Passiflora edulis peel extracts applied as an edible coating on strawberry (*Fragaria* × *ananassa*)

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ABSTRACT

This study evaluated the antioxidant and antifungal potential of ethanolic extracts obtained from passion fruit (*Passiflora edulis*) peel and their application as an active edible coating for extending the postharvest life of strawberry (*Fragaria* × *ananassa*). Peels from two botanical forms of *Passiflora edulis* (*P. edulis* f. *flavicarpa* and *P. edulis* f. *edulis*) and one additional species (*Passiflora ligularis*) were characterized in terms of color, extraction yield, and antioxidant activity using DPPH and ABTS assays. The antifungal activity of *P. edulis* peel extract against *Rhizopus stolonifer* was evaluated through a radial growth inhibition at concentrations ranging from 500 to 3000 ppm. The extract was incorporated into a carboxymethylcellulose-based edible coating and applied to strawberries by immersion. During 17 days of storage, color (CIELab parameters) and weight loss were monitored. *Passiflora edulis* showed the highest extraction yield and antioxidant capacity, particularly by the ABTS method. The extract exhibited a strong dose-dependent antifungal effect, with higher concentrations showing a marked reduction of mycelial growth under *in vitro* conditions. Coated strawberries showed greater stability in color parameters (L*, a*, and b*) and significantly reduced weight loss compared to the control, indicating delay in some physical changes associated with senescence. These results suggest that *P. edulis* peel, an agro-industrial by product, represents a promising source of bioactive compounds for the development of functional edible coatings capable of improving strawberry postharvest quality.

Key words: *Passiflora edulis*; edible coating; strawberry; antioxidant activity; antifungal control.

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INTRODUCTION

Among the most perishable fruits traded globally are berries, prized for their high antioxidant properties. In this regard, the strawberry (*Fragaria* × *ananassa*) is a fruit in high commercial demand due to its numerous sensory characteristics, nutritional value, and nutraceutical properties. This has led to a surge in demand and rapid expansion of

the strawberry industry in recent years, solidifying its position as a vital component of the global fruit sector (Hernández-Martínez *et al.*, 2023). However, its shelf life is limited due to its high metabolic activity, water activity, and nutrient content, resulting in a high susceptibility to fungal growth and proliferation during post-harvest storage (Saleh & Abu-Dieyeh, 2022). Therefore, preserving the fruit using various conservation techniques is essential.

Several studies have incorporated coatings as a strategy to improve the post-harvest preservation of berries. These coatings act as a protective barrier, helping to reduce various factors such as moisture loss, respiration rate, and microbiological deterioration caused by fungi and bacteria, thus extending shelf life. Furthermore, different natural compounds with biological activity (essential oils, antioxidants, antimicrobials, extracts) have been incorporated into the coatings, demonstrating greater efficacy, primarily in terms of microbiological control (Colin-Alvarez *et al.*, 2025).

In addition to the above, there is a growing interest in utilizing agro-industrial waste as a source of bioactive compounds. In this regard, the peels of *Passiflora* spp., particularly *Passiflora edulis*, are of high interest due to their high content of phenolic compounds and flavonoids (Rentería-Ortega *et al.*, 2023), with antioxidant, antimicrobial, and antifungal properties. Several studies have reported that extracts obtained from this biomass exhibit antifungal activity against microorganisms associated with food spoilage.

However, despite numerous studies in the literature reporting on the antioxidant capacity and bioactive composition of byproducts from various Passiflora varieties, as well as their application in the manufacture of edible films and coatings, there is currently limited information on the incorporation of Passiflora peel extracts into active coating systems specifically designed to control microorganisms such as *Rhizopus stolonifer* in the post-harvest stage. Therefore, this study evaluates the antioxidant and antifungal potential of Passiflora peel extracts and their application as a functional component in a carboxymethylcellulose based edible coating to extend the fruit's shelf life.

MATERIALS AND METHODS

Materials

Strawberry fruits (*Fragaria* × *ananassa*) were purchased from a local market in San Felipe del Progreso, State of Mexico, Mexico. The fruits were selected based on commercial maturity and uniform external quality attributes, including similar size, homogeneous red surface coloration, and absence of visible mechanical damage or fungal decay.

For the antifungal capacity tests, the fungus *Rhizopus stolonifer* was used and maintained in potato dextrose medium at room temperature until use in the trials.

In addition, passion fruit samples corresponding to two botanical forms of *Passiflora edulis* (*P. edulis* f. *flavicarpa* and *P. edulis* f. *edulis*) and one additional species (*Passiflora ligularis*) were obtained from a local market in Atlacomulco de Fabela, State of Mexico, Mexico. The fruits were selected at a semi-ripe stage based on external color and absence of visible deterioration. Because the plant material was obtained from commercial sources, no formal botanical voucher specimen or batch code was available.

Methods

Sample preparation

The fruit peel was manually removed and cut into approximately 0.5 cm×0.5 cm pieces. Subsequently, the material was dried in a food dehydrator (Rommelsbacher DA 900) at 35 °C for 12 h until reaching approximately 3% moisture content. The dried material was then ground using a coffee blade mill (Masterchef By Huken MK-CG-SS) and further subjected to manual size reduction using a mortar and pestle to obtain a finer powder. The resulting material was sieved through a series of progressively finer meshes, and the fraction corresponding to particles smaller than 1 μm was collected for subsequent extraction.

Soxhlet extraction

The extraction was performed using the Soxhlet method, as described by Castillo-Membreno & Ramírez, (2006), with modifications. Ten grams of the previously prepared sample were weighed, transferred to a cellulose cartridge, and placed in the extraction apparatus. Then, 250 mL of 96% ethanol was used as solvent, and the extraction was carried out under continuous reflux conditions for 5.5 h. The heating plate was set at approximately 180 °C to ensure that the solvent reached and maintained its boiling point (≈78 °C), thereby promoting continuous evaporation-condensation cycles within the Soxhlet system

To remove the solvent, the extract was concentrated by distillation for 1 h. Finally, the concentrate was transferred to an amber bottle, and the residual solvent was allowed to evaporate under room conditions. The obtained extracts were stored at 4 °C under refrigeration until further analysis.

