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MORALITY BEFORE KNOWLEDGE

Valorization of Cascara coffee waste as antimicrobial edible coating for enhancing the snake fruit quality

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ABSTRACT

Background: This study explores a strategy to decrease significant post-harvest losses due to spoilage. Edible coating on fruit can help maintain its quality and extend shelf life by slowing physiological processes such as respiration and transpiration. **Method:** The coating was formulated divided into two formulas, one is fresh Cascara coating while other is dried Cascara coating that was obtained by drying at 60 °C for 4 hours. Both 300 grams of Cascara were extracted by maceration with 96% ethanol (ratio 1:2) for 24 hours. Extracts were mixed with 2.5% (w/v) chitosan solution, 4 g glycerol, and 0.1% Tween 80, then homogenized using a magnetic stirrer. Washed and air-dried snake fruit fruits were dipped in the coating solution, dried at 50 °C for 30 minutes. The coating formulation included food grade glycerol as a plasticizer and was applied using a dipping method. Snake fruit that has been coated with the solution stored at room temperature and evaluated for its shelf life and antimicrobial activity. **Finding:** This research utilized Cascara extract as the main ingredient of an edible coating applied to snake fruit. As a result, Cascara can be used into functional materials since it has been investigated as a natural source of bioactive compounds, particularly phenolics, with notable antimicrobial potential and bioactive content of polyphenols. When applied as a snake fruit coating, Cascara-based edible coating can inhibit microbial growth and extend shelf life while maintaining fruit quality. **Conclusion:** This approach can be applied to underutilized by-products from coffee beans, reducing dependency on synthetic preservatives and plastics while also offering a promising alternative for antimicrobial edible coating to promote valorization, circular economy practices, and innovation in food packaging. **Novelty/Originality of this article:** This research introduces a novel application of coffee cherry by-products (Cascara) specifically formulated for snake fruit (*Salacca zalacca*), a tropical commodity with unique preservation challenges.

KEYWORDS: Cascara arabica; coffee Cascara; edible coating; snake fruit; valorization.

1. Introduction

Food loss and waste have become major global concerns, not only due to their economic impact but also because of their environmental consequences. According to the Food and Agriculture Organization (FAO), estimated at about 1.3 billion tons annually, contributes significantly to inefficient resource use and is responsible for approximately 8% of global greenhouse gas emissions. This large amount is significantly driven by fruit and vegetables, which account for 66% of the total food losses by weight globally along the supply chain (Porat et al., 2018). These total fresh fruit losses occur across harvesting, handling, storage, processing, packaging, transportation, retail, and consumer stages. Post-harvest losses throughout the supply chain can reach 25–50% (Bancal & Ray, 2024). In

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medium-to-high-income countries, food waste is primarily related to consumer behavior and stringent policies and quality standard requirements. For instance, in North America, Australia, and New Zealand, fruit and vegetable losses totaled 3% during postharvest handling and storage, 12% during distribution and retail marketing, and 28% at the consumer stage.

The main cause of post-harvest loss in fruits is their high perishability, especially when fresh. As living organisms, fresh fruits continue to metabolize and consume nutrients for survival throughout their shelf life after harvest. These metabolic processes, along with respiration, enzymatic breakdown, and microbial activity contribute to the degradation of nutrients, ultimately causing a reduction in the fruit's quality and quantity (Bancal & Ray, 2024). The presence of sugar/starch as a carbon source, protein as a nitrogen source, nutrients, and moisture creates an ideal environment for microbial growth, leading to contamination and subsequent damage. Furthermore, fresh fruit sold unpackaged or tied in bundles in markets can shorten its shelf life if not sold quickly (Elik et al., 2019). Therefore, packaging plays an important role in preserving the fruit's shelf life.

Among such fruits, snake fruit (*Salacca zalacca*) is one that is highly perishable and experiences quality deterioration after harvest, which is influenced by temperature, storage method, and microorganism activity. Its shelf life at room temperature is typically only 5–6 days (Djaafar et al., 2022). Research by Djaafar et al. (2022) found that individual packaging of snake fruit using Low Density Polyethylene (LDPE) plastic bags, when stored at a cooler temperature of 19−20.1°C, can maintain the freshness, texture, and color of the fruit flesh during storage more effectively than waxing the snake fruit with 5% galangal extract and secondary packaging, or using only secondary packaging (such as plastic baskets with oil coating or perforated cardboard boxes). However, the use of this plastic packaging for each snake fruit will increase the amount of plastic waste, which is difficult to decompose in nature and poses a serious threat to the environment.

