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Role of nano edible coating, packaging, and storage temperature in maintaining color, moisture content, and phenolic compounds of straw mushroom

Abstract. Straw mushrooms are among the most sought-after edible mushrooms, but their harvest is highly perishable due to their high respiration and transpiration rates, leading to a decline in quality during storage. The application of nano edible coating can cover the surface of straw mushrooms and maintain their freshness, while packaging and storage at low temperatures can maintain quality by inhibiting respiration and enzymatic activity. This study aims to evaluate the effects of nano edible coating, packaging types, and different storage temperatures on the color, moisture content, and phenolic compounds of straw mushrooms. The study was conducted at the Horticulture Laboratory, Faculty of Agriculture, Universitas Padjadjaran using a Completely Randomized Design (CRD) consisting of a combination of nano edible coatings (nano sodium alginate and nano aloe vera), packaging types (vacuum packaging, biodegradable, and wrap), and storage temperatures (room temperature (± 25 °C), 10 °C, and 5 °C) so that there are 18 treatment combinations. Each treatment was repeated twice, resulting in 36 experimental units at each observation time. Observations were conducted at 3 and 6 days after storage, resulting in 72 samples observed. The results showed that the combination of nano edible coating, packaging type, and different storage temperatures significantly affected the color, water content, and phenolic compounds of straw mushrooms. The combination of nano aloe vera with vacuum packaging at 10 °C had the best effect on the L^* , b^* , chroma, h° , total phenolic, and total flavonoid values of straw mushrooms during storage.

Keywords: Edible mushroom · Flavonoid · Perishable food

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Introduction

Straw mushroom (*Volvariella volvacea*) is an edible mushroom that is highly sought after due to its taste and nutritional content. Straw mushrooms possess a tasty flavor, so they are used in various foods (Hendrawani & Hulyadi, 2023). Straw mushrooms are also beneficial for health because they contain secondary metabolite compounds such as phenolics and flavonoids (Elawati et al., 2021; Ali et al., 2024). However, the straw mushroom harvest has a high respiration and transpiration rate so it is easily damaged compared to other fresh commodities (Wang et al., 2017). The high respiration and transpiration rates are caused by the mushroom not having a cuticle layer that protects it from mechanical damage and microbial attack during storage (Kumari & Baskaran, 2015; Castellanos-Reyes et al., 2021). According to research by Sakinah et al. (2020), straw mushrooms have a short shelf life at room temperature, for about 1-2 days. This shows that proper post-harvest treatment is necessary to maintain the quality of straw mushrooms.

Nano edible coating is a post-harvest technology that can maintain the quality of straw mushrooms during storage. Nano edible coating has a smaller particle size and a wider contact area, thus providing a better effect (Filho et al., 2021). The use of nano edible coating can maintain freshness and color (Saputra et al., 2023). Sodium alginate and aloe vera are examples of natural polysaccharides that can be used as nano edible coating materials. Nano coatings made from sodium alginate are able to form a gel that is hydrophilic, transparent, and shiny (Puscaselu et al., 2020). With these capabilities, sodium alginate coatings are able to maintain moisture, freshness, and improve the appearance of coated products (Parreidt et al., 2018). Nano coatings made from aloe vera can also maintain product freshness and appearance because they contain antioxidants, antimicrobials, and antifungals (Heř et al., 2019; Mendy et al., 2019).

Straw mushrooms are a storage condition-sensitive food product. Storage temperature affects respiration, microbial growth, and enzyme activity (Claassen et al., 2024). Inappropriate storage temperatures make mushrooms wet or dry, making them unsafe for consumption. Storage at high temperatures enhances mushroom respiration and enzyme

activity (Cliffe-Byrnes & O'Beirne, 2007; Iqbal et al., 2009; Silva et al., 2025). Elevated enzyme activity leads to nutritional degradation and discoloration of mushrooms (Nugraheni et al., 2023). Straw mushrooms can be kept under low-temperature storage to extend their freshness. However, very low temperatures lead to a reduction in quality. Freezing storage temperatures make mushroom cells freeze, leading to cell wall damage that, when thawed, degrades cell structure and tissue (Ilyas & Soeka, 2019; Tan et al., 2021). The deterioration of cells makes the mushrooms discolour and experience chemical changes (Moutia et al., 2024).

The temperature conditions of storage can affect the humidity of the air around the straw mushroom. Excessive humidity can reduce the quality of stored straw mushrooms. High humidity leads to condensation in the packing, especially when the temperature fluctuates (Dehghani et al., 2024). Condensed water in the packaging adheres to the mushroom, inducing the growth of microbes and causing color and texture alterations (Castellanos-Reyes et al., 2021). Excess water vapor from product respiration inside the packaging may condense and cause product shrinkage and deterioration (Basha et al., 2022). Low humidity in storage can deplete the moisture content (Gidado et al., 2024).

The deterioration in the quality of straw mushrooms due to condensation of water vapor within the packaging can be mitigated through the use of appropriate packaging methods. The packaging approach significantly influences the stability of mushroom quality during storage (Kumar et al., 2020). Packaging that effectively regulates humidity and restricts the inflow of external air can help preserve the physicochemical quality of mushrooms (Mahajan et al., 2008; Geyer et al., 2015). Furthermore, suitable packaging minimizes physical damage throughout the distribution chain and contributes to an extended shelf life (Joshi et al., 2018; Sharma et al., 2024).

In selecting appropriate packaging, it is essential to consider the characteristics of the packaging material, storage temperature, and duration. This study employed three types of packaging: vacuum, biodegradable, and wrap. Vacuum packaging is a sealed system with reduced oxygen levels, thereby limiting moisture accumulation resulting from respiration (Chetti et al., 2014; Chen et al., 2022). Wrap packaging helps prevent secondary microbial

contamination and reduces spoilage and weight loss (Dhall et al., 2012). Biodegradable packaging, in addition to being environmentally friendly, offers improved air permeability (Cheng et al., 2024).

Vacuum packaging occupies a smaller internal volume compared to biodegradable and wrap packaging, leading to differences in respiration activity and humidity levels within the package. The volume of the packaging space plays a crucial role in regulating the respiration rate of mushrooms, as the amount of available gas inside the package is directly influenced by this volume (Pogorzelska-Nowicka et al., 2020). Additionally, both storage temperature and duration significantly impact the respiration rate of mushrooms (Joshi et al., 2018). There is still a lack of research on how nano edible coating treatment, packaging type, and storage temperature affect straw mushroom quality. Based on these criteria, this study aims to evaluate the effects of nano edible coating, packaging types, and different storage temperatures on the color, moisture content, and phenolic compounds of straw mushrooms.