Extraction yield

The extraction yield was calculated from the mass of the concentrated extract obtained after partial solvent evaporation, using the following equation.

$$Performance(\%) = \frac{Mass\ of\ extract\ obtained\ (g)}{Initial\ dry\ sample\ mass\ (g)} \times 100 \quad (1)$$

CIE Lab Color Analysis

Color analysis was performed using the CIE L*a*b* system, following the guidelines of the International Commission on Illumination (CIE), with a Precision Colorimeter V2.0 colorimeter previously calibrated with black and white standards. For solid samples (fruits of *Fragaria* × *ananassa* and passionflower peels), measurements were taken directly on the surfaces, whereas for liquid samples (peel extracts), measurements were taken in glass cuvettes of constant thickness to avoid background interference. In both cases, at least three readings were taken per sample at different points, and the average L*, a*, and b* values were reported.

Antioxidant capacity

DPPH

The DPPH assay was performed using a 150 μmol/L solution prepared in methanol:water (80:20). The calibration curve was constructed with Trolox, and the extracts were evaluated from a 10 mg/mL stock solution diluted to 0-250 μL. In a microplate, 20 μL of sample was mixed with 180 μL of DPPH, incubated in the dark for 40 min, and the absorbance was measured at 515 nm using a Multiskan Go reader (Thermo Fisher Scientific).

The results were expressed as μmol Trolox equivalents per gram of extract (μmol TE/g), calculated from the calibration curve considering the dilution factor, the initial extract concentration, and the mass of extract used. This normalization ensured comparability between samples, and all measurements were performed within the linear response range of the DPPH assay (Bobo-García *et al.*, 2015).

$ABTS^{\bullet+}$

The $ABTS^{\bullet+}$ radical was generated by mixing equal parts of ABTS stock solutions (7 mmol/L) and potassium persulfate (2.45 mmol/L), which were incubated in the dark for 12-16 h. Before the assay, the solution was diluted with distilled water to an absorbance of 0.700 at 754 nm. The calibration curve was constructed using Trolox, and the extracts were prepared from a 10 mg/mL stock solution, diluted to 0-250 μL. For the analysis, 250 μL of diluted ABTS solution was mixed with 50 μL of the sample, and the absorbance was measured at 754 nm after 6 min using a microplate reader (Multiskan Go, Thermo Fisher Scientific).

The results were expressed as μmol Trolox equivalents per gram of extract (μmol TE/g), calculated from the calibration curve considering the dilution factor, the initial extract concentration, and the mass of extract used. This approach ensured that the reported antioxidant capacity corresponded to the intrinsic activity of the extract rather than to the volume of sample analyzed, and that measurements were performed within the linear range of the assay (Leite *et al.*, 2011).

Inoculum preparation and spore quantification

The fungus *Rhizopus stolonifer* was cultured in Petri dishes potato dextrose agar (PDA) for 15 days. After this time, 10 mL of sterile distilled water were added to each plate and the mycelium was gently scraped using a sterile glass rod to release the spores.

Subsequently, the resulting suspension was homogenized and diluted to obtain a 1:100 dilution. Spore counting was performed using a Neubauer chamber and an optical microscope, considering the four large quadrants, according to the method described by Meneses *et al.* (2001).

The spore concentration was expressed as spores per milliliter (spores/mL)

Preparation and application of the coating on strawberry (*Fragaria* × *ananassa*)

The edible coating was prepared following the methodology described by Mamani (2019) with some modifications, using a polysaccharide matrix composed of carboxymethylcellulose (CMC, 0.4 g), glycerol (1.2 mL), Tween 80 (0.8 mL), and sterile

distilled water (76.8 mL). *Passiflora edulis* extract was incorporated at different concentrations (500, 1000, 1500, 2000, 2500, and 3000 ppm) to obtain six different coatings.

The components were mixed and stirred for 40 min until a homogeneous solution was obtained. These concentrations were selected to evaluate their effect on the inhibition of mycelial growth of *Rhizopus stolonifer*. The coating was applied by immersion, as reported by Dai *et al*. (2025), with some modifications. The strawberries were completely submerged in the coating solution for 5 s and subsequently placed on racks to remove excess coating prior to inoculation.

In vivo antifungal assay on strawberries

The antifungal activity of the coatings was evaluated *in vivo* using strawberries (*Fragaria* × *ananassa*) artificially inoculated with *Rhizopus stolonifer*. Four fruits were used per treatment, with four independent replicates. The fruits were randomly assigned to the treatments. The coating was applied by immersion (5 s); the fruits were inoculated on the intact surface by spraying a suspension of *R. stolonifer* spores. A total volume of 690 μL was applied per treatment (distributed in three sprays), equivalent to approximately 2325 spores. A 10-minute resting period was allowed between inoculation and coating application to ensure proper inoculum adhesion.

The treated fruits were stored at 8 °C, and fungal growth was monitored over time. Two control conditions were included: (i) uncoated fruit (UC) and (ii) fruit coated with the polymeric matrix (CMC) without extract (CC), in order to differentiate the effect of the matrix from the bioactive compound. In addition, treatments with different concentrations of extract were evaluated to determine their antifungal activity.

Minimum Inhibitory Concentration of *P. edulis* extracts against *Rhizopus stolonifer*

Radial growth test in solid medium

The antifungal activity of *Passiflora edulis* peel extract against *Rhizopus stolonifer* was evaluated using a radial growth assay on potato dextrose agar (PDA). The method involved sterilizing the PDA, then adding the extract at different concentrations (500, 1000, 1500, 2000, 2500, and 3000 ppm) and mixing under sterile conditions until complete homogenization. The solution was then poured into sterile Petri dishes, allowed to solidify, and inoculated by placing a disc of SR mycelium in the center.

The dishes were stored at 25 °C to evaluate growth by measuring the diameter of the mycelial growth on different days (1, 2, 3, and 7). The minimum concentration required to inhibit visible mycelial growth was determined based on the reduction of radial growth compared to the control. The percentage of mycelial growth inhibition was calculated using the following equation:

$$Inhibition\ of\ micelial\ growth\,(\%) = \frac{T - Tr}{T} \times 100$$

where: T: radial growth of the control (mm); Tr: radial growth of the treatment (mm).

