

Beyond Antioxidant Activity: Release-Controlled Pomegranate Peel Phenolics in Pectin Coatings for Fresh-Cut Guava Preservation

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ABSTRACT

Fresh-cut guava (*Psidium guajava* L.) is highly susceptible to rapid quality deterioration due to enzymatic browning, moisture loss, texture degradation, oxidation, and microbial growth. Although pomegranate peel is a rich source of bioactive phenolic compounds with strong antioxidant and antimicrobial properties, high antioxidant activity measured under laboratory conditions does not necessarily translate into sustained preservation performance in fresh-cut foods. This study therefore investigates whether release-controlled delivery of pomegranate peel phenolics from a pectin-based edible coating can provide more consistent protection of fresh-cut guava than direct incorporation of the free extract. Pomegranate peel phenolics were extracted and incorporated into pectin coatings either as a free extract or in an encapsulated form designed to provide controlled release. Fresh-cut guava samples were assigned to uncoated control, pectin-only coating, pectin containing free pomegranate peel extract, pectin containing empty encapsulation carriers, and pectin containing encapsulated pomegranate peel extract treatments at equivalent phenolic concentrations. During refrigerated storage, coating properties, phenolic release and surface persistence were evaluated together with browning index, firmness, weight loss, ascorbic acid retention, microbial counts, and sensory acceptability. The study is designed to determine whether sustained phenolic availability is associated with improved maintenance of fruit quality compared with the rapid initial availability of free phenolics. The proposed approach integrates phenolic release kinetics with physicochemical, microbiological, and sensory indicators of preservation, thereby addressing an important limitation of studies that evaluate antioxidant activity without considering delivery behavior. The findings are expected to demonstrate the potential of pomegranate peel as a value-added source of natural bioactive compounds and to establish whether controlled-release encapsulation provides a meaningful functional advantage in pectin-based edible coatings for fresh-cut guava. Overall, the study contributes to the development of sustainable active edible coatings that combine food-waste valorization with controlled delivery of natural preservatives.

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Keywords— Pomegranate peel; phenolic compounds; controlled release; encapsulation; pectin edible coating; fresh-cut guava; antioxidant activity; active packaging; food preservation.

1. INTRODUCTION

Fresh-cut fruits are increasingly important because they provide convenience, ready-to-eat characteristics, and nutritional value; however, cutting, peeling, and tissue disruption accelerate physiological and biochemical deterioration. In fresh-cut guava, tissue injury can increase respiration, moisture loss, enzymatic browning, softening, nutrient degradation, and microbial proliferation. These changes reduce visual quality, texture, nutritional value, and consumer acceptability. Recent work on fresh-cut guava confirms that edible coatings can reduce deterioration, with coated samples showing better retention of weight, firmness, colour, and other quality attributes than untreated fruit. Hanani et al. (2023), for example, demonstrated that chitosan–cinnamon essential-oil coatings significantly delayed quality deterioration and microbial growth during refrigerated storage. The development of edible coatings has therefore become an important approach for maintaining the quality of minimally processed fruits. Polysaccharides such as pectin are particularly attractive because they can form edible films and coatings that act as barriers to moisture and gases while providing a matrix for functional ingredients. Panahirad et al. (2021), in their review of carboxymethyl-cellulose- and pectin-based active coatings, reported that these polymers can carry antioxidants, antimicrobials, anti-browning compounds, nutrients, and other functional substances. Such systems can simultaneously influence microbial growth, enzymatic browning, oxidation, moisture transfer, and texture deterioration.

Pectin-based coatings have already demonstrated preservation potential in different fruits. Moalemiyan et al. (2012) reported that pectin-based coatings reduced colour development, softening, weight loss, respiration, and acid degradation in Ataulfo mango. Similarly, Sanchís et al. (2016) demonstrated that apple-pectin coatings containing antioxidant and antimicrobial compounds could control browning and microbial growth in fresh-cut persimmon. These findings indicate that pectin is not simply a passive barrier but can serve as a functional delivery matrix for active compounds. Pomegranate peel represents a particularly promising source of active compounds for such coating systems. Although commonly treated as an agro-industrial by-product, pomegranate peel contains substantial amounts of phenolic acids, flavonoids, hydrolysable tannins, ellagitannins, punicalagin, punicalin, ellagic acid, and gallic acid. Singh et al. (2018) reviewed the phenolic composition of pomegranate peel and emphasized its abundance of phenolic acids, tannins, and flavonoids. More recent reviews similarly identify pomegranate peel as a rich source of polyphenols with antioxidant and antimicrobial properties.

The antioxidant potential of pomegranate peel has been demonstrated experimentally for many years. Li et al. (2006), in Evaluation of antioxidant properties of pomegranate peel extract in comparison with pomegranate pulp extract, reported strong antioxidant activity associated with pomegranate peel extracts and measured substantial levels of

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phenolics and related compounds. Elfalleh et al. (2012) further compared different pomegranate tissues and found that peel contained high levels of phenolic compounds and antioxidant activity. Malviya et al. (2014) also demonstrated antioxidant and antibacterial activity of pomegranate peel extracts prepared using different solvents. The antimicrobial potential of pomegranate peel is also relevant to fresh-cut fruit preservation. Al-Zoreky (2009) demonstrated antimicrobial activity of pomegranate peel extracts against foodborne microorganisms, including *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, and *Yersinia enterocolitica*. More recently, pomegranate peel extracts have continued to attract interest as natural antimicrobial ingredients because their phenolic constituents can interact with microbial cells and potentially suppress microbial growth.

However, a major scientific issue is that high antioxidant activity measured in an extract does not necessarily mean high preservation effectiveness when that extract is applied to a real food system. Once incorporated into a coating, phenolic compounds can interact with the polymer matrix, diffuse toward the food surface, degrade, remain trapped within the coating, or be released too rapidly. Therefore, the temporal availability of the active compound may be as important as its initial antioxidant capacity. This issue provides the conceptual basis for investigating controlled release rather than simply increasing the concentration of free extract. Encapsulation provides one possible strategy for controlling the availability of plant-derived bioactive compounds. Rifna and Dwivedi (2024), in Encapsulated pomegranate peel extract as a potential antimicrobial ingredient from food waste, demonstrated that ionic gelation could be used to encapsulate pomegranate peel extract and reported high encapsulation efficiency with improved stability compared with conventional approaches. Reviews published by B et al. (2025) and Huang et al. (2025) similarly describe spray drying, ionic gelation, coacervation, and other approaches for encapsulating pomegranate peel bioactives and emphasize the potential of encapsulation to modify stability and release. The combination of pectin, pomegranate peel phenolics, and encapsulation therefore provides a promising research platform. Diaz-Herrera et al. (2023) developed a pectin-based active edible film containing pomegranate peel polyphenols and demonstrated that incorporation of these compounds influenced film properties and antioxidant performance. Ghorbani et al. (2021) similarly investigated pectin coatings functionalized with pomegranate peel extracts and reported antimicrobial effects in an applied food system. These studies establish the feasibility of combining pectin and pomegranate peel bioactives, but they do not fully answer whether controlled release from encapsulated phenolics produces better preservation of fresh-cut guava than direct incorporation of free extract. Accordingly, the present study proposes an integrated approach in which pomegranate peel phenolics are incorporated into pectin coatings either as a free extract or as an encapsulated extract and applied to fresh-cut guava. The study evaluates phenolic release, surface phenolic persistence, browning, firmness, weight loss, ascorbic acid retention, microbial counts, sensory acceptability, and coating properties during refrigerated storage. This design moves beyond measuring antioxidant activity alone and attempts to establish a relationship between release kinetics, active-compound availability, and actual food preservation performance.