Materials and Methods

Time and Location. The research was conducted at the Horticulture Laboratory, Faculty of Agriculture, Universitas Padjadjaran, from September 2024 to March 2025. The straw mushroom samples used were sourced from farmers in Purwakarta. The samples were at the same harvest age, 15 days after sowing the seeds in the growing medium (not blooming/edged), and were free from damage.

Tools and materials. The tools used were a Mettler Toledo analytical balance type AG254 (Switzerland), a Memmert oven type UM300 (Germany), a Konica Minolta reflectance spectrophotometer type CM-600D (Japan), a grinder, a Shimadzu UV-Vis spectrophotometer type UV-1601 (Japan), a centrifuge, a BK-2000 ultrasonic cleaner, a vacuum sealer, a refrigerator, cooling storage, a freezer. The materials used are: semi-edge straw mushrooms, nano aloe vera, nano sodium alginate, methanol, distilled water, folin reagent, sodium carbonate, gallic acid, aluminum chloride, sodium acetate, quercetin, vacuum plastic, biodegradable plastic, styrofoam, and plastic wrap.

Preparation and Application of Nano edible Coating. Sodium alginate and aloe vera were used as coatings on straw mushrooms and subjected to nano-treatment. The nano-sodium alginate and nano aloe vera were produced by the Functional Nano Powder University Center of Excellence (Finder U-CoE) at Universitas Padjadjaran, Indonesia. The particle size of the nano edible coating was approximately 300 nm. A 1% nano edible coating was made by dissolving 1 g of nano-sodium alginate in 100 mL of distilled water, then mixing until uniform. The same process was used to prepare a 1% nano aloe vera solution. Fresh, cleaned straw mushrooms were coated by brushing with nano sodium alginate or nano aloe vera. The coated mushrooms were air-dried before packaging and storage.

Packaging and Storage. Straw mushrooms that have been coated using 1% nano sodium alginate or 1% nano aloe vera are then packaged using vacuum, biodegradable, wrap packaging of ± 100 g each. Packaging using vacuum packaging is done using a vacuum sealer. Wrap packaging uses plastic wrap or cling wrap and Styrofoam. Biodegradable packaging uses biodegradable plastic. The packaged mushrooms are stored at three temperatures, namely room temperature (± 25 °C), 10 °C and 5 °C for 6 days. Observations are made at 3 and 6 days after storage (DAS).

Experimental Design and Analysis. The experimental design used was a Completely Randomized Design (CRD). Treatments consisted of combinations of nano edible coating types (nano sodium alginate, nano aloe vera), packaging types (vacuum, biodegradable, and wrap packaging), and storage temperatures (room temperature (± 25 °C), 10 °C, and 5 °C). Each treatment combination had two replications, resulting in 36 experimental units. Each experimental unit consisted of approximately 100 g of straw mushroom, observed at 3 and 6 days after storage (DAS), resulting in 72 straw mushroom samples. The data obtained were tested for normality and homogeneity, then analyzed using analysis of variance (ANOVA) at a significance level of 5% to determine the effect of the given treatment. When the calculated F-value exceeded the critical F-value at the 5% significance level, mean separation was performed using the Scott-Knott advanced test at a 5% significance level with SmartStatsXL software.

Observation Parameters: Color. Color measurements were performed using a Konica Minolta reflectant spectrophotometer that can measure color quantitatively (Kusumiyati et al., 2022). Measurements were made at two points, namely the front and back of the straw mushroom, and were repeated three times. The data obtained per sample were averaged. The values displayed by the instrument are L^* , a^* , and b^* . The hue angle (h°) and chroma (C) were calculated using the following formula: hue = $\tan^{-1}(b/a)$ and chroma = $(a^2+b^2)^{1/2}$.

Moisture Content. Measurements were made by cutting 4 g of the straw mushroom fruit bodies, referring to SNI, and Kusumiyati et al. (2021). The sample was placed in a cup whose weight had been constant. The cup was placed in an oven at 105 °C for 3 hours. The sample was removed from the oven and cooled for 5 minutes in a desiccator before being weighed. Heating was repeated until the sample weight was constant. The formula for calculating water content is:

$$\text{Moisture content (\%)} = \frac{\text{fresh weight} - \text{dry weight}}{\text{fresh weight}} \times 100$$

Total Phenolic. A 100 mg sample of the dried sample was weighed and transferred into a 10 mL volumetric flask. Methanol solvent was added to the mark. The solution was extracted with a sonicator at room temperature for 60 minutes. The solution was transferred into a centrifuge tube and centrifuged for 10 minutes at 4000 rpm. The supernatant was transferred to a vial. Total phenolics were determined using a modified Folin-Ciocalteu (Sytar et al., 2018). A 0.3 mL sample was extracted, 0.2 mL of methanol and 2.5 mL of 10% Follin reagent were added, then incubated for 5 minutes at room temperature. 2 mL of 7.5% sodium carbonate was added and homogenized. The solution was incubated at room temperature for 60 minutes. A standard solution was prepared by dissolving 10 mg of gallic acid in 10 mL of methanol to obtain a gallic acid concentration of 1000 mg/L and diluting it to 20, 40, 80, 160, and 320 mg/L. The absorbance of the sample and standard was measured at a wavelength of 765 nm using a Shimadzu UV-1601 UV-Vis spectrophotometer (Japan). The total phenolic content in the sample was expressed in GAE mg/100 g using the calculation formula:

$$\text{Total phenolic} \left(\frac{\text{mg GAE}}{100 \text{ g}} \right) = \frac{C \cdot V}{B} \times 100$$

Note: C = Gallic acid concentration (mg/L); V = Volume of test solution (L); B = Sample weight (g)

