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Edible Antifungal Coatings Based on Litchi Chinensis Seed Starch Enriched With Pericarp Procyanidins for the Postharvest Preservation of Strawberries

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ABSTRACT

Strawberries are highly susceptible to fungal deterioration, making it necessary to search for natural strategies to prolong their postharvest life. The pericarp of litchi (*Litchi chinensis*) is a rich source of bioactive compounds, particularly procyanidins, which are recognized for their antioxidant and antimicrobial potential. In this study, procyanidins (PCs) were purified using Sephadex LH-20 and characterized by HPLC-MS. Their antifungal activity was evaluated against phytopathogenic fungi of postharvest relevance (*Fusarium* sp., *Colletotrichum* sp., *Geotrichum* sp., *Pestalotia* sp., and *Botrytis cinerea*). Subsequently, edible coatings based on wheat starch and litchi seed starch were formulated, with and without the incorporation of PCs, which were applied to strawberries stored for 96 h. The PCs showed strong antifungal activity, achieving 90%–100% inhibition of mycelial growth and sporulation, especially against *Pestalotia* sp. and *B. cinerea*. Strawberries coated with litchi starch enriched with PCs (LitPCs) showed a significant delay in fungal development, lower weight loss (3.28%), greater firmness retention, and a notable reduction in gray mold compared to control treatments. In addition, the LitPCs treatment retained higher antioxidant activity, attenuating the decline associated with senescence and microbial decomposition. These findings highlight the novelty of using litchi pericarp and seed (agro-industrial by-products) as sustainable sources for developing edible procyanidin-based coatings capable of effectively controlling postharvest fungal infection and maintaining strawberry quality.

1 | Introduction

Fruits and vegetables are highly vulnerable to a wide variety of phytopathogenic fungi, which cause rot diseases and lead to postharvest losses of up to 25% of global production, generating a considerable economic impact. Many of these microorganisms require damaged or injured tissue to establish infection, accelerating fruit deterioration through nutrient depletion and loss of commercial value. Among the main postharvest phytopathogenic fungi are *Penicillium* spp., *Alternaria alternata*, *Rhizopus stolonifer*, *Fusarium* spp., *Colletotrichum* spp., and *Botrytis cinerea* (Iglesias-Guevara and Sánchez-Torres 2024). Strawberries (*Fragaria* × *ananassa*) are particularly affected due to their high global consumption, with an annual production of approximately 8.9 million tons. However, their high-water content and delicate epidermis make them highly perishable and especially

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susceptible to fungal infections during storage. Furthermore, the loss of nutritional support from the mother plant after harvest increases lipid oxidation of the membrane, leading to greater permeability, cell leakage, and rapid deterioration, limiting their shelf life to approximately 5 days at room temperature (Xu et al. 2025).

Among postharvest pathogens, *Botrytis cinerea* stands out due to its economic relevance and aggressive behavior. This saprophytic fungus ranks second among all fungal pathogens in terms of economic and scientific importance and is capable of infecting more than 200 host species in temperate and tropical regions, causing annual losses estimated between 10 and 100 billion USD. In strawberries, gray mold caused by *B. cinerea* is considered the most severe postharvest disease, leading to fruit losses of up to 60% during storage and commercialization (Vitti et al. 2024). These characteristics make *B. cinerea* an appropriate and relevant model organism for evaluating postharvest antifungal strategies.

Given this scenario, the development of natural alternatives to control fruit spoilage has attracted increasing attention, driven by consumer concerns regarding synthetic antimicrobials, which may leave residues harmful to human health and the environment (Javanmardi et al. 2023). In this context, plant-derived bioactive compounds have emerged as promising candidates due to their safety and multifunctional properties. Litchi pericarp, an abundant agro-industrial byproduct, is particularly rich in procyanidins, which have demonstrated antioxidant, anti-inflammatory, and antimicrobial activities (Miranda-Hernández et al. 2019).

In parallel, edible coatings enriched with polyphenols have been proposed as an effective strategy to extend postharvest shelf life. These coatings act as barriers against moisture and gas exchange while serving as delivery systems for bioactive compounds, enhancing their protective effects on fresh produce (C. Yang et al. 2022). However, despite the recognized potential of procyanidins and edible coatings, limited information is available regarding the antifungal effectiveness of procyanidins extracted from litchi pericarp when incorporated into starch-based coatings under in vivo postharvest conditions. Therefore, the present study aimed to isolate and identify procyanidins from litchi pericarp and to evaluate their antifungal activity against *Botrytis cinerea* as well as their effectiveness when incorporated into starch-based edible coatings for the postharvest preservation of strawberries.

2 | Materials and Methods

2.1 | Plant Material

Litchi fruits (*Litchi chinensis*) were harvested in May 2022 from an orchard located in Huehuetlán, San Luis Potosí, Mexico, at an elevation of 380 m above sea level. The pericarp was dehydrated at room temperature, avoiding direct exposure to sunlight, and subsequently ground into a fine powder with an approximate particle size of 300 μm using a grinder (Model HC-700). The material was stored under controlled conditions at 25 ± 2°C until further analysis.

2.2 | Bioactive Compound Extraction and Purification

The litchi pericarp was dried and pulverized, followed by ultrasound (model 2510, BRANSON, USA, 40 Hz) extraction under the following conditions: solid/liquid ratio 1:23, temperature 47°C, ethanol concentration 52% for 20 min. To obtain the purified compounds, the method using Sephadex LH-20 (GE Healthcare Bio-Sciences AB SE-751 84 Uppsala, Sweden) was applied. First, Sephadex LH-20 (60 g) was suspended in water and hydrated for 72 h before it was manually packed in an open column. The crude extract of litchi pericarp (2 g in absolute ethanol) will be applied directly to the chromatographic packing, previously equilibrated with water, and subsequently, the mobile phase will be eluted: 0–4 h with water, 4–6 h with ethanol, and 6–7 h with acetone/water (70%, v/v). The fractions will be manually grouped for each solvent in the elution and evaporated under vacuum to remove the organic solvents. Finally, 3 fractions (aqueous, ethanol, and acetone) will be obtained (Wong-Paz et al. 2015).

