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Article

Study on Color Properties of *Auricularia auricula-judae* (Bull.) Quél. Affected by Nano Edible Coatings, Packaging Types, and Storage Temperatures

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Abstract. Wood ear mushroom is a traditional edible and medicinal mushroom widely consumed as a food supplement. The color of the fruit body is a crucial indicator of commercial quality that influences consumer purchasing interest. However, color quality can decrease due to inappropriate post-harvest technology. The application of nano edible coating, packaging, and storage temperature can help maintain color stability during storage. This study aims to determine the effect of nano edible coating, packaging, and storage temperature on the color of wood ear mushrooms based on the parameters L^*, a^*, b^*, Chroma, Hue, Browning Index, and color difference. The experimental design used was a Completely Randomized Design (CRD) with a combination of nano edible coating (sodium alginate and aloe vera), packaging (biodegradable, wrap, and vacuum plastic), and storage temperatures (±25 °C, 10 °C, and 5 °C). Each treatment was repeated twice, resulting in 38 experimental units, each consisting of 3 mushrooms, total of 114 mushrooms. The results showed that nano aloe vera with vacuum packaging at a storage temperature of 5 °C provided the best results in maintaining the color of the wood ear mushroom during storage, with the lowest lightness and color difference values.

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1. Introduction

Auricularia auricula-judae (Bull.) Quél. commonly known as the wood ear mushroom or the jelly ear mushroom, it is widely produced globally due to its high medicinal properties. This type of mushroom has antimicrobial [1], antioxidant [2], antibacterial [3], anti-inflammatory [4], anti-diabetic [5], and other properties. Wood ear mushrooms are among the edible mushrooms produced in Indonesia, with production reaching 63.16 tons (2022), centered in Central Java [6]. Globally, China is the largest producer, with production reaching 7.06 million tons in 2020 [7]. High production requires the industry to maintain product quality during storage, especially in terms of color appearance. However, wood ear mushrooms have a very high respiration rate, reaching 90% compared to other horticultural products, so they quickly experience quality decline or color changes [8], and a shelf life of only 1–3 days at room temperature [9].

Color is an important quality parameter of agricultural fresh products, such as wood ear mushrooms. Attractive visual appearance, including brightness and color uniformity, plays a major role in shaping consumer perceptions, also influencing consumption and purchasing decisions [10]. Cap color is an important commercial characteristic of wood ear mushrooms, where consumers prefer mushrooms with dark red to black caps [11]. Discoloration is generally an early indicator of quality decline, whether chemically, physiologically, or sensorially. Physical discoloration is a post-harvest problem for wood ear mushrooms caused by the browning process and ultimately leads to aging and consumer rejection [12].

Improper application of post-harvest technology, such as selecting inappropriate packaging materials, using ineffective edible coatings, or suboptimal storage temperatures, can accelerate the browning process. Therefore, proper post-harvest handling is crucial to inhibit browning reactions, maintain color stability, and extend product shelf life. Until now, research on post-harvest technology, especially the combination of nano edible coating, packaging, and storage temperature in maintaining the color of wood ear mushrooms, has not been conducted. Previous research has been more directed at the influence of one of these technologies on the color of other edible mushrooms, such as button mushrooms [13], oyster mushrooms [14], and shiitake mushrooms [15], as well as fruits [16-18].

Edible coating, packaging, and storage temperature each influence the color properties of edible mushrooms and fruits. Lightness values decreased during storage, but edible mushrooms coated with sodium alginate showed higher values than those uncoated [13]. The color change was more pronounced in fruit uncoated with aloe vera [16]. Vacuum packaging significantly reduced the browning index [19]. The lowest color change was observed in the combined treatment of low temperature and vacuum packaging [20].

Research related to the influence of nano edible coating on the color properties of edible mushrooms is still limited too, while most of the existing studies are more focused on fruits. Edible coatings with nanoparticles have been shown to maintain the color appearance of apples, red grapes, and tomatoes better than conventional edible coatings [21]. Alg-ZnO nanoparticles can maintain good fruit quality, control the occurrence of decay, and increase the shelf life of mango fruit [22]. Nano aloe vera is effective in increasing the shelf life of fresh-cut mangosteen and mangoes [23].

Therefore, this study aimed to determine the effect of a combination of nano edible coating, packaging, and storage temperature, as well as the best treatment that can maintain the color of wood ear mushrooms during storage. To our knowledge, this is the first study to explore the effects of combination of nano edible coating, packaging, and storage temperature on maintaining the color of wood ear mushrooms. The best combination of post-harvest technologies obtained can be used as a reference by the agricultural industry to maintain post-harvest quality and extend the shelf life of wood ear mushrooms during storage or distribution.

