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Alginate-based edible coating incorporating green tea extract for preserving postharvest quality and safety of white mushrooms (*Agaricus bisporus*)

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ABSTRACT

This study aimed to evaluate the effects of a sodium alginate based edible coating incorporated with green tea extract (GTE) (*Camellia sinensis*) on the postharvest quality attributes and antimicrobial activity against *Listeria monocytogenes* in white mushrooms during refrigerated storage. The phenolic profile of GTE was characterized, and its minimum inhibitory concentration (MIC) against L. *monocytogenes* (1.6 mg/mL) was determined. Sodium alginate coatings, with (ALG-GTE) or without GTE (ALG) at MIC (1.6 mg/mL), were characterized (functional groups, solubility in water, moisture, thickness, water contact angle and color) for their chemical and physical properties. The effects of ALG-GTE coatings on quality parameters (firmness, weight loss, color, pH, sugars and organic acids), enzymatic activity [polyphenol oxidase (PPO), peroxidase (POD) and pectin methylesterase (PME)], antimicrobial activity against L. *monocytogenes* (5 log CFU/g), and surface characteristics (3D optical profilometry) were assessed in white mushrooms (*Agaricus bisporus*) during refrigerated storage (8 days, 4 ± 1 °C, 90–95% RH). The ALG-GTE coatings preserved sugar composition, particularly rhamnose, reduced organic acids accumulation and delayed weight and firmness loss, reduced color changes, and decreased PME activity in coated white mushrooms. *L. monocytogenes* counts decreased by 1.4 log CFU/g after 1 day, and no viable cells were detected after 2 days (< 1.5 log CFU/g) in ALG-GTE coated white mushrooms. In addition, ALG-GTE coated white mushrooms exhibited smoother surfaces than uncoated samples. These findings highlight the potential of ALG-GTE coatings as a sustainable alternative capable of improving the microbiological safety and delaying the postharvest changes in fresh mushrooms.

1. Introduction

White mushrooms (*Agaricus bisporus*) are among the most popular and consumed edible fungi in the world, accounting for approximately 11% of global edible mushroom production (Dissemond, Franken, & Sari, 2025). They are appreciated for their characteristic texture and delicate flavor, constituting an alternative source of protein with high nutritional value, especially for vegans or vegetarians. Low in calories and fat but high in protein, fiber, and essential nutrients like iron, phosphorus, and B vitamins (De Cianni, Pippinato, & Mancuso, 2023), white mushrooms also contain bioactive compounds such as terpenoids, phenolic acids, sesquiterpenes, polyphenols, and polysaccharides (Antonelli & Donelli, 2023).

Factors such as high respiration rate, water loss, delicate and thin surface and accelerated browning result in a fast decline in the post-harvest quality in white mushrooms (Castellanos-Reyes, Villalobos-

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Carvajal, & Beldarrain-Iznaga, 2021; Jiang, Feng, Zheng, & Li, 2013). Because it is a product consumed raw, the cross-contamination during minimal processing is also of concern (Lake, van Overbeek, Baars, Abee, & den Besten, 2023). In recent years, foodborne outbreaks and recalls have been linked to fresh mushrooms due to contamination by relevant pathogens, such as *Listeria monocytogenes* [Centers for Disease Control and Prevention, 2026].

Between 2020 and 2022, cases of listeriosis associated with the consumption of contaminated enoki mushrooms resulted in 36 hospitalizations, 4 deaths, and more than 20 product recalls in different states in the United States (US) (Centers for Disease Control and Prevention, 2020; Centers for Disease Control and Prevention, 2025). Contamination of white mushrooms with L. *monocytogenes* has also led to the recall of sliced mushrooms in the US and Canada (Government of Canada, 2023; People, 2025). Listeriosis is estimated to be the third leading cause of death among foodborne illnesses, with a fatality rate of approximately 20%, due to its ability to survive in different environmental conditions, including refrigeration temperatures, and persist in fresh products during storage (Centers for Disease Control and Prevention, 2024; Lake et al., 2023).

Therefore, extending the shelf life of white mushrooms and reducing the risks of microbial contamination during storage is an important challenge for the food industry. Edible coatings are technologies proposed as alternatives to preserve mushrooms (Zhang et al., 2025). They are thin biopolymeric layers applied directly to food surfaces to reduce moisture loss, gas exchange, and microbial contamination (Sharma & Singh, 2025). Among the coatings, alginate-based coatings (ALG) have emerged as promising alternatives to meet the criteria of innovation and sustainability in the packaging industry, due to their biocompatibility. Biodegradability and capacity to incorporate bioactive compounds with antimicrobial and antioxidant properties, such as green tea extract (GTE) (Falcó et al., 2019; Hamann et al., 2022).

GTE derived from *Camellia sinensis* is rich in polyphenolic compounds, notably catechin (C), epicatechin (EC), epigallocatechin (EGC), and epigallocatechin-3-gallate (EGCG), compounds related to its antimicrobial and antioxidant activities (Hamann et al., 2022; Silva et al., 2023). Previous studies have shown that edible coatings incorporating GTE have the potential to reduce the growth of foodborne pathogens and improve the postharvest quality of fresh produce (Alav, Kutlu, Kına, & Meral, 2024; Sabaghi, Maghsoudlou, Khomeiri, & Ziaiifar, 2015; Yang et al., 2022).

However, the effects of ALG-GTE coating on microbial safety, metabolic changes, and physicochemical quality of white mushrooms during refrigerated storage remain poorly understood. Therefore, this study aimed to characterize the physic and chemical properties of the ALG-GTE coating and assess its effects on postharvest quality parameters, enzymatic activity, and antimicrobial activity against L. *monocytogenes* in white mushrooms during refrigerated storage.

2. Material and methods

2.1. Materials

Sodium alginate (Sigma-Aldrich, St. Louis, MO, USA), glycerol (Química Moderna, Barueri, SP, Brazil), sunflower oil (Cargill, PR, Brazil) and Tween 80 (Sigma-Aldrich, St. Louis, MO, USA) were used to prepare the alginate-based edible coatings (Fernandes et al., 2025). GTE (*Camellia sinensis*) was produced from dried green tea leaves through hydroethanolic extraction (Silva et al., 2023).

Fresh white mushrooms (*Agaricus bisporus*) were purchased from a local retail market in João Pessoa, Paraíba, Brazil. The mushrooms were selected based on the following criteria: uniform size, intact surface, absence of mechanical damage and browning (Ma et al., 2025).

2.2. Determination of phenolic compounds in green tea extract

A rapid performance method validated by Lima et al. (2024) was used to determine the phenolic compounds in GTE (Supplementary Material). The GTE was resuspended in 30% (*v*/v) methanol and filtered through a 0.45 μm nylon membrane (PVDF) (Millex-HA, Millipore, Bradford, USA) before being injected. The separation of the compounds was performed using an Eclipse Plus RRHT RP-C18 column (50 × 4.6 mm, 1.8 μm; Zorbax, SC, USA). The oven temperature was 40 °C, with a flow rate of 1.0 mL/min. 10 μL of the extract, previously diluted 1:3 v/v in phase A and filtered through a 0.45-μm membrane, was injected. Phenolic compounds were identified and quantified by comparing their retention times with those of external standards (Supplementary Material; Table S1), using calibration curves and spectral similarity analysis. The results were expressed as mg/kg.

