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Can Tannin-Coated Paper Packaging Extend the Shelf Life of Fresh Fruits?

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This study explores the potential of tannin-coated paper-based packaging to extend the shelf life of highly perishable fruits, with strawberries used as a model. Firstly, the antimicrobial properties of a tannin extract were assessed, demonstrating the most promising results against *Staphylococcus xylosus*. From this findings, two types of packaging were developed: untreated paper containers and containers coated with the tannin extract. Fresh strawberries were stored in these containers under controlled conditions (5°C, 85% relative humidity) for 19 days. Several parameters were monitored, including microbial growth, texture, colour evolution, weight loss and the fungicidal efficacy of the coated paper, with analysis performed every two days.
The results revealed no significant differences in microbial growth or quality parameters between the treated and untreated containers at the different time points. In addition, fungal growth was more pronounced in the tannin-coated containers. These findings suggest that the tannin coating did not enhance key preservation parameters. Instead, it may have accelerated degradation, possibly due to the presence of undesirable compounds that could have fostered fungal growth. These findings serve as the basis for future research that will refine coating formulations and application methods for wider adoption in the food packaging industry.

1. Introduction

Food preservation has become of primary importance in transforming the food production system into a more sustainable one. In this regard, plant-based extracts with antimicrobial and antioxidant activities have been explored for their integration into food packaging systems (Gupta et al. 2024). Among the different biomolecules, tannins, poly(phenolic) compounds widely available in plants, have been proposed for their well-known ability to disrupt microbial cell function and inhibit microbial growth (Ozogul et al. 2025).
The use of antimicrobial plant extract for coating packaging materials represents an effective method for improving the food shelf-life, preserving the freshness and prevent food spoilage. Vera et al. (2023) reviewed the potential of tannins for the production of active packaging, and the effectiveness of tannins incorporated into biopolymers for enhancing the shelf life were demonstrated with mango (Ma et al. 2021), grapes and cherry tomatoes (Halim et al. 2018).
In the present work, tannin extract was used for coating paperboard trays with the final aim to produce an active packaging solution. The effectiveness of this alternative packaging was evaluated by monitoring the quality parameters of strawberries and assessing the potential shelf-life improvements.

2. Materials and Methods

2.1 Materials

Pre-formed paper-based containers measured 10.5 x 5 x 10 cm, with a total volume of 525 cm^3 were used. Two groups were prepared for the trials and were represented by tannin-based coating containers and uncoated containers, representing the control samples. Fresh strawberries were provided by a local greenhouse and were selected as food model for their small size and short shelf-life. Only undamaged fruits were selected for the experiments.

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2.2 Antimicrobial activity of tannin extract

The antimicrobial activity of the tannin extract was evaluated against *Staphylococcus xylosus*, *Listeria innocua, Escherichia coli, Pseudomonas fluorescens* and *Saccharomyces cerevisiae* at the following concentrations: 0.5%, 0.25%, 0.125%, and 0.0625%. Inoculations were made with 2.5 mL of TSB 2X medium inoculated with the bacteria (1% inoculum) and 2.5 mL of tannin extract (total volume of 5 mL). The control consisted of 5 mL of TSB medium with 1% inoculum. After 24 hours of incubation, colony counts were performed.

2.3 Storage conditions

The containers were filled with strawberries by maintaining a net weight of 250 g for each container. The samples were stored in a climatic chamber set at 5°C and 85% relative humidity, under dark conditions. The containers were stored for 19 days and monitored every 2/3 days, for a total of 9 time points (Figure 1).

Figure 1: Pictures of samples during the different sampling and monitoring times. In the top row, the set of replicates in uncoated cardboard, in the bottom row, the set of replicates in tannin-coated cardboard.

2.4 Microbiological analysis

Microbiological analyses were performed on strawberries at the different time points. In particular, six strawberries were used from each container. The analysis involved mesophilic bacteria count (CMT) (ISO 15214:1998), yeast presence, and fungal contamination (ISO 21527 2:2008).