2. Experimental Section

2.1. Materials

The tools used in this experiment were a spectrophotometer reflectance (Konica Minolta, CM-600D, Japan), brushes, bowls, spoons, a vacuum sealer, a cooling storage, and a refrigerator. The materials used in this experiment were wood ear mushrooms, nano sodium alginate, nano aloe vera, distilled water, biodegradable plastic, wrap plastic, and vacuum plastic.

2.2. Methods

This experiment was conducted at the Horticulture Laboratory and Bale Tatanen, Faculty of Agriculture, Universitas Padjadjaran, March 2025. The research flowchart is shown in Figure 1.

The preparation of samples and nano edible coating materials, namely samples of wood ear mushrooms obtained from mushroom farmers in the Garut area, West Java. The wood ear mushrooms were selected based on the same harvest age (4 weeks after the pin head appeared), the fruit body had fully bloomed, the weight reached 20–60 g per fruit body, was free from visual symptoms of disease or any stains, and weighed at 80–90 g per sample. Harvesting was carried out in the morning on the same day as the treatment. Distribution of wood ear mushroom samples from farmers to the experimental location was done using a thick plastic with air in it to avoid damage. Nano edible coating was obtained by processing aloe vera and sodium alginate powder into nanoparticles by the Functional Nano powder University Center of Excellence (FiNder U-CoE), Universitas Padjadjaran, using the top-down method, namely high-energy ball milling [24]. The size of the edible coating nanoparticles obtained was 300 nm. The concentration of edible coating applied was 1% or 1 g in 100 mL of distilled water.

The samples were coated by brushing [25], air-dried (10 min), and packaged. After being packaged, the mushrooms are then stored at ±25 °C (laboratory), 10 °C (cooling storage), and 5 °C (refrigerator). Measurements were conducted on 2, 4, and 6 Days After Treatment (DAT), using two samples per treatment as individual replications. Color was measured on both upper and lower parts of wood ear mushrooms (3 mushrooms/replication) using a spectrophotometer reflectance (Konica Minolta, CM-600D, Japan) to obtain the L^*, a^*, and b^* values [13]. The instrument was calibrated before taking measurements with a standard white plate, and the sample was covered with aluminium foil to avoid light refraction. Parameters observed were L^*, a^*, b^*, Chroma [16], Hue [16], Browning Index [26], and Color Difference [27] with the following formula:

$$\text{Chroma}=\sqrt{(a^*)^2+(b^*)^2}$$

$$\text{Hue}=\text{Tan}^{-1}\left(\frac{b^*}{a^*}\right)$$

$$\text{BI}=\frac{100(x-0{,}31)}{0{,}17}\text{, where } x = (a^*+ 1{,}75\ L^*)/(5.645\ L^*+ a^* - 3.012\ b^*)$$

$$\text{Color difference } (\Delta E)=\sqrt{(L_0-L^*)^2+(a_0-a^*)^2+(b_0-b^*)^2}\text{, where 0 is the color of the control day 0}$$

The research design used was a Completely Randomized Design (CRD) with a combination of nano edible coating treatments—Nano Sodium Alginate (NSA) and Nano Aloe Vera (NAV)—packaging (biodegradable, wrap, and vacuum plastic), and storage temperatures (±25 °C, 10 °C, and 5 °C). A total of 18 treatment combinations and one control were each replicated two times, so that there were 38 experimental units. Each experimental unit consisted of 3 mushrooms, so there were 114 mushrooms and two mushrooms for the 0-day control. Data were analyzed using an additive linear model in a Completely Randomized Design (CRD). The analysis was performed with Microsoft Excel and SmartStatXL software. The homogeneity of variance test was performed using the Levene test, while the normality test was performed using the Shapiro-Wilk test to determine the data distribution. If the data were not normally distributed, data transformation was performed. Next, an analysis of variance (ANOVA) was performed to determine the effect of the treatment using the F test at the 5% significance level. If the F test results showed a significant difference, then the difference test was continued using the Scott-Knott method at the 5% significance level.

