mix-80 preserved TSS levels for up to 17 days. Moreover, the AgNP-incorporated treatments showed markedly reduced weight losses of 0.75, 0.64, and 0.28% for Mix-40, Mix-60, and Mix-80, respectively. At 17 and 19 storage days of storage, only the fruits treated with Mix-80 remained intact, with final weight loss values of 0.65 and 1.00%, respectively (Figure 4 B). Additionally, fruits treated with Mix-40 exhibited an acceptable visual appearance for up to 13 days, whereas those treated with Mix-80 maintained good visual quality until day 17. These results indicate that the incorporation of AgNPs into the coatings effectively slowed the ripening process, minimized dehydration, and reduced the respiration rate, thereby prolonging the shelf life of the dragon fruit (Misir et al., 2014; Gopalakrishnan et al., 2023). Gemail et al. (2023) showed that wax-AgNP coatings preserved TSS and original weight in coated fruits compared with control treatments by reducing microbial spoilage and moderating respiration. Similarly, Bizymis et al. (2023) reported that AgNP incorporation into edible films improved antimicrobial performance and altered film permeability, leading to better TSS retention in sweet cherries *Prunus avium* L.).

Furthermore, the developed coating was effective for preservation at low temperatures. Both weight loss and TSS values increased slowly after 43 days of storage at 10°C (Figure 5 A). A sharper increase was observed at day 48, when a weight loss of 1.25% and a TSS value 12.47% were recorded. In addition, the external appearance changed gradually but remained acceptable. Therefore, the results indicated that low-temperature storage at 10°C significantly reduced weight loss, maintained TSS content and visual appearance of the dragon fruit (Figure 5 B). Latif et al. (2025) observed that dragon fruit stored at 10°C exhibited stable total sugar contents during the first 7–14 days of 11.61 and 10.57°Brix for the super red, and white dragon fruit varieties, respectively, before the values declined with extended storage. This trend indicates a balance between sugar hydrolysis and respiratory catabolism. Similarly, Lata et al. (2024) reported that low-temperature storage slowed the decline in the nutritional quality of red and white dragon fruits, with TSS values of 12, and 11.5°Brix for red, and white varieties, respectively,

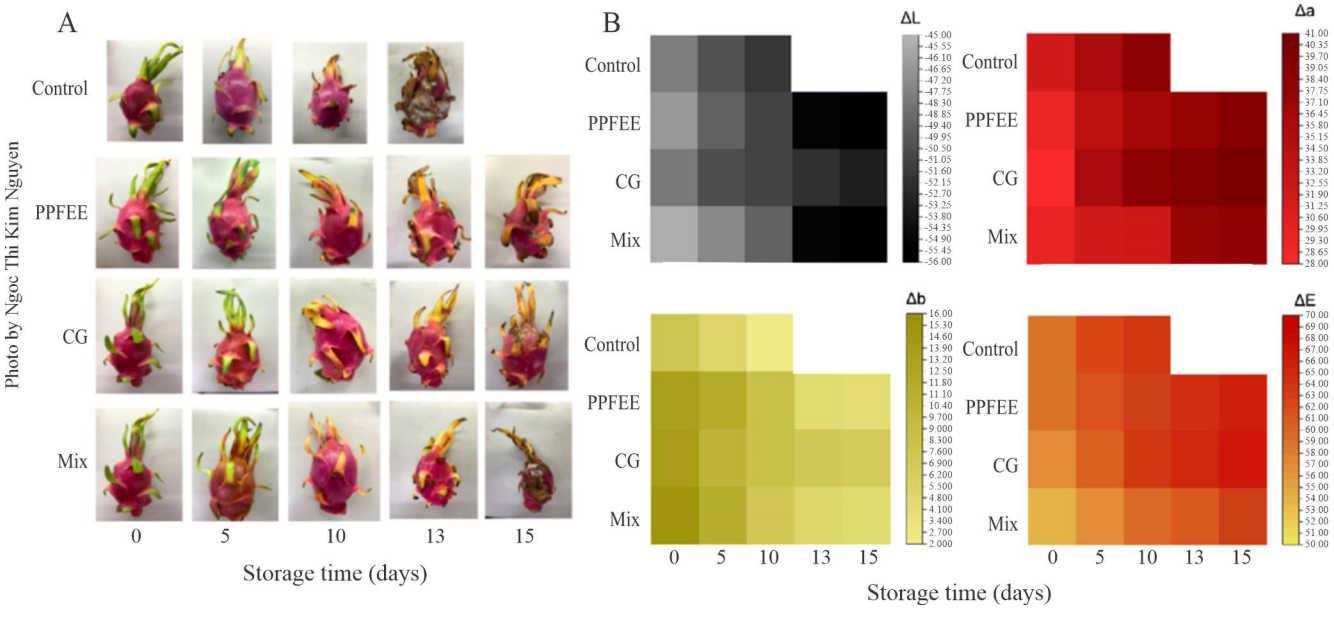

Figure 3. Visual appearance (A) and color parameters (B) of dragon (*Selenicereus undatus*) fruits subjected to cactus gel (CG), purple passion fruit epicarp extract (PPFEE), mix, and control treatments during storage.

which were maintained for a longer duration compared with those under ambient storage.