2.5 Color analysis

Colour parameters were measured with a CHROMA METER CR-400 (Konica Minolta). In particular, the CIELAB coordinates were assessed, including *L** (luminosity), *a** (red-green axis), and *b** (yellow-blue axis). *ΔE* was also calculated with the following equation Eq(1).

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

2.6 Texture analysis

Texture analysis was performed using a texture analyzer TX-700 device (Lamy Rheology Instruments) and the resistance to compression was measured with a cylindric probe 130037 and a speed of 0.33 mm/s, a trigger force of 0.01 N and a return position of 40 mm. For the analysis, three strawberries per containers were tested and the average forces were recorded.

2.7 Weight loss evaluation

Weight loss was monitored at each time points by using the following formula Eq(2):

$$\textbf{weight loss} = \frac{Wi - Wf}{Wi} \times 100 \quad (2)$$

Where Wi was the initial weight and Wf the final weight at the end of each time points.

2.8 Fungicidal activity of the paperboards

Coated and uncoated containers, before being in contact with strawberries, were tested for fungicidal activity following the UNI 110221:2002 standard. In particular, carton samples were sterilized and inoculated with *Aspergillus niger*, Penicillium spp., and *Paecilomyces fulvum* spores. Fungal growth was visually assessed after 25 days and classified based on the extent of contamination.

2.9 Statistical Analysis

For the experimental design, three biological replicates of containers were prepared for each time points, with a total of 54 containers. The results were reported as mean values ± standard deviation. Statistical analyses were performed by SPSS Statistics 25 software (IBM, USA). An independent t-test was performed to compare control and tannin-coated container results, while one-way analysis of variance (ANOVA) with Tukey's Post Hoc test was performed to assess significant differences during storage ($P < 0.05$).

3. Results and discussion

3.1 Antimicrobial activity of tannin extract

Tannin extract demonstrated strong antimicrobial activity against *Staphylococcus xylosus*, reducing the bacterial population by 4 logs at 0.5% concentration (from 10^8 to 10^4 cfu/mL). A 1 log reduction was observed for *Listeria innocua* at the same concentration (from 10^9 to 10^8 cfu/mL). On the contrary, no significant inhibition was noted for *Escherichia coli, Pseudomonas fluorescens* and *Saccharomyces cerevisiae.* The results suggest the selective antimicrobial activity of tannin extract, particularly against Gram-positive bacteria.

3.2 Microbiological analysis

Results about microbiological analysis are reported in Table 1 and showed that no significant reductions were determined in strawberries packaged in tannin-coated containers.

Table 1: Average levels of microbiological analyses of strawberries stored for 19 days in uncoated (control sample) and tannin-coated paperboard container. Results are expressed as ufc/100 cm². Asterix indicates significative differences in contamination level between coated and control samples.

Time (days)	Tannin-Coated Container CMT	Control Container CMT	Tannin-Coated Container Yeast	Control Container Yeast	Tannin-Coated Container Fungi	Control Container Fungi
0	5.00E+04	5.00E+04	3.00E+04	3.00E+04	8.30E+02	8.30E+02
2	3,00E+06	1,00E+06	2,00E+06	6,00E+05	ND*	7.6E+02*
5	4,00E+06	2,00E+06	6,00E+06	3,00E+06	3.90E+06*	8.5E+02*
7	2,00E+06	6,00E+06	3,00E+06	6,00E+06	3.60E+06*	7.7E+02*
9	3,00E+06	4,00E+05	2,00E+06	4,00E+05	2.30E+02	1.60E+02
12	3,00E+06	2,00E+05	7,00E+06	2,00E+05	1.50E+03	1.30E+03
14	9,00E+05	5,00E+06	1,00E+06	1,00E+06	3.10E+04	5.70E+04
16	3,00E+07	1,00E+06	2,00E+07	2,00E+06	1.90E+03	1.60E+03
19	4,00E+06	4,00E+06	4,00E+06	4,00E+06	6.50E+02	6.50E+02

In some cases, a significantly higher level of fungal contamination in samples stored in tannin-coated packaging was determined, as for example after 5 and 7 days of storage. These results contrasted with those demonstrated by Sharma et al. (2022), in which cherry tomatoes stored in PLA-PBAT incorporated with tannin acids showed a significantly lower bacterial count compared to tomatoes packaged in control samples.