2.3. Strain cultivation and inoculum preparation

L. monocytogenes serotype 1/2a lineage II strain C1–387, isolated from food (genome available at GenBank: CP006591.1, BioSample: SAMN02203127), was used as a test strain. Stock cultures were maintained at −80 °C in Brain Heart Infusion (BHI; HiMedia, India) containing 20% glycerol (*v*/v). The strain was grown in BHI broth at 37 °C for 24 h prior to use. The culture was centrifuged (4500 ×*g*, 15 min at 4 °C), cells were harvested, washed twice, and resuspended in sterile saline (0.85% NaCl, *w/v*). The cell suspension of each strain was adjusted to an optical density of 0.1 at 660 nm to obtain an inoculum of approximately 5 log CFU/mL (Luciano et al., 2023).

2.4. Determination of the minimum inhibitory concentration (MIC) against L. monocytogenes

The antimicrobial activity of GTE was evaluated using a microdilution assay. The GTE was prepared at a stock concentration of 52 mg/mL and 100 μL was added to the first well of the microplate, followed by twofold serial dilutions, yielding final concentrations ranging from 26 to 0.81 mg/mL. For each well containing diluted GTE (50 μL), 50 μL of bacterial inoculum was added (5 log CFU/mL; section 2.3), resulting in a final volume of 100 μL per well. The positive control consisted of MHB (50 μL) and inoculum (50 μL), while the negative control contained only GTE (100 μL) without inoculum. The microplates were incubated at 37 °C for 24 h. Prior to reading, p-iodonitrotetrazolium chloride (0.2 mg/mL) was added to each well (40 μL) as an indicator of microbial growth, followed by incubation at 37 °C for 30 min. The MIC was defined as the lowest concentration at which no visible bacterial growth was observed (i.e., no color change of the indicator, turbidity, or pellet formation). The results were expressed in μg/mL (Lopes et al., 2025).

2.5. Edible coatings solutions preparation

The edible coating solutions were prepared following the methodology proposed by Dias et al. (2023), and two formulations were prepared: alginate coating (ALG) and ALG incorporated with GTE (ALG-GTE) coating. Sodium alginate (1.5 g/100 mL) was dissolved in sterile distilled water heated to 70 °C under constant stirring (240 rpm) for 30 min using a magnetic stirrer with a heating plate (Dinâmica Química Contemporânea Ltda., Indaiatuba, SP, Brazil). Glycerol (0.75 g/100 mL) was added as a plasticizer to improve the flexibility of the coating, sunflower oil (0.04 g/100 mL) as a lipid to improve water barrier properties, and Tween 80 (0.05 g/100 mL) as a surfactant to improve adhesion to the white mushroom surface (Fernandes et al., 2025). For the ALG-GTE coating, GTE was incorporated into the ALG solution to reach a final concentration of 1.6 mg/mL (MIC value against the test strain), followed by homogenization using a magnetic stirrer for 2 min at

240 rpm and 25 °C (Amankwaah et al., 2020). Three formulations were tested: uncoated (uncoated white mushroom), ALG (white mushroom coated with ALG) and ALG-GTE (white mushroom coated with ALG incorporating GTE).

2.6. Physical and chemical characterization of the coatings

For characterization analyses, procedures previously described by Lopes et al. (2025) were followed. The ALG and ALG-GTE coatings dispersions were poured into 10 cm diameter plastic Petri dishes and left to dry at room temperature (25 ± 2 °C) for 48 h in a ventilated incubator. Subsequently, after drying, the films were peeled off and conditioned in a controlled storage room at 23 ± 2 °C and 50 ± 2% RH, for at least 72 h prior to testing.

The spectra of the ALG and ALG-GTE films were obtained with an FTIR spectrometer (PerkinElmer Precisely Spectrum 100, Waltham, MA, USA) equipped with an attenuated total reflectance (ATR) accessory (PIKE MIRacle™, PIKE Technologies, Fitchburg, WI, USA) with a diamond crystal plate. Spectra were acquired with 32 scans and a resolution of 4 cm^{-1} in the 4000–500 cm^{-1} region.

For the determination of moisture content, solubility in water (WS), each film sample was then placed in previously dried and weighed glass Petri dishes and dried in an oven at 105 °C for 24 h, or until a constant mass was obtained. The moisture content was calculated as the percentage of mass loss after drying and expressed on a dry basis, according to Eq. 1:

$$\text{Moisture}\ (\%) = [M1 - (M3 - M2)] \times 100 \quad (1)$$

where M1 corresponds to the initial mass of the film before drying, M2 represents the mass of the Petri dish, and M3 is the mass of the Petri dish and film after drying.

The WS was evaluated using the previously dried ALG and ALG-GTE films. These were immersed in 35 mL of distilled water at 25 °C for 5 min, then filtered through Whatman No. 1 filter paper. The remaining insoluble fraction was then dried at 105 °C for another 24 h. Solubility was determined using Eq. 2 (Lopes et al., 2025):

$$\text{Solubility}\ (\%) = ((M4 - M5)/M4) \times 100 \quad (2)$$

where M4 is the mass of the film after drying for 24 h at 105 °C and M5 corresponds to the mass of the insoluble residue after immersion in water and further drying.

The water contact angle (WCA) of ALG and ALG-GTE films was measured using a tensiometer (Attension Theta, Biolin Scientific, Gothenburg, Sweden) through the sessile drop technique (Laplace-Young method). A 3 μL drop was dispersed on the coating surface, and the contact angle was determined from the angle formed between the baseline and the lines tangent to the water drop surfaces. For each film, the mean WCA was calculated from measurements obtained after 5 s of water drop stabilization.

The thickness of ALG and ALG-GTE films was measured by a micrometer (Model M120, Adamel Lhomargy, Roissy-en-Brie, France) according to the procedures described by Pereira et al. (2019). The results were expressed in millimeters (mm).

Color measurements were carried out using a portable Chroma Meter CR-400 (Minolta Chroma, Osaka, Japan), with a *C D65 illuminant, a pulsed xenon lamp as the light source, an 8 mm measurement aperture, a closed cone configuration, and a 2° standard observer, corresponding to the CIE 1931 colorimetric system (x–λ, y–λ, z–λ). Color parameters [lightness (L), redness ($+a$) or greenness ($-a$), and yellowness ($+b$) or blueness ($-b$)] were determined according to the CIELab system (Pereira et al., 2019). The color of the films was expressed as the total color difference (ΔE), calculated using Eq. 3:

$$\Delta E = \left[\left(L_{film} - L_{standard}\right)^2 + \left(a_{film} - a_{standard}\right)2 + \left(b_{film} - b_{standard}\right)2 \right]^{1/2} \quad (3)$$

2.7. Edible coatings application on white mushrooms

White mushrooms were immersed in coating solutions described in subsection 2.5 for 2 min, drained for 30 s, and subsequently immersed in a 2% (w/v) calcium chloride solution (Dinâmica Química, São Paulo, Brazil) for 1 min to induce gelation and crosslinking through polymeric bonds. After coating, the samples were placed in 150 mL polypropylene packaging containing filter paper previously sterilized under ultraviolet light, air-dried under controlled airflow for 2 h at 25 °C in a biological safety cabinet, and then stored under refrigeration at 4 ± 1 °C and 90–95% relative humidity (RH) for 8 days, according to Louis et al. (2021) with adaptations.

2.8. Determination of white mushrooms quality parameters

The weight loss, firmness, color, total soluble solids (TSS), pH, and titratable acidity (TA) considered the treatments: uncoated, ALG and ALG-GTE during storage (0, 4, and 8 days). Weight loss was calculated as the difference between the initial and final weights of each sample over the time interval (Huang, Qian, Jiang, & Zheng, 2019). Results were expressed as percentage weight loss using Eq. 4.

$$\text{Weight loss}\ (\%) = [(Wi - Wf/Wi)^{*}100] \quad (4)$$

where Wi represents the initial weight and Wf corresponds to the final weight.