Edible coatings are thin layers made from consumable materials that are applied directly to the surface of food products and function as barriers against mass transfer, such as water vapor, O_2, and CO_2. It is commonly used as a primary wrapper made from biological materials such as carbohydrate-based polysaccharides, proteins, and lipids that are selective on permeable membranes, making it possible to extend the shelf life of products (Kirana, 2017). Starch-based food coatings, such as those derived from cassava peel waste, are commonly used for their ability to prevent dehydration, fat oxidation, browning, and reduce respiration rates by forming a membrane that is selectively permeable to CO_2 and O_2 gas exchange (Sembara et al., 2021). However, starch matrices are hydrophilic, which can increase water vapor permeability and promote moisture retention within the protective layer. The higher the starch content, the greater the potential for water vapor to be trapped or bound within it. This has the potential to create conditions that allow microbial growth. In addition, palm stearin oil has been used as a raw material for edible coatings to improve water vapor permeability and flexibility and to give the surface a glossy effect. However, research conducted by Widyasaputra et al. (2024) on snake fruit shows that adding stearin concentrations of up to 0.6% is not enough to maintain the quality of snake fruit, and snake fruit coated with stearin does not have significantly different quality compared to uncoated snake fruit at a level of 5%. This indicates that passive moisture barriers alone may not be sufficient to maintain the quality of snake fruit. Handayani et al. (2018) in their research found that the addition of bioactive compounds such as bay leaf extract to starch-based edible coatings can increase functional value due to the antimicrobial effects of tannins, flavonoids, and essential oils contained therein. However, the system will depend on the hydrophilic starch matrix, and its performance may vary depending on the concentration and extract-matrix interaction. Considering these limitations, attention is increasingly focused on alternative bioactive sources derived from agro-industrial waste, which can provide active functions while supporting sustainable food preservation strategies.

Indonesia is one of the largest coffee-producing and exporting countries in the world consisting of two types of coffee, namely Arabica coffee and robusta coffee, leading to the high consumption of this product. However, this high demand for coffee beverages generates substantial by-product waste such as coffee cherry skin and pulp, termed Cascara (Liang et al., 2025). Cascara, or often known as coffee husk is a solid residue from coffee processing. It is rich in polysaccharides and active molecules, often used to enhance polymer matrices for packaging (Turan et al., 2024 ; Oliveira et al., 2021). Coffee Cascara contains macronutrients such as carbohydrates, soluble fibers, minerals and proteins (Liang et al., 2025). Moreover, coffee skin by-products also show other potential bioactive polyphenol compounds such as chlorogenic acid, caffeic acid, gallic acid, rutin, and other phenolics, which contribute substantially to its antioxidant and antimicrobial potential (Lestari et al., 2022), indicating the potential of Cascara as a natural preservative agent.

However, the use of Cascara as an edible coating for fresh fruit remains limited. Most existing research focuses on Cascara for functional beverages, while its direct application in extending the shelf life of fruit remains underexplored. Therefore, this study explores the use of coffee Cascara waste as an edible coating with antimicrobial properties and the ability to extend the relatively short shelf life of snake fruit (*Salacca zalacca*). This paper addresses how to maintain snake fruit quality and prolong shelf life in a safe, sustainable way by utilizing coffee waste. Then, this research utilized Cascara extract to valorize coffee Cascara waste by extracting its bioactive compounds for antimicrobial application as the main ingredient of an edible coating applied to snake fruit. This approach aims to reduce post-harvest losses through the application of bioactive coatings while promoting sustainable waste management in the coffee industry and to assess the feasibility of coffee Cascara extract as a bioactive edible coating by observing its effect on visual deterioration and storage stability of snake fruit.

2. Methods

2.1 Research design and treatment variables

This study employed an observational approach, focusing on the visual assessment of physical changes in snake fruit (*Salacca zalacca*) coated with a Cascara-based edible coating. The research aimed to evaluate the effectiveness of Cascara extracts derived from coffee by-products in maintaining visual quality and delaying spoilage of snake fruit during storage at room temperature. Visual quality is a critical determinant of consumer acceptance for fresh fruits, particularly for snake fruit, which is highly susceptible to surface discoloration, moisture loss, and fungal contamination during postharvest storage.

Three experimental treatments were applied: uncoated snake fruit as the control, snake fruit coated with fresh Cascara extract, and snake fruit coated with dried Cascara extract. These treatments were designed to compare the functional performance of Cascara extracts subjected to different processing conditions, as drying is known to influence the stability and concentration of bioactive compounds. Observations were conducted on days 0, 3, 5, and 9 of storage at room temperature to monitor progressive changes and evaluate the coating's ability to preserve fruit quality over time. These observation intervals were selected to represent early, mid, and late storage periods, allowing clear identification of deterioration patterns, coating performance dynamics, and the onset of visible spoilage symptoms under ambient storage conditions during storage periods.

The materials used in this study included snake fruits of the pondoh variety, which is commonly found in traditional markets. Fruit should be free from visible defects, mechanical damage, and microbial contamination to ensure uniform initial quality. Additional materials consisted of sterile distilled water, 96% ethanol as the extraction solvent, Arabica coffee Cascara obtained from Tani Hutan Cibulao Hijau group, chitosan powder, glycerol, and Tween 80. The utilization of Cascara aligns with sustainable food processing principles by valorizing coffee-processing by-products with high functional potential. The equipment used included a food dehydrator (Getra) for Cascara drying, a magnetic stirrer (RIO) for homogenizing coating solutions, an analytical balance (Ohaus) for accurate weighing, a grinder, and standard laboratory glassware such as Erlenmeyer flasks and funnels (Pyrex). Supporting tools included stainless steel bowls, filter paper, filter cloths, measuring cups, trays, stirring rods, spoons, and food tongs to facilitate extraction and coating application.