Experimental design and statistical analysis

All trials were performed in triplicate using a completely randomized design. The data obtained were subjected to analysis of variance (ANOVA) to evaluate the effect of the different concentrations of *Passiflora* spp. extract. For the postharvest evaluation, a two-factor ANOVA was applied considering treatment (coating concentration) and storage time (days) as independent factors, as well as their interaction (Day × Treatment). Each sampling day was analyzed using independent fruit samples. When significant differences were detected, means were compared using Tukey's multiple comparisons test, considering a significance level of $p \leq 0.05$. Results are expressed as mean ± standard deviation. Statistical analysis was performed using Minitab software, version 22.

RESULTS AND DISCUSSION

Peel color and extracts

The color determination is shown in Table 1, revealing significant differences in the CIELab parameters of the peels of the three Passiflora species. These differences indicate that, beyond external morphological variations, there are distinct physicochemical characteristics associated with each species.

Passiflora edulis f. *flavicarpa* exhibited the highest L* and b* values, reflecting a lighter and more yellow coloration, has been described in the literature as characteristic of yellow-colored varieties, although pigment composition was not evaluated in this study. In contrast, *P. edulis* f. *edulis* showed the lowest L* values, corresponding to a darker coloration, which has been reported in previous studies as a characteristic of darker-colored peels (Fonseca *et al*., 2022). However, it is important to note that the present study did not include a direct quantification of phenolic compounds or detailed phytochemical profiling; therefore, these associations should be interpreted with caution.

In this context, the observed differences in color are discussed only as measurable physicochemical attributes. Nevertheless, in this study, such interpretations are limited to indirect evidence derived from color parameters.

This trend was maintained after the ethanolic extraction process (Table 2), where the extract of *Passiflora edulis* f. *edulis* retained lower lightness values compared to the other

Table 1. CIELab color of passionflower fruit peel.

Species	L*	a*	b*
Passiflora edulis f. *flavicarpa*	66.92±9.06 [a]	1.29±0.27 [b]	38.70±7.00 [b]
Passiflora edulis f. *edulis*	32.98±3.39 [b]	15.08±3.76 [a]	10.27±1.39 [c]
Passiflora ligularis	59.02±2.32 [a]	15.74±2.40 [a]	54.60±4.39 [a]

Table 2. CIELab color from ethanolic extracts of passionflower peel.

Species	L*	a*	b*
Passiflora edulis f. *flavicarpa*	38.37±2.69 [a]	18.69±4.67 [a]	21.30±6.59 [a]
Passiflora edulis f. *edulis*	23.82±0.62 [c]	11.27±3.55 [b]	4.91±1.39 [b]
Passiflora ligularis	31.67±4.17 [b]	12.33±5.21 [b]	8.14±3.57 [b]

species. This indicates that the color characteristics of the raw material were preserved after extraction under the conditions evaluated. However, the relationship between extract color and its metabolic composition or antioxidant potential was not directly evaluated and should not be inferred beyond the observed colorimetric behavior.

Although previous studies have reported correlations between extract color intensity and bioactive compound content in active coating systems, such relationships depend on specific compositional analyses. Therefore, in the present work, the observed differences in color should be interpreted strictly as physicochemical descriptors rather than direct indicators of bioactive compound concentration or functional activity.

Ethanol extraction yield

Regarding extraction yield, Figure 1 shows that the highest extraction yield was obtained with the *P. edulis* f. *edulis* variety, attributed to the high metabolic density of the tissue and the fact that the *P. edulis* f. *edulis* peel concentrates polyphenols, flavonoids, pectins, and other secondary metabolites associated with structural and chemical defense functions (Fonseca *et al.*, 2022). A higher yield means that a greater load of bioactive compounds is obtained per unit of residue, improving the technological viability of the process. Furthermore, when these extracts are used as part of protective barriers, the likelihood of the coating having a better physiological impact on the fruit increases. In accordance with the above, Shahdadi *et al.* (2025) reported, in active coatings on strawberries, that the systems efficacy depends largely on the effective load of functional compounds incorporated into the polymer matrix.

Antioxidant activity in ethanolic extracts of passionflower peel

The results obtained from the different antioxidant activity tests using the DPPH method (Figure 2) revealed that sample *Passiflora edulis* f. *edulis* with a value of 176±3.54 μmol TE/g, followed by *Passiflora edulis* f. *flavicarpa* with a concentration of 130.5±12.37 μmol TE/g. Conversely, the *Passiflora ligularis* sample (62.40±4.24 μmol TE/g) showed a significant difference from the other samples ($p=0.002$) according to Tukey's test. It is important to note that these quantifications were optimized by working within an extract concentration

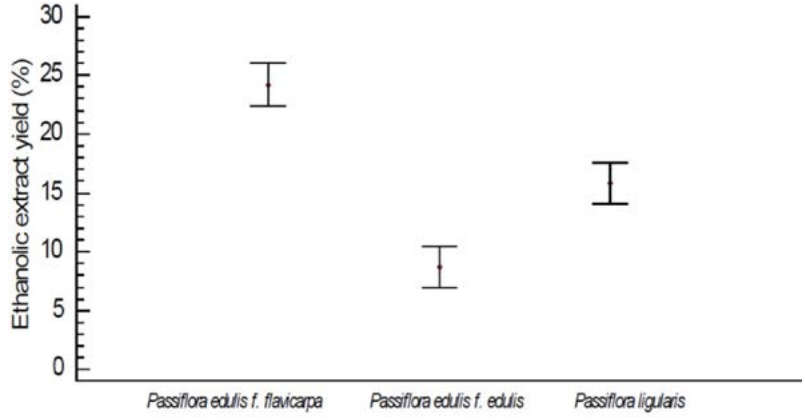

Figure 1. Yield (%) of ethanolic extraction from passionflower peel.