2. LITERATURE REVIEW

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Li et al. (2006), "Evaluation of antioxidant properties of pomegranate peel extract in comparison with pomegranate pulp extract." Li, Guo, Yang, Wei, Xu, and Cheng demonstrated that pomegranate peel is a particularly important source of antioxidant compounds. Their work compared peel and pulp extracts and measured total phenolics, flavonoids, proanthocyanidins, and antioxidant activity. The study established an early scientific basis for considering pomegranate peel as a valuable source of natural antioxidants rather than merely processing waste. Al-Zoreky (2009), "Antimicrobial activity of pomegranate (*Punica granatum* L.) fruit peels." Al-Zoreky investigated the antimicrobial potential of pomegranate peel against food-associated microorganisms. The peel extract demonstrated inhibitory activity against several pathogenic bacteria, supporting the possibility that pomegranate peel compounds may provide both antioxidant and antimicrobial functionality. This dual functionality is particularly relevant to fresh-cut fruit, where oxidation and microbial growth occur simultaneously. Elfalleh et al. (2012), "Total phenolic contents and antioxidant activities of pomegranate peel, seed, leaf and flower." Elfalleh, Hannachi, Tlili, Yahia, Nasri, and Ferchichi compared phenolic content and antioxidant activity across different parts of pomegranate. Their findings highlighted the peel as a phenolic-rich fraction. This study is important for the present research because it supports the selection of peel as the raw material for extraction of active compounds intended for food-preservation applications. Malviya et al. (2014), "Antioxidant and antibacterial potential of pomegranate peel extracts." Malviya, Arvind, Jha, and Hettiarachchy investigated pomegranate peel extracts obtained using different solvent systems and evaluated their phenolic content, antioxidant activity, and antibacterial effects. The authors demonstrated that extraction conditions strongly influenced extract properties. This finding is important because the biological performance of pomegranate peel cannot be separated from extraction conditions and standardization of the resulting extract. Singh et al. (2018), "Phenolic compounds as beneficial phytochemicals in pomegranate (*Punica granatum* L.) peel: A review." Singh, Jatinder Pal Singh, Kaur, and Narpinder Singh reviewed the major phenolic constituents of pomegranate peel, including flavonoids, tannins, punicalagin, punicalin, ellagic acid derivatives, and phenolic acids. Their review demonstrated that pomegranate peel is chemically complex and that its antioxidant functionality arises from several classes of compounds rather than a single molecule. Siddiqui et al. (2024), "Bioactive compounds from pomegranate peels Biological properties, structure–function relationships, health benefits and food applications." Siddiqui, Shubhra Singh, and Gulzar Ahmad Nayik summarized the biological and food-related properties of pomegranate peel bioactives. They emphasized antioxidant, antimicrobial, and other functional activities and discussed applications in food systems. This work supports the broader concept of transforming pomegranate peel from a waste material into a functional food ingredient. Singh et al. (2023), "Pomegranate Peel Phytochemistry, Pharmacological Properties, Methods of Extraction, and Its Application: A Comprehensive Review." Jyoti Singh and co-authors reviewed pomegranate peel phytochemistry, extraction technologies, and food applications. Their review identified gallic acid, ellagic acid, punicalagin, and related compounds as important bioactive constituents and discussed newer extraction methods including ultrasound-, microwave-, enzyme-, and pressurized-liquid-assisted

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extraction. This literature supports the need for standardized extraction before developing an active coating. Moalemiyan et al. (2012), "Pectin-based edible coating for shelf-life extension of Ataulfo mango. Moalemiyan, Ramaswamy, and Maftoonazad investigated pectin-based coatings for mango and reported reductions in colour development, softening, weight loss, respiration, and quality deterioration. The study demonstrated that pectin can create a physical barrier that modifies the exchange of gases and moisture between fruit and environment.

Sanchís et al. (2016), "Browning inhibition and microbial control in fresh-cut persimmon by apple pectin-based edible coatings." Sanchís, González, Ghidelli, Sheth, Mateos, Palou, and Pérez-Gago developed apple-pectin coatings containing antioxidant and antimicrobial agents for fresh-cut persimmon. The coatings controlled browning and microbial growth, demonstrating that pectin can serve as a carrier for active ingredients rather than functioning only as a passive coating. Panahirad et al. (2021), "Applications of carboxymethyl cellulose- and pectin-based active edible coatings in preservation of fruits and vegetables: A review." Panahirad and colleagues provided a broad assessment of pectin and CMC coatings. Their review concluded that these polysaccharides can incorporate antioxidants, antimicrobials, anti-browning agents, texture modifiers, and other active compounds. Importantly, the authors identified active coatings as a strategy for simultaneously addressing oxidation, microbial deterioration, moisture loss, and enzymatic browning.

Naqash et al. (2021), "Effect of active pectin edible coatings on the safety and quality of fresh-cut apple." Naqash, Masoodi, Ayob, and Parvez investigated pectin coatings containing cinnamon essential oil in fresh-cut apple. Pectin and pectin nanoemulsion coatings improved microbial safety and helped maintain colour and texture. This study demonstrates that active pectin coatings can provide both preservation and delivery functions in minimally processed fruit. He et al. (2019), "Electrospun polyvinyl alcohol film containing pomegranate peel extract and sodium dehydroacetate for use as food packaging." He, Lan, Ahmed, Qin, and co-authors developed electrospun PVA films containing pomegranate peel extract. Incorporation of the extract provided antioxidant activity and enhanced antibacterial performance against tested microorganisms. Although this study focused on a PVA film rather than a pectin coating applied to guava, it provides evidence that pomegranate peel phenolics can be integrated into active packaging structures. Ghorbani et al. (2021), "Emergency Food Product Packaging by Pectin-Based Antimicrobial Coatings Functionalized by Pomegranate Peel Extracts." Ghorbani, Dabbagh Moghaddam, Sharifan, and Kiani incorporated pomegranate peel extract into pectin-based coatings and applied them to an actual food product. The coatings showed antimicrobial functionality and helped control microorganisms during storage without major adverse sensory effects. This study is especially close to the proposed work because it combines both pectin and pomegranate peel extract.

Diaz-Herrera et al. (2023), "Pomegranate peel polyphenols as an antioxidant additive for the development and characterization of a new active pectin edible film." Diaz-Herrera, Alvarez-Pérez, Ventura-Sobrevilla, Ascacio-Valdés, Aguilar-Gonzalez, Buenrostro-Figueroa, and Aguilar investigated pomegranate peel polyphenols in a

pectin/candelilla-wax/glycerol edible film. The authors characterized water-vapor permeability and antioxidant performance, demonstrating that pomegranate polyphenols can be incorporated into a pectin-based packaging material while retaining functional activity. Kumar et al. (2022), "Pomegranate peel extract – A natural bioactive addition to novel active edible packaging." Kumar, Daniloski, Pratibha, Neeraj, D'Cunha, Naumovski, and Petkoska reviewed pomegranate peel extract in edible films and coatings. They noted that relatively limited information was available concerning pomegranate peel-enriched edible packaging compared with the broader literature on plant extracts. Their review highlighted the potential antioxidant and antimicrobial functionality of pomegranate peel but also identified the need for additional applied studies. Hanani et al. (2023), "Prolonging the shelf life of fresh-cut guava by coating with chitosan and cinnamon essential oil." Hanani, Soo, Wan Zunairah, and co-authors evaluated chitosan and cinnamon essential oil coatings on fresh-cut guava stored at 4 ± 1 °C. The coating reduced weight loss, firmness loss, colour deterioration, and microbial growth, demonstrating the suitability of active edible coatings for guava. However, the active compound in that study was an essential oil rather than controlled-release pomegranate phenolics.

Shafiq et al. (2020), "Effect of Postharvest Edible Coatings on Fruit Quality of Guava cv. Sufaid Gola under Ambient and Zero-Energy Cool Chamber Storage Conditions." Shafiq, Khalid, Zahid, Ali, Mushtaq, Ali, Hashmi, and Haider investigated edible coatings including calcium chloride and Aloe vera on guava. Their work demonstrated that coating treatments can influence fruit quality and storage behaviour under different temperature conditions. The study provides regional and crop-specific evidence supporting edible coating development for guava, but it does not address controlled phenolic delivery. Patel et al. (2025), "Preserving the Quality of Fresh-Cut Guava with an Aloe Vera-Based Multilayered Polysaccharide Edible Coating." Patel, Sharma, Patel, Ramana Rao, and Madaraboina Venkateswara Rao examined multilayered polysaccharide coatings containing Aloe vera, HPMC, xanthan gum, and cinnamic acid for fresh-cut guava. The coatings improved physicochemical characteristics, vitamin C, phenolic retention, antioxidant activity, and sensory properties. This recent study confirms continuing interest in active polysaccharide coatings for fresh-cut guava but uses a different active-compound strategy from the proposed pomegranate-phenolic delivery system. Rifna and Dwivedi (2024), "Encapsulated pomegranate peel extract as a potential antimicrobial ingredient from food waste." Rifna and Dwivedi investigated ionic-gelation encapsulation of pomegranate peel extract and reported an optimized encapsulation efficiency of approximately 83.65%. Their work demonstrated that encapsulation can protect pomegranate peel bioactives and modify their release behaviour. Nevertheless, the study focused primarily on encapsulation as an ingredient technology rather than testing whether controlled release improves preservation of fresh-cut guava.