Total Flavonoid. A 100 mg sample of the dried sample was weighed and transferred into a 10 mL volumetric flask. Methanol solvent was added to the mark. The solution was extracted with a sonicator at room temperature for 60 minutes. The solution was transferred into a centrifuge tube and centrifuged for 10 minutes at 4000 rpm. The total flavonoid measurement procedure refers to Sytar et al. (2018), which has been modified. 1 mL of the extracted sample was added with 2 mL of methanol, 0.1 mL of 10% aluminum chloride, 0.1 mL of 1 M sodium acetate, and 1.8 mL of distilled water. The solution was homogenized, then incubated at room temperature for 30 minutes. A blank was also prepared using the same procedure, but the sample was replaced with methanol. A standard solution was prepared by dissolving 10 mg of quercetin in 10 mL of methanol, obtaining a quercetin concentration of 1000 mg/L, and then diluting it to 4, 8, 16, 32, 64, and 128 mg/L. The absorbance of the sample and standard was measured at a wavelength of 435 nm using a Shimadzu UV-VIS Spectrophotometer (Japan). The absorbance of the standard measurement was used to create a calibration curve. The total flavonoid content in the sample was expressed in QE mg/100 g.

$$\text{Total flavonoid} \left(\frac{\text{mg QE}}{100 \text{ g}} \right) = \frac{C \cdot V}{B} \times 100$$

Note: C = Quercetin concentration (mg/L); V = Volume of test solution (L); B = Sample weight (g)

Results and Discussion

Color (L^* value). The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on mushroom color in terms of L^* values. The combination treatment of nano sodium alginate with wrap packaging at a temperature of 10 °C showed the highest L^* value, which was not significantly different from the combination treatment of nano aloe vera with vacuum packaging at a temperature of 10 °C and significantly different from other combination treatments, especially at a temperature of 5 °C (Table 1). The above treatment also showed a constant L^* value during 6 days of

storage. Semi-fresh straw mushrooms have a bright grayish-light brown color. Color changes indicate a decrease in the quality of straw mushrooms during storage (Khan et al., 2021)

The L* value indicates the lightness and whiteness of the color, with a value of 100, a decrease towards 0 indicates browning (Kamali et al., 2024). A higher and constant L* value indicates freshness and better appearance of the straw mushrooms. A constant L* value during storage indicates that the combination of nano sodium alginate treatment with wrap packaging at a temperature of 10 °C can maintain the freshness and quality of the straw mushrooms during storage. The L* value was positively correlated with other color parameters except the a* value, water content, and total flavonoids during 6 days of storage (Figure 1). Thus, color changes are closely related to changes in the biochemical compounds of straw mushrooms during storage.

The combination treatment of nano edible coating with all packaging at 5 °C showed a

lower L* value compared to the storage temperature of 10 °C. The decrease in the L* value indicates a change in the color of the straw mushrooms during storage. The darker color of the button mushrooms is in line with the decrease in the L* value (Lin & Sun, 2019).

Cold stress can damage membrane integrity and increase cell membrane permeability, which contributes to chilling injury symptoms (Li et al., 2023). Damage to the cell membrane causes the polyphenol oxidase (PPO) enzyme in its bound form to change into its free form, increasing the free form of the PPO enzyme (Zou et al., 2025). The increase in the free form of PPO is in line with the number of PPO enzymes that oxidize phenolic compounds. Oxidation of phenolic compounds by the PPO enzyme forms quinone compounds and ultimately causes melanin clumping. Melanin clumping causes browning in straw mushrooms at a storage temperature of 5 °C. PPO enzyme activity is the main cause of browning (Harisha et al., 2023).

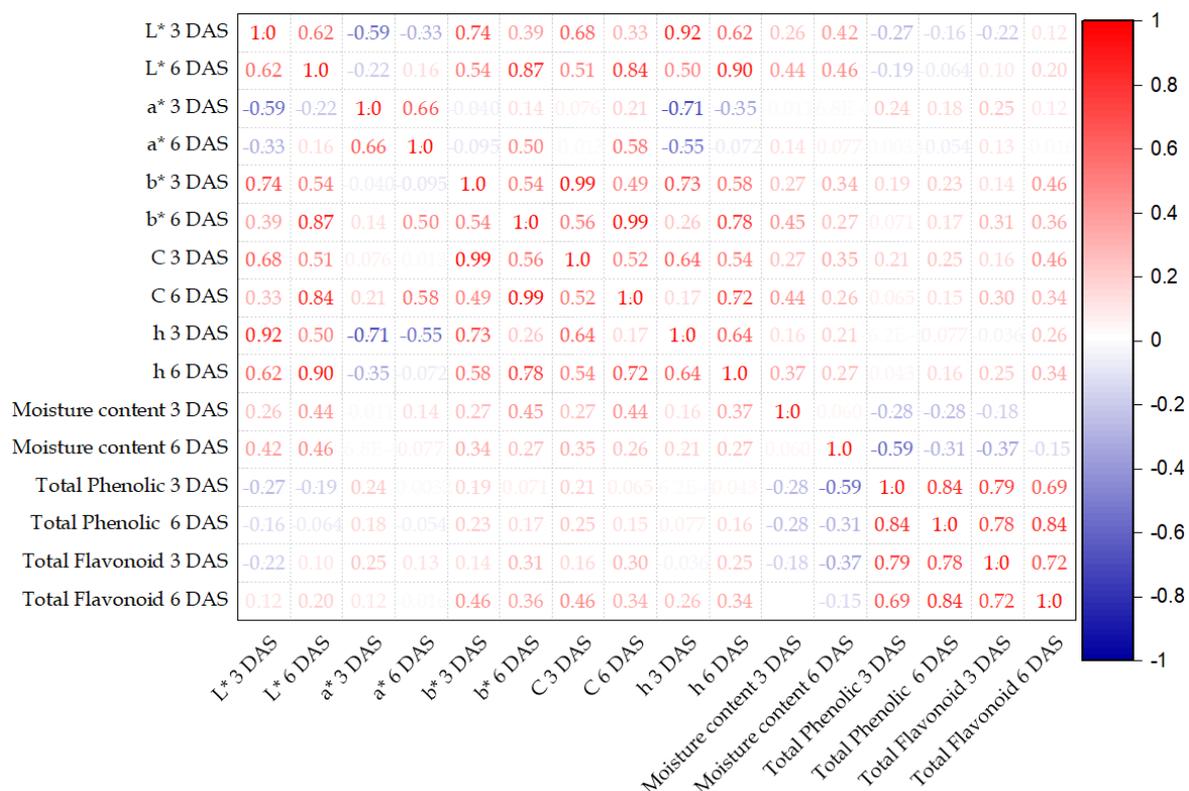


Figure 1. Correlation of all observation parameters during 6 days of storage (DAS)