2.3 | Identification by HPLC-MS

High-performance liquid chromatography was used for the identification of the fractionated compounds under the following conditions: an autosampler (Varia ProStar 410), including a ternary pump and PDA detector (Varian ProStar 330), with an ion trap mass spectrophotometer (Varian 500 MS IT), was used with an electrospray ion source. A Denali C18 column (150 mm × 2.1 mm, 3 μm; Grace, USA) with a temperature of 30°C, 3% v/v acetic acid (solvent A), acetonitrile (solvent B), and a flow rate of 0.3 mL/min was used as a mobile phase. The gradient was as follow: 3% B at the beginning continuing with a linear increase to 9% from 0 to 5 min, 16% B in 5–15 min, and 50% B from 15 to 45 min. Subsequently, the column was washed and conditioned. The volume output was injected directly into the mass spectrometer source, without partitioning and in negative [MH]-1 mode. Nitrogen was used as nebulizer gas and helium as buffer. Ion source conditions were as follows: voltage 5.0 Kv and capillary voltage and temperature 90.0 V and 350°C. Data were analyzed in MS Workstation V 6.9 software. The samples were scanned in the m/z range 50–2000. Finally, the compounds were identified in a database of bioactive compounds (WorkStation Version 2.0 database, VARIAN, Palo Alto CA, USA) (Miranda-Hernández et al. 2019).

2.4 | Hydrolyzable Tannins

The quantification of hydrolyzable tannins in the aqueous (AF), ethanolic (EF), and acetone (AcF) fractions was performed by the Folin–Ciocalteu method (Wong-Paz et al. 2015). A 20 μL aliquot of the sample was mixed with 20 μL of Folin–Ciocalteu reagent in a well. After 5 min, 20 μL of Na_2CO_3 (0.01 M) was added for 5 min, then diluted with 125 μL of distilled water and measured at 790 nm using a Biobase EL10 A spectrophotometer (Biobase Biodustry, China). The results were expressed as mg AGE/g DB.

2.5 | Condensed Tannins

The quantification of condensed tannins in the aqueous (AF), ethanolic (EF), and acetone (AcF) fractions was determined by the HCl-Butanol technique (Valencia-Hernández et al. 2022). 250 μL of sample was mixed with 1.5 mL of HCl-Butanol and 50 μL of ferric reagent NH_4Fe (SO_4), mixed by vortexing, and placed in a water bath at 95°C for 40 min. The samples were allowed to cool and transferred to a microplate and measured at 550 nm using a Biobase EL10 A spectrophotometer (Biobase Biodustry, China). The results were expressed as mg ECatechin/g DB.

2.6 | Evaluation of Antioxidant Activity

Antioxidant activity in the aqueous (AF), ethanolic (EF), and acetone (AcF) fractions was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (diammonium 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonate), and FRAP (ferric reducing antioxidant power) techniques. Based on these results, the fraction with the highest antioxidant activity was selected for subsequent antifungal assays.

2.6.1 | DPPH Radical Inhibition

For DPPH radical inhibition, prepare a 60 μM solution in methanol. Subsequently, in a 96-well microplate, 7 μM of the sample was mixed with 193 μM of the DPPH solution and kept in the dark for 30 min. After this time, the absorbance was measured at 517 nm, using methanol as a blank, using a Biobase EL10 A spectrophotometer (Biobase Biodustry, China), and the results were expressed in mg ETrolox/g DB (Brand-Williams et al. 1995).

2.6.2 | ABTS Radical Inhibition

An aqueous solution of potassium persulfate (2.45 mM) and ABTS (7 mM) was prepared in a 1:2 ratio and kept in the dark for 12 h. Subsequently, a solution adjusted to an absorbance of 0.700 nm with ethanol was prepared. From this solution, 190 μL of adjusted ABTS was taken, 10 μL of sample was added, and the absorbance was measured at 734 nm using a Biobase EL10 A spectrophotometer (Biobase Biodustry, China). The results were expressed in mg ETrolox/g DW (Estrada-Gil et al. 2022).

2.6.3 | FRAP Assay

The reaction was performed by adding 10 μL of sample to a 96-well microplate, followed by 290 μL of FRAP reagent, incubation at 37°C for 15 min, and reading at 593 nm using a Biobase EL10 A spectrophotometer (Biobase Biodustry, China). The results were expressed in mg ETrolox/g DW (Casas-Rodríguez et al. 2024).

2.7 | Evaluation of Antifungal Activity

Since the acetone fraction (AcF) exhibited the highest antioxidant activity, it was dried at 40°C in an incubator (Quincy Lab, series 140, model 12-140), and, from this point onward, it is referred to as purified procyanidins (PCs).

Antifungal activity was evaluated using the poisoned medium method (Rojas et al. 2020). The microbial strains *Fusarium* sp. (isolated from tomato crops in Sinaloa, Mexico), *Colletotrichum* sp. (isolated from papaya soil), *Geotrichum* sp. (isolated from postharvest tomato), *Botrytis cinerea*, and *Pestalotia* sp. (isolated from strawberry and raspberry) used in this study were isolated and provided by Greencorp Biorganiks de México S.A. de C.V. The strains were cryopreserved and reactivated on potato dextrose agar (PDA) before use. The PDA was prepared and sterilized in an autoclave (Presto, model 79291). After cooling, purified procyanidins (PCs) were mixed in different concentrations (62.5, 125, 250, and 500 ppm) and poured into petri dishes. Subsequently, a 0.5 cm diameter explant of each microorganism was placed in the center of the plate and incubated at 37°C in an incubator (Sheldon Manufacturing Ing., model G16, USA). Radial growth was measured with a Vernier caliper, and photographic evidence was recorded.

Wheat starch and litchi seed were extracted with 0.25% NaOH in a 1:10 ratio at a temperature of 30°C in an incubator shaker at 150 rpm (New Brunswick Scientific, model Innova 44, USA) for 11 h (Kaur et al. 2024). The coating was then prepared with 3% starch and 50% glycerol (w/w) at 95°C on a heating plate (Barnstead International, model SPI31325, USA) for 20 min (Alemu et al. 2022). Once the time had elapsed, it was left to cool and the procyanidins were added.