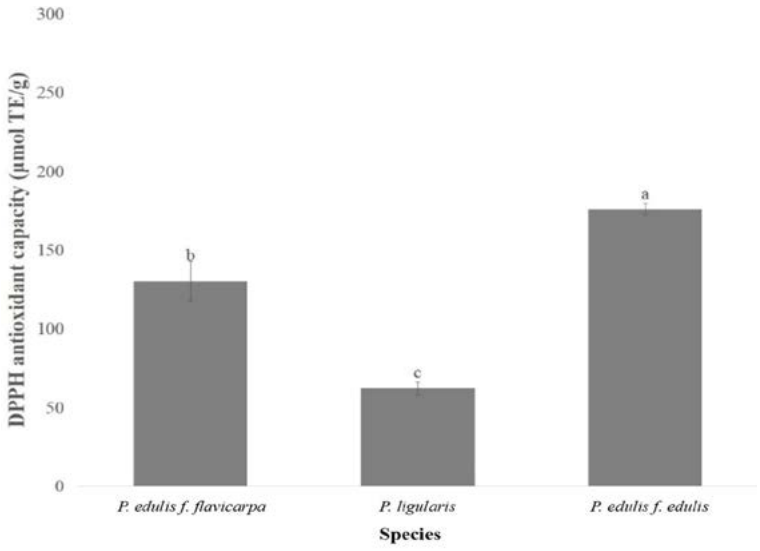

Figure 2. Antioxidant capacity determined by the DPPH method in *Passiflora* spp. peel extracts. Different letters above the bars indicate significant differences between samples (p=0.002).

range (100 to 250 mg/mL) that ensured linearity of the response. The concentration of 100 mg/mL was determined to be the most appropriate to prevent DPPH radical saturation, ensuring that absorbance readings remained within the methods detection limits and preventing underestimation of activity per gram of sample (Molyneux, 2004; Kedare & Singh, 2011). This is possibly because the measured antioxidant capacity can vary with the ratio of DPPH radical to antioxidants and with the experimental conditions used, which can affect the accessibility of antioxidants to the radical in complex matrices or at high concentrations of compounds (Prior & Schaich, 2005).

Furthermore, in the ABTS method (Figure 3), the observed trend was different ($p<0.000$), with sample *P. ligularis* exhibiting the highest antioxidant capacity at 266±14.1 μmol

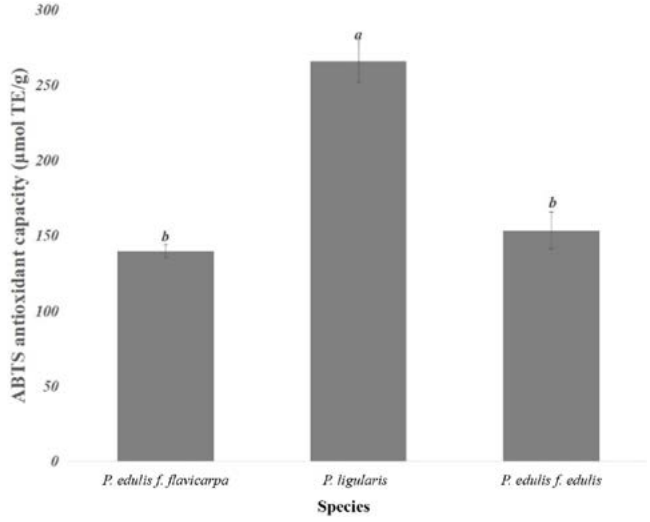

Figure 3. Antioxidant capacity determined by the ABTS method in *Passiflora* spp. peel extracts. Different letters above the bars indicate significant differences between samples (p=0.000).

TE/g. This value significantly exceeded those recorded for *P. edulis* f. *edulis* (153.68±12.05 μmol TE/g) and *P. edulis* f. *flavicarpa* (139.93±4.35 μmol TE/g). According to Tukey's test, *P. ligularis* ($p<0.000$) different significance from *P. edulis* f. *flavicarpa* and *P. edulis* f. *edulis* (Figure 3).

The numerical superiority of the ABTS values over those of DPPH is consistent with that reported by Floegel *et al.* (2011). It is attributed to the ABTS radicals capacity to react with a wider range of hydrophilic and lipophilic compounds present in the peel matrix. This difference in reactivity suggests that *Passiflora* spp. extracts possess a diverse phytochemical profile, and certain compounds, possibly hydrophilic, exhibit a greater affinity for the electron-transfer mechanism of the ABTS assay (Magalhaes *et al.*, 2014).

Several studies on *Passiflora* spp. by-products have reported that the peel contains higher concentrations of phenolic compounds and flavonoids than the pulp and seeds, resulting in superior antioxidant activity. For instance, the peel of *P. maliformis* has shown antioxidant capacities of 23.21±1.16 μmol TE/g (ABTS) and 11.87±0.59 μmol TE/g (DPPH). In comparison, *Passiflora edulis* f. *edulis* has yielded values of 33.45±2.50 μmol TE/g and 15.29±0.76 μmol TE/g for ABTS and DPPH, respectively (Taborda *et al.*, 2021). These findings align with the ABTS>DPPH pattern observed in the present study and highlight *P. edulis* f. *edulis* as the species with the highest antioxidant potential. This trend suggests that the phytochemical profile of *P. edulis* f. *edulis* peel possesses a greater affinity for the ABTS radical cation than for the DPPH radical.

Furthermore, when comparing these results with studies on conventional matrices, primarily *Passiflora* pulp, it is evident that the antioxidant capacity of the external tissue (peel) significantly surpasses that of the pulp. A study investigating the pulp of various *Passiflora* species cultivated in Ecuador reported ABTS values from 30.32±0.06 to 43.00±0.70 μmol TE/g, with *P. edulis* f. *flavicarpa* demonstrating the highest response (Viera *et al.*, 2022). These results confirm that *Passiflora* peel is a superior source of antioxidant compounds. Free radicals are unstable, highly reactive species derived primarily from oxygen, nitrogen, and sulfur, which can lead to the formation of Reactive Oxygen Species ($ROS^{\bullet}$) and Reactive Nitrogen Species RNS), and Reactive Sulfur Species ($RSS^{\bullet}$) (Carocho & Ferreira, 2013). The ABTS assay is a broad-spectrum method that interacts with these species due to its sensitivity to both hydrophilic and lipophilic antioxidants. *In vitro* studies have shown its effectiveness in neutralizing the peroxyl ($ROO^{\bullet}$) and hydroxyl ($OH^{\bullet}$) radicals (Koroleva *et al.*, 2014). Consequently, the high ABTS values obtained in this study suggest that *Passiflora* spp. extracts possess a significant potential to neutralize physiologically relevant radicals, potentially reducing lipid peroxidation and oxidative stress.