2.2 Preparation and application of the edible coating

Cascara was selected as the primary bioactive ingredient due to its high content of phenolic compounds with antimicrobial and antioxidant activity. These bioactive compounds are expected to inhibit spoilage microorganisms and reduce oxidative degradation, thereby extending fruit shelf life. Cascara contains a complex matrix of phytochemicals, including chlorogenic acid, flavonoids, and other secondary metabolites, each with distinct polarity, molecular weight, and solubility characteristics. As a result, an extraction solvent with multifunctional properties is required. Ethanol extraction of Arabica coffee Cascara pulp has been widely reported for phytometabolite profiling and biological activity assessment (Silva, 2021; Lestari et al., 2023). In this study, 96% ethanol was selected due to its semi-polar nature, which enables efficient extraction of both polar and non-polar compounds. This selection follows the "like dissolves like" principle, whereby solvent polarity must correspond to that of the target solutes to maximize extraction efficiency (Solikhah & Solikhah, 2024). Ethanol (C_2H_5OH) possesses a hydroxyl group that confers hydrophilic properties and hydrogen-bonding capacity, as well as a two-carbon ethyl group that contributes hydrophobic characteristics. This dual functionality allows ethanol to solubilize a broad range of bioactive compounds, making it particularly suitable for extracting Cascara phytochemicals.

The extraction process was conducted using maceration, a cold extraction technique performed at room temperature (approximately 15–20°C). Maceration is advantageous for Cascara extraction because many of its key antioxidant compounds, such as chlorogenic acid and volatile furan derivatives, are thermolabile and susceptible to degradation or polymerization when exposed to elevated temperatures. Conventional hot extraction methods, including decoction and aqueous infusion, often require temperatures above 90°C, which may compromise the integrity of these compounds. The use of 96% ethanol enables effective extraction without heat application, thereby preserving bioactive compound stability and functionality (Jiamjariyatam et al., 2023).

Chitosan powder was incorporated into the coating formulation to enhance fruit preservation through multiple mechanisms. Chitosan functions as a physical barrier against mass transfer, an antimicrobial agent, and a modulator of fruit physiological metabolism (Dai et al., 2025). When applied to fruit surfaces, chitosan forms a semi-permeable film that is solid, elastic, and transparent. This film acts as a selective barrier to oxygen (O_2) and carbon dioxide (CO_2), reducing the respiration rate of the fruit. By limiting oxygen diffusion into the tissue and restricting carbon dioxide efflux, chitosan coatings create a modified atmosphere condition that slows metabolic processes associated with ripening and senescence. In addition to gas regulation, chitosan films also reduce water vapor loss, thereby minimizing dehydration and maintaining fruit firmness during storage (Ulya et al., 2025).

Beyond its physical properties, chitosan exhibits intrinsic antimicrobial activity due to its polycationic structure, which enables electrostatic interactions with negatively charged microbial cell membranes. This interaction disrupts membrane integrity, leading to leakage of intracellular components and inhibition of microbial growth. Chitosan has been shown to suppress respiration rates, reduce weight loss, and inhibit postharvest pathogens such as Botrytis cinerea and Penicillium spp. (Muñoz-Tébar et al., 2023). Its effectiveness has been consistently demonstrated across various horticultural commodities (Wang et al., 2024).

Glycerol was added as a plasticizer to improve the mechanical properties of the chitosan-based coating. Glycerol reduces intermolecular forces between polymer chains, resulting in increased flexibility and elasticity. In the absence of glycerol, coatings tend to become rigid and susceptible to cracking during drying, which may compromise their barrier function (Sanchez-Tamayo et al., 2024). Whereas Tween 80 (polysorbate 80) was included as a non-ionic surfactant to enhance the homogeneity of the coating solution and improve its adhesion to the fruit surface. Coating formulations containing both hydrophilic and hydrophobic components are prone to phase separation; therefore, Tween 80 functions as an emulsifier that stabilizes the mixture. This results in a more uniform, transparent, and glossy coating layer, which enhances both functional performance and visual appeal (Parreidt et al., 2018). Both glycerol and polysorbate 80 used in this study are compliant with the Codex General Standard for Food Additives (GSFA) (Codex Alimentarius Commission, 1995) and recognized by BPOM (BPOM, 2019). While glycerol is listed with GMP status, polysorbate 80 is subject to specific maximum level restrictions depending on the food category.