The firmness was determined using a texture analyzer (TA.XT2i; Stable Micro Systems Inc.) equipped with a cylindrical stainless-steel probe (P/6 mm diameter) operating in compression mode. The pre-test, test, and post-test speeds were set at 2, 1, and 10 mm s^{-1}, respectively (Louis et al., 2021). The color measurements were taken at the upper, lower, and lateral surfaces of the samples as described above (subsection 2.6). TSS, pH, and TA were determined according to AOAC methods 983.17, 981.12, and 942.15, respectively (AOAC, 2016; Supplementary Material).

2.9. Determination of sugars and organic acids in coated mushrooms

Sugars and organic acids were determined by HPLC. White mushroom extract previously prepared was injected (10 μL) for the simultaneous determination of sugars (maltose, glucose, fructose, and rhamnose), and organic acids (citric, tartaric, malic, succinic, lactic, formic, acetic, propionic, and butyric), following the validated methodology of Coelho et al. (2018) (Supplementary Material). Chromatographic separation was carried out at 70 °C with a flow rate of 0.7 mL/min using an isocratic mobile phase composed of 0.004 mol/L sulfuric acid in aqueous solution (Sigma-Aldrich, St. Louis, USA). Separation was performed using a Hi-Plex H column (300 × 7.7 mm, 8.0 μm) protected by a PL Hi-Plex H guard column (5 × 3 mm) (Agilent Technologies, Santa Clara, USA). Organic acids were detected using the DAD at 210 nm, whereas sugars were detected using the RID. External standard calibration curves were used for quantification. All compounds showed R^2 values ≥0.998 (Table S2).

2.10. Determination of polyphenol oxidase (PPO), peroxidase (POD), and pectin methylesterase (PME) activity

The extraction procedure and enzymatic activity assays for PPO, POD, and PME were determined according to de de Oliveira et al. (2020), with some modifications (Supplementary Material). The analyses were performed during storage (0, 4, and 8 days) at 4 ± 1 °C. To determine PPO and POD activities, 0.5 mL of white mushroom enzymatic extract was used. For PPO, the extract was mixed with 2.5 mL of 0.07 M catechol (20 s, 30 ± 1 °C) and the absorbance was read at 420 nm (A_{420}). For POD, the extract was mixed with 2.5 mL of 1% guaiacol and 0.2 mL of 1.5% (v/v) hydrogen peroxide (20 s at 30 ± 1 °C) and the

absorbance was read at 470 nm (A_{470}). One unit of PPO or POD activity was defined as the increase in absorbance at 420 or 470 nm per minute per gram of sample (U min^{-1} g^{-1}).

PME activity was evaluated by titration of the carboxylic groups released during pectin demethylation, using a potentiometer equipped with a combined glass electrode (Q400AS, Quimis, São Paulo, Brazil) with 0.05 M NaOH to achieve a pH constant of 7.5. The reaction mixture was titrated with 0.05 M NaOH to maintain the pH at 7.5. One unit of PME activity was defined as the amount of enzyme required to catalyze pectin demethylation, corresponding to the consumption of 1 mmol of NaOH per minute, and the results were expressed in mmol L^{-1} min^{-1} (Supplementary Material).

2.11. ALG-GTE coating antimicrobial activity

The analysis was performed in accordance with Min et al. . (2023) with some adaptations. To simulate post-processing cross-contamination, ALG-GTE coated white mushrooms were contaminated after the coating application. All samples were immersed in an L. *monocytogenes* inoculation bath (approximately 5 log CFU/mL) and gently stirred for 30 s, followed by air-drying in a biological safety cabinet for 30 min. The samples were then packaged in polypropylene containers and stored under refrigeration at 4 ± 1 °C and 90–95% RH for 8 days. At each interval (0, 1, 2, 4, 6 and 8 days), the samples were homogenized in saline solution (1:9; *w/v*) using stomacher bags (Stomacher®, Biomaster, Brazil) for 1 min and then diluted serially to 10^{-5} in saline solution. Aliquots of each dilution were plated using the drop plate technique on selective Oxford agar (HiMedia, Mumbai, India) and incubated at 37 °C for 24 h. The limit of detection was 1.5 log CFU/g.

2.12. Surface characteristics of coated white mushrooms

The surfaces of uncoated and ALG/ALG-GTE coated white mushrooms were evaluated for roughness and waviness. Surface roughness parameters, including arithmetic mean roughness (Sa), maximum surface height (Sz), and mean profile roughness (Ra), were measured using a non-contact 3D optical profilometer (Talysurf CCI MP, Leicester, UK), with a cut-off length of 0.34 mm, 50× magnification, numerical aperture of 0.4, and scanning speed of 1×, operating in 'XYZ' mode during storage (0, 4, and 8 days) at 4 ± 1 °C, according to de Dias et al. . (2023) with adaptations (Supplementary Material).

2.13. Statistical analysis

All analyses were done in three genuine replicates. Results are expressed as mean ± standard deviation. Data were subjected to analysis of variance (ANOVA), followed by Tukey's test, with a significance level of $p < 0.05$, using OriginPro 2025 software (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. GTE phenolics and MIC value

A total of 29 compounds were identified, including phenolic acids, flavonols, flavanols, flavanones, stilbenes, anthocyanins, proanthocyanidins, and one non-phenolic organic acid (Table S3). Among these, flavanols such as catechin (77.15 mg/kg), epicatechin (108.33 mg/kg), and epigallocatechin gallate (239.41 mg/kg), proanthocyanidins including procyanidin A2 (253.39 mg/kg), procyanidin B1 (505.27 mg/kg), and procyanidin B2 (1270.94 mg/kg), stilbenes such as cis-resveratrol (966.84 mg/kg) and trans-resveratrol (387.40 mg/kg), and the phenolic acid gallic acid (2987.36 mg/kg) are widely reported for their antimicrobial properties (Silva et al., 2023). MIC against L. *monocytogenes* was 1.6 mg/mL of GTE.

3.2. ALG and ALG-GTE coatings properties

The FTIR spectra results of the ALG, ALG-GTE films, and pure GTE are shown in Fig. 1. The pure extract was examined to identify specific functional groups responsible for any spectral changes observed between the extract and the coatings. Both films showed a broad band in the region of 3258 cm^{-1} assigned to the –OH stretching vibrations and water molecules involved in hydrogen bonds. The GTE spectra showed a more linear trend in the region corresponding to the stretching vibrations of OH, abundant in phenolic compounds, compared to ALG and ALG-GTE films.

The ALG spectra exhibited characteristic absorption bands at 1584 cm^{-1} and 1388 cm^{-1} attributed to the asymmetric and symmetrical stretching of COO^{-}, 1010 cm^{-1} to the stretching of C–O–C, and 894 cm^{-1} indicating the presence of vibrations associated with OH deformation, related to glycerol, and symmetric C—O stretching. The ALG-GTE spectra showed a broader peak at 1598 cm^{-1} compared to ALG at 1582 cm^{-1} and the pure extract at 1574 cm^{-1}. These peaks correspond to the aromatic C═C stretching vibrations of phenolic compounds, such as catechins, and to the asymmetric stretching of the COO^{-} groups of alginate. Furthermore, the bands in the range of 1476 cm^{-1} (ALG-GTE) to 1390 cm^{-1} (ALG), can be attributed mainly to C—H bending vibrations, while those from 1010 cm^{-1} (ALG) to 1024 cm^{-1} (ALG-GTE) to the stretching vibrations of the C—O and C–O–C groups, commonly attributed to the alginate backbone (Fig. 1).