This bioactivity is further supported by research on other *Passiflora* tissues. For example, tea derived from *P. edulis* leaves yielded an ABTS concentration of 19.2±0.50 μmol TE/g, with *in vivo* studies demonstrating an increase in glutathione reductase activity. This suggests that the bioactive compounds present in the genus can prevent ROS formation and reduce oxidative stress by enhancing endogenous antioxidant defenses (Da Silva *et al.*, 2013). Overall, these findings demonstrate that *Passiflora* tissues exhibit consistent and robust antioxidant activity across different matrices and methodologies.

In vitro antifungal activity of *Passiflora edulis* peel extract against *Rhizopus stolonifer*: minimum inhibitory concentration and mycelial growth inhibition

Figure 4 shows the results obtained regarding the growth of *Rhizopus stolonifer* over time. The radial growth of the mycelium demonstrates that the antifungal effect of the *Passiflora edulis* peel extract against the pathogen depends on the dose used. In the control sample, almost complete colonization of the Petri dish was observed from the first few days, while a higher concentration of the extract progressively reduced mycelial growth. At 3000 ppm, growth remained practically nonexistent until day 7, indicating almost total and sustained inhibition, and concentrations of 2500-3000 ppm also showed minimal growth. In contrast, at ≤2000 ppm, a progressive recovery in growth was observed, indicating a loss of the antifungal effect.

Based on the absence of visible growth at the end of the assay, the *in vitro* MIC (potato dextrose agar) was determined to be 3000 ppm, consistent with reports for *R. stolonifer* in agar dilution assays (Colín-Álvarez *et al.*, 2025). This behavior demonstrates that insufficient doses allow for the recovery or growth of the pathogen as has been documented in *in vitro* and *in vivo* studies in strawberry (Triunfo *et al.*, 2023; Shahdadi *et al.*, 2025).

In addition to the MIC determination, the percentage of mycelial growth inhibition was calculated to describe the magnitude and temporal stability of the antifungal effect at each concentration. The mycelial growth of *Rhizopus stolonifer* showed a dose-dependent antifungal effect of *Passiflora edulis* peel extract. At concentrations of 2500 ppm or higher, inhibition rates close to 100% were observed by day 7 (2500 ppm, ≈99.4%; 3000 ppm, ≈99.6%), whereas lower doses lost efficacy over time (2000 ppm, ≈87.6%; 1500 ppm, ≈31.4%). This behavior is consistent with the definition of the MIC in agar dilution assays; in this regard, Colin-Álvarez *et al.* (2025) reported an MIC of 500 ppm for cinnamon essential oil against *R. stolonifer*.

In contrast, the hydroalcoholic extract evaluated in this study required higher concentrations to achieve total inhibition, likely due to differences in composition and diffusion in the medium (Saleh & Abu-Dieyeh, 2022; Fonseca *et al.*, 2022). Furthermore, the loss of efficacy at inhibitory doses confirms that insufficient concentrations allow growth recovery, which helps explain the lower efficacy observed under *in vivo* conditions compared to *in vitro* assays (Triunfo *et al.*, 2023; Shahdadi *et al.*, 2025).

In vivo antifungal effect of *Passiflora edulis* extract based coatings on strawberries artificially inoculated with *Rhizopus stolonifer*

Regarding the effect of *Passiflora edulis* extract (PEE) as part of the coating applied to strawberries (*Fragaria* × *ananassa*), similar to the *in vitro* study, it showed a concentration-dependent antifungal effect against *Rhizopus stolonifer* in strawberries stored at 8 °C (Figure 5). At low concentrations (500-1500 ppm), only partial development of the pathogen was observed, while at concentrations of 2000-2500 ppm, growth was postponed until later stages of storage. At a concentration of 3000 ppm, the greatest inhibition was observed, with no visible growth until day 17. However, the coating was not able to postpone fruit deterioration, as bleeding appeared, causing weight loss, suggesting that physiological deterioration may precede fungal colonization.