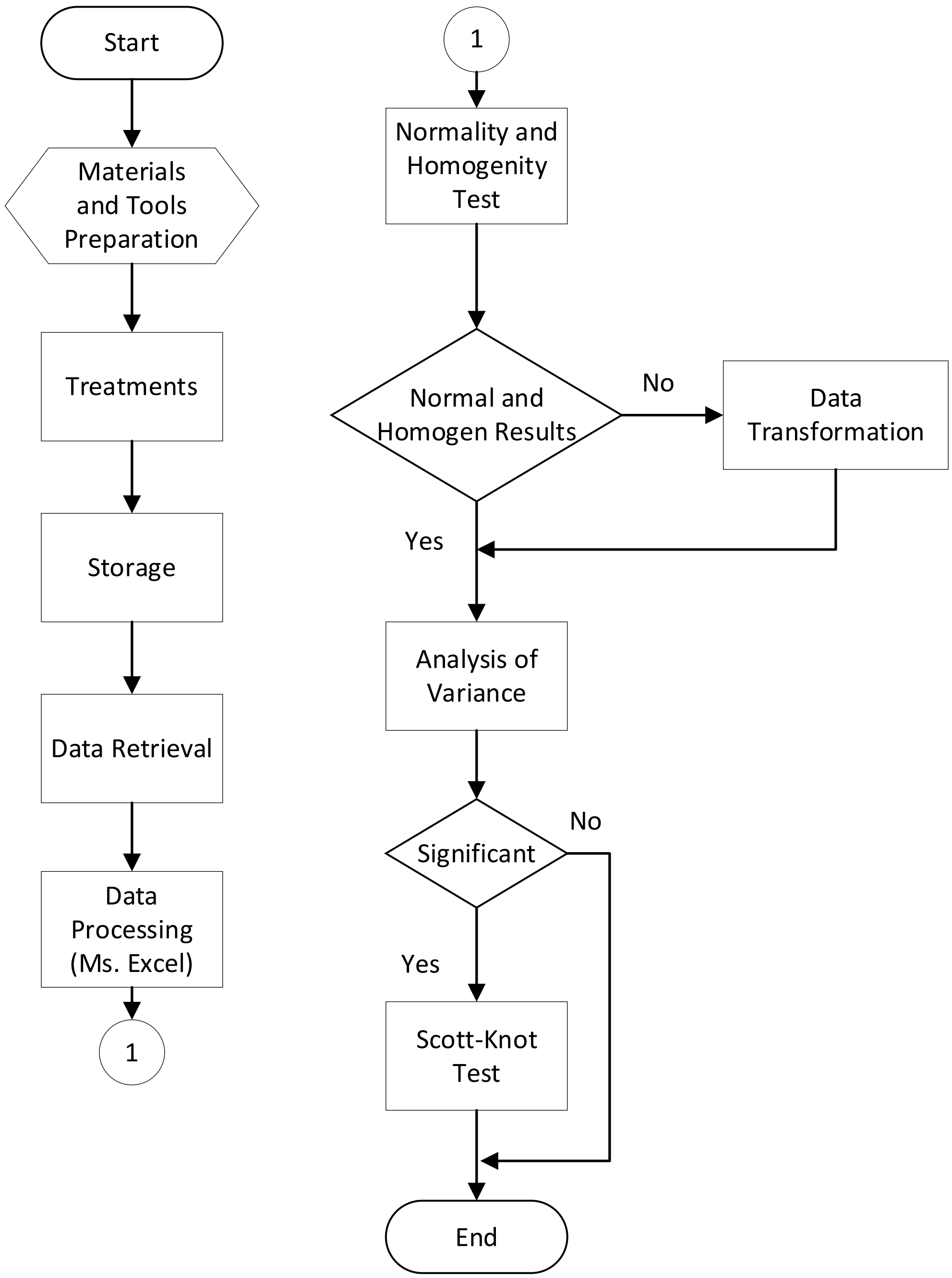

Figure 1. Schematic/Flowchart of research. Number one (1) is the next step of data processing

3. Results and Discussion

3.1. Lightness (L^*)

Lightness indicates the level of brightness of the fruiting body surface of the wood ear mushroom at three observation times, namely 2, 4, and 6 DAT. Lightness is also a key indicator of browning, a common quality problem in stored mushrooms [8]. The Scott-Knott test was used to group treatments based on significant differences in lightness values. The highest lightness value on 2 DAT was shown in the nano aloe vera treatment with vacuum packaging at ±25 °C (42.52, group "c"), which was significantly different from most other treatments, signifying the onset of browning (Table 1). This is indicated by the browning index value, which, although not statistically significant, this treatment tends to give a higher value (Table 3). The treatment with the lowest lightness value was nano aloe vera with vacuum packaging at 5 °C (26.41, group "a"), and several other treatments, which were also in group a, showed lower brightness values. Other treatments, such as control (39.55) and nano sodium alginate with plastic wrap at a temperature of ±25 °C (40.85), are included in group "c", which means their lightness values are not significantly different from the highest treatment.