Table 1. Effect of the combination of nano edible coating, type of packaging, and different temperatures on L* value of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	L*	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	56.27 a	51.06 c
Nano SA + biodegradable + temperature 25 °C	53.55 a	44.07 b
Nano SA + wrap + temperature 25 °C	54.98 a	56.05 d
Nano SA + vacuum + temperature 10 °C	56.88 a	55.53 d
Nano SA + biodegradable + temperature 10 °C	52.62 a	48.88 c
Nano SA + wrap + temperature 10 °C	62.70 a	62.78 d
Nano SA + vacuum + temperature 5 °C	50.66 a	51.04 c
Nano SA + biodegradable + temperature 5 °C	50.12 a	40.80 b
Nano SA + wrap + temperature 5 °C	38.54 a	49.71 c
Nano AV + vacuum + temperature 25 °C	52.13 a	54.19 d
Nano AV + biodegradable + temperature 25 °C	47.42 a	36.69 b
Nano AV + wrap + temperature 25 °C	60.84 a	50.75 c
Nano AV + vacuum + temperature 10 °C	52.01 a	55.03 d
Nano AV + biodegradable + temperature 10 °C	48.34 a	47.91 c
Nano AV + wrap + temperature 10 °C	62.61 a	58.44 d
Nano AV + vacuum + temperature 5 °C	55.94 a	48.34 c
Nano AV + biodegradable + temperature 5 °C	43.63 a	29.04 a
Nano AV + wrap + temperature 5 °C	43.58 a	48.02 c

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; DAS = days after storage; SA = Sodium Alginate; AV = Aloe Vera.

In this study, straw mushrooms showed symptoms of chilling injury during storage at 5 °C. A temperature of 5 °C is considered extremely cold for straw mushrooms, which grow optimally at high temperatures (35 °C). Extreme cold storage can trigger chilling injury, which increases PPO enzyme activity, resulting in browning (Sogvar et al., 2020). Browning can reduce the visual and commercial quality of straw mushrooms. Nano edible coatings consisting of sodium alginate and aloe vera, packaged in wrap at 10 °C, produced the highest and most consistent L* values during storage. PPO enzyme activity increased with storage time (Zhao et al., 2021). However, the application of nano edible coatings can inhibit PPO enzyme activity during storage.

The application of nano sodium alginate can inhibit browning in straw mushrooms during storage. Sodium alginate has various biological activities, such as antioxidant, antimicrobial, and biocompatibility. In line with research Louis et al. (2021), the sodium alginate coating can maintain the color of button mushrooms during storage. Sodium alginate coating is transparent, biocompatible, biodegradable, and semipermeable (Kenny et al., 2025). Sodium alginate coating can prevent moisture loss by reducing transpiration (Wang et al., 2020).

Sodium alginate coating has low permeability to fat and oxygen (Nair et al., 2020). Thus, sodium alginate coating can slow oxidation that triggers enzymatic browning reactions.

Aloe vera can also inhibit enzymatic browning because it contains natural antioxidants such as phenolics and flavonoids (Takeungwongtrakul et al., 2022). Enzymatic browning is a chemical reaction that occurs when the PPO enzyme oxidizes phenols to quinones (Gupta et al., 2022). Mohebbi et al. (2012) reported that aloe vera coating can reduce browning of button mushrooms during storage.

Wrap and vacuum packaging reduce and inhibit oxygen contact from the outside into the package during storage, compared to biodegradable packaging. This can reduce the oxidation reaction that causes browning in straw mushrooms. The color of enoki mushrooms can be maintained for 6 days of storage using vacuum packaging (Choi et al., 2022). Therefore, the combination of nano sodium alginate or nano aloe vera with wrap packaging at a temperature of 10 °C has been proven to maintain the lightness of the color of straw mushrooms.

Color (a* value). The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on

mushroom color in terms of a^* values. The combination of nano aloe vera with biodegradable packaging at 25 °C and 10 °C showed significantly different a^* values compared to most other treatments, especially at 5 °C (Table 2). This treatment also showed a constant a^* value for 6 DAS. A constant a^* value indicates that the treatment can maintain the freshness of straw mushrooms during storage. A low a^* value indicates the color of fresh straw mushrooms is not striking.

A positive a^* represents red, whereas a negative a^* represents green (Bahreini et al., 2024). The rise in the value of a^* represents a red color, which signifies enzymatic browning of straw mushrooms. Several variables affect enzymatic browning, such as oxygen, phenolic substances, PPO enzymes, and peroxidase (POD), which lead to edible mushroom browning (Sharma et al., 2024). An increase in the a^* value indicates undesirable color changes in straw mushrooms. POD enzymes are associated with undesirable changes in product flavor and color (Singh et al., 2018).

The application of nano aloe vera coating can inhibit the enzymatic browning process by limiting oxygen contact with straw mushrooms at temperatures of 25 °C and 10 °C. Aloe vera coating in antibacterial, protecting the straw mushrooms

from microbial attack that causes colour and appearance changes (Falahati et al., 2024). This agrees with da Silva et al. (2023), finding that aloe vera coating can effectively decrease the discoloration of shiitake mushrooms during storage. Aloe vera coating also contains natural antioxidants that can inhibit the activity of the PPO enzyme. However, its effectiveness decreases at temperatures below 5 °C due to tissue and cell damage caused by cold stress (Figure 2).

Enzymatic browning is linked to membrane breakdown during tissue degeneration (Wang et al., 2024). Extrinsic and intrinsic factors control browning in edible mushrooms. Moisture content, respiration rate, and microbial activity are internal, whereas relative humidity and storage temperature are external (Liang et al., 2024). The decrease in the respiration rate is in line with the lowered metabolic activity that is accountable for straw mushroom browning. Storage temperature significantly affects metabolic processes such as respiration, microbial growth, and enzyme activity, which cause product deterioration (Claassen et al., 2024). Low temperature is capable of retarding metabolic activity, preserving quality (Silva et al., 2025). In line with research by Li et al. (2022), a temperature of 10 °C can inhibit browning of shiitake mushrooms during storage.