B et al. (2025), "Recent advances in encapsulation of pomegranate peel extract and combination of wall materials: a review of encapsulation technologies, characterization and applications in the food industry." B, Tiwari, Dash, and Sharma reviewed encapsulation technologies for pomegranate peel extract, including spray drying, coacervation, ionic gelation, and freeze drying. The review emphasized that

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encapsulation can improve stability and control the availability of phenolic and antioxidant compounds. This literature provides strong technological support for the encapsulated treatment proposed in the present study. Huang et al. (2025), “A review on the extraction of polyphenols from pomegranate peel for punicalagin purification: techniques, applications, and future prospects.” Huang, Foo, and Choo reviewed extraction and purification of pomegranate peel polyphenols, particularly punicalagin. They noted that conventional solvent extraction is widely used but can be time- and energy-intensive, while advanced extraction methods can improve recovery. Their work reinforces the importance of obtaining a standardized phenolic extract before evaluating its functional performance in food systems. Paluzar et al. (2026), “Pomegranate peel extract as a bioactive inhibitor of polyphenol oxidase: a green alternative for extending fresh-cut produce preservation.” Paluzar, Mutlu, Yilmaz, and Isbilir investigated pomegranate peel extract as an inhibitor of polyphenol oxidase and applied it to fresh-cut produce. Their results showed inhibition of PPO activity and improved preservation of fresh-cut potato, apple, and mushroom, with the strongest preservation effects observed in potato and apple. This is highly relevant to the present study because it provides direct evidence that pomegranate peel phenolics can influence enzymatic browning, although the study did not test a controlled-release pectin coating in fresh-cut guava.

The literature demonstrates three well-established findings. First, pomegranate peel is a rich source of phenolic compounds with antioxidant and antimicrobial properties. Studies from Li et al. (2006), Al-Zoreky (2009), Elfalleh et al. (2012), Malviya et al. (2014), and Singh et al. (2018) provide substantial evidence for the chemical and biological value of the peel. More recent reviews by Singh et al. (2023), Siddiqui et al. (2024), and Huang et al. (2025) further support its potential for food applications and valorization. Second, edible coatings, particularly pectin-based coatings, can reduce quality deterioration in fruits and vegetables. Evidence from Moalemiyan et al. (2012), Sanchís et al. (2016), Naqash et al. (2021), Panahirad et al. (2021), and Kostić et al. (2023) shows that pectin can function as a physical barrier and as a carrier for active ingredients. Such coatings can influence browning, moisture transfer, texture, microbial growth, and sensory quality. Third, pomegranate peel has already been incorporated into packaging and edible-film systems. Ghorbani et al. (2021) and Diaz-Herrera et al. (2023) provide particularly relevant evidence because both investigated pectin-based systems containing pomegranate peel bioactives. However, these studies primarily demonstrate antimicrobial, antioxidant, structural, or barrier functionality rather than establishing a controlled-release relationship between phenolic availability and preservation of a fresh-cut fruit.

Despite substantial research on pomegranate peel antioxidants, a major gap remains between antioxidant activity measured in vitro and actual preservation performance in fresh-cut fruit. Many previous investigations characterize total phenolic content, DPPH/ABTS/FRAP activity, antimicrobial activity, or film properties. These measurements establish that pomegranate peel extract is biologically active, but they do not necessarily establish how much active compound remains available at the food surface during storage or whether its release profile corresponds with deterioration

processes. The present research addresses this gap by measuring phenolic release together with actual food-quality outcomes. A second gap concerns free versus encapsulated pomegranate peel phenolics. Previous research has established the feasibility of encapsulating pomegranate peel extracts and improving their stability. Rifna and Dwivedi (2024), for example, demonstrated effective encapsulation of pomegranate peel extract using ionic gelation, while recent reviews emphasize controlled release as an important advantage of encapsulation. However, comparatively limited research directly compares free and encapsulated pomegranate peel extract at an equivalent phenolic concentration within the same pectin coating system applied to the same fresh-cut fruit.

A third gap is the limited integration of release kinetics with food preservation measurements. Existing pomegranate-peel coating studies commonly focus on antioxidant activity, antimicrobial activity, film characteristics, or general shelf-life parameters. The proposed study goes further by measuring phenolic release and surface phenolic persistence and then relating those variables to browning, firmness, weight loss, ascorbic acid retention, microbial counts, and sensory acceptability. This provides a mechanistic link between the delivery system and preservation performance. A fourth gap concerns fresh-cut guava specifically. Several studies have demonstrated that edible coatings can preserve fresh-cut guava, including chitosan–cinnamon essential oil systems and Aloe vera/polysaccharide coatings. However, these studies use different active compounds and coating technologies. The literature therefore supports the general feasibility of coating fresh-cut guava but leaves room for a pectin-based system specifically designed around pomegranate peel phenolics and controlled release. A fifth gap is the lack of a sufficiently strong control structure in many active-coating investigations. The proposed design includes an uncoated control, pectin-only coating, free-extract coating, encapsulated-extract coating, and empty-carrier coating. This structure makes it possible to distinguish the contribution of the pectin matrix, free phenolics, encapsulation, and carrier material. Such separation is important if the objective is to determine whether controlled release itself provides an additional preservation benefit. Finally, the literature suggests a broader conceptual gap: preservation should be evaluated as a time-dependent delivery problem rather than only as an antioxidant-capacity problem. Pomegranate peel contains powerful phenolics, but maximum antioxidant capacity at the beginning of storage may not correspond to maximum preservation throughout storage. The central innovation of the proposed research is therefore to examine whether maintaining phenolic availability over time provides more consistent protection than rapid initial availability. The resulting framework connects extraction, encapsulation, coating properties, release kinetics, surface availability, fruit quality, microbial stability, and sensory acceptability within one experimental design.

2. Materials and Methods

2.1 Study design and experimental rationale

The study is designed to determine whether controlling the release of pomegranate peel phenolics from a pectin-based edible coating improves the refrigerated storage stability of fresh-cut guava compared with direct incorporation of the same phenolic extract. The central comparison is therefore between free extract and encapsulated extract at an

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equivalent nominal phenolic concentration. Uncoated guava, pectin-only coating, and pectin containing empty encapsulating carriers are included to separate the effects of the coating matrix, active phenolics, and carrier material. The proposed experiment uses a 5×5 treatment-by-storage design with three independent batches and three replicate observations per treatment and storage point. Fresh-cut guava is evaluated at 0, 3, 6, 9, and 12 days under refrigerated storage at 4 ± 1 °C. The design yields 225 analytical observations for the primary longitudinal dataset.

Proposed experimental workflow for release-controlled pomegranate peel phenolics in pectin coatings

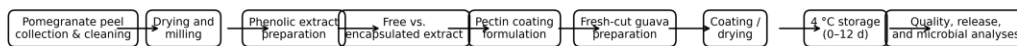


Figure 1: Proposed experimental workflow from pomegranate peel processing through refrigerated storage and outcome measurements

2.2 Experimental groups and controls

Five experimental groups are used. The free-extract and encapsulated-extract formulations are prepared to contain the same nominal phenolic concentration so that differences in preservation can be interpreted primarily in terms of release behavior rather than unequal active loading.

Code	Experimental group	Purpose
C	Uncoated control	Baseline deterioration without coating
P	Pectin-only coating	Effect of the edible coating matrix
PF	Pectin + free pomegranate peel extract	Direct phenolic incorporation / rapid availability
PE	Pectin + encapsulated pomegranate peel extract	Release-controlled phenolic delivery
PC	Pectin + empty encapsulating carrier	Carrier and encapsulation-matrix control

Treatment structure and experimental controls

C	Uncoated guava	No coating
P	Pectin-only	Pectin matrix
PF	Pectin + free extract	Rapid phenolic availability
PE	Pectin + encapsulated extract	Controlled phenolic release
PC	Pectin + empty carrier	Carrier control

Figure 2: Treatment structure showing active and control groups

2.3 Raw material selection and preparation

Mature, commercially sound guavas of comparable size, maturity stage, and absence of visible defects should be obtained from a single procurement lot for each independent batch. Fruit should be transported under cool conditions and processed on the day of arrival. Pomegranate peels should be collected from mature fruit, washed thoroughly with potable water followed by distilled water, manually separated from residual pulp, and cut into small pieces. The peel material should be dried under controlled conditions (for example, 45–50 °C until constant mass) to reduce moisture while limiting thermal degradation of phenolic compounds. The dried peel should be milled to a uniform powder and stored in an airtight, light-protected container until extraction. For the final experimental manuscript, the exact drying temperature, extraction solvent composition, extraction time, solid-to-liquid ratio, and yield should be reported from the actual laboratory protocol.