Table 1. Impact of different nano edible coatings, packaging, and storage temperatures on the lightness in wood ear mushroom

Treatment	Lightness (L^*)		
	2 DAT	4 DAT	6 DAT
Control	39.55 c	37.02 b	41.25 c
NSA + vacuum + ±25 °C	35.74 b	35.56 b	38.38 c
NSA + wrap + ±25 °C	40.85 c	37.05 b	39.51 c
NSA + biodegradable + ±25 °C	36.05 b	40.21 b	39.43 c
NSA + vacuum + 10 °C	28.09 a	22.78 a	25.08 a
NSA + wrap + 10 °C	28.51 a	27.75 a	31.86 b
NSA + biodegradable + 10 °C	27.63 a	29.26 a	34.54 c
NSA + vacuum + 5 °C	36.31 b	36.08 b	39.89 c
NSA + wrap + 5 °C	39.27 c	39.02 b	37.78 c
NSA + biodegradable + 5 °C	36.08 b	37.39 b	36.50 c
NAV + vacuum + ±25 °C	42.52 c	38.08 b	38.51 c
NAV + wrap + ±25 °C	34.05 b	34.99 b	30.46 b
NAV + biodegradable + ±25 °C	30.88 a	31.28 a	34.23 c
NAV + vacuum + 10 °C	38.38 c	36.49 b	32.40 b
NAV + wrap + 10 °C	35.26 b	35.75 b	33.61 b
NAV + biodegradable + 10 °C	36.91 b	34.64 b	36.36 c
NAV + vacuum + 5 °C	26.41 a	25.10 a	28.18 a
NAV + wrap + 5 °C	34.05 b	33.52 b	29.49 b
NAV + biodegradable + 5 °C	33.87 b	34.84 b	35.69 c

High lightness values in wood ear mushrooms indicate a color change from dark red to brighter. In this study, changes in lightness were most common in treatments with high temperatures. This is consistent with research by Manolopoulou and Varzakas (2016) that found that the higher the storage temperature, the greater the change in lightness [28]. Temperature fluctuations significantly impact enzyme activity [29]. Changes in lightness are associated with increased metabolism, involving several enzymatic and non-enzymatic reactions, leading to browning [30-31]. Browning in mushrooms occurs due to spontaneous oxidation and/or activation of tyrosinase, an enzyme belonging to the PPO family [32-33]. High temperatures accelerate these processes. Mushrooms stored at lower temperatures (5 °C and 13 °C) exhibited slower and more gradual changes in gas composition, indicating a decrease in metabolic rate [8].

On the fourth day after treatment, lightness values generally decreased in several treatments. The nano sodium alginate treatment with all packaging types at 10 °C and the nano aloe vera treatment with vacuum packaging at 5 °C remained in group "a", with darker lightness values. Darker lightness indicates a consistent visual color of the wood ear mushroom. This is also indicated by the low color difference value in this treatment (Table 5). This demonstrates that the nano edible coating of sodium alginate and aloe vera at low temperatures can maintain the lightness of the wood ear mushroom. This is in line with research by Gholami et al. (2017) that enzymatic browning is less effective against color changes in coated mushrooms [12]. Treatments such as the control and other treatments included in group "b" showed brighter lightness values than group "a". However, at 4 DAT, no treatments fell into group "c". This suggests that the highest lightness at 4 DAT did not reach the same level as at 2 DAT.

Most lightness values increased again on the 6th day after treatment. The control treatment (41.25, group "c") had the highest lightness value, in contrast to the other treatments. Low temperature treatments, such as nano sodium alginate with vacuum packaging at 10 °C (25.08, group "a") and nano aloe vera with vacuum packaging at 5 °C (28.18, group "a"), still showed the lowest lightness value and were significantly different from other treatments. The low lightness value indicates that nano edible coating with vacuum packaging can reduce lightness changes during 6 days of storage. This is because nano aloe vera and sodium alginate have active compounds, such as antioxidants, that can reduce oxidative stress in wood ear mushrooms [34] and suppress the activity of the PPO enzyme that causes browning [35]. The low oxygen content in vacuum packaging also reduces the activity of the PPO enzyme [36].

3.2. a^*, b^*, Chroma, and Browning Index

Results of ANOVA for a^*, b^*, chroma, and browning index across all storage periods (2, 4, and 6 DAT) showed no significant differences between treatments. This is indicated by the same letter for all mean values for each parameter, indicating that variation between treatments was not strong enough to statistically influence the color properties of the wood ear mushroom (Tables 2 and 3). The a^* parameter describes the intensity of red-green, the b^* parameter describes yellow-blue, and the chroma parameter describes the intensity or saturation of color. A higher chroma value indicates a brighter and more saturated color. Although not statistically significant, descriptively, it can be seen that the nano sodium alginate treatment with vacuum and wrap at ±25 °C (B and C) and nano aloe vera with vacuum at ±25 °C (K) tend to have higher a^* and chroma values than other treatments, especially at 6 DAT (Figures 2 and 3). The b^* value is relatively stable in almost all treatments, with a slight decrease in some samples during storage (Figure 2).