Table 1 presents the thickness, moisture content, solubility in water (WS), color properties, and water contact angle (WCA) measurements of ALG and ALG-GTE films. The thickness showed values of 0.038 mm and 0.036 mm for the ALG and ALG-GTE films, respectively ($p > 0.05$). For moisture content, the values were 27.29% for the ALG and 26.20% for the ALG-GTE film ($p > 0.05$). WS was >90% and did not differ between ALG and ALG-GTE ($p > 0.05$). The WCA measurements were 47.65° and 54.28° ($p < 0.05$) for the ALG and ALG-GTE films, respectively (Table 1; Fig. S1). L*, a*, b*, and ΔE* values are shown in Table 1. No differences were observed between ALG and ALG-GTE films ($p > 0.05$).

3.3. White mushrooms quality parameters

Figs. 2 and 3 show the weight loss and firmness in uncoated and coated white mushrooms during storage, respectively. The weight loss increased in all samples from the 4th day of refrigerated storage ($p < 0.05$) until the end of the evaluated period. Final values of weight loss reached 6.35 ± 0.14% in uncoated mushrooms, while lower values ($p < 0.05$) were observed in coated samples, with 4.75 ± 0.06% and 3.57 ± 0.15% for ALG and ALG-GTE coated white mushrooms, respectively (Fig. 2).

The firmness gradually decreased from the 4th day of storage until the end of the evaluated period in all mushrooms, as shown in Fig. 3. However, white mushrooms coated with ALG-GTE exhibited lower firmness loss ($p < 0.05$) throughout storage compared to the other treatments. At the end of storage, firmness values were 3.06 ± 0.08 for uncoated white mushrooms, and 3.64 ± 0.05 and 7.13 ± 0.09 for ALG and ALG-GTE coated white mushrooms, respectively (Fig. 3).

Table 2 presents the color parameters of uncoated and coated white mushrooms during storage, and the visual appearance of white mushrooms is shown in Fig. 4. L* values gradually decreased from the 4th day of storage in uncoated and ALG coated white mushrooms ($p < 0.05$), while in ALG-GTE coated samples the reduction was observed only on the 8th day of storage ($p < 0.05$). ALG-GTE coated white mushrooms showed higher final L* values compared to the other treatments indicating less surface browning ($p < 0.05$). The a* and b* values increased throughout storage for all treatments ($p < 0.05$).

The final chroma values also increased over time in both uncoated, ALG and ALG-GTE coated samples ($p < 0.05$). For °Hue values, uncoated white mushrooms showed a decrease from the 4th day until the end of storage, while in ALG coated white mushrooms, the reduction occurred

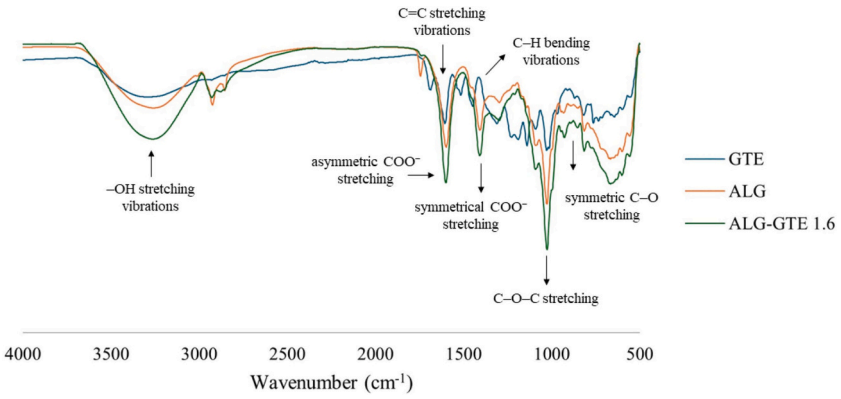

Fig. 1. FTIR spectra of pure green tea extract (GTE), alginate (ALG), and alginate green tea extract (ALG-GTE). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Thickness, moisture content, water solubility (WS), water contact angle (WCA) and color parameters of alginate coating (ALG) and alginate green tea extract (ALG-GTE) coating.[A-B]

	Thickness (mm)	Moisture (%. Dry Basis)	Solubility in Water (%)	WCA (°)	L*	a*	b*	ΔE
ALG (control)	0.038 ± 0.002 ^{A}	27.29 ± 0.16 ^{A}	90.37 ± 5.03 ^{A}	47.65 ± 1.81 ^{B}	85.62 ± 0.82 ^{A}	2.94 ± 0.12 ^{A}	- 4.19 ± 0.37 ^{A}	1.26 ± 0.17 ^{A}
ALG-GTE	0.036 ± 0.002 ^{A}	26.20 ± 0.93 ^{A}	93.21 ± 3.76 ^{A}	54.28 ± 2.60 ^{A}	86.25 ± 1.43 ^{A}	3.15 ± 0.10 ^{A}	- 4.48 ± 0.12 ^{A}	1.19 ± 0.61 ^{A}

$^{A-B}$: Mean values in the same column followed by different uppercase letters differ significantly different between coatings ($p < 0.05$) according to Tukey's test.

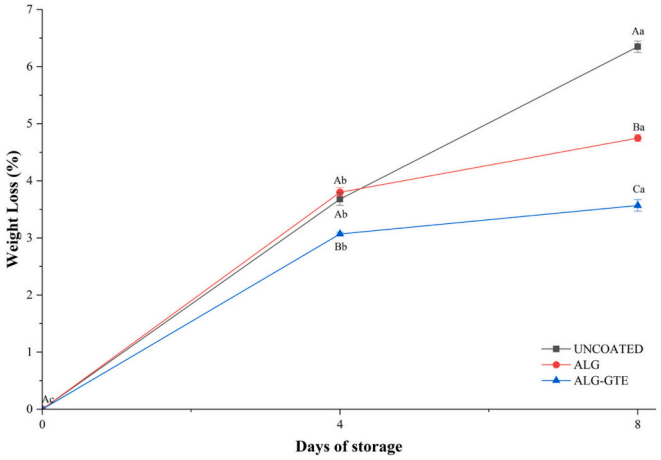

Fig. 2. Weight loss of uncoated and coated with alginate (ALG) or alginate green tea extract (ALG-GTE) white mushrooms during 8 days of refrigerated storage (4 ± 1 °C). Uppercase superscript letters indicate significant differences ($p < 0.05$) among treatments according to Tukey's test. Lowercase superscript letters indicate significant differences ($p < 0.05$) over storage time at the same treatment ($p < 0.05$), according to Tukey's test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

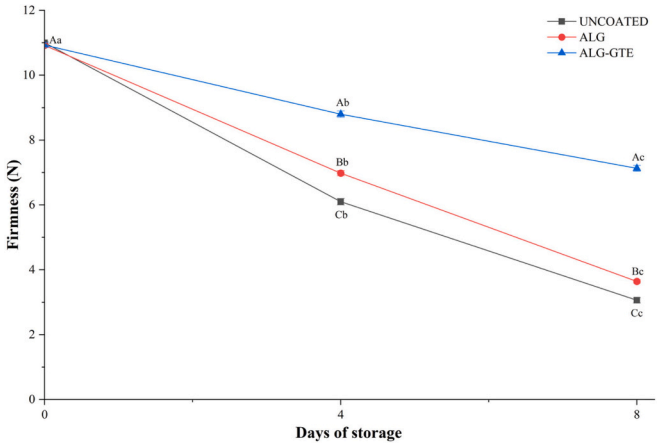

Fig. 3. Firmness of uncoated and coated with alginate (ALG) or alginate–green tea extract (ALG-GTE) white mushrooms during 8 days of refrigerated storage (4 ± 1 °C). Uppercase superscript letters indicate significant differences ($p < 0.05$) among treatments according to Tukey's test. Lowercase superscript letters indicate significant differences ($p < 0.05$) over storage time at the same treatment ($p < 0.05$), according to Tukey's test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on the 8th day ($p < 0.05$). No changes were observed in ALG-GTE coated mushrooms ($p > 0.05$).