For the application of the coating, fresh strawberries from the local market were selected (10 per treatment), disinfected with 2% chlorine, and then dried at room temperature. For application to the strawberries, they were immersed for 3–5 s in 100 mL of different coating solutions prepared for each treatment and contained in beakers: control without any treatment (Ctrl), control with wheat starch only (CtrlW), wheat starch with procyanidins (WPCs), litchi seed starch (CtrlLit), and litchi seed starch with procyanidins (LitPCs) solutions and left to dry at room temperature. Each strawberry was immersed in a sterile solution containing of 1×10^3 spores/mL of *Botrytis cinerea* under aseptic conditions in a laminar flow hood (Scorpion Scientific, model A-80000, Biobase, China), allowed to dry at room temperature, and stored at 4°C in a refrigerator (Mabe, model MH0-77V09). Samples were taken at 0, 48, and 96 h and evaluated for weight loss rate, hardness, color, pH, °Brix, and antioxidant activity of the strawberries (C. Yang et al. 2022; Yu et al. 2024).

2.8 | Statistical Analysis

Statistical analysis was performed using analysis of variance (ANOVA), followed by Tukey's multiple comparison test, with a significance level of $p < 0.05$ to identify significant differences between treatments.

3 | Results and Discussion

3.1 | Determination of Polyphenol Content and Identification by HPLC-MS

Partial purification of the crude extract of litchi pericarp was performed by open column chromatography using Sephadex LH-20, yielding three fractions: aqueous (AF), ethanolic (EF), and acetone (AcF). Figure 1 shows the content of hydrolyzable tannins (HT) and condensed tannins (CT), which ranged from 21 to 207 mg EGA/g DB and 44–626 mg EC/g DB. These results coincide with those reported by Xie et al. (2023), who obtained 142 mg EAG/gBS of hydrolyzable tannins, and are higher than those reported by Tan et al. (2024). The results obtained show a higher tannin content in the AcF fraction ($p > 0.05$) compared to the AF and EF fractions. Separation using the Sephadex LH 20 chromatographic method is widely used in the separation of polyphenolic and nonpolyphenolic compounds (Toro-Uribe et al. 2020), either by size exclusion or solvent affinity, and a wide variety of solvents, such as water, alcohols, ketones, and ethers, can be used. Separation is mainly determined by the molar mass and differences in hydrogen bonds between the components dissolved in the mobile phase and the matrix (Křenek et al. 2014).

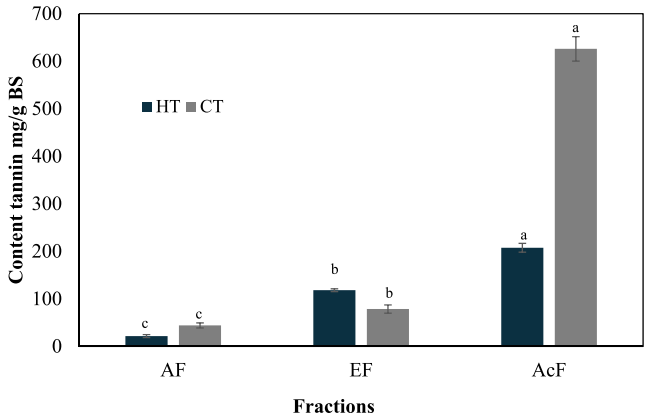


FIGURE 1 | Hydrolyzable tannin (HT) and condensed tannin (CT) content of fractions obtained from *Litchi chinensis* pericarp extract. Aqueous fraction (AF), ethanolic fraction (EF), and acetone fraction (AcF).

The results obtained show that fractionation with Sephadex LH-20 allows efficient separation of the bioactive compounds present in the litchi pericarp according to their polarity and molecular weight (Chen et al. 2023).

The qualitative profile of the bioactive compounds in each fraction was identified using HPLC-MS and is shown in Table 1. In the aqueous fraction (AF), hydroxycinnamic acids, such as caffeic acid 4-O-glucoside and 1-caffeoylquinic acid, were mainly identified. Flavonoids and other phenolic compounds were identified in the EF, including galagyl hexoside, catechol, (+)-catechin, (−)-epicatechin, and rutin or its isomer. In the AcF, mainly condensed tannins (flavonoids) of the procyanidin type were detected, such as procyanidin type B dimer, procyanidin type A trimer, and procyanidin type A dimer. These results are consistent with those described by Tan et al. (2024), who, after purification using a macroporous LX-7 resin with a separation principle similar to Sephadex LH-20, were able to identify catechin, procyanidins A2, and B1. This suggests that these metabolites are characteristic of the litchi pericarp.

3.2 | Biological Activity

3.2.1 | Antioxidant Activity

Antioxidant activity determined by DPPH, ABTS, and FRAP radical inhibition showed a marked difference between the fractions obtained (Figure 2). The ethanol fraction (EF) and acetone fraction (AcF) showed greater free radical scavenging

TABLE 1 | Identification of bioactive compounds in fractions obtained from partial purification of the optimized extract of Litchi chinensis pericarp.

T	Time	M-Z	Tentative compound	Family
Aqueous fraction				
1	11.85	340	Caffeic acid 4-O-glucoside	Hydroxycinnamic acids
2	9.48	352.6	1-Caffeoylquinic acid	
Ethanolic fraction				
1	17.88	780.2	Galagyl-hexoside	—
2	36.16	108.9	Catechol	—
3	45.05	288.9	(+)-catechin	Flavonoid
4	48.02	288.9	(−)-epicatechi	Flavonoid
5	49.24	608.8	Quercetin rhamnosyl-glucoside (Rutin) or rutin isomer	Flavanols
Acetone fraction				
1	41.83	576.8	Procyanidin type B dimer	Flavonoid
2	45.05	862.6	Procyanidin type A trimer	Flavonoid
3	48.02	862.5	Procyanidin type A trimer	Flavonoid
4	49.27	574.9	Procyanidin type A dimer	Flavonoid

capacity against DPPH 2400 mg eqTrolox/gBS, and the AcF fraction showed greater activity in the ABTS (2200 mg eqTrolox/gBS) and FRAP (1700 mg eqTrolox/gBS) assays. In contrast, the aqueous fraction (AF) exhibited considerably lower values compared to EF and AcF.