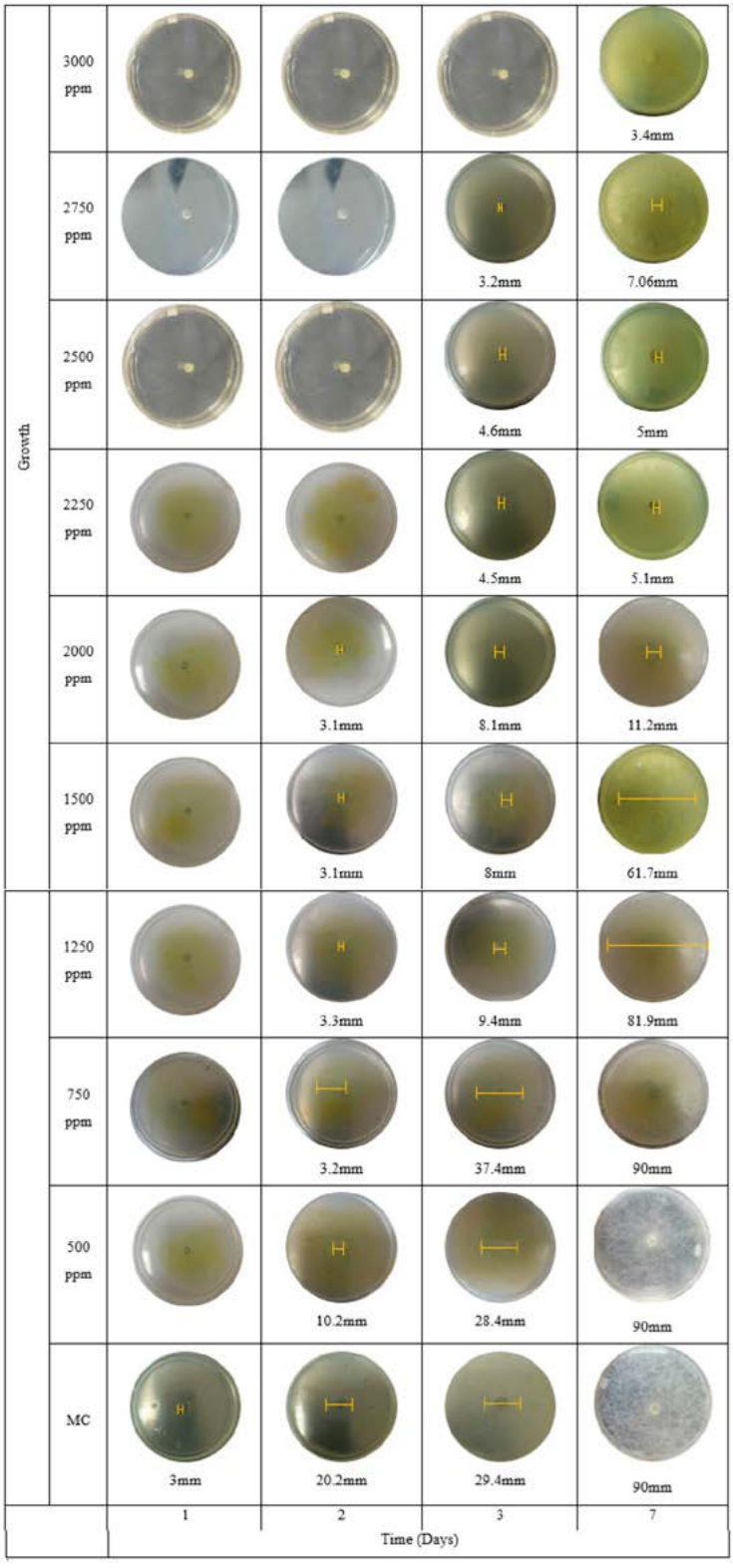

Figure 4. Monitoring of radial growth of *Rhizopus stolonifer* mycelium against *Passiflora edulis* extracts.

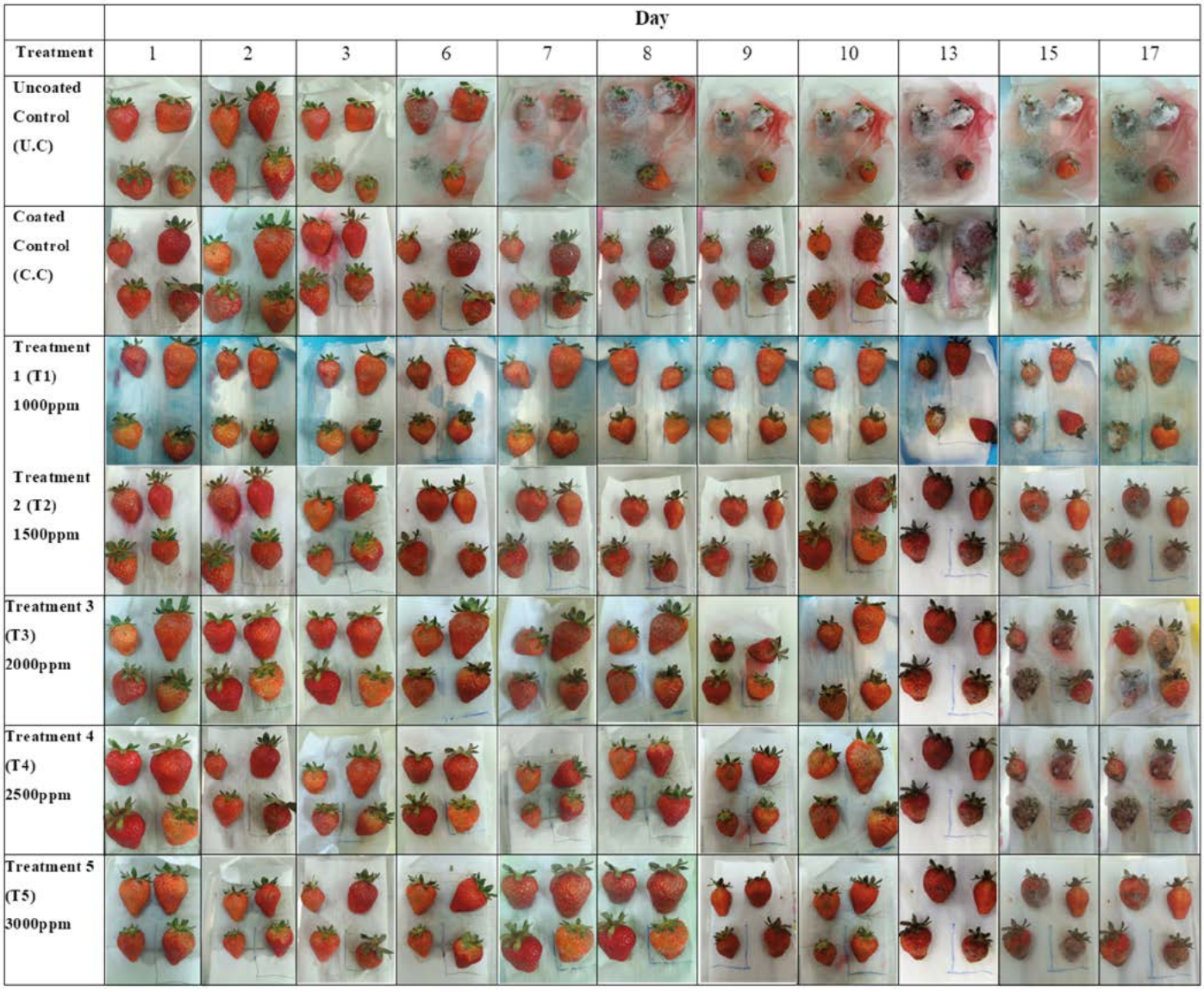

Figure 5. Visual evolution of strawberries infected with *Rhizopus stolonifer* and coated with an edible coating formulated with *Passiflora edulis* extract during storage.