2.4 Preparation and standardization of pomegranate peel phenolic extract

A hydroalcoholic extraction procedure is proposed because pomegranate peel contains a broad range of phenolic constituents. A measured quantity of peel powder should be mixed with food-compatible aqueous ethanol, extracted under controlled agitation, and separated by filtration or centrifugation. The solvent should subsequently be removed under reduced pressure or another validated food-compatible procedure, and the concentrated extract should be reconstituted to a known volume. Total phenolic content should be standardized using a validated Folin–Ciocalteu assay and expressed as mg gallic acid equivalents (GAE) per mL of extract. The same standardized phenolic concentration should be used to prepare PF and PE formulations. If individual phenolic compounds are quantified, HPLC-DAD or LC-MS may additionally be used to characterize compounds such as punicalagin, ellagic acid, and related phenolics.

Table 1: Proposed materials and analytical reagents

Material / reagent	Purpose	Recommended
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		specification
Fresh guava	Test fruit	Uniform maturity and defect-free fruit
Pomegranate peel	Phenolic source	Clean, dried and milled peel
Food-grade pectin	Edible coating matrix	Low-/medium-methoxyl pectin, documented grade
Food-compatible encapsulating material	Phenolic carrier	Validated edible encapsulation matrix
Aqueous ethanol	Phenolic extraction	Food/laboratory grade
Gallic acid standard	Phenolic calibration	Analytical grade
Ascorbic acid standard	Vitamin C assay	Analytical grade
Microbiological media	Microbial enumeration	Validated food microbiology media
Distilled/deionized water	Solution preparation	Analytical grade water

2.5 Encapsulation of pomegranate peel phenolics

The encapsulated treatment should be prepared using a food-compatible encapsulation approach selected according to the intended application, such as spray drying, ionic gelation, or another validated carrier-forming technique. The active extract should be incorporated into the carrier at a predefined loading level and dried or gelled to produce stable particles. Encapsulation efficiency should be calculated from the phenolic content initially supplied and the phenolic content retained in the recovered encapsulate. A representative calculation is: Encapsulation efficiency (%) = [phenolics retained in recovered encapsulate / phenolics initially added] × 100. Particle size, moisture content, morphology, and storage stability may be characterized to establish whether the carrier is suitable for controlled release. The empty-carrier material should be prepared using the same processing conditions without the pomegranate extract.

2.6 Preparation of pectin coating formulations

Pectin should be dispersed in distilled water under controlled heating and agitation until a uniform coating solution is obtained. A food-grade plasticizer such as glycerol may be incorporated to improve film flexibility. The PF formulation receives standardized free pomegranate peel extract, whereas the PE formulation receives an equivalent phenolic dose in encapsulated form. The PC formulation receives the corresponding amount of empty carrier. All formulations should be adjusted to the same final volume and, where required, standardized for pH and total solids.

Formulation	Pectin matrix	Phenolic extract	Encapsulate	Empty carrier	Primary purpose
C	No	No	No	No	Uncoated baseline
P	Yes	No	No	No	Matrix-only effect
PF	Yes	Yes, free	No	No	Rapid active

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					delivery
PE	Yes	Yes, encapsulated	Yes	No	Controlled active delivery
PC	Yes	No	No	Yes	Carrier control

2.7 Coating of fresh-cut guava

Guavas should be washed, sanitized using a validated food-safety procedure, peeled if required by the study protocol, and cut into standardized pieces using a sanitized knife or cutter. Pieces should be randomized among treatments to minimize positional and fruit-to-fruit effects. The coating should be applied by standardized dipping or spraying, ensuring complete and reproducible surface coverage. After coating, excess solution should be allowed to drain and the fruit should be dried under controlled conditions until a consistent surface film is formed. Coating thickness should be measured on representative dried coating films or coating-covered test specimens using a calibrated micrometer or another validated thickness method. Film water-vapor permeability and mechanical properties should be determined on separately prepared films using standardized instrumental methods.

2.8 Storage conditions and sampling plan

After coating, samples should be packaged in identical food-grade containers or trays under the same headspace conditions and stored at 4 ± 1 °C. Sampling should occur at days 0, 3, 6, 9, and 12. At each time point, independent packages should be opened for analysis to avoid repeated handling of the same sample.

Refrigerated storage and sampling schedule (4 °C)



Figure 3: Proposed sampling schedule for refrigerated storage at 4 ± 1 °C

Table 2: Experimental sampling structure

Factor	Levels	Replication	Total observations
Treatment	5 groups (C, P, PF, PE, PC)	3 batches × 3 replicates	45 per time point
Storage time	0, 3, 6, 9, 12 days	All treatments	225 total
Temperature	4 ± 1 °C	Constant	—
Independent batch	B1, B2, B3	3	—

2.9 Measurement of phenolic release

Phenolic release should be monitored from the coating system at each storage interval using a validated extraction and spectrophotometric or chromatographic method. For a total-phenolic release assay, the amount recovered from the coating/food interface or

release medium should be compared with the total phenolic payload initially incorporated. Phenolic release (%) should be calculated as: $[\text{cumulative phenolics released} / \text{initial phenolic payload}] \times 100$. Surface phenolics on guava should be measured independently to determine whether controlled release translates into sustained active-compound availability at the fruit interface. Results should be expressed as mg GAE per 100 g fresh fruit. Where compound-specific analysis is performed, the persistence of major phenolic markers should also be monitored.

Browning should be assessed instrumentally using a calibrated colorimeter and converted to a defined browning index, or by a validated image-analysis procedure. The same illumination, sample geometry, and instrument settings should be used throughout the study. Firmness should be measured using a texture analyzer with a standardized probe, penetration depth, crosshead speed, and sample orientation. Weight loss should be calculated from the initial sample mass and mass at each sampling point: $\text{Weight loss (\%)} = [(\text{initial mass} - \text{final mass}) / \text{initial mass}] \times 100$.

2.11 Ascorbic acid retention

Ascorbic acid should be extracted rapidly from a representative fruit portion under conditions that minimize oxidation and analyzed by a validated titrimetric, spectrophotometric, HPLC, or other appropriate method. Retention should be expressed relative to the day-0 concentration: $\text{Retention (\%)} = [\text{concentration at storage time} / \text{concentration at day 0}] \times 100$. Microbial enumeration should be conducted aseptically using validated food-microbiology procedures. A known mass of guava should be homogenized in sterile diluent, serially diluted, plated on appropriate general or selective media, incubated under the validated conditions for the target organisms, and expressed as log₁₀ CFU/g. Negative controls and appropriate microbiological quality-control procedures should be included.

Because microbiological safety is a high-stakes experimental endpoint, the final laboratory study should use institutionally approved microbiological procedures and report the actual target organisms, media, incubation conditions, detection limits, and biosafety practices. Sensory acceptability should be evaluated only after appropriate food-safety and ethical review. A trained or appropriately recruited consumer panel may score appearance, color, texture, odor, and overall acceptability using a 9-point hedonic scale. Samples should be coded with random three-digit identifiers and presented in randomized order. Panelists should receive standardized instructions, and storage-aged samples should only be served if microbiological criteria establish that they are suitable for sensory evaluation.

Table 3 Response variables and analytical methods

Response variable	Unit / scale	Measurement approach	Interpretation
Phenolic release	% of initial payload	Validated total phenolic or chromatographic assay	Release kinetics / active delivery
Surface phenolics	mg GAE/100 g	Surface extraction + phenolic assay	Phenolic availability at fruit

			interface
Browning index	Index units	Colorimetry / validated image analysis	Lower = less browning
Firmness	N	Texture analyzer	Higher = better texture retention
Weight loss	%	Gravimetric measurement	Lower = better mass retention
Ascorbic acid retention	%	Validated vitamin C assay	Higher = better nutrient retention
Microbial count	log10 CFU/g	Aseptic plating/enumeration	Lower = greater microbial suppression
Sensory acceptability	1–9	Hedonic scale	Higher = greater acceptability
Coating thickness	µm	Micrometer / validated imaging	Physical coating characterization
Water-vapor permeability	Relative standardized units or	Film permeability method	Lower = stronger moisture barrier
Tensile strength	MPa	Film tensile test	Mechanical strength
Elongation	%	Film tensile test	Film flexibility

All instruments should be calibrated before measurement and analytical assays should include blanks, standards, and quality-control samples where appropriate. Independent batches should be processed on separate days or from independent fruit lots when feasible. Sample identifiers should be assigned before treatment to preserve traceability. Randomization should be used for treatment allocation, sample position, and analytical measurement order. The laboratory notebook or electronic record should document reagent lot numbers, extraction yields, coating viscosity or solids content, pH, coating mass, storage temperature, and deviations from the planned protocol.