The efficacy of this coating was comparable to that reported in previous studies using chitosan, pectin, and *Aloe vera*-based coatings. However, while those conventional formulations primarily reduced water loss and delayed surface deterioration, they offered limited protection against microbial activity and oxidative degradation (Chutichudet & Chutichudet, 2011; Asniati et al., 2023; Sharvani et al., 2024; Virda et al., 2024). In contrast, the significantly enhanced shelf life of dragon fruits treated with AgNPs-

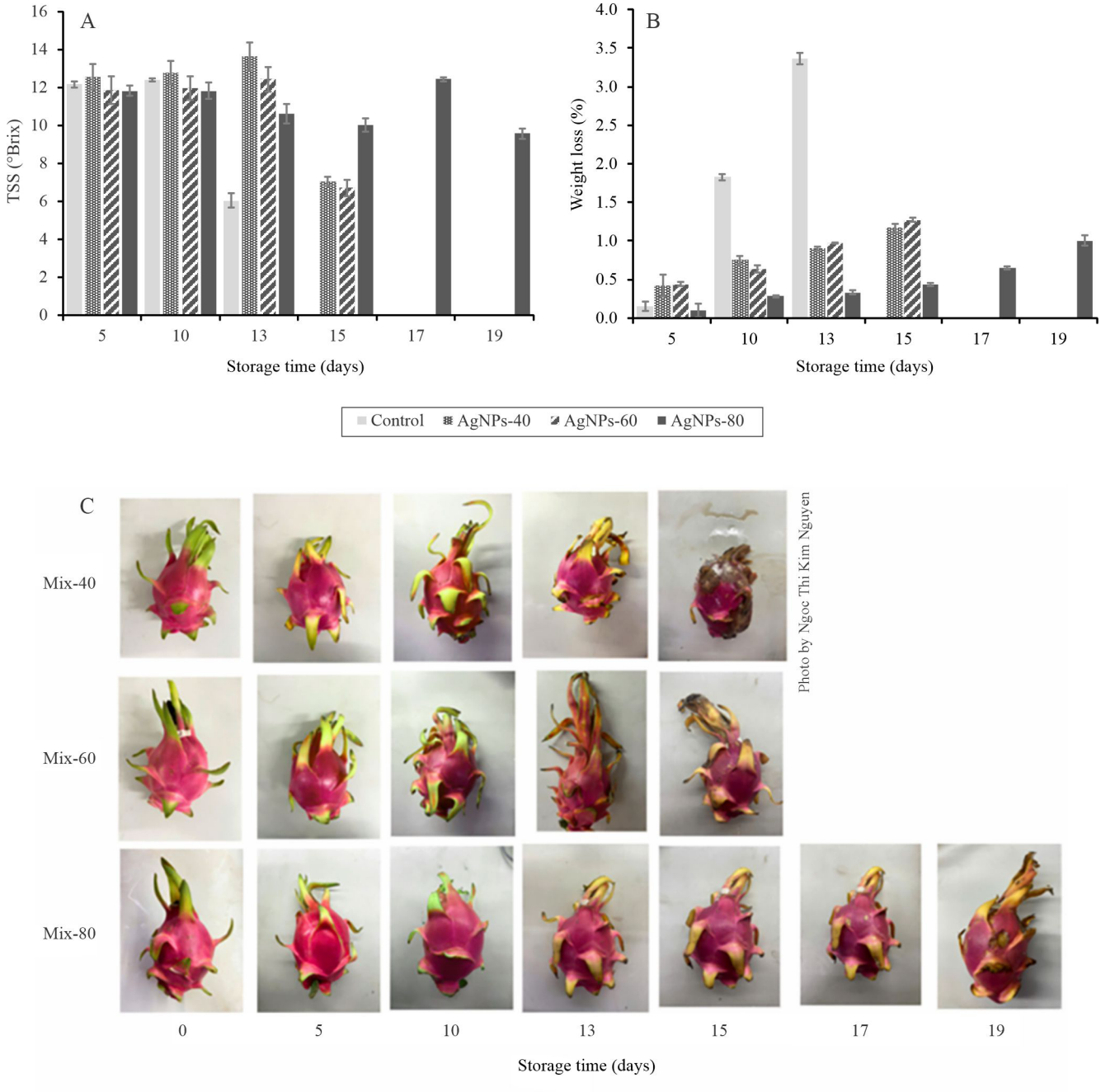

Figure 4. Effects of coating containing silver nanoparticles (AgNPs) on total soluble solid (TSS) content (A), weight loss (B), and visual appearance (C) of dragon (*Selenicereus undatus*) fruits during storage.