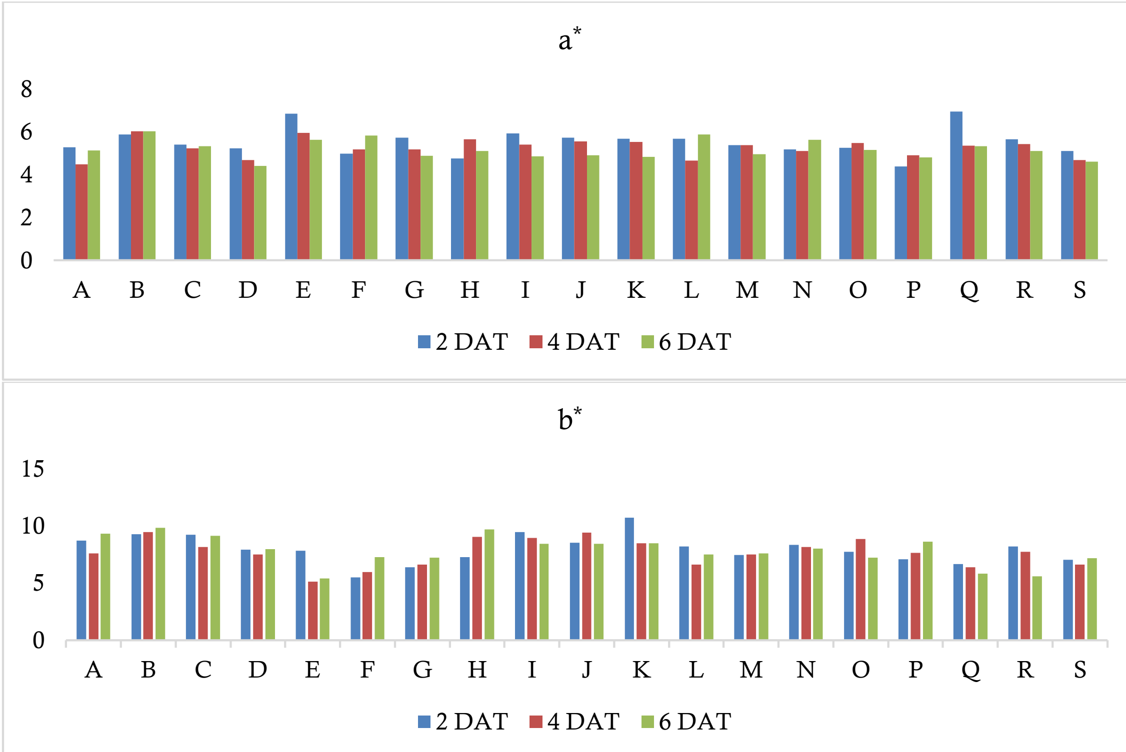

Figure 2. Effect of Treatments on a* and b* Value of Wood Ear Mushroom During Storage. DAT: Days After Storage. A: Control, B: NSA + Vacuum + ±25 °C, C: NSA + Wrap + ±25 °C, D: NSA + Biodegradable + ±25 °C, E: NSA + Vacuum + 10 °C, F: NSA + Wrap + 10 °C, G: NSA + Biodegradable + 10 °C, H: NSA + Vacuum + 5 °C, I: NSA + Wrap + 5 °C, J: NSA + Biodegradable + 5 °C, K: NAV + Vacuum + ±25 °C, L: NAV + Wrap + ±25 °C, M: NAV + Biodegradable + ±25 °C, N: NAV + Vacuum + 10 °C, O: NAV + Wrap + 10 °C, P: NAV + Biodegradable + 10 °C, Q: NAV + Vacuum + 5 °C, R: NAV + Wrap + 5 °C, S: NAV + Biodegradable + 5 °C

The browning index parameter is used to measure the intensity of enzymatic color changes, particularly in mushrooms, which occur due to the interaction between phenolic compounds and oxidative enzymes such as PPO [8]. Browning index (BI) values showed varying and insignificant trends, but nano sodium alginate treatment with vacuum at 10 °C (E) and nano aloe vera with vacuum packaging at 5 °C (Q) tended to have higher BI values at the beginning of storage, which may indicate a faster browning rate. In contrast, nano aloe vera treatment with biodegradable plastic at 5 and 10 °C (P and S) showed BI values that tended to be lower throughout the storage period. Generally, increased browning occurs at higher temperatures due to higher respiration rates, which increase the enzymatic oxidation of phenolic compounds [29]. Browning pigments occur when O_2 reacts with enzymes found in mushrooms [14]. The stable BI value at all storage temperatures demonstrates that the nano edible coating and packaging effectively maintain the color of the wood ear mushrooms. The stable BI value in the control is also due to the absence of differences in the a* and b* values, where these values are components in the BI calculation.