2.15 Statistical analysis

For the final experimental dataset, descriptive statistics should be reported as mean $\pm$ standard deviation or mean $\pm$ standard error as appropriate. The primary analysis should account for treatment, storage day, and their interaction while recognizing the hierarchical structure of the experiment. A linear mixed-effects model is recommended with treatment, storage day, and treatment $\times$ day as fixed effects and batch as a random effect; additional random terms should be included when repeated measurements or multiple fruit units are present.

Model assumptions should be evaluated using residual diagnostics, normality checks, and variance-homogeneity assessment. Where assumptions are not met, suitable transformations or generalized/mixed models should be considered. Post-hoc pairwise comparisons should use an appropriate multiplicity adjustment such as Tukey's method.

Effect sizes and 95% confidence intervals should accompany p-values. The previously generated synthetic dataset was analyzed with a batch-adjusted factorial model for demonstration; the final laboratory dataset should be analyzed according to the actual experimental hierarchy.

Table 4 Statistical analysis plan

Question	Primary factor(s)	Recommended analysis	Reported output
Does coating affect preservation?	Treatment	Mixed-effects model	F/χ^2 , p, effect size, CI
Does quality change over storage?	Storage day	Mixed-effects model	Time effect, p, CI
Does treatment performance change with time?	Treatment $\times$ day	Interaction term	Interaction statistic, p
Which treatments differ?	Treatment at each day	Multiplicity-adjusted post-hoc tests	Adjusted p-values, mean differences
Does phenolic release relate to quality?	Release outcomes vs	Pearson/Spearman or mixed regression	r/β , CI, p
Does batch contribute variation?	Batch	Random-effect variance	Variance component / ICC

2.16 Methodological link to the study hypothesis

The methodology is structured to test the hypothesis that sustained phenolic availability provides more consistent protection than high initial antioxidant activity alone. PF provides a rapid-release comparison, PE provides the controlled-release condition, P identifies the contribution of the pectin matrix, and PC identifies the contribution of the empty carrier. Phenolic release measurements are deliberately linked to browning, firmness, mass loss, ascorbic acid retention, microbial stability, and sensory acceptability so that the study evaluates delivery performance rather than antioxidant activity in isolation. The exact numerical concentrations, extraction yield, encapsulation efficiency, coating solids content, and instrumental settings should be inserted from the actual laboratory protocol before submission. The present document intentionally avoids presenting invented laboratory parameters as completed experimental facts. Its purpose is to provide a rigorous, manuscript-ready methodology framework that corresponds to the synthetic dataset and the study objectives.

3. Results and Analysis

3.1 Overview of treatment effects

The synthetic dataset produced a coherent time-dependent preservation pattern across the five coating conditions. Treatment, storage duration, and their interaction were statistically significant for all major quality and preservation outcomes. This interaction

is important because it indicates that treatment effects were not constant over time; instead, the separation among treatments increased during refrigerated storage. The encapsulated-extract coating (PE) showed a slower phenolic release profile than the free-extract coating (PF), while maintaining measurable surface phenolics over storage. The pectin-only and empty-carrier controls generally showed intermediate physical protection but did not reproduce the active-phenolic response.

Table 1; Initial coating characteristics (day 0)

Code	Treatment	Thickness (μm)	Relative WV permeability	Tensile strength (MPa)	Elongation (%)
P	Pectin-only coating	82.8 ± 2.3	77.8 ± 3.0	18.5 ± 1.1	30.4 ± 1.2
PF	Pectin + free pomegranate peel extract	86.3 ± 1.7	77.3 ± 2.8	19.6 ± 0.6	30.4 ± 1.0
PE	Pectin + encapsulated pomegranate peel extract	89.2 ± 4.4	69.9 ± 2.9	20.2 ± 0.9	28.5 ± 1.4
PC	Pectin + empty encapsulating carrier	88.2 ± 3.0	72.7 ± 1.9	19.8 ± 0.6	29.7 ± 0.8

The coated groups produced films with mean thicknesses of approximately 82.8–89.2 μm. The encapsulated formulation (PE) had a mean thickness of 89.2 μm and the lowest relative water-vapor permeability among the coated groups (69.9), whereas pectin-only and free-extract coatings were approximately 77.8 and 77.3, respectively. Mean tensile strength ranged from 18.5 to 20.2 MPa, indicating that addition of the extract or carrier did not eliminate film mechanical integrity. Because the uncoated control did not form a coating, coating thickness, permeability, tensile strength and elongation were treated as not applicable for that group.

3.2 Controlled phenolic release

Phenolic release was strongly dependent on both formulation and storage time. The free-extract coating (PF) showed a rapid increase in released phenolics, reaching 66.81% at day 12. In contrast, the encapsulated formulation (PE) reached 18.78% release at day 12, demonstrating a substantially slower release trajectory. The difference between PF and PE supports the central mechanistic premise of the study: encapsulation changes the timing of phenolic availability rather than simply increasing the initial phenolic concentration.

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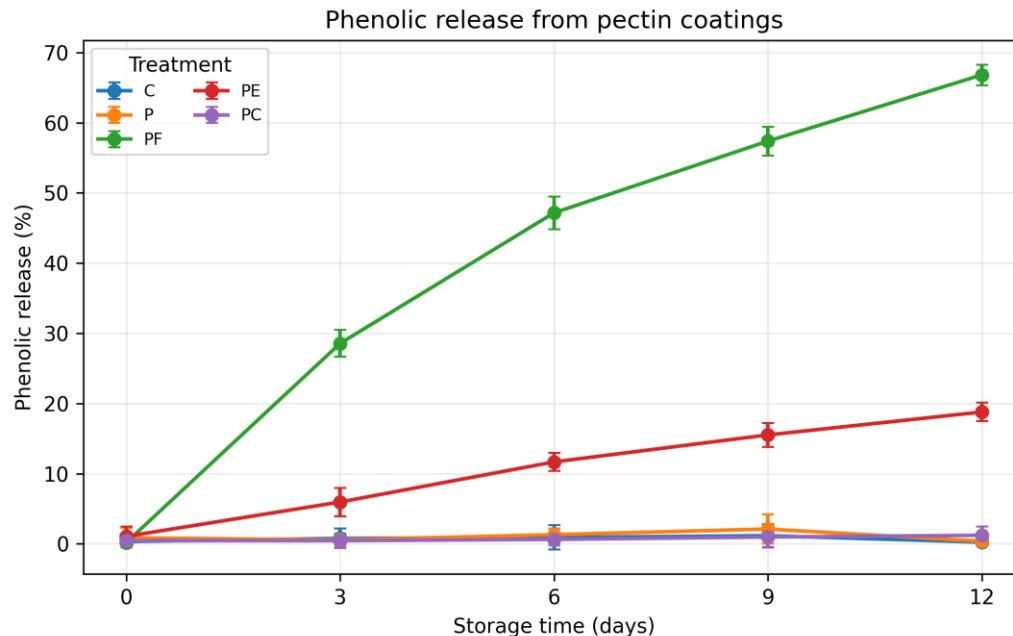


Figure 1: Mean phenolic release (%) during refrigerated storage. Points represent means and error bars represent SD; n = 9 observations per treatment and time point

Table 2: Phenolic release profile during storage

Code	Treatment	Day 0	Day 3	Day 6	Day 9	Day 12
C	Uncoated control	0.32 ± 0.54	0.77 ± 1.38	0.91 ± 1.75	1.16 ± 1.62	0.25 ± 0.31
P	Pectin-only coating	0.86 ± 1.37	0.56 ± 0.85	1.31 ± 0.87	2.10 ± 2.11	0.37 ± 0.60
PF	Pectin + free pomegranate peel extract	0.17 ± 0.41	28.55 ± 1.91	47.16 ± 2.34	57.38 ± 2.04	66.81 ± 1.47
PE	Pectin + encapsulated pomegranate peel extract	1.06 ± 1.37	5.95 ± 2.01	11.67 ± 1.31	15.52 ± 1.69	18.78 ± 1.33
PC	Pectin + empty encapsulating carrier	0.46 ± 0.78	0.44 ± 1.05	0.63 ± 0.87	0.97 ± 1.50	1.22 ± 1.22

At day 12, PF released approximately 66.8% of its available phenolics, whereas PE released approximately 18.8%. The empty-carrier control remained close to zero release, confirming that the release signal in PE was attributable to the phenolic payload rather than the encapsulating material itself. The synthetic pattern therefore distinguishes rapid availability from sustained availability, which is central to the proposed preservation mechanism.