Table 2. Effect of the combination of nano edible coating, packaging type, and different temperatures on the a^* value of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	a^*	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	9.12 a	12.16 c
Nano SA + biodegradable + temperature 25 °C	8.08 a	8.23 a
Nano SA + wrap + temperature 25 °C	8.43 a	9.01 a
Nano SA + vacuum + temperature 10 °C	8.89 a	11.32 b
Nano SA + biodegradable + temperature 10 °C	7.81 a	9.60 b
Nano SA + wrap + temperature 10 °C	8.12 a	10.94 b
Nano SA + vacuum + temperature 5 °C	9.32 a	10.66 b
Nano SA + biodegradable + temperature 5 °C	9.66 a	13.84 d
Nano SA + wrap + temperature 5 °C	11.60 b	14.78 d
Nano AV + vacuum + temperature 25 °C	11.45 b	11.43 b
Nano AV + biodegradable + temperature 25 °C	7.97 a	7.81 a
Nano AV + wrap + temperature 25 °C	9.17 a	10.35 b
Nano AV + vacuum + temperature 10 °C	10.50 b	11.67 b
Nano AV + biodegradable + temperature 10 °C	8.05 a	8.53 a
Nano AV + wrap + temperature 10 °C	7.71 a	10.29 b
Nano AV + vacuum + temperature 5 °C	10.13 b	9.89 b
Nano AV + biodegradable + temperature 5 °C	11.18 b	9.88 b
Nano AV + wrap + temperature 5 °C	11.30 b	14.66 d

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.



Figure 2. Color changes of straw mushrooms stored at 5 °C for 3 days: a) nano sodium alginate + vacuum packaging, b) nano sodium alginate + biodegradable packaging, c) nano aloe vera + vacuum packaging, d) nano aloe vera + wrap packaging.

Color (b^*). The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on mushroom color in terms of b^* values. The combination treatment of nano aloe vera with vacuum packaging at a temperature of 10 °C showed the highest b^* value, which was significantly different from other combination treatments, especially the nano sodium alginate combination (Table 3). This combination treatment also showed a constant b^* value during storage. The constant b^* value during storage indicates the treatment's ability to maintain the freshness of straw mushrooms.

The b^* value consists of positive and negative b^* . A positive b^* value indicates a yellow color, while a negative b^* value indicates a blue color (Huo et al., 2024). Nano aloe vera coating treatment can maintain the brownish-yellow color of semi-ripened straw mushrooms during storage. Aloe vera contains flavonoid compounds that can ward off free radicals and act as antioxidants (Tizazu & Bekele, 2024; Wariyah et al., 2024). Mirshekari et al. (2019) also reported that aloe vera coating can reduce the activity of the PPO enzyme, which causes browning in button mushrooms. Several treatments also showed decreases and increases in b^* values during storage.

The decrease and increase in the b^* value during storage are indicators of browning in straw mushrooms. The decrease in the b^* value is a result of the degradation of flavonoid compounds and carotenoid pigments that give the yellow color (Giménez et al., 2015). The oxidation of natural color compounds is exacerbated by temperature and the presence of oxygen, which causes a decrease in quality (Liang et al., 2024). The results of the study showed an increase in the b^* value in several combination treatments, especially at a temperature of 5 °C.

The combination treatment of nano sodium alginate with all packaging at a temperature of 5 °C experienced an increase in the b^* value at 6 DAS (Figure 3). Temperatures that are too low tend to cause post-harvest chilling damage, which actually accelerates browning (Sharma et al., 2024). This temperature accelerates the damage to cell membranes, thereby increasing the oxidation of natural color compounds (Zou et al., 2025). Damage to cell membranes causes an increase in the PPO enzyme, which can oxidize phenolic compounds that form quinone and melanin compounds (Harisha et al., 2023).

A temperature of 5 °C can cause cold stress that triggers the accumulation of free radicals and accelerates cell and tissue damage. Cell and tissue damage causes excessive release of the PPO enzyme, which oxidizes phenolic compounds to quinones through enzyme catalysis. Quinones react with amino acids to form melanin, causing browning in mushrooms (Fu et al., 2023). The increase in PPO enzyme activity increases quinones and melanin, which are indicators of browning of the *Phlebotomus portentosus* fungus (Kong et al., 2025).

Color (Chroma). The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on mushroom color in terms of chroma values. The combination treatment of nano aloe vera with vacuum packaging at 10 °C showed a significantly different chroma value compared to other combination treatments, especially with biodegradable packaging. Biodegradable packaging for all nano edible coatings and storage temperatures showed a lower chroma value and increased during storage. Biodegradable packaging has poor barrier properties, especially against moisture and air (Ivankovic et al., 2017).

Table 3. Effect of the combination of nano edible coating, packaging type, and different temperatures on the b^* value of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	b^*	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	34.52 c	34.21 c
Nano SA + biodegradable + temperature 25 °C	27.60 b	19.20 a
Nano SA + wrap + temperature 25 °C	28.17 b	27.88 b
Nano SA + vacuum + temperature 10 °C	31.99 c	37.10 c
Nano SA + biodegradable + temperature 10 °C	24.91 a	27.18 b
Nano SA + wrap + temperature 10 °C	30.67 c	35.66 c
Nano SA + vacuum + temperature 5 °C	28.14 b	31.56 c
Nano SA + biodegradable + temperature 5 °C	24.66 a	24.96 b
Nano SA + wrap + temperature 5 °C	20.87 a	31.64 c
Nano AV + vacuum + temperature 25 °C	35.78 c	36.36 c
Nano AV + biodegradable + temperature 25 °C	24.10 a	16.01 a
Nano AV + wrap + temperature 25 °C	33.17 c	26.71 b
Nano AV + vacuum + temperature 10 °C	30.99 c	36.65 c
Nano AV + biodegradable + temperature 10 °C	23.16 a	25.03 b
Nano AV + wrap + temperature 10 °C	29.96 c	35.51 c
Nano AV + vacuum + temperature 5 °C	33.14 c	29.88 c
Nano AV + biodegradable + temperature 5 °C	23.73 a	13.21 a
Nano AV + wrap + temperature 5 °C	23.36 a	32.72 c

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

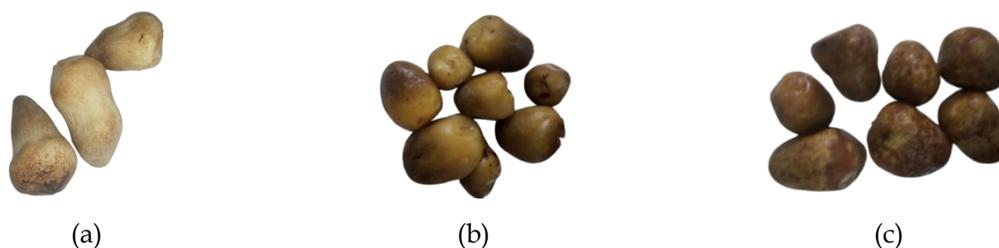


Figure 3. Changes in the color of straw mushrooms during 3 days of storage in the combination treatment of nano sodium alginate at a temperature of 5 °C with various packaging: a) fresh straw mushrooms, b) vacuum packaging, c) biodegradable packaging.