Table 2. Impact of different nano edible coatings, packaging, and storage temperatures on the a* and b* value in wood ear mushroom

Treatment	a*			b*		
	2 DAT	4 DAT	6 DAT	2 DAT	4 DAT	6 DAT
Control	5.29 a	4.49 a	5.14 a	8.71 a	7.57 a	9.34 a
NSA + vacuum + ±25 ℃	5.89 a	6.03 a	6.02 a	9.28 a	9.44 a	9.85 a
NSA + wrap + ±25 ℃	5.41 a	5.22 a	5.34 a	9.24 a	8.15 a	9.14 a
NSA + biodegradable + ±25 ℃	5.22 a	4.68 a	4.42 a	7.93 a	7.51 a	7.95 a
NSA + vacuum + 10 ℃	6.84 a	5.95 a	5.63 a	7.82 a	5.11 a	5.42 a
NSA + wrap + 10 ℃	4.97 a	5.17 a	5.82 a	5.49 a	5.98 a	7.27 a
NSA + biodegradable + 10 ℃	5.73 a	5.18 a	4.88 a	6.39 a	6.59 a	7.20 a
NSA + vacuum + 5 ℃	4.76 a	5.65 a	5.11 a	7.27 a	9.03 a	9.69 a
NSA + wrap + 5 ℃	5.92 a	5.41 a	4.87 a	9.44 a	8.93 a	8.42 a
NSA + biodegradable + 5 ℃	5.73 a	5.55 a	4.91 a	8.51 a	9.39 a	8.44 a
NAV + vacuum + ±25 ℃	5.69 a	5.54 a	4.83 a	10.71 a	8.46 a	8.48 a
NAV + wrap + ±25 ℃	5.69 a	4.65 a	5.88 a	8.22 a	6.61 a	7.52 a
NAV + biodegradable + ±25 ℃	5.38 a	5.37 a	4.96 a	7.44 a	7.50 a	7.60 a
NAV + vacuum + 10 ℃	5.17 a	5.11 a	5.62 a	8.32 a	8.17 a	8.02 a
NAV + wrap + 10 ℃	5.25 a	5.48 a	5.16 a	7.74 a	8.87 a	7.22 a
NAV + biodegradable + 10 ℃	4.38 a	4.92 a	4.80 a	7.10 a	7.65 a	8.64 a
NAV + vacuum + 5 ℃	6.94 a	5.35 a	5.33 a	6.68 a	6.40 a	5.84 a
NAV + wrap + 5 ℃	5.65 a	5.42 a	5.11 a	8.19 a	7.71 a	5.57 a
NAV + biodegradable + 5 ℃	5.11 a	4.69 a	4.60 a	7.02 a	6.62 a	7.17 a

The stable a*, b*, chroma, and browning index values during storage may be due to the effectiveness of the sodium alginate and aloe vera nano edible coating in maintaining the stability of the color pigments [37], [38]. Nano edible coating can also form a thin, homogeneous layer that reduces gas diffusion, oxidation, and water evaporation [39], thereby preventing the oxidation of pigments responsible for color intensity, such as anthocyanins and carotenoids [40], [41]. The packaging used also had a medium oxygen content (plastic wrap and biodegradable packaging) to low (vacuum packaging), thereby maintaining the stability of the natural coloring compounds. The vacuum packaging used can also protect the wood ear mushrooms from exposure to light and oxygen, both of which are the main factors that can affect the chroma value [42]. When combined with an edible coating, the packaging becomes part of an active packaging system that can inhibit color degradation. At high temperatures, the combination of nano edible coating with packaging can also suppress enzymatic reactions, such as PPO activity that triggers non-enzymatic browning. Low temperatures can also inhibit the thermal degradation of pigments such as carotenoids found in wood ear mushrooms [43].

Table 3. Impact of different nano edible coatings, packaging, and storage temperatures on the chroma and browning index in wood ear mushroom