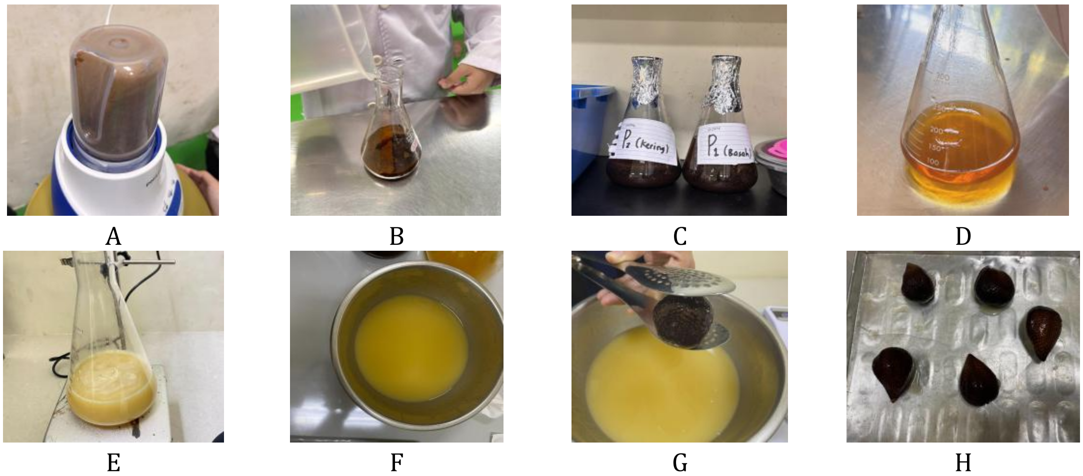

Fig. 1. The process of formulating Cascara-coffee edible coating: A) Pulverization of Cascara into powder; B) Addition of 96% ethanol; C) Maceration; D) Maceration result after 2 hours; E) Homogenization process; F) Edible coating solution; G) Coating process; H) Coating result

Edible coatings were prepared using fresh and dried Cascara. Fresh Cascara was processed immediately, while dried Cascara was obtained by drying at 60°C for 4 hours. For each treatment, 300 g of Cascara were extracted by maceration with 96% ethanol at a ratio of 1:2 (w/v) for 24 hours. The extracts were combined with a 2.5% (w/v) chitosan solution, 4 g glycerol, and 0.1% Tween 80, then homogenized using a magnetic stirrer. Snake fruits were washed and air-dried prior to coating. The fruits were immersed in the coating solution, drained, and dried at 50°C for 30 minutes before storage at room temperature. Visual changes were evaluated based on skin and flesh characteristics, including color alteration and mold growth. Observations were recorded descriptively and quantified using a 1–5 scoring scale to represent the degree of physical deterioration during storage. Antimicrobial activity was further assessed through a literature-based evaluation of Cascara bioactive compounds and their documented inhibitory effects on spoilage microorganisms.

3. Results and Discussion

This research began with a preparatory stage, which involved discussion with the supervising lecturer to refine the research objectives, experimental design, and work schedule. During this stage, an extensive literature review was conducted to obtain information regarding the antimicrobial properties of Cascara, principles of edible coating formulations, and the postharvest characteristic of snake fruit. Following the planning phase, the quantities of materials and equipment required for the experimental work were determined based on the established research design. Fresh snake fruits were purchased from a local fruit store in Bogor. The fruits were then sorted manually to minimize variability among samples. The primary material, Cascara, was sourced from a coffee plantation in Cisarua, Bogor, while other chemical components were procured from a laboratory chemical supplier. The experimental phase involved the preparation and application of Cascara-based edible coatings. Two types of Cascara extracts, fresh and dried, were prepared to evaluate the effect of processing conditions on coating effectiveness.

Table 1. Monitoring the condition of post-coating snake fruit skin

	Control	Dried Cascara	Fresh Cascara
Day 0			
Day 1			
Day 2			
Day 3			

The use of both forms was intended to compare the retention of bioactive compounds, as fresh Cascara is expected to preserve more heat-sensitive constituents, while dried Cascara offers better stability and handling properties. The coating process was conducted by dipping each fruit into the respective solution, followed by drying at 50°C for 30 minutes. All samples were subsequently stored at room temperature for observation on a divided tray. The final stage of research involved visual observation and data collection to assess the physical changes in fruit appearance and effectiveness of the edible coating in preserving the quality of snake fruit.

3.1 Visual quality score of snake fruit skin

The visual observation of snake fruit coated with coffee Cascara-based edible coating was carried out on day 0, 3, 5, and 9 of storage. The parameters in Figure 2 are the skin of the snake fruit. The overall looks of the control treatment do indicate the presence of significant changes, where the colors degrade even after 3 days of storage. The color looks like a medium brown and a hint of dullness was spotted during the observation. Snake fruit with dried Cascara treatment shows no dullness until the degradation on day 5 and starts to decrease on day 9.