The results obtained show that antioxidant activity is strongly influenced by the compounds present, identified in Table 1. The fraction with the highest antioxidant activity was FcA, which is consistent with the condensed tannin content (Figure 1) and, according to HPLC analysis, this fraction contains type A and B procyanidins. The literature reports that procyanidins contain multiple phenolic hydroxyl groups in their structure, which gives them the ability to donate electrons, conferring antioxidant activity (S. Li et al. 2012; X. Li et al. 2018; Sui et al. 2021). This process can occur through the abstraction of a hydrogen atom at the C2 position by the DPPH radical, generating a quinone meturo intermediate. Subsequently, an intermolecular rearrangement occurs, leading to the formation of an ether bridge between carbons C2u and C7t. At that moment, the DPPH radical (violet color) is reduced to DPPH-H (yellow color)

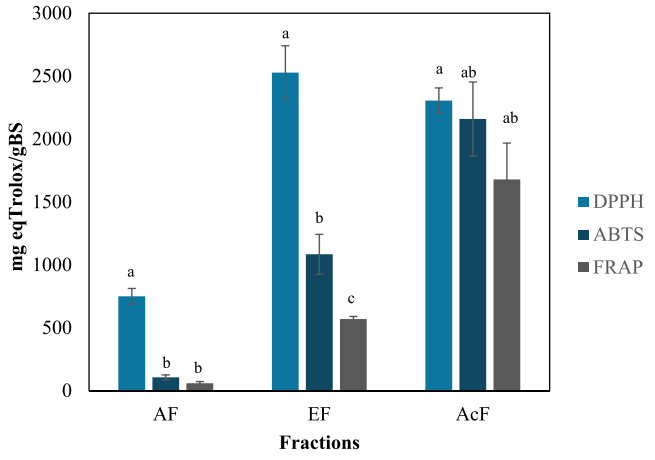


FIGURE 2 | Antioxidant activity of fractions obtained from *Litchi chinensis* pericarp extract expressed in mg eqTrolox/g dry weight.

(Fischer et al. 2025). This may explain the increase in antioxidant activity observed in AcF, which is rich in procyanidins. This high antioxidant capacity not only contributes to the neutralization of free radicals but is also associated with various biological activities, such as antimicrobial (Sui et al. 2016), which is why the AcF fraction was selected to continue with antifungal evaluations due to its antioxidant activity, due to the presence of procyanidins.

3.2.2 | Antifungal Activity

The antifungal activity of AcF, now called procyanidins (PCs), was evaluated against five phytopathogenic fungi of postharvest importance (*Geotrichum* sp., *Colletotrichum* sp., *Fusarium* sp., *Pestalotia* sp., and *Botrytis* cinerea) over a period of 5 days to determine their effectiveness as natural control agents. Figure 3 shows that all concentrations evaluated (62.5–500 ppm) had an inhibitory effect. *Botrytis cinerea* and *Pestalotia* sp. were the most sensitive fungi, with an inhibition percentage reaching more than 95% even at the lowest concentration. Hou et al. (2020) report obtaining more than 80% inhibition against *B. cinerea*; however, this was with a crude polyphenol extract at a concentration of 200 ppm, unlike this study, which obtained more than 90% inhibition at a lower concentration (62.5 ppm). *Fusarium* sp and *Colletotrichum* sp showed intermediate inhibition rates of around 70%–80%. Rojas et al. (2020) report obtaining between 30% and 50% inhibition for *Fusarium oxysporum* and *Colletotrichum gleosporoides* from polyphenols extracted from mango peel. On the other hand, Lahmar et al. (2017) they report achieving 75% inhibition of *Fusarium oxysporum* with a crude extract of *Pergularia tomentosa* containing condensed tannins, although this was at a concentration of 1000 ppm. In contrast, *Geotrichum* sp. showed lower susceptibility, with inhibition values ranging from 50% to 62% at all concentrations evaluated.

Figure 4 shows an optical microscopy analysis stained with cotton blue. Figure 4a shows the control of *Fusarium* sp without treatment, where abundant mycelium with thick hyphae and

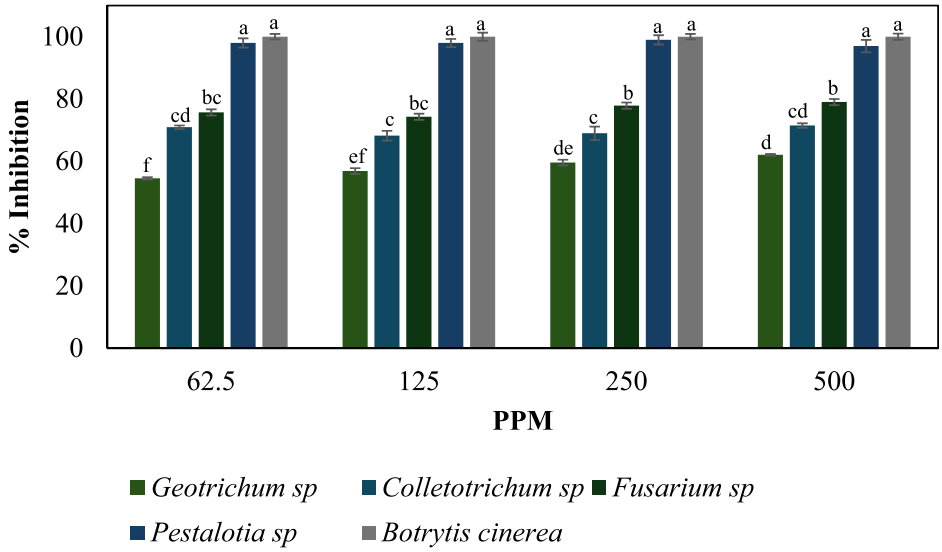


FIGURE 3 | Antifungal activity of purified procyanidins from *Litchi chinensis* pericarp extract expressed as % inhibition.