TA values decreased ($p < 0.05$) in uncoated mushrooms from the 4th day of storage, while no significant change ($p < 0.05$) was observed in coated samples throughout the storage period (Table S4). At the end of storage, pH values were lower ($p < 0.05$) for uncoated white mushrooms compared to coated samples (Table S4). Regarding TSS, uncoated white mushrooms showed a gradual reduction ($p < 0.05$), while ALG-GTE coated white mushrooms maintained higher TSS values ($p < 0.05$) than the other treatments (Table S4).

3.4. Sugars and organic acids

Table 3 shows the sugar concentrations of the samples during storage. Maltose values decreased in all treatments from the 4th day onward, while glucose levels remained stable in the samples coated with ALG and ALG-GTE ($p > 0.05$). On the 8th day of storage, both maltose and glucose concentrations were below the limit of detection in the uncoated white mushrooms. In uncoated and ALG coated white mushrooms the rhamnose values decreased during storage ($p < 0.05$), while

Table 2
Color parameters of uncoated and coated with alginate (ALG) or alginate green tea extract (ALG-GTE) white mushrooms during 8 days of storage at 4 ± 1 °C.[A-C, a-c]

Parameters	Storage (day)		
	0	4	8
L*			
Uncoated	70.48 ± 0.19^{Aa}	58.22 ± 1.26^{Bb}	55.90 ± 0.47^{Bb}
ALG	70.09 ± 1.70^{Aa}	61.98 ± 0.84^{Bb}	57.14 ± 0.12^{Bc}
ALG-GTE	70.83 ± 0.26^{Aa}	70.17 ± 1.07^{Aa}	63.85 ± 1.16^{Ab}
a*			
Uncoated	3.39 ± 0.08^{Ab}	3.32 ± 0.04^{Ab}	5.11 ± 0.01^{ABa}
ALG	3.45 ± 0.06^{Ab}	3.04 ± 0.02^{Bc}	5.37 ± 0.15^{Aa}
ALG-GTE	3.55 ± 0.02^{Ab}	2.56 ± 0.10^{Cc}	4.66 ± 0.12^{Ba}
b*			
Uncoated	16.17 ± 0.03^{Ac}	15.21 ± 0.09^{Bb}	19.56 ± 0.07^{Ba}
ALG	16.30 ± 0.20^{Ab}	15.47 ± 0.16^{Bb}	20.90 ± 0.33^{Aa}
ALG-GTE	16.12 ± 0.21^{Ac}	17.93 ± 0.34^{Ab}	20.15 ± 0.17^{ABa}
Chroma			
Uncoated	16.72 ± 0.17^{Ab}	15.03 ± 0.10^{Bc}	20.34 ± 0.10^{Ba}
ALG	16.35 ± 0.29^{Ab}	15.76 ± 0.08^{Bb}	21.41 ± 0.08^{Aa}
ALG-GTE	16.20 ± 0.12^{Ac}	17.53 ± 0.33^{Ab}	20.53 ± 0.28^{Ba}
°Hue			
Uncoated	78.77 ± 0.35^{Aa}	76.56 ± 0.28^{Bb}	68.78 ± 0.21^{Cc}
ALG	78.03 ± 0.89^{Aa}	78.08 ± 0.32^{ABa}	72.52 ± 0.07^{Bb}
ALG-GTE	78.71 ± 0.74^{Aa}	78.62 ± 0.70^{Aa}	77.81 ± 0.24^{Aa}

$^{A-C}$: Mean values in the same column followed by different uppercase letters differ significantly different between coatings ($p < 0.05$) according to Tukey's test.
$^{a-c}$: Mean values in the same row followed by different lowercase letters differ significantly different between storage times ($p < 0.05$) according to Tukey's test.

ALG-GTE coated white mushrooms maintained rhamnose values over time ($p > 0.05$) (Table 3).

Regarding organic acids (Table 4), citric and malic acid values remained stable during storage in all treatments ($p > 0.05$). Succinic acid increased ($p < 0.05$) in uncoated and ALG coated white mushrooms, while ALG-GTE coated white mushrooms showed a slight increase ($p < 0.05$) on the 4th day, followed by a subsequent decrease ($p < 0.05$). Formic acid concentrations increased on the 4th day in all treatments ($p < 0.05$), however, ALG and ALG-GTE coated white showed a subsequent decrease ($p < 0.05$). Final values were higher in uncoated white mushrooms compared to those coated with ALG and ALG-GTE ($p < 0.05$) (Table 4).

Table 3
Concentration of sugar in uncoated and coated with alginate (ALG) or alginate green tea extract (ALG-GTE) white mushrooms during 8 days of storage at 4 ± 1 °C.[A-C, a-c]

Parameters	Samples	Storage [Day (g/100 g)]		
		0	4	8
Maltose	Uncoated	1.192 ± 0.03^{Aa}	0.038 ± 0.01^{Ab}	<LOD
	ALG	1.180 ± 0.09^{Aa}	0.040 ± 0.02^{Ab}	0.049 ± 0.04^{Ab}
	ALG-GTE	1.195 ± 0.04^{Aa}	0.064 ± 0.05^{Ab}	0.045 ± 0.01^{Ab}
Glucose	Uncoated	0.027 ± 0.02^{Aa}	0.035 ± 0.05^{Aa}	<LOD
	ALG	0.029 ± 0.02^{Aa}	0.041 ± 0.03^{Aa}	0.031 ± 0.03^{Aa}
	ALG-GTE	0.025 ± 0.01^{Aa}	0.046 ± 0.06^{Aa}	0.030 ± 0.02^{Aa}
Rhamnose	Uncoated	1.464 ± 0.05^{Aa}	1.251 ± 0.04^{Bb}	1.159 ± 0.03^{Bb}
	ALG	1.449 ± 0.04^{Aa}	1.367 ± 0.05^{ABab}	1.325 ± 0.04^{ABb}
	ALG-GTE	1.439 ± 0.03^{Aa}	1.464 ± 0.03^{Aa}	1.335 ± 0.05^{Aa}

LOD: Limit of detection.
$^{A-C}$: Mean values in the same column followed by different uppercase letters differ significantly different between coatings ($p < 0.05$) according to Tukey's test.
$^{a-c}$: Mean values in the same row followed by different lowercase letters differ significantly different between storage times ($p < 0.05$) according to Tukey's test.