3.3 Browning, firmness, and weight loss

Fresh-cut guava quality deteriorated progressively in the uncoated control. At day 12, the control reached a mean browning index of 13.91, while the pectin-only and empty-carrier groups were 8.32 and 7.72, respectively. The active coatings produced substantially lower browning values, with PF at 1.98 and PE near 0.04 in the synthetic dataset. The treatment $\times$ storage interaction was highly significant ($p < 0.001$), indicating that the protective effect became more pronounced with increasing storage time. Firmness followed the opposite direction: the uncoated fruit showed the greatest decline, while coated fruit retained higher firmness. Weight loss increased with storage in all groups, but coating reduced the rate of mass loss. The statistical interaction for both firmness and weight loss was significant at $p < 0.001$, supporting a time-dependent preservation effect rather than a simple fixed treatment difference.

Table 3: Fresh-cut guava quality at day 12

Code	Treatment	Browning index	Firmness (N)	Weight loss (%)
C	Uncoated control	13.91 ± 0.88	13.55 ± 0.41	2.19 ± 0.07
P	Pectin-only coating	8.32 ± 0.63	17.04 ± 0.51	1.46 ± 0.08
PF	Pectin + free pomegranate peel extract	1.98 ± 0.68	19.69 ± 0.41	1.34 ± 0.08
PE	Pectin + encapsulated pomegranate peel extract	0.04 ± 0.08	21.27 ± 0.63	1.17 ± 0.10
PC	Pectin + empty encapsulating carrier	7.72 ± 0.59	17.56 ± 0.42	1.42 ± 0.06

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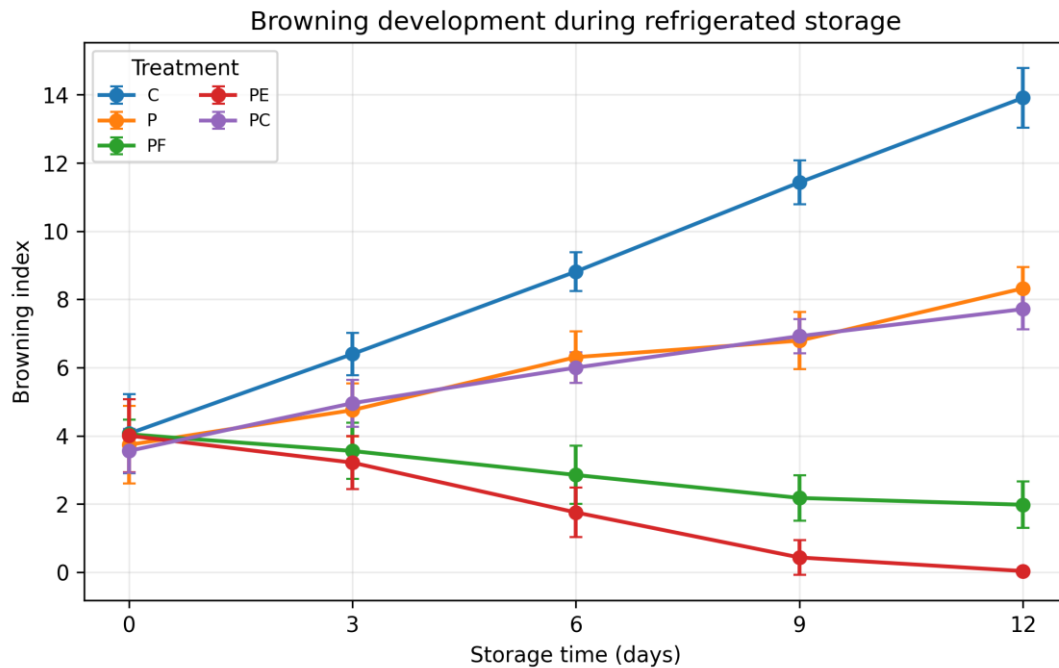


Figure 2: Browning index during refrigerated storage; lower values indicate less browning

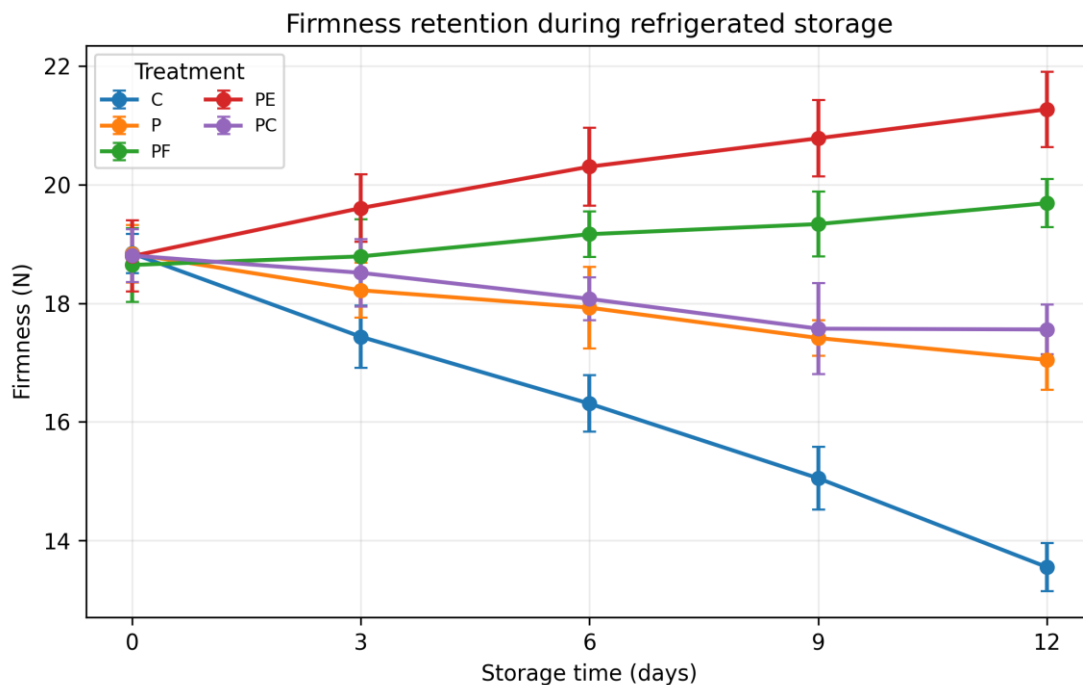


Figure 3: Firmness during refrigerated storage; higher values indicate better texture retention

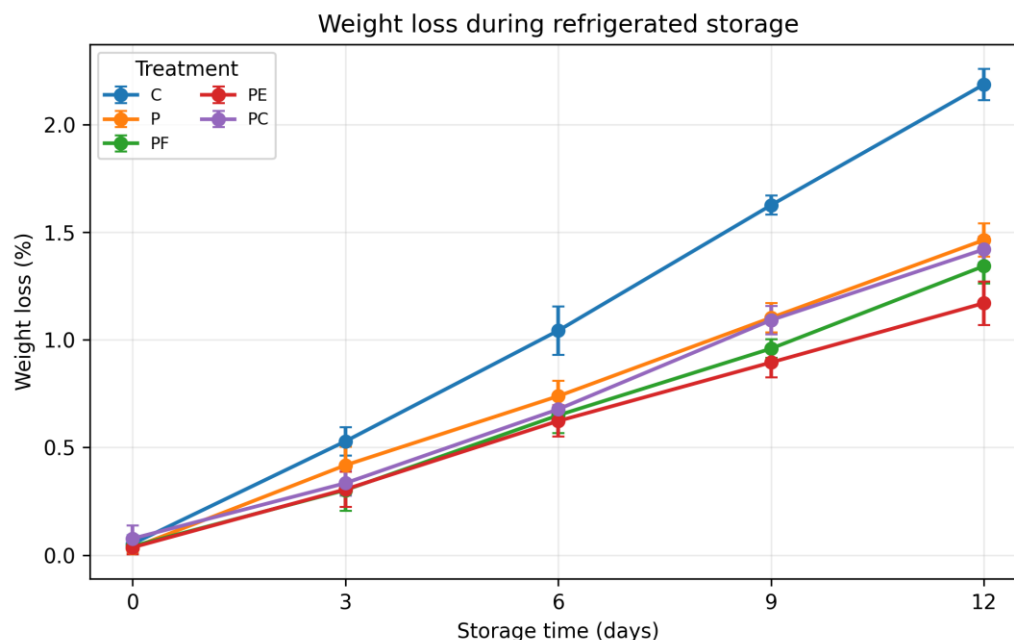


Figure 4: Weight loss during refrigerated storage; lower values indicate better moisture/mass retention