Treatment	Chroma			Browning Index		
	2 DAT	4 DAT	6 DAT	2 DAT	4 DAT	6 DAT
Control	10.55 a	9.15 a	10.96 a	35.89 a	31.03 a	36.33 a
NSA + vacuum + ±25 °C	11.28 a	11.54 a	12.04 a	44.17 a	46.50 a	44.04 a
NSA + wrap + ±25 °C	11.06 a	10.04 a	10.96 a	36.24 a	38.52 a	41.91 a
NSA + biodegradable + ±25 °C	9.86 a	9.29 a	9.40 a	37.83 a	31.63 a	35.10 a
NSA + vacuum + 10 °C	10.53 a	8.04 a	7.99 a	55.60 a	44.55 a	42.09 a
NSA + wrap + 10 °C	7.60 a	8.11 a	9.62 a	35.45 a	41.80 a	45.59 a
NSA + biodegradable + 10 °C	8.71 a	8.71 a	9.17 a	43.43 a	40.55 a	37.63 a
NSA + vacuum + 5 °C	9.07 a	11.01 a	11.37 a	35.14 a	43.42 a	40.54 a
NSA + wrap + 5 °C	11.49 a	10.86 a	10.15 a	41.45 a	38.00 a	35.56 a
NSA + biodegradable + 5 °C	10.77 a	11.37 a	10.26 a	39.83 a	43.46 a	38.57 a
NAV + vacuum + ±25 °C	12.41 a	10.42 a	10.18 a	42.97 a	37.42 a	35.73 a
NAV + wrap + ±25 °C	10.36 a	8.36 a	9.89 a	40.88 a	33.58 a	46.35 a
NAV + biodegradable + ±25 °C	9.67 a	9.60 a	9.56 a	43.21 a	42.47 a	38.65 a
NAV + vacuum + 10 °C	10.14 a	9.99 a	10.23 a	38.81 a	38.30 a	40.49 a
NAV + wrap + 10 °C	9.80 a	10.81 a	9.42 a	38.19 a	42.97 a	37.27 a
NAV + biodegradable + 10 °C	8.83 a	9.55 a	10.23 a	30.90 a	36.33 a	36.68 a
NAV + vacuum + 5 °C	9.79 a	8.56 a	8.15 a	49.37 a	45.93 a	37.69 a
NAV + wrap + 5 °C	10.17 a	9.67 a	7.82 a	41.82 a	41.41 a	35.46 a
NAV + biodegradable + 5 °C	9.07 a	8.49 a	8.89 a	35.37 a	31.78 a	32.72 a

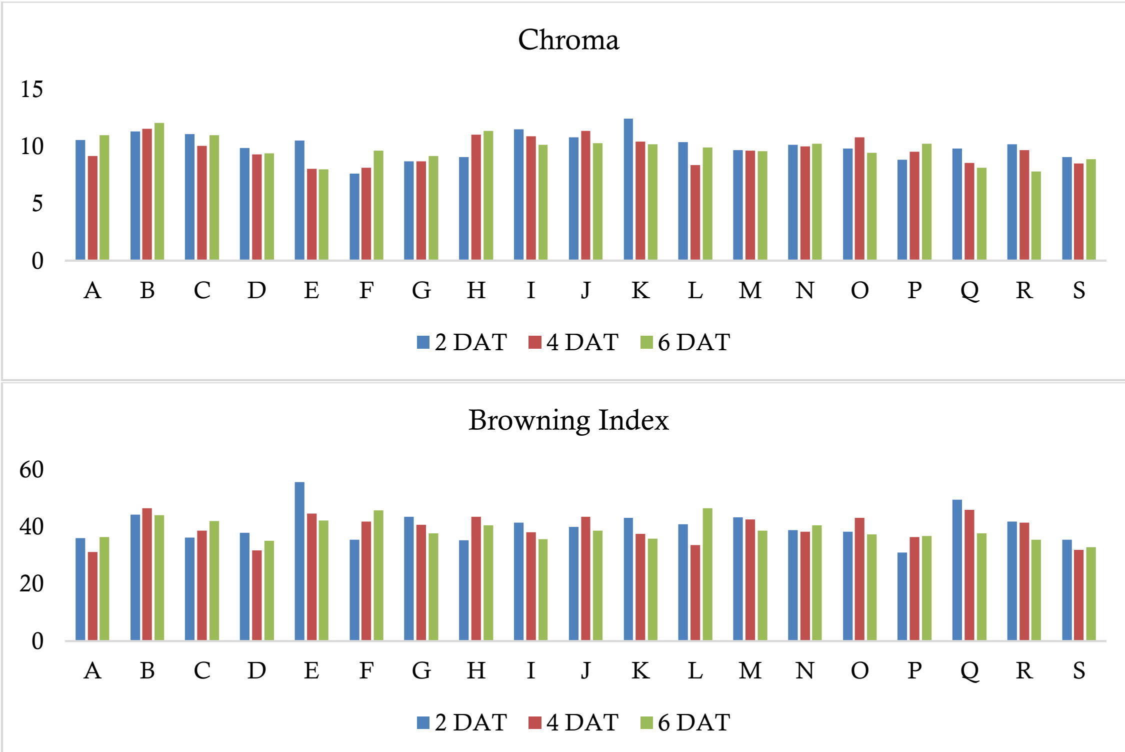

Figure 3. Effect of Treatments on Chroma and Browning Index of Wood Ear Mushroom during Storage. DAT: Days after Storage. A: Control, B: NSA + Vacuum + ±25 °C, C: NSA + Wrap + ±25 °C, D: NSA + Biodegradable + ±25 °C, E: NSA + Vacuum + 10 °C, F: NSA + Wrap + 10 °C, G: NSA + Biodegradable + 10 °C, H: NSA + Vacuum + 5 °C, I: NSA + Wrap + 5 °C, J: NSA + Biodegradable + 5 °C, K: NAV + Vacuum + ±25 °C, L: NAV + Wrap + ±25 °C, M: NAV + Biodegradable + ±25 °C, N: NAV + Vacuum + 10 °C, O: NAV + Wrap + 10 °C, P: NAV + Biodegradable + 10 °C, Q: NAV + Vacuum + 5 °C, R: NAV + Wrap + 5 °C, S: NAV + Biodegradable + 5 °C