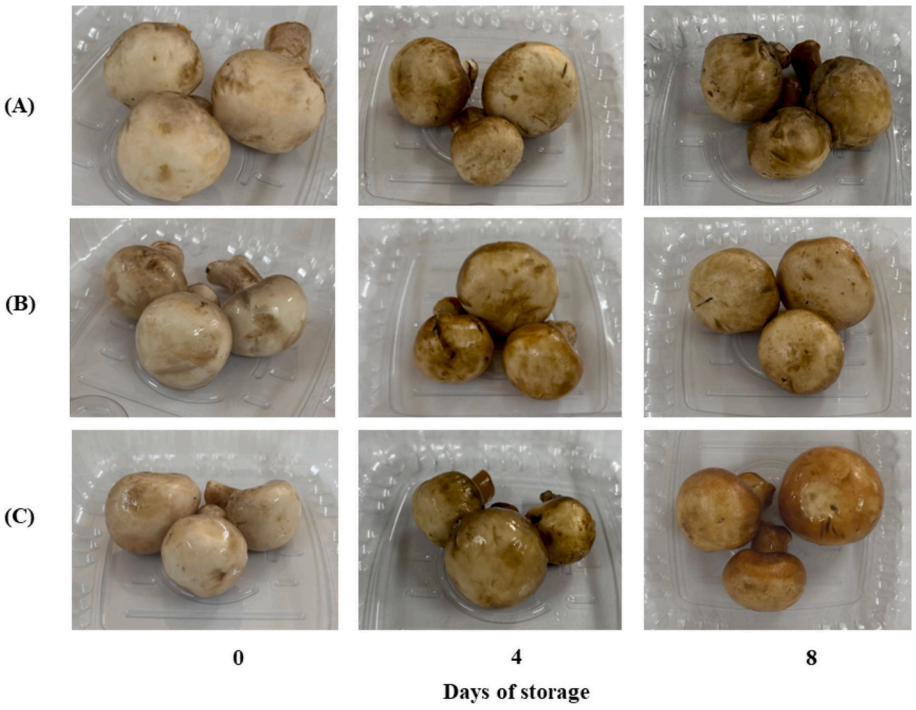

Fig. 4. Visual appearance of uncoated (A) and coated with alginate (ALG; B) or alginate green tea extract (ALG-GTE; C) white mushrooms during 8 days of refrigerated storage (4 ± 1 °C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Concentrations of organic acids in uncoated and coated with alginate (ALG) or alginate green tea extract (ALG-GTE) white mushrooms during 8 days of storage at 4 ± 1 °C.[A-C, a-c]

Organic acids	Samples	Storage [Day (g/100 g)]		
		0	4	8
Citric acid	Uncoated	0.017 ± 0.02^{Aa}	0.027 ± 0.01^{Aa}	0.034 ± 0.01^{Aa}
	ALG	0.018 ± 0.01^{Aa}	0.018 ± 0.01^{Aa}	0.016 ± 0.02^{Aa}
	ALG-GTE	0.015 ± 0.01^{Aa}	0.017 ± 0.02^{Aa}	0.019 ± 0.01^{Aa}
Malic acid	Uncoated	0.034 ± 0.02^{Aa}	0.037 ± 0.01^{Aa}	0.040 ± 0.03^{Aa}
	ALG	0.032 ± 0.01^{Aa}	0.046 ± 0.03^{Aa}	0.039 ± 0.01^{Aa}
	ALG-GTE	0.030 ± 0.02^{Aa}	0.045 ± 0.05^{Aa}	0.034 ± 0.01^{Aa}
Succinic acid	Uncoated	0.107 ± 0.03^{Aa}	0.290 ± 0.06^{Aa}	0.333 ± 0.08^{Aa}
	ALG	0.103 ± 0.02^{Ab}	0.313 ± 0.07^{Aa}	0.269 ± 0.05^{Aab}
	ALG-GTE	0.109 ± 0.04^{Ab}	0.233 ± 0.05^{Aa}	0.174 ± 0.03^{Ab}
Formic acid	Uncoated	1.148 ± 0.02^{Ab}	2.393 ± 0.04^{Aa}	2.571 ± 0.07^{Aa}
	ALG	1.131 ± 0.03^{Ab}	1.653 ± 0.03^{Ca}	1.207 ± 0.05^{Bb}
	ALG-GTE	1.244 ± 0.05^{Ab}	1.956 ± 0.04^{Ba}	1.180 ± 0.02^{Bb}

[A-C] : Mean values in the same column followed by different uppercase letters differ significantly different between coatings ($p < 0.05$) according to Tukey's test.
[a-c] : Mean values in the same row followed by different lowercase letters differ significantly different between storage times ($p < 0.05$) according to Tukey's test.

3.5. Enzymatic activity in in white mushrooms

Enzymatic activity in uncoated and ALG and ALG-GTE coated white mushrooms is shown in Fig. 5. PPO and POD levels did not change throughout storage for any of the treatments tested ($p > 0.05$) (Fig. 5AB). PME activity increased during storage in uncoated mushrooms ($p < 0.05$). In contrast, PME activity decreased during storage in ALG-GTE coated white mushrooms ($p < 0.05$), with lower final activity observed in this treatment compared to the others ($p < 0.05$) (Fig. 5C).

3.6. Antimicrobial activity of ALG-GTE coatings on white mushrooms

The antimicrobial activity of ALG-GTE coatings against L. *monocytogenes* in white mushrooms during 8 days of storage (4 ± 1 °C) is presented in Fig. 6. *L. monocytogenes* counts increased by 1.45 log CFU/g over the 8 days of storage in uncoated white mushrooms ($p < 0.05$). In ALG-GTE coated white mushrooms, *L. monocytogenes* counts decreased by 1.39 log CFU/g after 1 day of storage ($p < 0.05$), and no viable cells (< 1.5 log CFU/g) were detected after 2 days of storage.

3.7. Surface characteristics of coated white mushrooms

Fig. 7 presents the 3D topography of a representative area of uncoated, ALG, and ALG-GTE mushrooms surface during storage (0, 4 and 8 days). The ALG-GTE coated white mushroom (Fig. 7C) showed a smoother and more homogeneous surface with lower final roughness values ($p < 0.05$) compared to uncoated (Fig. 7A) and ALG coated mushrooms (Fig. 7B). Sa, Sz and Ra values were higher ($p < 0.05$) for ALG coated (3.67, 21.70 and 0.11 μm) and uncoated white mushrooms (6.03, 21.70 and 0.11 μm) than for those coated with ALG-GTE (3.26, 11.21 and 0.06 μm).

4. Discussion

GTE phenolic profile showed catechins as major compounds, consistent with literature reports (Singh et al., 2022). These compounds are widely recognized for their antimicrobial and antioxidant properties, which are mainly attributed to their ability to disrupt microbial cell membranes, interfere with intracellular metabolic processes through the formation of hydrogen bonds between phenolic compounds and enzymes, and induce oxidative stress in bacterial cells (Meremäe, Raudsepp, Rusalepp, Laun, & Roasto, 2025).

The addition of GTE to the ALG coating did not alter moisture content, solubility in water, thickness, or color parameters, while increasing the WCA. The findings suggest that the incorporation of GTE did not compromise the structural integrity of the coating, maintaining the mechanical and adhesion properties, as well as the moisture retention capacity and color properties (Min, Priyadarshi, Ezati, Rhim, & Kim, 2023; Wardak et al., 2024). These results are important because they indicate that GTE can be incorporated into alginate-based coatings without compromising their technological properties. Also, maintaining the color parameters in this matrix is important since color influences consumer preferences (Szymkowiak, Antoniak, Kulawik, & Jamróz, 2025).

The increase in WCA ($p < 0.05$) observed in the ALG-GTE coating suggests a reduction in surface wettability, possibly due to the presence of aromatic polyphenolic structures from GTE that modify the surface energy, which may enhance water barrier properties and moisture resistance of the coating (Ning et al., 2025).

The FTIR spectral changes observed following the incorporation of GTE into the alginate matrix can be attributed primarily to intermolecular interactions, rather than the formation of new chemical bonds. The increase in band intensity in the hydroxyl region suggests a greater contribution from hydrogen bonding interactions, likely due to the presence of hydroxyl groups from phenolic compounds in GTE interacting with alginate and glycerol (Benlloch-Tinoco, Gentile, Taylor, & Girón-Hernández, 2025; Lopes et al., 2025). Similarly, changes observed in the region associated with carboxylate groups indicate interactions between the alginate matrix and the phenolic compounds, suggesting the formation of hydrogen bonds within the polymeric matrix. These interactions can alter the local chemical environment of the functional groups, leading to variations in the intensity and shape of the band. Variations in the region associated with the deformation vibrations of aliphatic groups also reinforce the interactions between the GTE polyphenols and the alginate matrix (Benlloch-Tinoco et al., 2025; Moura-Alves et al., 2023).