numerous spores can be observed. Figure 4b shows treatment with PCs at 500 ppm, where a thinner and more dispersed mycelium is observed, with no spores present. This may be due to procyanidins and other phenolic compounds that exert their antifungal activity mainly by disrupting the fungal cell membrane, inhibiting essential enzymes, and altering cell morphology. The hydroxyl groups in their structure interact with the lipids in the membrane, destabilizing it and causing the release of essential molecules, such as ATP, which leads to cell death. In addition, these compounds can inhibit enzymes crucial to the survival of the fungus, such as pectinases and cellulases, affecting its ability to infect and degrade host tissues. They can also induce deformations in the fungal mycelium and cytoplasmic coagulation, affecting cell functionality. At the same time, procyanidins can strengthen the host's cell wall, creating a physical barrier that prevents pathogen penetration. These combined mechanisms result in the loss of cellular integrity of the fungus and its eventual death, providing an effective defense against fungal infections (Lahmar et al. 2017).

Figure 5 shows the antifungal activity of PCs against *Fusarium* sp, *Colletotrichum* sp, *Geotrichum* sp, *Pestalotia* sp, and *Botrytis cinerea* at different concentrations (500, 250, and 125 ppm) compared to the untreated control. In the control plates, all fungi showed abundant and homogeneous mycelial growth, covering almost the entire medium. However, as the concentration of PCs increased, a progressive inhibition of fungal growth was observed. These results confirm that PCs exert an antifungal effect, being most effective against *Botrytis cinerea*, followed by *Pestalotia* sp. Therefore, in the next section, *Botrytis cinerea* was selected for in-vivo evaluation.

3.3 | Application of PCs Coatings to Strawberries

3.3.1 | Physicochemical of Strawberries

Figure 6 shows the effect of starch coatings with PCs on the preservation of strawberries inoculated with Botrytis cinerea during 96 h of storage. In the control treatments, which are untreated strawberries (Ctrl) and wheat starch control (CtrlW), rapid development of fungal colonies was observed, with severe rot at 96 h. These results coincide with those reported by Wang et al. (2025), who observed obvious symptoms of infection from the first day, which intensified after 3 days. Similarly, the wheat starch coating (WPCs) showed obvious mycelium growth, although slightly less than in the controls. In contrast, strawberries treated with lychee starch (CtrlLit) showed less progression of infection, whereas treatment with lychee starch with PCs (LitPcs) was the most effective as it delayed mycelial growth by 96 h compared to the control, which coincides with the findings of Lin et al. (2025), who observed that the application of proanthocyanidins significantly reduced rot by up to 50% after 6 days. On the other hand, *Botrytis cinerea* can produce toxins and enzymes, such as pectinases, cellulases, and polygalacturonases, that damage the cell wall and induce necrosis in cell tissues (Kunadu et al. 2025; Leite et al. 2023). In this study, the starch coating, mainly lychee seed starch with the incorporation of PCs, acted as a physical barrier to inhibit or delay the infection process (Wang et al. 2025).

Weight loss is an essential indicator for assessing the postharvest quality of fruits as it is closely related to water loss caused by transpiration and respiration. In the case of strawberries, their thin and fragile skin makes them more susceptible to dehydration, which causes wilting, tissue shrinkage, and a decrease in firmness. These parameters not only affect their appearance and sensory attributes, such as color and aroma, but also favor the development of pathogens (Kumar et al. 2025; Mou et al. 2025). Table 2 shows the results of weight loss. The control treatments (Ctrl and CtrlW) showed a weight loss of 13.6% and 35% in 96 h. Meanwhile, the WPCs treatment recorded the highest loss of 50%. In contrast, the lychee starch and PCs treatments were the most effective in reducing weight loss, with values of 4% and 3%, indicating better control of dehydration.

Firmness is another parameter for evaluating fruit quality, and it tends to decrease during storage. This is due to the degradation of pectin and other cell wall components (W. Yang et al. 2024). In addition, enzymes produced by the fungus, such as pectinases and cellulases, degrade the cell wall, leading to a loss of firmness (Kunadu et al. 2025). Table 2 shows the results obtained for firmness from 0 to 48 h, where a progressive

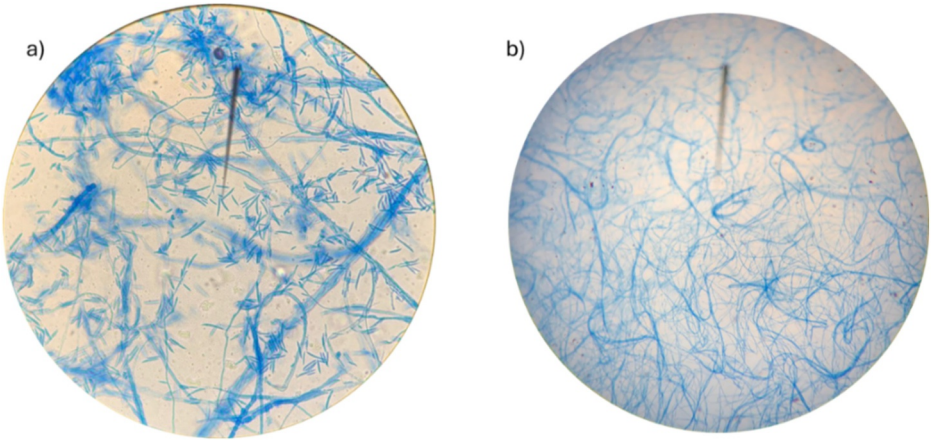


FIGURE 4 | Antifungal activity, (a) control of *Fusarium* sp without treatment and (b) treatment with PCs at 500 ppm observed under a microscope (40X), PDA medium, incubated at 28°C for 5 days.