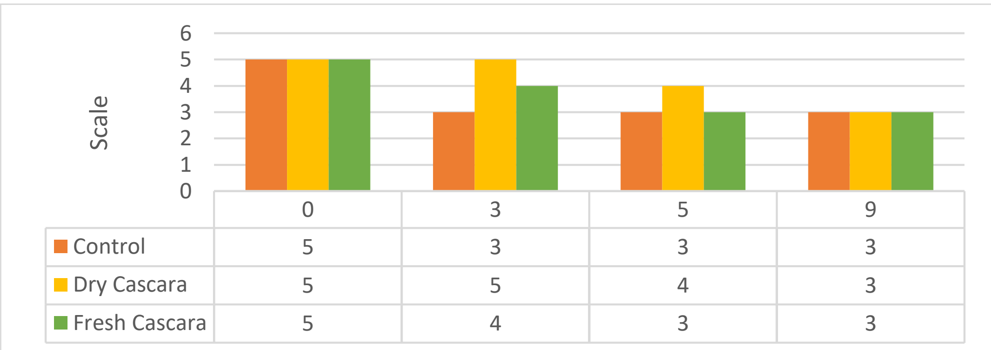

Fig. 2. Average progression of visual quality score of snake fruit skin

This indicates that the coating helps the snake fruit to keep its fresh brown appearance. Meanwhile, the fresh Cascara treatment indicates no significant changes with the control and only can keep the fresh brown color until day 3. The application of Cascara based edible coatings should be reliable to keep snake fruit in good form when it is distributed. However, based on this research, there's lackness of coating to keep the snake fruit's appearance from decreasing. The dried Cascara shows a better result from keeping the brown colour of the snake fruit. The drying process using a food dehydrator can concentrate the active compounds, although some are lost due to heat (Bresciani et al., 2014). On the other hand, fresh Cascara contains more water, resulting in a thinner, more rapid-deterioration layer.

Table 2. Monitoring the condition of post-coating snake fruit flesh

	Samples
Day 3	
Day 5	
Day 9	

*Notes: the sequence of snake fruit treatments in the picture above are fresh Cascara edible coating, dried Cascara edible coating, and control

Based on Figure 3, the initial color of the snake fruit flesh in all treatments showed a score of 5, indicating a fresh yellow appearance. As the storage period progressed, the color gradually decreased in intensity. In contrast, the samples coated with dried Cascara extracts maintained their yellowish tone slightly better throughout storage, although a decrease in brightness was still observed. The application of dried Cascara edible coating helps the snake fruit from the mold as it is spotted in the fruit on day 9. This indicated that the coating helped the fruit from the mold grow in the snake fruit flesh. While the fresh Cascara is found to fasten the decay of the fruit snake that can be caused by several factors, such as the tip of the fruit. We found that the snake fruit that is safer and more flexible to use is the snake fruit with a round tip that can prevent edible coating from getting inside.

Same as previous discussion from Table 1, dried Cascara edible coating shows more reliable results to be applied for managing the snake fruit quality. This indicates that even with the same formulation, Cascara treatment shows a significant difference. Accelerated shelf-life testing of coating snake fruit revealed promising results, indicating the potential from the growth of mold and to keep either the skin or flesh quality as the same as its harvested. The better performance of dried Cascara coatings is likely associated with better film formation and more uniform surface coverage, which can reduce oxygen permeability and moisture loss with lower water activity. In addition, the concentration of phenolic compounds in dried Cascara may enhance its antimicrobial and antioxidant activity, thereby slowing down microbial proliferation and oxidative deterioration during storage. These combined effects contribute to delayed quality degradation and suggest that dried Cascara-based coatings have strong potential as an effective postharvest treatment for snake fruit compared to fresh Cascara-based edible coatings.

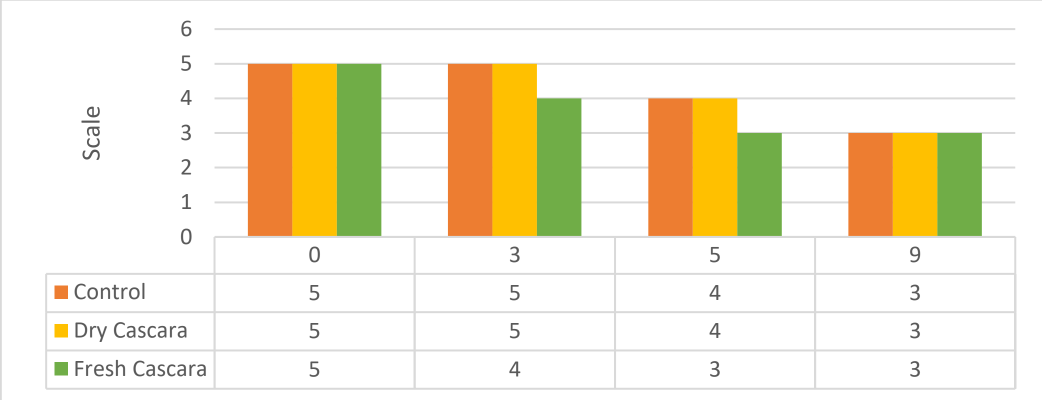

Fig 3. Average progression of visual quality score of snake fruit flesh

During postharvest storage, physical changes in fruit such as weight loss, texture softening, shrinkage, and wilting occur mainly due to ongoing physiological processes like respiration and transpiration. The significant changes in samples may be due to the semi-permeable barrier formed by the edible coating that restricts the movement of O_2, CO_2, water, and solutes between the coated fruit and its surrounding environment (Saleem et al., 2022). Our research indicates if the coating layer is too thick or improperly formulated, it can also alter gas permeability excessively, potentially leading to anaerobic conditions that may affect texture negatively, showing how formulation characteristics influence physical outcomes. Together, these mechanisms explain why uncoated fruits experience faster physical deterioration while snake fruit with dried Cascara edible coating retain quality longer due to lower respiration, reduced water loss, and limited oxidative damage.