Overall, the alginate matrix remained chemically stable after incorporation of GTE, suggesting homogeneous incorporation of the extract into the polymer matrix. The relatively low concentration of GTE compared to the main components of the coating may be insufficient to induce distinct spectral changes detectable by FTIR (Lopes et al., 2025). Similar behavior was reported for alginate/chitosan-based coatings synthesized with two-phase condensates of oregano and turmeric, in which the coatings exhibited characteristic peaks similar to the controls, with only minor shifts in the bands (Such et al., 2023).

The ALG-GTE coating demonstrated barrier properties and was effective in delaying weight loss, an important deterioration marker, when compared to other treatments ($p < 0.05$). These results suggest that the coating favored the resistance to the passage of O_2, CO_2, moisture, and solute movement, acting as an effective semipermeable barrier. In addition, the phenolic compounds present in GTE may contribute to the reduction of oxidative stress and the maintenance of cell membrane integrity, decreasing intracellular water loss of mushrooms during storage (Kaur et al., 2023; Li, Han, Wang, & Wu, 2023).

Also, the ALG-GTE coating was effective in reducing firmness loss, which may be related to the inhibition of degradative enzymes associated with softening, delayed water loss, maintenance of cell turgor pressure, and preservation of tissue structural integrity during storage

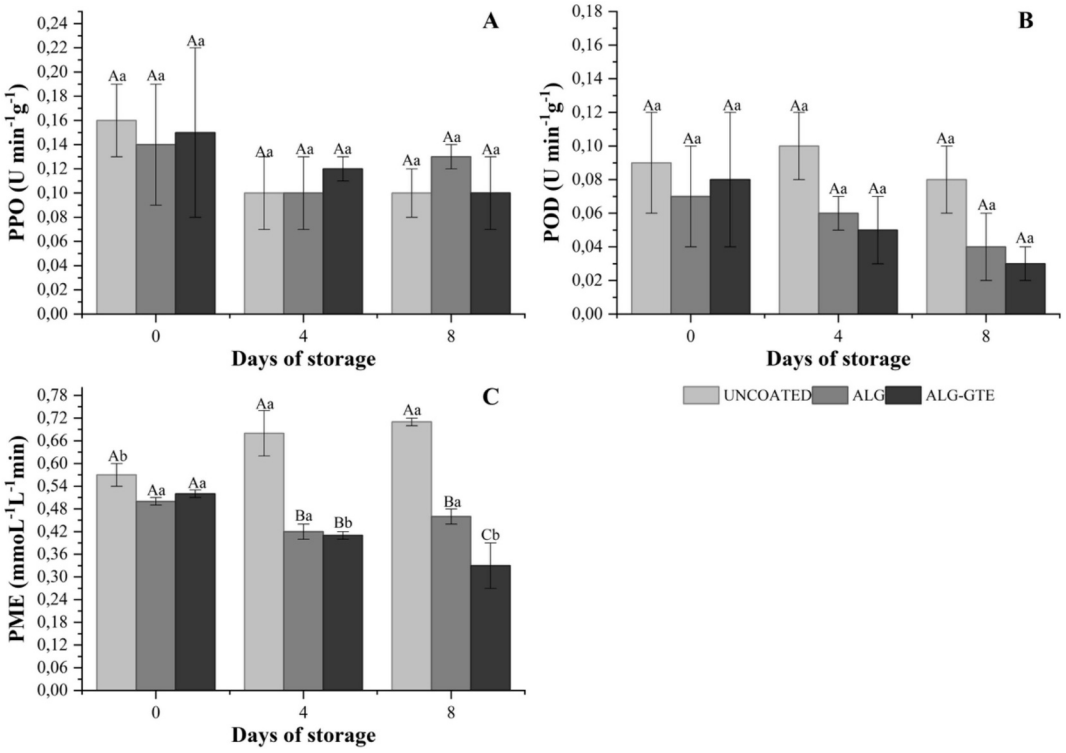

Fig. 5. Enzymatic activity of polyphenol oxidase (PPO; A), peroxidase (POD; B), and pectin methylesterase (PME; C) in uncoated and coated with alginate (ALG) or alginate–green tea extract (ALG-GTE) white mushrooms during 8 days of storage (4 ± 1 °C). Uppercase superscript letters indicate significant differences ($p < 0.05$) among treatments according to Tukey's test. Lowercase superscript letters indicate significant differences ($p < 0.05$) over storage time at the same treatment ($p < 0.05$), according to Tukey's test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

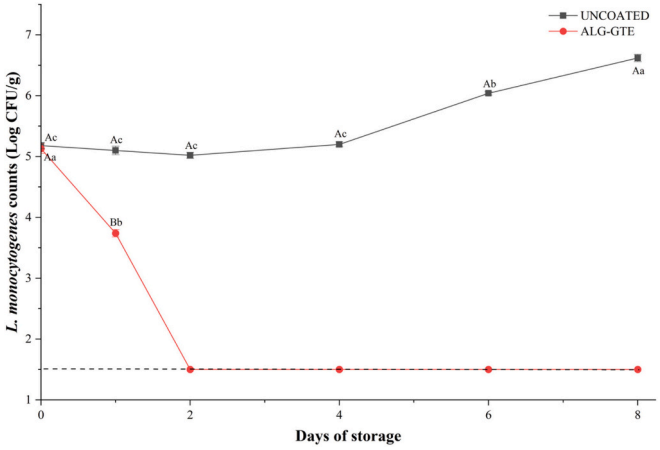

Fig. 6. Antimicrobial activity of alginate–green tea extract (ALG-GTE) coating against *Listeria monocytogenes* in white mushrooms during 8 days of refrigerated storage (4 ± 1 °C). Uppercase superscript letters indicate significant differences ($p < 0.05$) between uncoated and ALG-GTE coated white mushrooms, according to Tukey's test. Lowercase superscript letters indicate significant differences over storage time at the same treatment ($p < 0.05$), according to Tukey's test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Huang et al., 2019). Ulfa, Ningrum, and Supriyadi. (2024) observed firmer texture and slower softening rate in star fruits coated with an edible coating containing GTE during storage for 13 days at 29 °C, when compared to uncoated fruits.

This coating further delayed the browning of white mushrooms during storage. Browning is one of the main postharvest changes in white mushrooms and is generally associated with oxidative reactions involving phenolic compounds, resulting in the formation of dark pigments and a reduction in product quality and shelf life (Sapna, Sharma, Pathak, Yadav, & Gautam, 2024; Zhu et al., 2024). This effect can be attributed to the barrier properties of the alginate matrix and the antioxidant compounds present in GTE, which may reduce oxygen availability and limit oxidative reactions on the mushroom surface.

The maintenance of glucose levels in ALG and ALG-GTE coated white mushrooms, compared to the absence in uncoated samples at the end of storage, may indicate a lower consumption of soluble sugars during postharvest metabolism. Also, the slight increase on TSS content, may occur during storage because of biochemical changes and the solubilization of other compounds (Zhang et al., 2024).