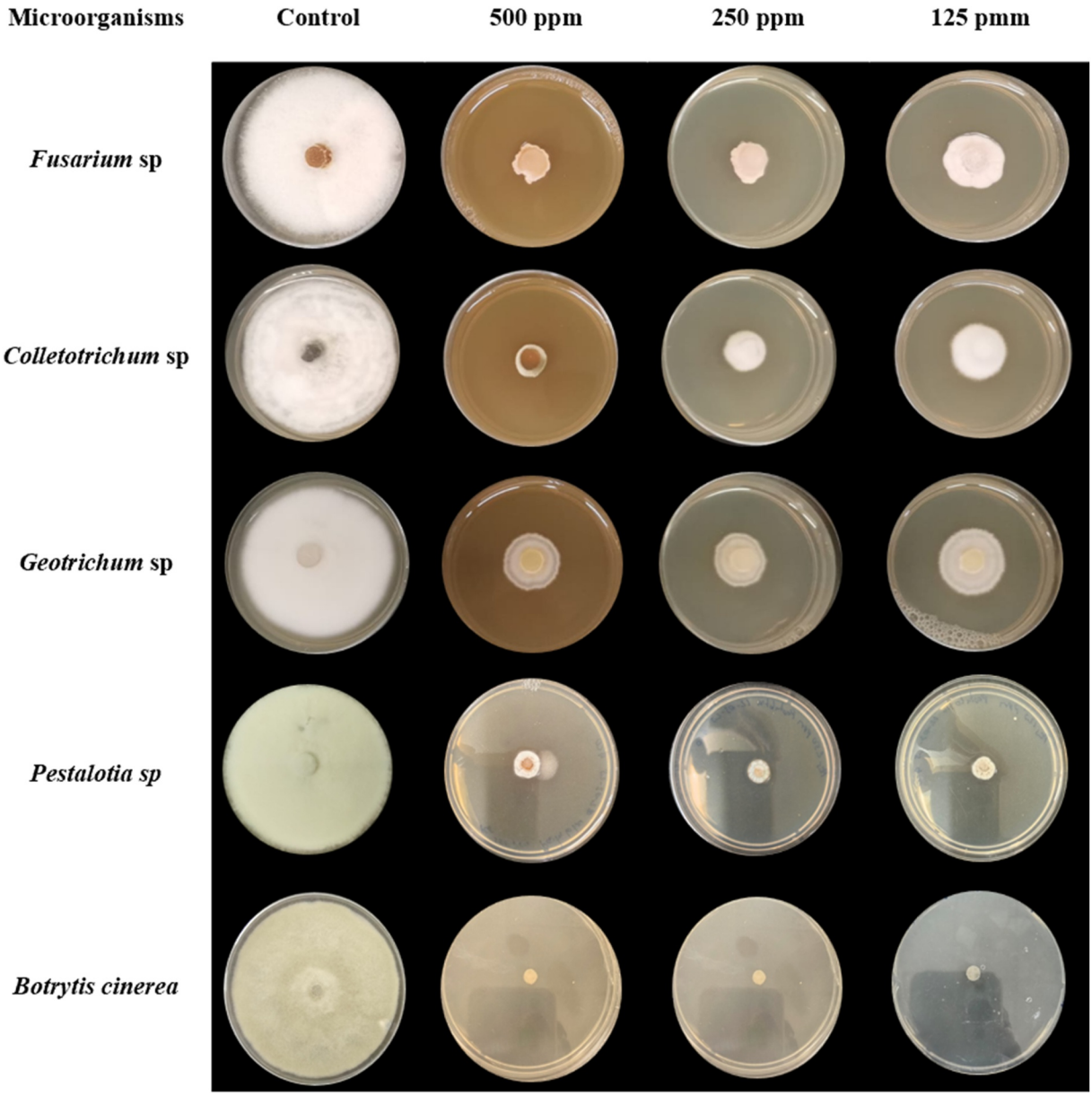


FIGURE 5 | Photographs of the antifungal activity of PCs against phytopathogenic fungi, *Fusarium* sp, *Colletotrichum* sp, *Geotrichum* sp, *Pestalotia* sp, and *Botrytis cinerea* for 5 days.

decrease is observed in all treatments during storage, being more evident in the controls (Ctrl and CtrlW). Strawberries treated with litchi starch (CtrlLit and LitPCs) maintained higher firmness values compared to the other groups, reflecting a delay in tissue softening. Color is a quality parameter that impacts consumer perception of fruit freshness. Figure 7 shows the results obtained for strawberry color with the treatments; however, no changes were observed during storage. These results are consistent with those reported by Lin et al. (2025).

The pH remained stable during storage between 3.4 and 3.60, indicating that the application of the coatings did not alter the acidity of the strawberries (Yıldırım-Yalçın et al. 2022). Soluble solids ranged between 6.3 and 7.4°Brix during the first 48 h; however, at 96 h, a decrease between 4.6 and 5.6°Brix was observed. These results are contrary to those reported by Kumar et al. (2025), who report soluble solids between 8.4 and 8.57, attributing this high soluble solids content to rapid water loss. This indicates that starch coatings and PCs can slow down water loss, and PCs may also be inhibiting the enzymes that degrade the cell wall. It should be noted that the incorporation of polyphenols in a coating acts as an antioxidant agent, limiting oxygen diffusion, which contributes to lower generation of reactive oxygen species and preservation of cell membrane integrity, thereby reducing the rate of water loss (Yıldırım-Yalçın et al. 2022). Initial values ranged from 0.46 to 51, increasing to a range of 0.81–0.86 at 96 h. Acidity is an important indicator of fruit preservation as acid reduces the growth of microorganisms and inhibits degradation enzymes. Titratable acidity also affects texture, flavor, and organoleptic profile (Leite et al. 2023). On the other hand, the titratable acidity of strawberries showed a progressive increase during storage (Table 2). This increase may be due to the degradation of sugars that are used as substrates in metabolic processes (W. Yang et al. 2024).