Regarding the control samples, deterioration was observed from day 3, confirming the fruit's high susceptibility to *Rhizopus stolonifer* (ER). This behavior is consistent with reports for active coatings on strawberries, where efficacy depends strongly on the dosage of the incorporated bioactive agent (Triunfo *et al*., 2023; Shahdadi *et al*., 2025), and with studies showing that low concentrations allow *Rhizopus* to recover, while high doses suppress its growth for a longer period (Colín-Álvarez *et al*., 2025; Saleh & Abu-Dieyeh, 2022). Overall, the results confirm that EPE acts as an active system whose efficacy is critically dose dependent.

CIELab strawberry color with *Passiflora edulis* extract coating

In the analysis of the CIELab parameter, strawberry color was found to be a highly sensitive attribute during storage, as the fruit's physiological processes involve changes in

pigments, oxidative state, and epidermal integrity. In this study, L*, a*, and b* all changed with respect to time and coating type, confirming that color was influenced by both storage time and treatment conditions. This behavior is consistent with that described for strawberries coated with active systems (González-Cuello *et al.*, 2022; Shahdadi *et al.*, 2025; Feng *et al.*, 2024).

Parameter L*

Regarding the L* parameter, a treatment-dependent response was observed during storage (Figure 6). Specifically, in the control group, L* decreased more irregularly and markedly, with progressive darkening during storage, as reported by Feng *et al.* (2024). In contrast, the coated fruits maintained more stable L* values which may indicate that the coating contributed to delaying visible darkening under the evaluated conditions (Shahdadi *et al.*, 2025; González-Cuello *et al.*, 2022). This greater stability is consistent with that reported for strawberries coated with active Aloe vera-based systems enriched with rosemary (Shahdadi *et al.*, 2025).

Parameter a*

The a* parameter (reddish tones) showed a time- and treatment-dependent response. In the control samples (without extract), the fruits exhibited uneven variations, with a* initially intensifying and subsequently showing accelerated pigment degradation during senescence (Feng *et al.*, 2024). In contrast, coated fruits displayed more stable a* trajectories, which may reflect a more gradual change in color during storage, which is consistent with reports for active systems (Shahdadi *et al.*, 2025; González-Cuello *et al.*, 2022).

Although anthocyanin degradation has been associated in the literature with oxidative processes (Feng *et al.*, 2024), in the present study no direct measurements of oxidative status, antioxidant activity within the fruit, or interactions between the extract and the coating matrix were performed. Therefore, the observed color stability should be interpreted based on the experimental results, without attributing it to a specific biochemical mechanism.

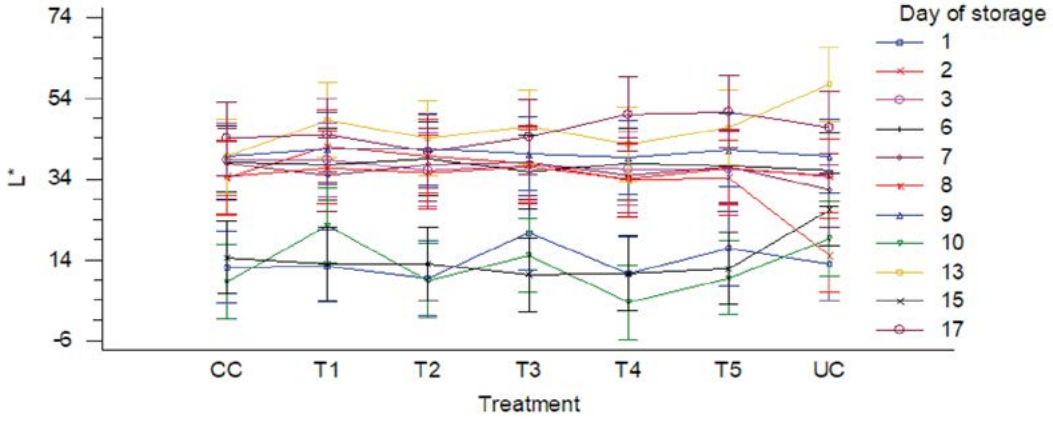

Figure 6. Day × Treatment Interaction on the L* Parameter over 17 Days of Shelf Life of Strawberries Coated with *Passiflora edulis* Extracts.

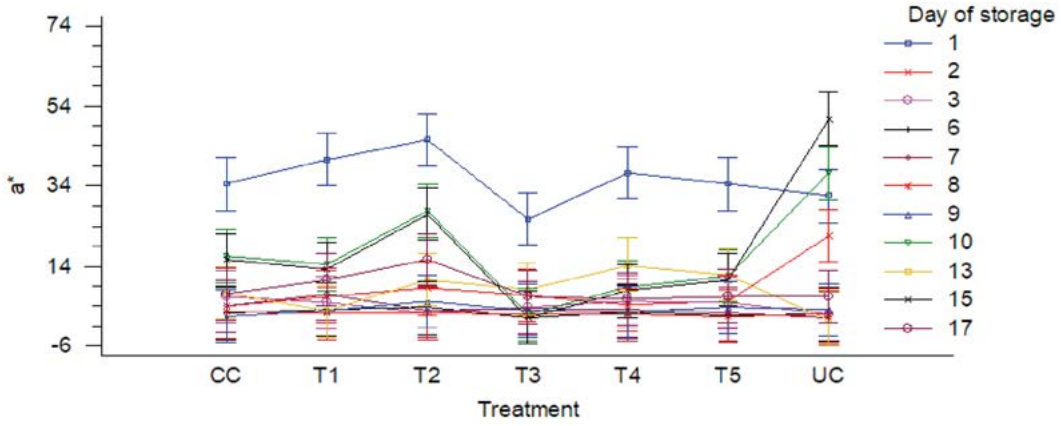

Figure 7. Day × Treatment Interaction on the a* Parameter over 17 Days of Shelf Life of Strawberries Coated with *Passiflora edulis* Extracts.