3.3 Color analysis

The analysis of *L*, a* e b** parameters showed that there were not significative differences between strawberries stored in tannin-coated containers and those stored in the control packaging. On the contrary, significative differences ($P < 0.05$) were determined for ΔE value in function of storage time (Figure 2).

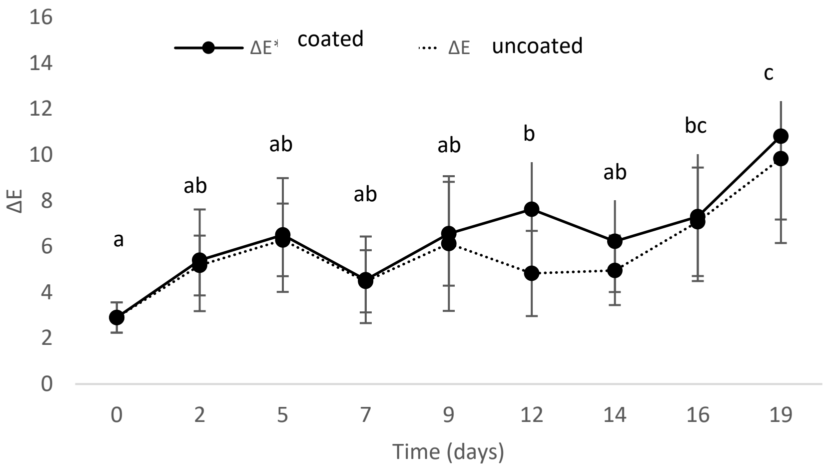

Figure 2: Variation in colour (ΔE) of strawberries contained in coated and uncoated trays. Data are expressed as mean and standard deviation. Different letters indicate significative differences among time points (P< 0.05).

Results demonstrated the significantly increase over storage time in ΔE parameter and a progressive colour change in strawberries. The color change in strawberries is attributed to enzymatic processes related to ripening, including the oxidation of phenol compounds, which is responsible of strawberry darkening (Wicklund et al. 2005). In this direction, the tannin extract did not demonstrate to influence oxidative processes or to inhibit enzymatic browning.

3.4 Texture analysis

Texture analysis was performed in order to assess fruit firmness, and the results are reported in Figure 3.

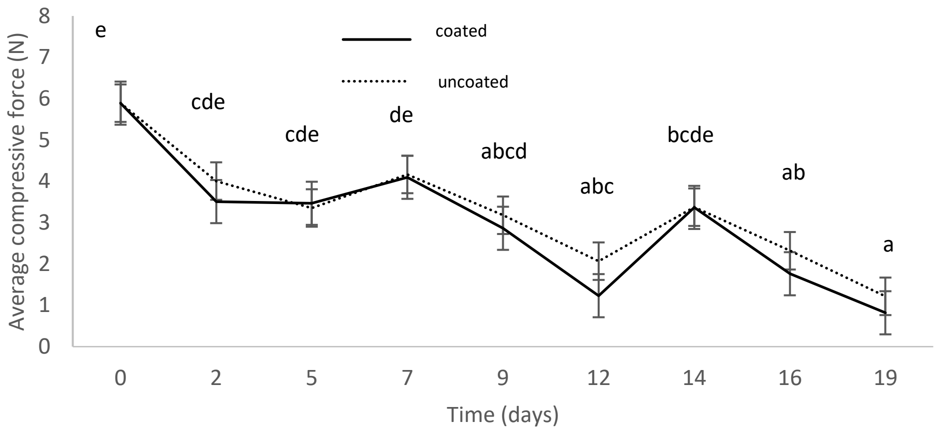

Figure 3: Variation in firmness of strawberries contained in coated and uncoated trays. Data are expressed as mean and standard deviation of average compressive force. Different letters indicate significative differences among time points (P< 0.05).