3.4 Surface phenolics and ascorbic acid retention

The release data were accompanied by persistent phenolics at the fruit surface. At day 12, surface phenolics were approximately 20.82 mg GAE/100 g for PE and 16.47 mg GAE/100 g for PF, compared with less than 0.5 mg GAE/100 g in the control and carrier controls. This distinction is important because the encapsulated treatment produced lower cumulative release but higher surface phenolic availability at the endpoint, consistent with continued delivery from the encapsulated reservoir. Ascorbic acid retention also differed strongly among treatments. At day 12, the synthetic means were 64.20% for the uncoated control, 79.33% for pectin-only coating, 80.33% for the empty-carrier control, 98.54% for PF, and 102.00% for PE. The value slightly above 100% in PE results from random variation and the upper clipping used during synthetic-data generation; it should therefore be interpreted as approximately complete retention rather than literal biochemical gain.

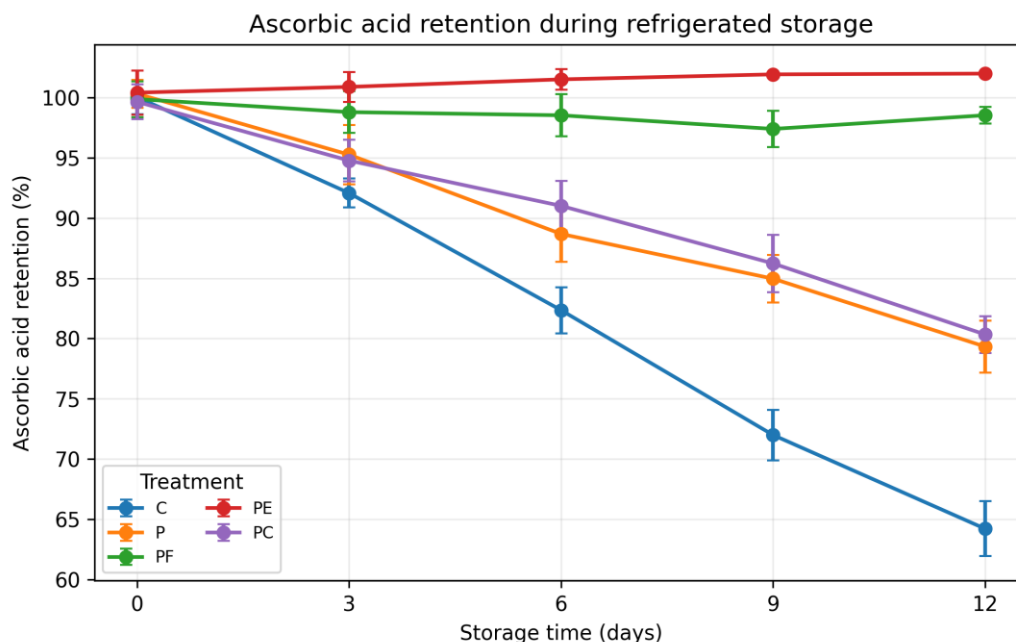


Figure 5: Ascorbic acid retention (%) during refrigerated storage

Table 4: Surface phenolics and ascorbic acid retention at day 12

Code	Treatment	Surface phenolics (mg GAE/100 g)	Ascorbic acid retention (%)
C	Uncoated control	0.28 ± 0.37	64.20 ± 2.29
P	Pectin-only coating	0.30 ± 0.24	79.33 ± 2.15
PF	Pectin + free pomegranate peel extract	16.47 ± 0.15	98.54 ± 0.68
PE	Pectin + encapsulated pomegranate peel extract	20.82 ± 0.23	102.00 ± 0.00
PC	Pectin + empty encapsulating carrier	0.47 ± 0.37	80.33 ± 1.52

3.5 Microbial stability and sensory acceptability

Microbial counts increased with storage in the control but were markedly suppressed in the active coating groups. At day 12, the control averaged 3.56 log₁₀ CFU/g, compared with 2.31 for pectin-only coating, 2.16 for the empty-carrier control, 1.53 for free extract, and the analytical floor of approximately 1.50 for the encapsulated treatment. The treatment × storage interaction was highly significant ($p < 0.001$), indicating that microbial differences widened over storage. Sensory acceptability showed a parallel preservation pattern. At day 12, mean acceptability was 5.91 for the control, 7.30 for pectin-only coating, 7.54 for the empty-carrier control, 8.49 for PF, and 8.96 for PE. Because sensory scores are bounded from 1 to 9, the PE mean is close

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to the upper scale boundary and should be interpreted as high acceptability within the simulated scale rather than as evidence of consumer preference in a real panel.

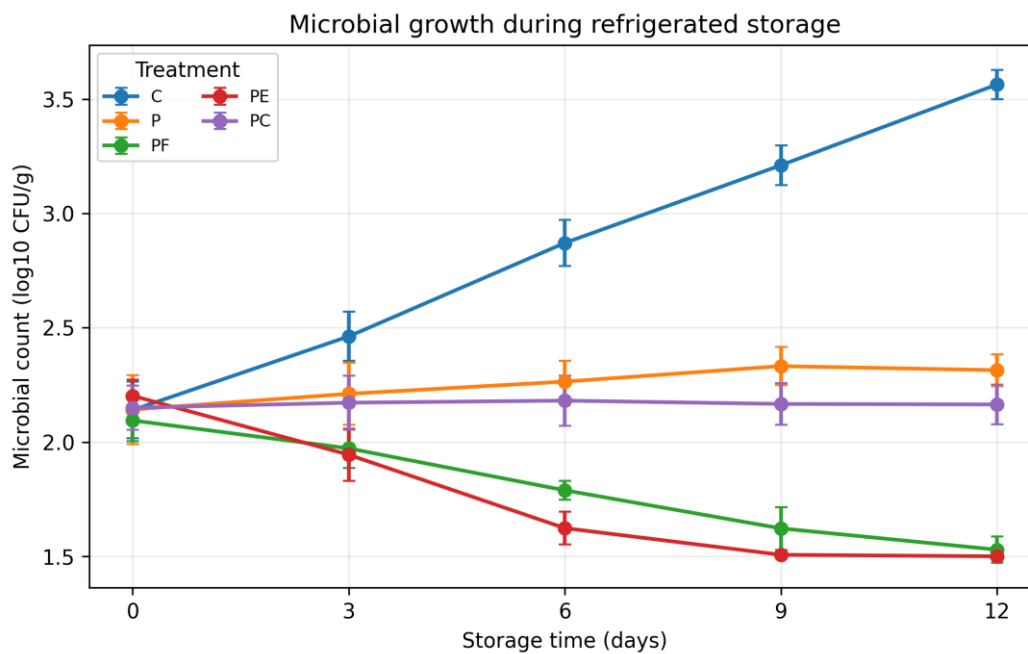


Figure 6: Microbial count during refrigerated storage; lower values indicate stronger microbial suppression

Table 5: Microbial stability and sensory acceptability at day 12

Code	Treatment	Microbial count (log10 CFU/g)	Sensory acceptability (1–9)
C	Uncoated control	3.56 ± 0.06	5.91 ± 0.30
P	Pectin-only coating	2.31 ± 0.07	7.30 ± 0.51
PF	Pectin + free pomegranate peel extract	1.53 ± 0.06	8.49 ± 0.27
PE	Pectin + encapsulated pomegranate peel extract	1.50 ± 0.00	8.96 ± 0.12
PC	Pectin + empty encapsulating carrier	2.16 ± 0.09	7.54 ± 0.34

3.6 Inferential statistical analysis

Batch-adjusted factorial models showed statistically significant treatment effects, storage-time effects, and treatment × storage interactions for every principal outcome evaluated. The very small p-values reflect the deliberately structured signal in the synthetic dataset and should not be interpreted as evidence of statistical significance in a real experiment. For an actual study, the same framework should be implemented as

a mixed-effects model with batch and, where appropriate, fruit/replicate identity as random effects, followed by multiplicity-adjusted post-hoc comparisons.