The chroma value indicates color purity or intensity (Pandiselvam et al., 2023). A high and consistent chroma value during storage indicates freshness and good post-harvest visual quality of straw mushrooms. The combination of nano aloe vera with vacuum packaging at 10 °C showed a high and constant chroma value during storage. Aloe vera coating contains natural antioxidant compounds such as aloe-emodin and ascorbic acid, which can maintain the color attributes of the product (Nicolau-Lapeña et al., 2021). The application of aloe vera coating can inhibit color changes in button mushrooms during storage (Mirshekari et al., 2019).

The combination treatment of nano sodium alginate with all packaging and the combination of nano aloe vera with wrap packaging at a temperature of 5 °C showed a low chroma value at 3 DAS and increased at 6 DAS. The increase in chroma value indicates browning in straw mushrooms. This is in line with research by Nunes et al. (2024) that the increase in chroma value is in line with the browning of white shimeji mushrooms. A temperature of 5 °C can cause cell damage, resulting in phenolic compounds and PPO enzymes meeting outside the cells, and enzymatic browning occurs.

Table 4. Effect of the combination of nano edible coating, packaging type, and different temperatures on the chroma value of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	Chroma	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	35.71 b	36.33 c
Nano SA + biodegradable + temperature 25 °C	28.78 a	20.90 a
Nano SA + wrap + temperature 25 °C	29.40 a	29.30 b
Nano SA + vacuum + temperature 10 °C	33.20 b	38.79 c
Nano SA + biodegradable + temperature 10 °C	26.17 a	28.84 b
Nano SA + wrap + temperature 10 °C	31.73 b	37.30 c
Nano SA + vacuum + temperature 5 °C	29.68 a	33.31 c
Nano SA + biodegradable + temperature 5 °C	26.49 a	28.61 b
Nano SA + wrap + temperature 5 °C	23.90 a	34.95 c
Nano AV + vacuum + temperature 25 °C	37.58 b	38.11 c
Nano AV + biodegradable + temperature 25 °C	25.39 a	17.82 a
Nano AV + wrap + temperature 25 °C	34.41 b	28.65 b
Nano AV + vacuum + temperature 10 °C	32.72 b	38.46 c
Nano AV + biodegradable + temperature 10 °C	24.53 a	26.46 b
Nano AV + wrap + temperature 10 °C	30.94 b	36.98 c
Nano AV + vacuum + temperature 5 °C	34.67 b	31.48 c
Nano AV + biodegradable + temperature 5 °C	26.24 a	16.50 a
Nano AV + wrap + temperature 5 °C	25.95 a	35.93 c

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

Table 5. Effect of the combination of nano edible coating, packaging type, and different temperatures on the h° value of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	h°	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	75.16 b	70.30 c
Nano SA + biodegradable + temperature 25 °C	73.70 b	66.33 b
Nano SA + wrap + temperature 25 °C	73.30 b	72.08 c
Nano SA + vacuum + temperature 10 °C	74.47 b	73.05 c
Nano SA + biodegradable + temperature 10 °C	72.36 b	70.52 c
Nano SA + wrap + temperature 10 °C	75.18 b	72.94 c
Nano SA + vacuum + temperature 5 °C	71.37 b	71.33 c
Nano SA + biodegradable + temperature 5 °C	68.61 b	62.55 b
Nano SA + wrap + temperature 5 °C	60.85 a	64.88 b
Nano AV + vacuum + temperature 25 °C	72.19 b	72.55 c
Nano AV + biodegradable + temperature 25 °C	71.59 b	63.96 b
Nano AV + wrap + temperature 25 °C	74.56 b	68.83 c
Nano AV + vacuum + temperature 10 °C	71.24 b	72.34 c
Nano AV + biodegradable + temperature 10 °C	70.93 b	71.17 c
Nano AV + wrap + temperature 10 °C	75.54 b	73.82 c
Nano AV + vacuum + temperature 5 °C	72.92 b	71.68 c
Nano AV + biodegradable + temperature 5 °C	64.77 a	53.22 a
Nano AV + wrap + temperature 5 °C	64.17 a	67.54 c

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

Color (h° value). The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on

mushroom color in terms of h° values. The combination treatment of nano aloe vera with vacuum packaging at a temperature of 10 °C showed a hue value (h°) that was significantly

different from other combination treatments, especially the combination with biodegradable packaging at a temperature of 5 °C (Table 5). This treatment also showed a constant value during 6 days of storage. The constant h° value during storage indicates the treatment's ability to maintain color and is one indicator of the freshness of straw mushrooms. Differences in storage temperatures showed different effects on the color of straw mushrooms, especially on the h° value. This indicates that 10 °C can inhibit the activity of the PPO enzyme that causes browning without damaging the straw mushroom tissue. In line with research Kumari & Baskaran (2015) The temperature of 10 °C can reduce the activity of the PPO enzyme in oyster mushrooms.

The h° value indicates the type of color or color angle in the color spectrum (Shameena et al., 2024). A decreasing h° value indicates browning, resulting in a decrease in the visual and commercial quality of straw mushrooms. The combination treatment of nano sodium alginate and nano aloe vera with all packaging at a temperature of 10 °C is able to maintain the h° value during storage. Nano sodium alginate and nano aloe vera can protect mushrooms against a decrease in h° value at a storage temperature of 10 °C. Sodium alginate coating can form a semipermeable protective layer, reducing the rate of respiration and oxidation (Kalita et al., 2025). However, the layer formed is less dense compared to nano sodium alginate. Aloe vera coating has natural antibacterial and antioxidant activity and slows down color changes (Habibi et al., 2022).

Vacuum packaging shows a better effect than biodegradable packaging and wrap packaging in maintaining h° values, especially at a temperature of 5 °C. It can reduce oxygen in the packaging, thereby slowing the oxidation reaction that causes browning. Storage temperature significantly affects the h° value. A temperature of 5 °C indicates a lower h° value. Temperatures that are too low or extreme (≤ 5 °C) can cause chilling injury, which triggers metabolic reactions that cause faster browning (Farcuh, 2025).