3.2 Antimicrobial properties

Based on antimicrobial properties, Cascara, the dried outer peel or husk of the coffee cherry, is recognized as a rich source of phenolic and flavonoid compounds that exhibit strong antioxidant and antimicrobial properties under laboratory conditions (*in vitro*) (Sales et al., 2023). These bioactive compounds such as chlorogenic acid, catechins, tannins, and anthocyanins are known to disrupt microbial cell membranes, interfere with lipid metabolism, and bind essential enzymatic proteins, thereby inhibiting microbial growth and functioning as natural fungicides against yeasts and molds. In particular, Sholichah et al. (2018) demonstrated that Cascara extract could reduce *E. coli* populations by over 90% at a 5% concentration, confirming its significant antibacterial potential. Similarly, strong antifungal activity of Cascara extract against *Candida albicans*, *Aspergillus niger*, and *Penicillium* species which are fungi commonly associated with fruit decay such as snake fruit (*Salacca zalacca*), with inhibition zones reaching up to 17 mm. This fungicidal activity has been attributed mainly to chlorogenic acid and tannins, which can compromise fungal cell wall biosynthesis and structural integrity.

Despite this promising evidence, the antimicrobial efficacy observed in *in vitro* studies has not been fully replicated *in vivo* during the storage of coated fruits. Based on literature and visual observations, this discrepancy can be attributed to several interconnected factors, including the degradation of bioactive compounds, limited release of active substances from the coating matrix, insufficient physical barrier performance, and complex microbial-microenvironment interactions on the fruit surface. One of the primary challenges is the instability of phenolic compounds such as chlorogenic acid, which are highly susceptible to oxidation induced by light, oxygen exposure, and ambient temperature. Without adequate protection, the concentration of active agents in the coating layer declines significantly within a few days of storage at room temperature due to oxidative reactions, explaining why Cascara-coated snake fruits may still exhibit decay despite containing antimicrobial compounds.

Additionally, the physical properties of the coating matrix play a critical role in determining effectiveness. Hydrocolloid-based coatings commonly made from alginate, Arabic gum, or carboxymethylcellulose tend to have high water vapor permeability, limiting their ability to retain fruit moisture. As a result, the fruit softens more rapidly, and cracks may form as the fruit surface shrinks, allowing oxygen and microbes to penetrate. Conversely, an excessively thick layer can overly restrict gas exchange, leading to anaerobic respiration, browning, and moisture accumulation beneath the coating, conditions that promote fungal growth (Singh et al., 2022). Moreover, microbial-environmental interactions on the fruit surface further complicate coating performance. The nutrient-rich and moist surface of snake fruit serves as an ideal substrate for microbial colonization. These microorganisms can secrete oxidative and lipolytic enzymes that accelerate polyphenol degradation, thereby reducing the functional activity of Cascara extracts (Tilley et al., 2023).

Given these challenges, the Cascara postharvest process must be carefully designed to preserve the integrity of its bioactive compounds and maintain their antimicrobial and antifungal activities throughout application. Fresh Cascara should be processed within 24 hours after pulping to avoid fermentation, which can reduce phenolic content and encourage microbial contamination. If immediate processing is not possible, the material should be refrigerated at 4-10°C in sealed containers to suppress enzymatic degradation and oxidative activity. Before drying, the Cascara should be briefly rinsed to remove impurities without prolonged soaking, as this may leach water-soluble phenolics. Drying should proceed gradually, first under shade, then in a hot-air oven at 40-50°C until moisture reaches approximately 8-10%. Higher temperatures (>60°C) accelerate polyphenol degradation and loss of antioxidant activity. Dried Cascara should then be stored in airtight or vacuum-sealed dark containers at low temperatures to minimize oxygen and light exposure. To enhance oxidative stability and achieve a more controlled release of active compounds, Cascara extract can be converted into microencapsulated or nano emulsified forms. Spray-drying with maltodextrin has been shown to effectively protect polyphenols from oxygen and heat (Pateiro et al., 2021; López-Polo et al., 2021). On a laboratory scale, nano emulsions can be prepared using lecithin as a natural surfactant and high-speed homogenization to create micro–nano dispersions that improve stability and bioavailability. These encapsulation methods not only enhance the chemical stability of phenolics but also extend their antimicrobial activity over time.

Chitosan as a film-forming agent can be blended with plasticizers such as glycerol (0.5-1.5%) to maintain flexibility in its formulation. Because such films are inherently hydrophilic, incorporating hydrophobic additives such as beeswax, stearin, or hydrogenated vegetable oils (0.5-2%) is recommended to reduce water vapor permeability (WVP) and improve moisture resistance. Singh et al. (2022) reported that the addition of hydrophobic components and cross-linking agents such as calcium chloride ($CaCl_2$, 1-2%) significantly improved the mechanical strength and water retention of edible coatings. A bilayer system, with an inner bioactive layer containing Cascara extract and an outer hydrophobic layer for physical protection, is further suggested to balance both biological and physical protective functions (López-Polo et al., 2021). During coating application, the fruit should be dried in a shaded, well-ventilated area to prevent light-induced oxidation, and subsequently stored below 15°C to minimize respiration and degradation rates (Luo et al., 2022). Cold storage also suppresses microbial growth, allowing the Cascara-based coating to display its antimicrobial and anti-fungal potential more effectively.