In addition, rhamnose levels were maintained throughout storage on ALG-GTE coated white mushrooms, which may be associated with its role in structural cell wall polysaccharides and glycoconjugates. This suggests that the coating may contribute to the preservation of tissue structure and may reduce cell wall degradation-associated changes during postharvest senescence of this matrix (Chávez-Santiago et al., 2025). Furthermore, the lower increase in formic acid observed in ALG-GTE coated white mushrooms suggests a slower progression of degradation processes during storage, indicating a delay in quality deterioration (Dias et al., 2023).

The activity of PPO and POD was not affected by the coatings in this study, the reduction in browning was observed in coated samples possibly due to chemical reactions related to a limited oxygen barrier provided by the coating rather than to enzymatic activity (Fatima, Kumar, & Bhadauria, 2024; Khojah et al., 2021). Further studies should explore the browning mechanisms beyond these results. The ALG-GTE coating retarded the increase of PME, which corroborates firmness results. Since PME is involved in pectin modification and subsequent changes in cell wall structure, its reduced activity suggests a slower progression of tissue softening during storage (Kumar et al., 2023). The incorporation of natural extracts into edible coatings may

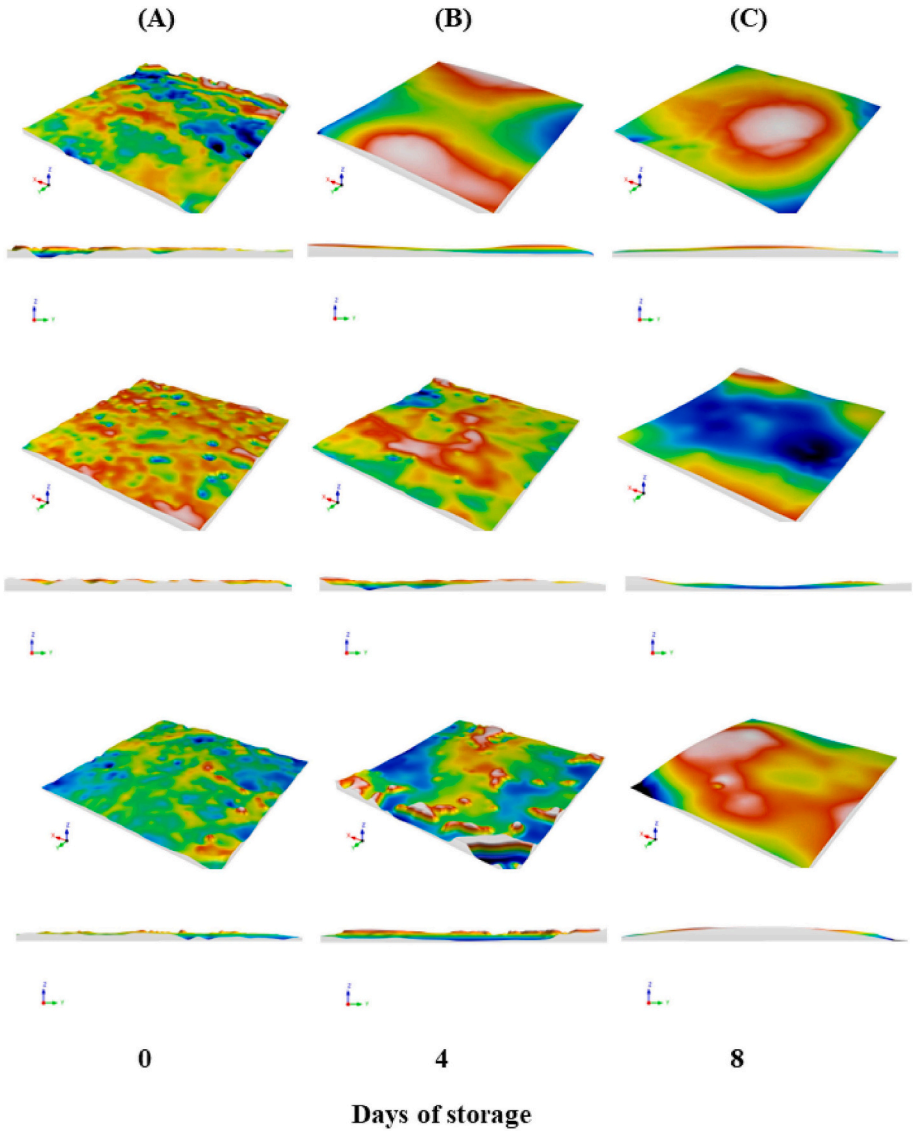

Fig. 7. 3D profilometric analysis of surface characteristics of white mushrooms: uncoated (A), coated with alginate (ALG; B) or alginate–green tea extract (ALG-GTE; C), in XYZ mode during 8 days of storage (4 ± 1 °C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

favor the maintenance of firmness due to the presence of bioactive compounds capable of affecting metabolic processes related to the cell wall (Salsabiela et al., 2022). The reduced PME activity in ALG-GTE coated samples suggests limited pectin modification, contributing to the preservation of the structure of white mushrooms.

In addition to preserving physicochemical quality, edible coatings may also contribute to microbial safety by inhibiting the growth of pathogenic microorganisms. Our results demonstrated the antimicrobial activity of edible coatings against L. *monocytogenes* over storage. The ALG-GTE coating may have contributed to the gradual release of GTE polyphenols onto the mushroom surface, supporting the antimicrobial activity observed during storage (Kaur et al., 2023; Sharma & Singh, 2025).

Previous studies also reported antimicrobial activity of edible coatings in mushrooms. Min et al. (2023) observed that chitosan-based coatings incorporating sulfur quantum dots reduced the growth of L. *monocytogenes* (~5 log CFU/mL) in coated enoki mushrooms. In chitosan-coated samples, counts decreased to approximately ~2.5 log CFU/mL after 6 days of storage. In contrast, the 3% chitosan/SQD coating significantly reduced L. *monocytogenes* counts (<1 log CFU/mL) over the same period. In contrast, growth in the uncoated samples continued throughout storage.

In general, the coated mushrooms were measurably smoother, more homogeneous, and less irregular when compared to uncoated mushrooms. Edible coatings with a more homogeneous microstructure are associated with greater mechanical resistance, better adhesion to the substrate, and greater capacity to retain bioactive compounds, which are desirable characteristics for applications in fresh products (Janith et al., 2026). In addition, the reduction in surface roughness observed in ALG-GTE coated white mushrooms may be related to lower dehydration and delayed degradation during storage, tending to a lower permeability to water vapor and gases.

5. Conclusion

The results demonstrated that ALG-GTE coating acts as a potential preservation system capable of simultaneously improving microbial safety and delaying postharvest deterioration of white mushrooms. The antimicrobial activity against L. *monocytogenes* and the preservation of quality parameters suggest that the coating functions both as a physical

barrier and as a carrier for antimicrobial polyphenols. These findings highlight the potential of ALG-GTE coatings as sustainable alternatives for the preservation of fresh mushrooms and other highly perishable foods. Future studies should explore alternative strategies for incorporating GTE into the coating matrix to optimize its stability and antimicrobial efficacy, investigate its activity against other foodborne pathogens and spoilage microorganisms, and assess its impact on the sensory quality of coated mushrooms.

CRediT authorship contribution statement

Jade Morais Alves: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Bruna Heloiza Gomes da Silva:** Writing – original draft, Methodology, Investigation, Formal analysis. **Adma Nadja Ferreira de Melo:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation. **Louise Iara Gomes de Oliveira:** Writing – review & editing, Methodology, Formal analysis. **André Ulisses Dantas Batista:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Marcos dos Santos Lima:** Writing – review & editing, Validation, Methodology, Formal analysis. **Ruthchelly Tavares da Silva:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Maria Manuela Pintado:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Marciane Magnani:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2026.120051.

Data availability

Data will be made available on request.

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