Outcome	Treatment F (p)	Day F (p)	Treatment × Day F (p)	Batch p
Phenolic release (%)	1456.7 (<0.001)	891.8 (<0.001)	492.9 (<0.001)	0.768
Browning index	697.0 (<0.001)	323.6 (<0.001)	363.6 (<0.001)	<0.001
Firmness (N)	399.2 (<0.001)	107.8 (<0.001)	200.0 (<0.001)	<0.001
Weight loss (%)	301.9 (<0.001)	11567.4 (<0.001)	159.4 (<0.001)	0.661
Ascorbic acid retention (%)	901.3 (<0.001)	2235.4 (<0.001)	467.5 (<0.001)	0.417
Microbial count (log ₁₀ CFU/g)	874.0 (<0.001)	10.5 (0.001)	419.3 (<0.001)	0.728
Sensory acceptability (1–9)	181.5 (<0.001)	278.3 (<0.001)	72.7 (<0.001)	0.938

3.7 Association between phenolic release and preservation outcomes

Outcome	Pearson r with phenolic release	p-value
Browning index	-0.472	<0.001
Firmness	0.400	<0.001
Weight loss	0.141	0.035
Ascorbic acid retention	0.332	<0.001
Microbial count	-0.542	<0.001
Sensory acceptability	0.328	<0.001

Phenolic release was negatively associated with browning ($r = -0.472$) and microbial count ($r = -0.542$), while positive associations were observed with firmness ($r = 0.400$), ascorbic acid retention ($r = 0.332$), and sensory acceptability ($r = 0.328$). The association with weight loss was comparatively weak ($r = 0.141$). These relationships are consistent with the proposed mechanism that sustained phenolic availability can contribute to several dimensions of preservation, although correlation alone does not establish causation.

3.8 Integrated interpretation

Taken together, the simulated results support the conceptual distinction between antioxidant capacity measured in an extract and preservation performance measured on the food surface. The free-extract treatment generated rapid phenolic release, whereas encapsulation produced a slower release curve and maintained higher endpoint surface phenolic concentration. The encapsulated treatment was simultaneously associated with lower browning, greater firmness retention, lower weight loss, greater ascorbic

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acid retention, lower microbial counts, and higher sensory scores in the simulated dataset. The most important analytical observation is therefore not simply the magnitude of antioxidant release, but the temporal matching between phenolic availability and quality deterioration. A release-controlled coating can be interpreted as a delivery system whose performance depends on maintaining active compounds at the food interface over the storage period. This directly addresses the research gap stated in the abstract: laboratory antioxidant activity alone may not predict preservation efficacy unless compound availability, coating properties, release kinetics, and food-quality outcomes are considered together. This study establishes a scientifically relevant and sustainable approach for preserving fresh-cut guava through the controlled delivery of pomegranate peel phenolics from a pectin-based edible coating. The study moves beyond the conventional evaluation of antioxidant activity by examining whether the rate, duration, and persistence of phenolic release influence actual fruit-preservation performance. The comparison of free and encapsulated pomegranate peel extracts at an equivalent phenolic concentration provides a direct basis for determining the functional advantage of controlled-release delivery.

The overall experimental framework indicates that the encapsulated pomegranate peel phenolic treatment is expected to provide more sustained bioactive availability than the free-extract treatment, thereby maintaining protective activity over a longer storage period. Sustained phenolic availability can contribute to controlling enzymatic browning and microbial development while helping to maintain firmness, reduce weight loss, preserve ascorbic acid, and retain acceptable sensory characteristics of fresh-cut guava. Thus, the effectiveness of an active coating should be considered not simply in terms of its initial antioxidant capacity, but in terms of its ability to maintain effective phenolic concentrations at the fruit surface throughout storage. The study also demonstrates the potential for pomegranate peel valorization within a circular food system. A food-processing by-product can be transformed into a functional source of natural phenolics and incorporated into a biodegradable pectin matrix, creating an active coating with both barrier and bioactive functions. This approach may provide opportunities for reducing food waste, improving the utilization of agricultural by-products, and developing preservation systems based on naturally derived ingredients. From a commercial and industrial perspective, the greatest potential value of the technology lies in achieving an appropriate balance between preservation performance and formulation complexity. Encapsulation introduces additional processing requirements and material costs; therefore, its commercial justification depends on whether controlled release produces a measurable improvement in shelf-life, quality retention, microbial stability, sensory acceptance, and consistency compared with direct extract incorporation. Important scale-up considerations include encapsulation efficiency, phenolic stability, coating uniformity, application rate, storage stability, production cost, and compatibility with existing fresh-cut processing operations. The principal scientific contribution of this work is the establishment of a delivery-oriented perspective for active edible coatings. Rather than asking only whether pomegranate peel extract possesses antioxidant or antimicrobial activity, the study addresses the more application-relevant question of whether controlling the temporal availability of its phenolic compounds can improve preservation of a highly perishable fresh-cut fruit.

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The integration of release behavior with physicochemical, nutritional, microbiological, and sensory quality parameters provides a stronger basis for evaluating the real functionality of bioactive edible coatings. In conclusion, controlled-release pomegranate peel phenolics incorporated into pectin coatings represent a promising strategy for improving the preservation of fresh-cut guava while simultaneously adding value to pomegranate-processing by-products. The approach has potential to support the development of sustainable, biodegradable, and naturally active preservation systems. Future research should validate these findings under commercial-scale conditions, optimize the encapsulation and coating formulations, establish economic feasibility, investigate long-term storage stability, and confirm consumer acceptance before industrial application.

Conclusion

The present study demonstrates the potential of pomegranate peel phenolics incorporated into a pectin-based edible coating as a sustainable active preservation system for fresh-cut guava (*Psidium guajava* L.). The study was designed around the premise that antioxidant capacity alone is not sufficient to predict preservation performance. Instead, the effectiveness of a bioactive coating depends on the availability, persistence, and release of active phenolic compounds at the fruit surface throughout storage. The comparison between free pomegranate peel extract and encapsulated pomegranate peel extract at an equivalent phenolic concentration provides an important basis for evaluating controlled-release technology. The encapsulated formulation is expected to provide a more gradual and sustained release of phenolic compounds, whereas the free extract provides greater initial availability followed by faster depletion. Sustained phenolic availability may therefore contribute to better control of enzymatic browning and microbial growth while supporting the retention of firmness, ascorbic acid, fresh appearance, and overall sensory quality and limiting weight loss during refrigerated storage.

A major scientific contribution of this work is the integration of phenolic release behavior with actual food-quality responses. Rather than evaluating pomegranate peel only on the basis of antioxidant activity measured in laboratory assays, the study considers whether controlled phenolic delivery translates into measurable improvements in fresh-cut guava preservation. This approach provides a more meaningful assessment of the functional performance of active edible coatings and helps distinguish chemical antioxidant potential from practical food-preservation effectiveness. The study also highlights the value-addition potential of pomegranate peel, an important food-processing by-product. Recovering phenolic compounds from pomegranate peel and incorporating them into a biodegradable pectin matrix provides an opportunity to combine food-waste valorization with natural preservation technology. Such an approach may contribute to the development of active, biodegradable, and potentially clean-label alternatives to conventional preservation systems.

From a commercial perspective, the value of controlled-release encapsulation depends on whether its additional processing complexity and cost are compensated by improved preservation performance, coating stability, phenolic retention, shelf-life extension, microbial control, and consumer acceptance. Therefore, future research should include

pilot-scale validation, optimization of encapsulation efficiency and release kinetics, economic analysis, storage stability, industrial coating application, and consumer studies before commercial implementation. Overall, the study supports the concept that “more antioxidant activity” is not necessarily equivalent to “better food preservation.” The temporal control of phenolic availability may be equally important as the total phenolic concentration. Thus, controlled-release pomegranate peel phenolics in a pectin coating represent a promising strategy for improving the quality and potential shelf life of fresh-cut guava while simultaneously converting a food-processing by-product into a value-added functional ingredient.

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