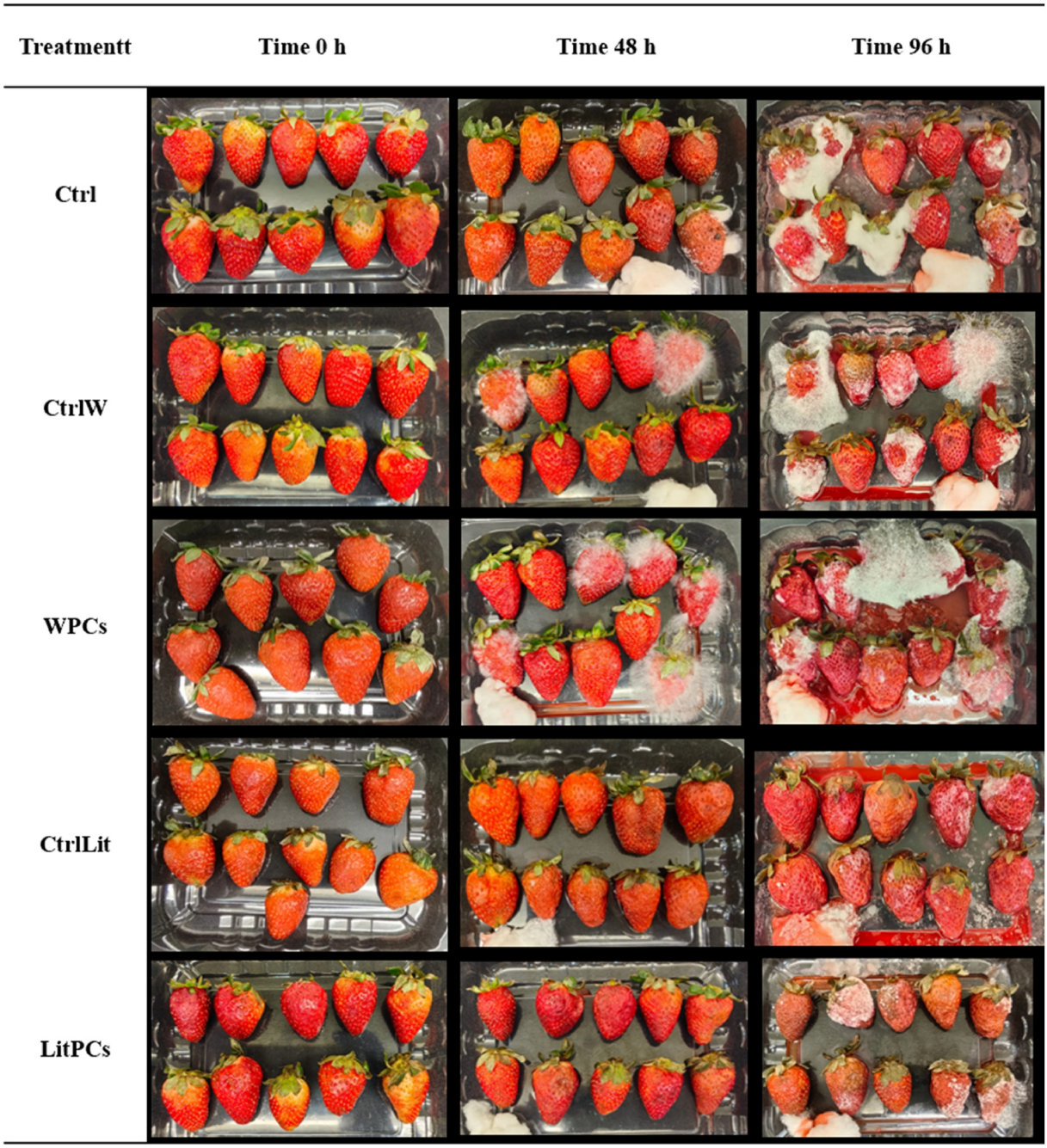


FIGURE 6 | Photographs of strawberries during storage (0, 48, and 96 h).

3.3.2 | Antioxidant Activity of Strawberries

Figure 8 shows the percentage of DPPH radical inhibition in strawberries subjected to different treatments during storage. The Ctrl initially showed the highest antioxidant capacity (65%), followed by CtrlW, WPCs, and CtrlLit (50%), whereas the LitPCs treatment showed the lowest value (30%). However, at 48 h, the CtrlW, WPCs, and CtrlLit treatments remained stable (50%–57%), whereas LitPCs showed an increase (55%) and Ctrl decreased (42%). After 96 h of storage, a decrease below 35% was observed, except for CtrlLit and LitPCs, which remained stable in the range of 45%–50%. The decrease in antioxidant activity can be attributed to senescence processes and microbial decomposition (Kumar et al. 2025). In this regard, the LitPCs treatment managed to delay the loss of antioxidant activity, suggesting that the incorporation of PCs in starch coatings provides additional protection to the tissue during storage.

4 | Conclusion

This study demonstrates the novel valorization of litchi (*Litchi chinensis* Sonn.) pericarp as a sustainable source of bioactive procyanidins and their functional integration into edible starch-based coatings for postharvest applications. The purified procyanidins, identified as types A and B by HPLC-MS, showed

TABLE 2 | Quality parameters of strawberries during postharvest storage.

Treatment	Weight loss (%)	Firmness (*N*)		pH			°Brix			Titratable acidity		
		0 h	48 h	0	48	96	0	48	96	0	48	96
Ctrl	13.62	0.93 ± 0.53	1.03 ± 0.3	3.6 ± 0.05	3.5 ± 0.03	3.5 ± 0.01	6.4 ± 0.54	6.8 ± 0.44	4.6 ± 0.4	0.47 ± 0.04	0.60 ± 0.06	0.86 ± 0.19
CtrlW	35.21	1.1 ± 0.50	0.89 ± 0.5	3.5 ± 0.04	3.5 ± 0.06	3.4 ± 0.04	6.3 ± 0.8	6.2 ± 1	4.6 ± 0.5	0.51 ± 0.09	0.55 ± 0.07	0.83 ± 0.17
WPCs	50.32	1.45 ± 0.4	0.39 ± 0.2	3.6 ± 0.19	3.5 ± 0.04	3.5 ± 0.009	7.4 ± 0.5	7.4 ± 0.89	5.6 ± 2	0.46 ± 0.08	0.54 ± 0.04	0.81 ± 0.16
CtrlLit	4.07	1.35 ± 0.6	1.3 ± 0.2	3.5 ± 0.09	3.6 ± 0.13	3.4 ± 0.07	7.1 ± 0.7	6.4 ± 1.5	5.2 ± 0.95	0.49 ± 0.07	0.51 ± 0.06	0.86 ± 0.08
LitPCs	3.28	1.35 ± 0.2	0.95 ± 0.4	3.5 ± 0.04	3.5 ± 0.03	3.4 ± 0.05	7.4 ± 0.89	7.1 ± 0.7	5.5 ± 0.57	0.51 ± 0.05	0.56 ± 0.05	0.85 ± 0.1