Extreme temperatures can also accelerate cell membrane damage and PPO enzyme activity. A decrease in the h° value indicates browning in straw mushrooms. The decrease in the hue value is caused by the activity of the PPO enzyme that causes browning (Liang et al., 2024). Thus, the combination treatment of Nano sodium

alginate and nano aloe vera with wrap packaging at a temperature of 10 °C is the best combination in maintaining the h° value of straw mushrooms.

Moisture Content. The results of the analysis of variance showed that the combination of nano edible coating, packaging type, and different storage temperatures significantly affected the moisture content of straw mushrooms at 3 DAS and did not significantly affect the moisture content at 6 DAS (Table 6). The combination treatment of nano sodium alginate with vacuum packaging at a temperature of 10 °C showed the highest air content, which was significantly different from other combination treatments, especially the combination treatment with biodegradable packaging at 3 DAS. The combination of nano sodium alginate with vacuum packaging at a temperature of 10 °C showed a constant moisture content during storage (3 and 6 DAS). Thus, the combination treatment of nano sodium alginate with vacuum packaging at a temperature of 10 °C can maintain the freshness of straw mushrooms during storage.

Straw mushrooms are an agricultural commodity with a relatively high moisture content. Moisture content is an indicator of the post-harvest technology's ability to maintain freshness, with a constant moisture content being optimal. In this study, the treatment of nano sodium alginate and nano aloe vera coating with vacuum packaging and wrap at temperatures of 10 °C and 5 °C showed a higher water content compared to the combination treatment with biodegradable packaging in 3 DAS. This may be because sodium alginate and aloe vera can inhibit transpiration in mushrooms, which causes water loss. According to Martínez-Cano et al. (2022) The application of sodium alginate edible coating can form a semipermeable layer, thereby reducing water loss and weight loss.

The vacuum packaging used is also more effective in maintaining moisture than biodegradable packaging. Vacuum packaging inhibits mushroom respiration due to controlled atmospheric conditions and minimal air contact with the product (Sakinah et al., 2020). Moradinezhad & Dorostkar (2021) also stated that vacuum packaging can minimize water loss through transpiration and maintain relative humidity within the package. Therefore, vacuum packaging proved more effective in maintaining mushroom moisture during storage than other packaging.

The moisture content of mushrooms in biodegradable packaging showed a lower value than in other packaging. This may be due to the relatively high air and water vapor permeability of biodegradable packaging. This relatively high permeability allows the moisture content in the mushrooms to easily escape, resulting in a decrease in moisture content during storage. Furthermore, maintaining the internal moisture of mushrooms in biodegradable packaging is difficult. The higher and more constant moisture content at a storage temperature of 10 °C also indicates that the respiration and transpiration of straw mushrooms can be inhibited. Iqbal et al. (2009), reported that the respiration rate of button mushrooms decreased at 8 °C and increased at 20 °C. Therefore, the combination of nano sodium alginate with vacuum packaging at 10 °C can be applied to maintain the freshness of straw mushrooms during storage.

Total Phenolic. The results of the analysis of variance showed that the nano edible coating treatment, packaging type, and storage temperature had a significant effect on the total phenolic content of mushrooms. The combination of nano aloe vera with vacuum packaging at temperatures of 10 °C showed a

significantly different total phenolic content compared to other treatments during storage (Table 7). The treatment also showed a constant total phenolic content during storage. A constant total phenolic content indicates the treatment's ability to maintain the quality of straw mushrooms during storage.

Phenolic compounds are bioactive compounds with high antioxidant activity. Phenolic compounds in edible mushrooms act as natural antioxidants (Chun et al., 2021). The total phenolic content indicates the functional value of mushrooms and is related to resistance to oxidation and browning (Liang et al., 2024). The combination treatment of nano aloe vera with vacuum packaging at a storage temperature of 10 °C showed the highest total phenolics. Aloe vera has antioxidant properties because it contains phenolic compounds (Mensah et al., 2025). These phenolic compounds include aloin, aloesin, and aloe emodin (Solaberrieta et al., 2022). These compounds are antioxidants, thus maintaining freshness, inhibiting the activity of the PPO enzyme, and stabilizing phenolic compounds during storage. Mirshekari et al. (2019), reported that aloe vera coating can increase the total phenolic content of button mushrooms during storage.

Table 6. Effect of the combination of nano edible coating, type of packaging, and different temperatures on the moisture content of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	Moisture content (%)	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	90.36 b	91.09 a
Nano SA + biodegradable + temperature 25 °C	86.78 a	91.85 a
Nano SA + wrap + temperature 25 °C	90.80 b	94.75 a
Nano SA + vacuum + temperature 10 °C	90.81 b	89.57 a
Nano SA + biodegradable + temperature 10 °C	88.99 a	89.18 a
Nano SA + wrap + temperature 10 °C	90.84 b	91.24 a
Nano SA + vacuum + temperature 5 °C	90.58 b	89.37 a
Nano SA + biodegradable + temperature 5 °C	87.89 a	88.28 a
Nano SA + wrap + temperature 5 °C	89.90 b	91.16 a
Nano AV + vacuum + temperature 25 °C	88.89 a	90.26 a
Nano AV + biodegradable + temperature 25 °C	90.78 b	82.81 a
Nano AV + wrap + temperature 25 °C	90.33 b	94.90 a
Nano AV + vacuum + temperature 10 °C	89.71 b	88.13 a
Nano AV + biodegradable + temperature 10 °C	88.19 a	89.20 a
Nano AV + wrap + temperature 10 °C	90.67 b	91.86 a
Nano AV + vacuum + temperature 5 °C	90.47 b	90.32 a
Nano AV + biodegradable + temperature 5 °C	88.89 a	89.66 a
Nano AV + wrap + temperature 5 °C	90.69 b	89.94 A

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

Vacuum packaging can control the atmosphere in the packaging, thereby reducing oxygen availability (Chen et al., 2022). Limited oxygen availability can inhibit phenol oxidation, which causes browning in straw mushrooms. A temperature of 10 °C can maintain total phenolic content because it inhibits PPO enzyme activity and is not too cold to trigger chilling injury.