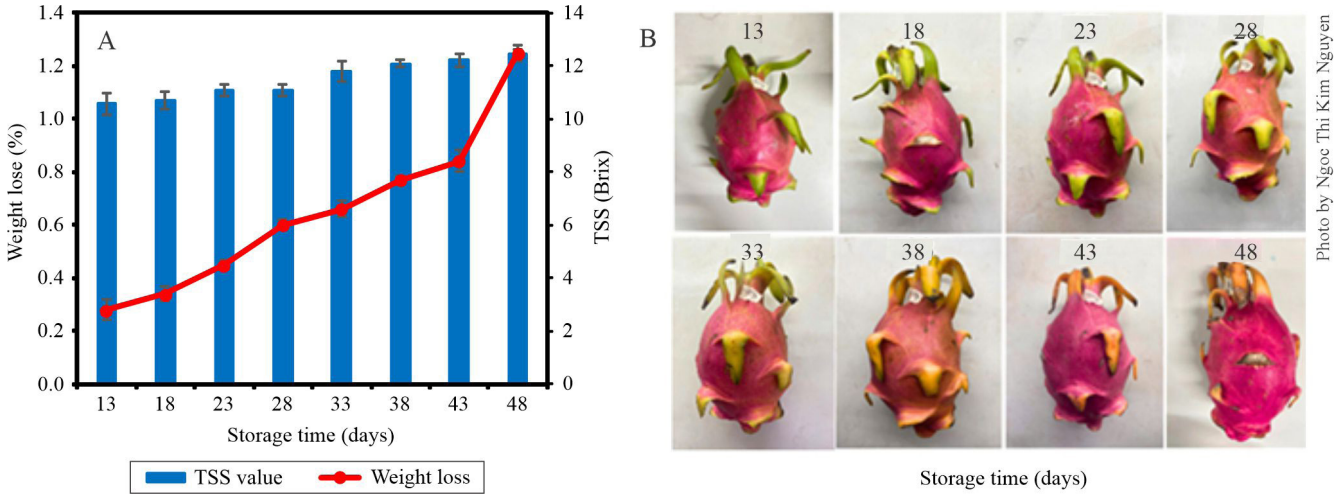

Figure 5. Total soluble solid (TSS) content, weight loss (A), and visual appearance (B) of dragon (*Selenicereus undatus*) fruit coated with Mix-80 during storage at 10°C.

incorporated treatments in this study is attributed to the combined effects of the coating components (Nxumalo & Fawole, 2022; Chen et al., 2024). Specifically, CG forms a physical barrier that limits moisture loss, while the PPFEE/AgNPs matrix operates via complementary mechanisms. It supresses microbial growth on the fruit surface, thereby reducing enzymatic degradation of sugars by spoilage organisms (Kamaraj et al., 2020), and modulates physiological processes such as respiration and ethylene production, which are closely linked to carbohydrate depletion during ripening (Mariah et al., 2022). As a result, the combination of CG, PPFEE, and green-synthesized AgNPs achieved superior performance, maintaining fruit quality for 17 days at 25°C.

Conclusions

1. Edible coatings formulated from cactus gel (CG) and purple passion fruit epicarp extract (PPFEE) incorporated with green-synthesized AgNPs effectively delay the postharvest deterioration of dragon fruit.

2. The PPFEE serves as both a phytochemical-rich bioactive component and a reducing and stabilizing agent for AgNP synthesis, while the CG functions as a semipermeable film matrix.

3. The resulting composite coating presents antioxidant and antibacterial activities, significantly reducing weight loss, slowing changes in total soluble solids, and maintaining acceptable visual quality during storage compared with uncoated fruits.

4. The combination of natural hydrocolloids with fruit-processing byproducts and green nanotechnology represents a promising strategy for extending the storage life of dragon fruit.

5. Since AgNPs are incorporated into a food-contact coating, further studies are required to evaluate nanoparticle migration, long-term safety, and regulatory compliance before large-scale commercial application.

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The authors declare no conflicts of interest.

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