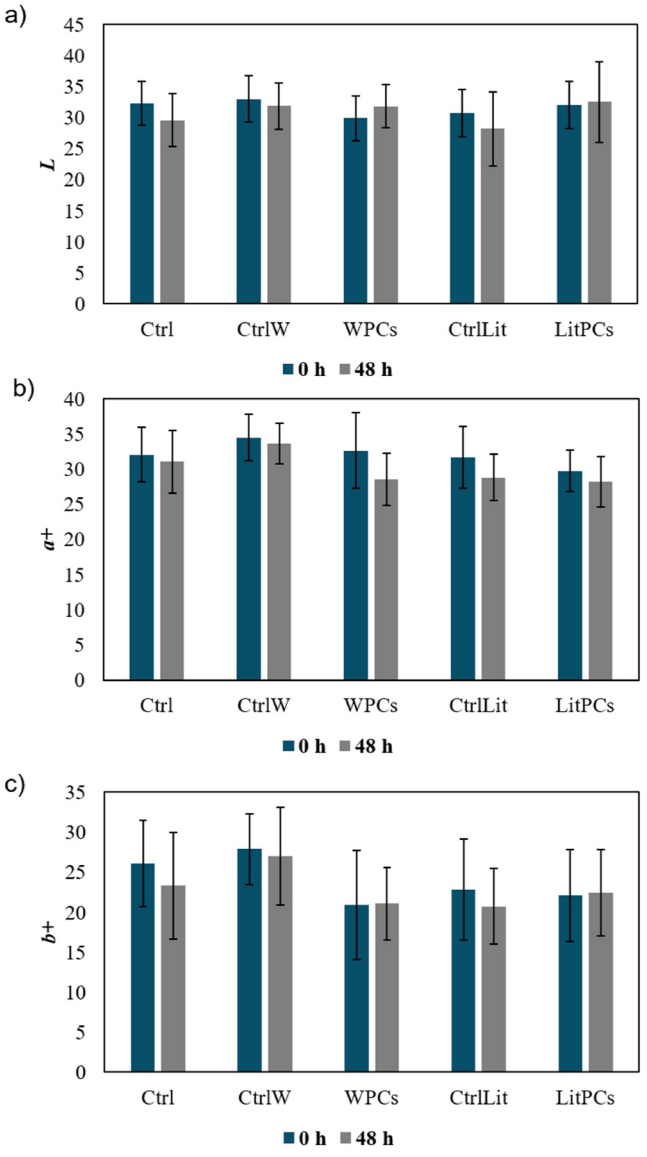


FIGURE 7 | Color values of strawberry samples (a) *L (Luminosity)*, (b) *a+ (tendency toward red tones)*, and (c) *b+ (tendency toward yellow tones).*

high antioxidant capacity and strong in vitro antifungal activity against major phytopathogenic fungi. When incorporated into litchi starch-based coatings, these compounds effectively delayed the development of *Botrytis cinerea* in strawberries, reduced weight loss, maintained firmness, preserved key physicochemical parameters, and maintained antioxidant activity during refrigerated storage.

Despite these promising findings, some limitations should be acknowledged, such as the laboratory scale of the experiments, the relatively short storage period evaluated, and the focus on a single fruit-pathogen system. Furthermore, in vivo antifungal performance can be influenced by interactions between the bioactive compounds and the food matrix as well as by environmental storage conditions.

Future research should focus on optimizing procyanidin concentrations, exploring synergistic effects with other

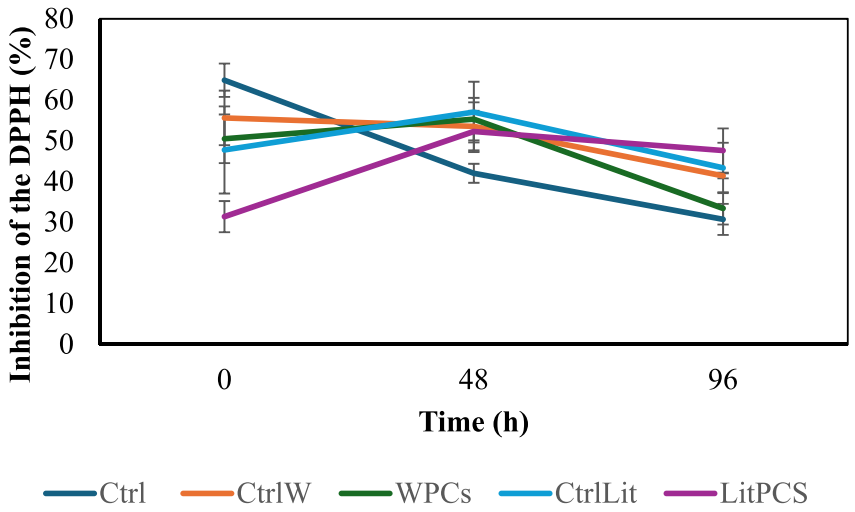


FIGURE 8 | Percentage of DPPH radical inhibition in strawberries.

antimicrobials or natural biopolymers, and investigating controlled-release mechanisms in starch-based matrices. In addition, validation under commercial storage conditions and scale-up studies will be essential to confirm the practical and industrial applicability of these active coatings as natural alternatives for postharvest preservation in the agrifood industry.

Author Contributions

G.C.O.: conceptualization, methodology, formal analysis, writing – review and editing. J.S.C.: methodology, supervision. J.A.A.V.: methodology, supervision. O.B.A.P.: methodology, supervision. J.E.W.P.: methodology, supervision. M.L.F.L.: methodology, supervision. C.N.A.: conceptualization, supervision, formal analysis, writing – review and editing, visualization, project administration, funding acquisition.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data and materials are available by direct request.

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