Total Flavonoid. The results of the analysis of variance showed that the combination of nano edible coating treatment, packaging type, and storage temperature had a significant effect on the total flavonoids of straw mushrooms during storage (Table 8). The combination treatment of nano aloe vera with vacuum packaging at a storage temperature of 10 °C showed the highest total flavonoids, which were significantly different from other treatments. The use of nano edible coating can maintain quality during storage because aloe vera contains polysaccharides such as glucomannan and acemannan (Moghaddasi & Kumar Verma, 2011; Sefrienda et al., 2020). Aloe vera coating also acts as an air barrier for straw mushrooms so that

they can maintain freshness and quality during storage.

Flavonoids are a major group of phenolic compounds that function as natural antioxidants (Huyut et al., 2017). The higher the total flavonoid content, the higher the antioxidant activity of edible mushrooms (Kozarski et al., 2015). However, antioxidant activity can decrease during storage due to the degradation of flavonoid compounds by the PPO enzyme. Based on research results, the use of nano aloe vera with vacuum packaging at a temperature of 10 °C can maintain the total flavonoid content of straw mushrooms during storage.

The stability of total flavonoids during storage is due to the application of aloe vera coating containing natural antioxidants that can inhibit the activity of the PPO enzyme (Ali et al., 2019). Vacuum packaging also supports the performance of nano aloe vera in inhibiting the activity of the PPO enzyme by reducing oxygen, which causes oxidation reactions. Storing straw mushrooms at a temperature of 10 °C can inhibit the activity of the PPO enzyme without causing chilling injury.

Table 7. Effect of the combination of nano edible coating, type of packaging, and different temperatures on total phenolics of straw mushrooms at 3 and 6 days after storage (DAS)

Treatment	Total Phenolic (mg GAE/100g)	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	1,615.63 i	3.16 g
Nano SA + biodegradable + temperature 25 °C	1,396.11 h	2.92 e
Nano SA + wrap + temperature 25 °C	270.71 a	2.77 c
Nano SA + vacuum + temperature 10 °C	1,822.54 j	3.34 h
Nano SA + biodegradable + temperature 10 °C	1,184.05 g	3.07 f
Nano SA + wrap + temperature 10 °C	310.48 a	2.47 a
Nano SA + vacuum + temperature 5 °C	1,361.90 h	3.02 f
Nano SA + biodegradable + temperature 5 °C	1,191.59 g	2.88 d
Nano SA + wrap + temperature 5 °C	1,085.00 f	2.71 c
Nano AV + vacuum + temperature 25 °C	1,970.87 k	3.19 g
Nano AV + biodegradable + temperature 25 °C	1,650.71 i	2.74 c
Nano AV + wrap + temperature 25 °C	522.86 c	2.52 b
Nano AV + vacuum + temperature 10 °C	2,042.86 l	3.32 h
Nano AV + biodegradable + temperature 10 °C	1,429.76 h	3.18 g
Nano AV + wrap + temperature 10 °C	414.13 b	2.56 b
Nano AV + vacuum + temperature 5 °C	1,379.13 h	3.07 f
Nano AV + biodegradable + temperature 5 °C	955.95 e	2.94 e
Nano AV + wrap + temperature 5 °C	779.37 d	2.72 c

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

Table 8. Effect of the combination of nano edible coating, type of packaging, and different temperatures on total flavonoids in straw mushrooms at 3 and 6 days after storage

Treatment	Total flavonoid (mg QE/100g)	
	3 DAS	6 DAS
Nano SA + vacuum + temperature 25 °C	168.16 c	226.06 c
Nano SA + biodegradable + temperature 25 °C	115.99 a	98.19 a
Nano SA + wrap + temperature 25 °C	126.31 b	140.85 b
Nano SA + vacuum + temperature 10 °C	218.05 d	289.04 d
Nano SA + biodegradable + temperature 10 °C	140.21 b	164.65 b
Nano SA + wrap + temperature 10 °C	63.12 a	73.12 a
Nano SA + vacuum + temperature 5 °C	246.77 e	122.48 b
Nano SA + biodegradable + temperature 5 °C	204.22 d	120.85 b
Nano SA + wrap + temperature 5 °C	178.40 c	89.43 a
Nano AV + vacuum + temperature 25 °C	244.82 e	193.58 c
Nano AV + biodegradable + temperature 25 °C	145.82 b	108.26 a
Nano AV + wrap + temperature 25 °C	89.61 a	139.93 b
Nano AV + vacuum + temperature 10 °C	321.42 f	334.75 e
Nano AV + biodegradable + temperature 10 °C	233.40 e	199.50 c
Nano AV + wrap + temperature 10 °C	92.16 a	77.09 a
Nano AV + vacuum + temperature 5 °C	155.67 c	186.91 c
Nano AV + biodegradable + temperature 5 °C	95.57 a	125.00 b
Nano AV + wrap + temperature 5 °C	83.30 a	87.38 a

Note: Means followed by the same lowercase alphabet in the same column are not significantly different based on Scott-Knott Test at 5 %; SA = Sodium Alginate; AV = Aloe Vera.

The results of this study indicate that the combination of nano edible coating, packaging type, and different storage temperatures have important implications in increasing shelf life and maintaining the quality of straw mushrooms, especially for post-harvest applications in perishable commodities. The use of nano aloe vera coating with vacuum packaging at 10 °C has important implications as an effective post-harvest technology in maintaining the color and phenolic components of straw mushrooms, thus potentially increasing their shelf life and commercial value during storage. These findings open up opportunities for future research to evaluate more stable nano edible coating formulations, examine their interactions with various types of packaging, and assess their effectiveness under different storage conditions and at larger production scales. However, this study still has limitations, such as the limited types of nano edible coatings, the limited variation in nano coating concentrations tested, the observation period is too long, and the lack of a more in-depth evaluation of physiological and microbiological changes in mushrooms (e.g., enzymes that play a role in color changes and metabolite compounds of straw mushrooms, as well as disease incidence

parameters), so further research is needed to produce more comprehensive recommendations.

Conclusion

Straw mushroom harvest is easily damaged, so the quality decreases during storage. The results of the study showed that the combination treatment of nano aloe vera with vacuum packaging at a temperature of 10 °C gave the best effect on color parameters (L^* , b^* , chroma, h° values), total phenolics, and total flavonoids of straw mushrooms during storage. The ability of the post-harvest combination treatment above can improve the economy by increasing shelf life, maintaining quality, and reducing post-harvest losses of straw mushrooms. Further research can be done with pre-harvest treatment to improve the quality and shelf life of straw mushroom fruit bodies.

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