Results demonstrated that there were no significative differences (*P*> 0.05) between the texture of strawberries stored in the control containers and those stored in the tannin-coated paperboards. On the contrary, the storage time significantly influenced (*P*< 0.05) the firmness of strawberries, with the average compression force that significantly decreased along the monitoring period, mainly due to pectin degradation (Peretto et al. 2014).

3.5 Weight loss evaluation

Weight loss in fruits is associated with respiratory frequency, moisture evaporation through the skin, and the activity of malate dehydrogenase, which consumes carbohydrates in the fruit, leading to weight loss (Hurtado et al. 2021). Rapid moisture loss from the skin is a major factor contributing to the perishability of strawberries. Generally, lower weight loss results in longer shelf life and freshness (Gidado et al. 2024). The results about strawberries weight loss are shown in Figure 4.

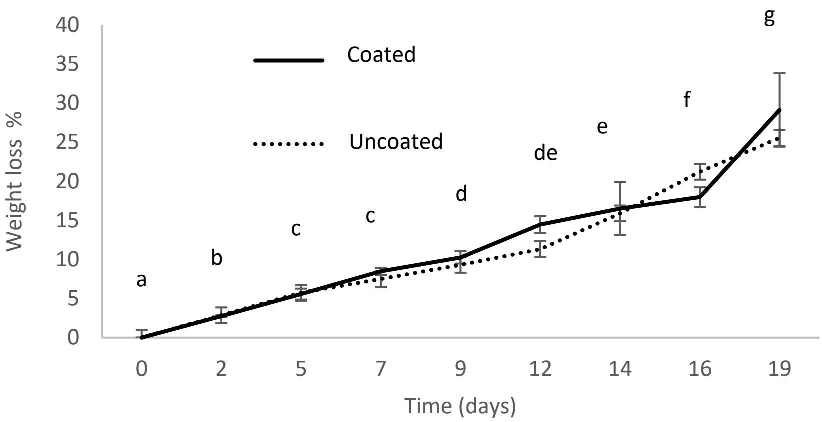

Figure 4: Strawberries weight loss during the monitoring period. Results are expresses as weight loss %, respect to the initial weight at time 0. Data are expressed as mean and standard deviations. Different letters indicate significative differences among time points (P< 0.05).

The results show no significant differences ($P > 0.05$) between treated and untreated samples. Opposite results were obtained by Halim et al. (2018) when a chitosan and gelatine-based film incorporated with tannins was wrapped around tomatoes and grapes, demonstrating a lower % of weight loss compared to the corresponding control samples. By considering the effect of storage on fruit weight loss, significant differences ($P< 0.05$) were identified over time. The weight loss percentage increased with storage time, reaching a maximum of 34.4% for treated samples and 26.8% for untreated samples, both observed at the end of the storage period.

3.6 Fungicidal activity of the paperboards

In order to assess if the antimicrobial activities of tannin extract were maintained after its coating on paperboard, the fungicidal activity of containers before food contact was determined as well. The results demonstrated that tannin-coated paperboards exhibited weak fungal growth, while no development were observed in untreated paperboards. These results may be attributed to the nature of the coating used, with the tannin extract which may still contain sugars or other compounds that promote microbial growth.

4. Conclusions

In the present work, tannin extract was used for preparing coated paperboards to be used as packaging for strawberries, with the final aim to improve their shelf-life. The results revealed no significant differences in microbial growth or quality parameters between strawberries stored in treated and untreated containers at different time points. Taking all together, these findings suggest that the tannin coating did not enhance key quality parameters. Instead, it may have accelerated strawberries degradation, possibly due to the presence of undesirable compounds in tannin extract that could have fostered fungal growth.
This study highlights the challenges of developing effective active packaging using natural bio-based coatings and underscores the need for further optimization to meet the dual objectives of sustainability and functionality. These findings serve as the basis for future research that will refine coating formulations and application methods for wider adoption in the food packaging industry.

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