Parameter b*

The same behavior was observed as in the a* parameter, with b* showing a time- and treatment-dependent response. Similarly, in the control samples, a greater dispersion in the b* values was observed, showing a greater loss of chromatic purity during storage (González-Cuello *et al.*, 2022).

While coated fruits exhibited more stable b* values, showing a delay in hue changes during storage, these variations reflect possible chemical changes in the pigments and modifications in the tissue microstructure, which can affect the interaction of light with the fruit surface (Feng *et al.*, 2024). This behavior is consistent with what has been reported for coated strawberries, where coated systems have been associated with improved color stability during storage (Shahdadi *et al.*, 2025; González-Cuello *et al.*, 2022).

Weight loss kinetics in strawberries coated with *Passiflora edulis* extract during 17 days of shelf life

The weight loss of the control sample (15.16 to 8.92 g; ≈41.2%) demonstrated that strawberries are highly susceptible to dehydration, associated with their high respiration

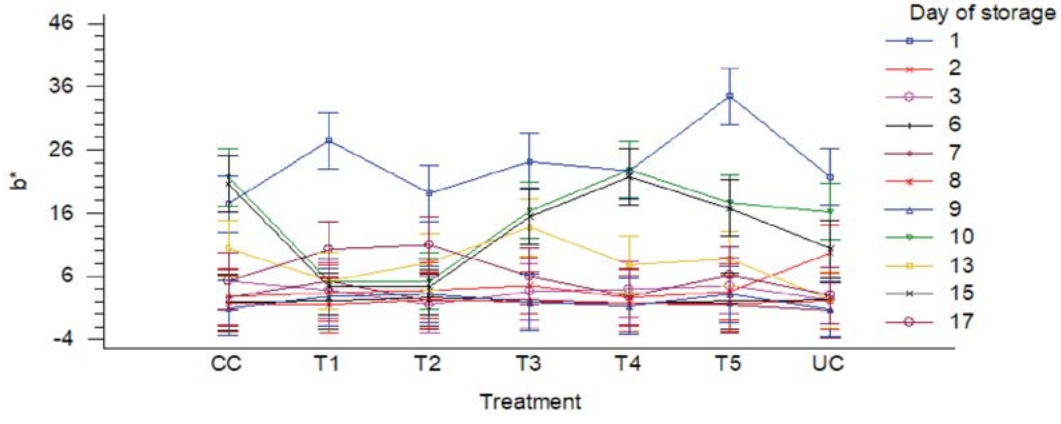

Figure 8. Day × Treatment Interaction on the b* Parameter over 17 Days of Shelf Life of Strawberries Coated with *Passiflora edulis* Extracts.

rate, intense transpiration, and inefficient cuticle (Figure 9). These results are consistent with studies conducted under more severe conditions, where losses of up to 53.62% have been observed in just a few days, while coatings significantly reduce this process (Triunfo *et al.*, 2023), even under refrigeration (González-Cuello *et al.*, 2022), and in different coating systems (Saleh & Abu-Dieyeh, 2022; da Silveira *et al.*, 2025; Shahdadi *et al.*, 2025). Based on the above, the results confirm that coating with *P. edulis* extract reduced fruit dehydration. Furthermore, weight loss was found to be directly related to microbial deterioration, as dehydration promotes loss of turgor and the formation of microfractures that facilitate fungal colonization, as shown in Figure 5. In this regard, research has demonstrated that coatings simultaneously reduce water loss and fungal growth (Saleh & Abu-Dieyeh, 2022; Triunfo *et al.*, 2023; Colín-Álvarez *et al.*, 2025; Shahdadi *et al.*, 2025). This effect is probably due to the combined action of a physical mechanism (semipermeable barrier to water vapor and gases) and a biological one, associated with the antioxidant and antifungal activity of the *P. edulis* extract (Lam & Ng, 2009; Fonseca *et al.*, 2022).

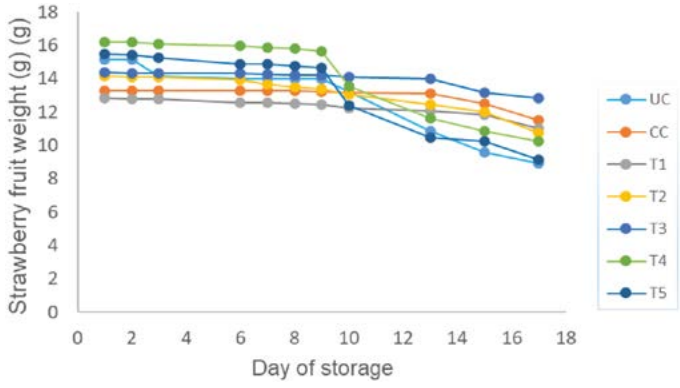

Figure 9. Weight loss of strawberries coated with *Passiflora edulis* ethanolic extract during 17 days of shelf life.

CONCLUSIONS

The research confirmed that the peel of *Passiflora edulis*, an agro-industrial residue, is a significant source of bioactive compounds with antioxidant and antifungal activity. Of the species evaluated, *P. edulis* had the highest extraction yields and also exhibited the highest antioxidant capacity; therefore, it was selected for the formulation of the edible coating. Regarding the ethanolic extract, it showed an antifungal effect against *Rhizopus stolonifer* under *in vitro* conditions, with the effect being strongly concentration-dependent. A minimum inhibitory concentration of 3000 ppm was identified using the radial growth assay. The loss of inhibitory efficacy at low concentrations demonstrated that low or insufficient doses lead to a recovery of fungal growth.

In the *in vivo* study, the incorporation of *P. edulis* extract into an edible coating applied by immersion to strawberries delayed fungal growth during refrigerated storage, reduced weight loss, and maintained greater stability of color parameters compared to the control. These results indicate that the coating helps delay senescence and postharvest-deterioration processes in the fruit.

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