While Cascara has demonstrated strong antimicrobial and antifungal activity in vitro, translating this potential into in vivo applications requires careful attention to postharvest handling, extraction, stabilization, and formulation processes. Furthermore, the tools and containers used in this process, especially for edible coating production, must be sterile to avoid bacterial contamination. Implementing these strategies can preserve Cascara's bioactive integrity, optimize coating performance, and ultimately support its development as a sustainable natural preservative for perishable fruits such as snake fruit. Optimizing processing parameters and application techniques is essential to ensure consistent performance under real storage conditions and to maximize the protective function of Cascara-based edible coatings throughout the postharvest period.

Formulation and optimization at each stage significantly influence the performance of edible coating applications. In addition to formulation issues, the natural morphology (shape) of the snake fruit is considered a key factor limiting coating effectiveness. In the case of snake fruit, the shape of the fruit tip affects how well the coating adheres and dries. Samples with tapered tips tend to form deeper gaps and creases between the scales, which can trap the wet coating solution and create microenvironments that favor microbial growth if drying is not rapid. Conversely, snake fruits with rounder and tightly packed tips provide a smoother surface, allowing for more uniform coating distribution and faster drying, thereby reducing contamination risks. Therefore, the selection of fruit morphology should be considered an important practical parameter in edible coating applications for snake fruit.

Although Cascara is known to contain bioactive compounds with antimicrobial potential, the effectiveness observed during snake fruit storage is strongly influenced by how these compounds interact with the coating matrix and the fruit surface under real storage conditions. In this study, antimicrobial performance was inferred from visual quality preservation rather than direct microbiological measurements, reflecting a practical, in vivo postharvest scenario. These findings support the feasibility of Cascara-based edible coatings as a proof-of-concept approach for postharvest quality management.

3.3 Potential application of Cascara edible coating

Nowadays, edible coatings are widely studied for use in perishable foods such as beverages, flesh, poultry, and fresh fish. The high-water content of these products makes them vulnerable to microbial growth. Consequently, food packaging is an important strategy to reduce food waste during distribution and consumer storage (Perez-Vazquez et al., 2023). Edible coatings have been widely studied as an eco-friendly postharvest strategy to maintain quality and extend the shelf life of perishable horticultural products. The ideas are to be alternative to traditional plastic food packaging since they can enhance the shelf life of F&Vs by reducing their respiration rate and loss of water and protecting them from physical damage and microbial spoilage, preventing postharvest loss (Perez-Vazquez et al., 2023).

Cascara is rich in polysaccharides and active molecules, often used to enhance polymer matrices for packaging, making it suitable to be the base for edible coating solution. Based on research by Turan et al. (2024), Cascara films demonstrated good water vapor and oxygen barrier properties, vital for food preservation by testing on hazelnuts, revealed promising results, indicating the coating's efficacy in inhibiting secondary oxidation and potentially increasing the shelf life two-fold compared to uncoated nuts. Such findings provide relevant evidence that Cascara can suggest feasibility in edible coating systems for fruits beyond model applications.

Climacteric fruits such as mango, banana, and papaya undergo rapid ripening due to ethylene production, leading to accelerated textural softening and quality loss under ambient conditions. Edible coatings have emerged as new technology for safe maintenance and the improvement of quality of fresh fruits by their application immediately after harvest to reduce water loss and mechanical and microbial damage, prevent favorable volatiles losses, and delay senescence (Ncama et al., 2018). The combination of functional biopolymers with natural antioxidants and antimicrobials with polysaccharides such as chitosan, starch, and dextrin etc and other components may be added to extend their application (Escamilla-García et al., 2018).

Non-climacteric fruits such as snake fruit, grapes, strawberries, and citrus also benefit from edible coatings, particularly in reducing weight loss and microbial spoilage. Maintaining moisture and microbial control is critical for these fruits because surface dehydration and fungal contamination are among the primary causes of deterioration. The coffee husk pectin-based coatings on grapes effectively inhibited the growth of *S. aureus* with a significant inhibition zone increase while also demonstrating weight loss, pH, total soluble solids (TSS), and titratable acidity (TA) were better maintained in coated grapes compared to the control (Divyashri et al., 2024). This research shows although direct evidence of antimicrobial activity from Cascara coatings on fruits is still emerging, analogous studies using Cascara or coffee husk pectin composites as the solutions base have shown significant inhibition zones against common microorganisms, indicating potential for Cascara to be applied on wide range of postharvest products.

The valorization of Cascara into edible coatings also aligns with sustainability goals in agricultural systems. It can minimally process fruits and vegetables. Not until there, the impact of edible coatings on fruits and vegetables can drive economic growth through the following days by improving market access and reducing food waste while promoting sustainable agricultural practice. The reduction of food waste also can enhance economic savings, creating more efficient practices that can increase the profitability of the retailers (Alemu et al., 2025).

An edible coating also provides an opportunity to access the global trade market. The ability of coating to extend the shelf life of fresh postharvest products such as fruits and vegetables can open doors to niche markets that fulfill the demand for fresh and premium products, which contributes to greater sales volume and improved profitability. The application of edible coating may also lead to energy savings throughout the supply chain, benefiting producers, retailers, and logistics providers economically (Alemu et al., 2025). Overall, existing studies on Cascara-derived and coffee by-product-based edible coatings highlight their considerable potential for application across a wide range of fruit commodities. Improvements in barrier properties, antioxidant capacity, and antimicrobial activity support their effectiveness in maintaining freshness, reducing postharvest losses, and contributing to more sustainable food systems. With further research on formulation and application, Cascara-based edible coatings have the potential to emerge as a functional and sustainable alternative to conventional postharvest treatments.

Though the related research about Cascara-based edible coating is still improving, specific studies focusing on how the underutilized application towards tropical fruits is still limited. Snake fruit (*Salacca zalacca*), is fruit that is consumed by many people in Indonesia but is highly perishable due to its relatively high moisture content and susceptibility to microbial degradation during room temperature storage. The scaly skin structure, while offering some physical protection because it's also firm and thick, does not sufficiently prevent moisture loss and quality degradation in postharvest. Consequently, the development of an effective, natural, and biodegradable coating system is essential to maintain the postharvest quality of the snake fruit. Cascara-based edible coatings, enriched with biopolymer such as chitosan, have the potential to form semi-permeable layers on snake fruit surfaces that can maintain gas exchange to inhibit growth of microorganisms. Moreover, the incorporation of Cascara into coating formulations provides an added functional value due to its phenolic compounds and antioxidant activity, which may delay oxidative degradation. Therefore, the application of Cascara-based edible coating on snake fruit is promising for its feasibility to tackle tropical fruit postharvest process and support sustainability.

4. Conclusions

This study confirms that Cascara has a strategic position as resources that can be studied and utilized scientifically, rather than merely being residues from the main production process. Through a systematic approach, this study shows that the utilization of Cascara can be directed towards the creation of added value that is relevant in both academic and practical context. The use of Cascara as an edible coating for snake fruit does not rule out other possible applications for other fruits. The findings reinforce the understanding that innovations based on local resources and agro-industrial waste, can make a real contribution to the development of applied science. By positioning coffee waste as a legitimate and valuable object of research, the study contributes to a paradigm shift from a linear approach to a more efficient and responsible approach to resource utilization. Overall, the results of the study broaden the discourse on optimizing Cascara and provide a sufficiently strong scientific basis for further development at a more applied level.

However, the results obtained in the study should be viewed as an initial stage in a more comprehensive development process. Future research should focus on strengthening safety and stability through more in-depth testing. Quantitative microbiological analysis is an important direction for the research to ensure that the products or materials produced meet quality and safety requirements. Analysis of microbial counts, identification of potential pathogens, and evaluation of microbiological dynamics during storage are necessary steps to obtain a more complete picture of the suitability of the coating application. This approach has a role at scientific foundation in responding to regulatory requirements international standards thus focusing on microbiological aspects will increase scientific credibility and strength, and the position of research results in the context of broader utilization.

In the context of sustainability, this research is strongly relevant to efforts to reduce postharvest waste and improve resource efficiency in the coffee industry. The utilization of Cascara as valuable material as a natural antimicrobial fruit coating, especially snake fruit, supports the principle of the circular economy by extending the life cycle of resources and reducing environmental pressure caused by waste disposal. In addition to environmental implications, this approach also opens up opportunities for a commercial application that can provide additional economic value for agro-industry players and coffee producing communities by connecting scientific, practical and sustainability aspects, this research offers a rational and responsible framework for coffee by-products waste utilization. With the support of postharvest industrial skills studies, the results of Cascara-based coating for snake fruit have the potential to move from the conceptual realm to sustainable application, this study can be seen as a starting point that encourages the development of sustainability-based innovation, as well as a reference for further research aimed at bridging science with the needs of the agro-industry in the future.

In addition to strengthening security aspects, future research should focus on evaluating the feasibility of the process on a larger scale. The transition from laboratory scale to pilot and industrial scale is a crucial stage that determines the potential for real implementation for the research is expected to examine quality consistency, process efficiency, and energy resource requirements at a more representative production scale. The integration of the process into existing coffee by-products processing systems also needs to be analyzed to ensure that the proposed innovation can be adopted without requiring significant infrastructure changes. This approach will provide a more realistic picture of the technical and economic challenges while also opening up dialogue between researchers and industry players.

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Author Contribution

Conceptualization, L.H.S.Z., K.A.N., and S.L.R.; Methodology, L.H.S.Z.; Software, —; Validation, L.H.S.Z., K.A.N., S.L.R., and D.Y.H.; Formal Analysis, L.H.S.Z. and K.A.N.; Investigation, S.L.R.; Resources, S.L.R.; Data Curation, S.L.R., K.A.N.; Writing – Original Draft Preparation, L.H.S.Z.;

Writing – Review & Editing, S.L.R. and K.A.N.; Visualization, K.A.N.; Project Administration, S.L.R.; Funding Acquisition, S.L.R.; Supervising, D.Y.H.

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All data supporting the findings of this study are available within the manuscript. Additional data can be provided upon request from the corresponding author.

Conflicts of Interest
The authors declare no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the author used Grammarly and DeepL to assist in improving clarity, structure, and language refinement of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the final content of the publication.

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