3.3. Hue

Hue is the color degree that indicates the dominant color nuance (e.g., reddish, yellowish, greenish, and others). The Scott-Knott test results showed that at 2 and 4 DAT, there were significant differences between treatments (Table 4). At 2 DAT, most treatments produced group "b" (Hue values between 52–62, while several treatments, such as nano sodium alginate vacuum-packed at 10 °C and nano aloe vera vacuum-packed at 5 °C, were classified as group "a" (lower Hue, ranging from 44–48). According to Hutching (1999), a color description with a hue range of 18–54 is red, and 54–90 is yellow-red [44]. This indicates that treatments at low temperatures of 10 °C and 5 °C tend to cause a color shift toward a lower hue, which can indicate a color change toward redness or a loss of yellowness. This is shown by the lower color difference value in this treatment (Table 5), which indicates its ability to maintain the dark red color of the wood ear mushroom.

Table 4. Impact of different nano edible coatings, packaging, and storage temperatures on the hue in wood ear mushroom

Treatment	Hue		
	2 DAT	4 DAT	6 DAT
Control	56.42 b	53.27 c	59.00 a
NSA + vacuum + ±25 °C	56.65 b	56.87 c	56.35 a
NSA + wrap + ±25 °C	57.57 b	57.31 c	60.54 a
NSA + biodegradable + ±25 °C	56.00 b	56.83 c	60.52 a
NSA + vacuum + 10 °C	48.27 a	39.79 a	42.92 a
NSA + wrap + 10 °C	47.19 a	49.48 b	50.55 a
NSA + biodegradable + 10 °C	47.94 a	49.95 b	53.82 a
NSA + vacuum + 5 °C	55.44 b	57.68 c	60.53 a
NSA + wrap + 5 °C	58.31 b	57.19 c	54.60 a
NSA + biodegradable + 5 °C	53.34 b	56.92 c	55.35 a
NAV + vacuum + ±25 °C	62.05 b	54.18 c	56.52 a
NAV + wrap + ±25 °C	53.31 b	53.82 c	52.09 a
NAV + biodegradable + ±25 °C	49.31 a	52.96 c	53.03 a
NAV + vacuum + 10 °C	57.84 b	55.74 c	50.33 a
NAV + wrap + 10 °C	54.25 b	57.63 c	52.04 a
NAV + biodegradable + 10 °C	53.31 b	51.77 c	55.13 a
NAV + vacuum + 5 °C	44.67 a	46.69 b	47.59 a
NAV + wrap + 5 °C	55.43 b	56.10 c	47.89 a
NAV + biodegradable + 5 °C	52.31 b	53.16 c	53.27 a

This difference becomes more apparent at 4 DAT, where the hue groups "a", "b", and "c" begin to separate more clearly, reflecting a significant effect of treatment on short-term color stability. However, at 6 DAT, all treatments revert to one group (letter "a"), meaning that color differences based on hue are no longer statistically significant. This indicates that after a storage period of more than 5 days, the color of the wood ear mushroom tends to become homogeneous again, regardless of the initial treatment. The a^* and b^* values also show the same results for all treatments at 6 DAT (Table 2).

In general, differences in hue occur early in storage, indicating that low-temperature treatment (especially at 10 °C) can accelerate natural color degradation, such as decreased carotenoid or flavonoid pigmentation. This is in line with research by Ge et al. (2022) on mandarin oranges, where storage at low temperatures inhibits pigment synthesis and causes chlorophyll accumulation that masks the carotenoid color [45]. However, over time, the color of the commodity adjusts or degrades uniformly, so that it no longer shows significant differences between treatments by day 6. Techniques that maintain mushroom characteristics can extend shelf life, but quality declines that occur over time still result in color homogenization [46].

3.4. Color Difference (ΔE)

The color difference (ΔE) parameter measures the total color change relative to the initial conditions. ΔE provides a comprehensive overview of the visual shift in color, including the L^*, a^*, and b^* parameters. Based on the Scott-Knot test, there were significant differences between treatments regarding ΔE, especially at 2 and 6 DAT (Table 5). At 2 DAT, low-temperature treatments, such as nano sodium alginate vacuum-packed at 10 °C and nano aloe vera vacuum-packed at 5 °C, showed the lowest ΔE values (around 28–30), indicating that the color of the wood ear mushroom was more stable than the control. The same results were also shown by this treatment for the lightness and hue parameters at 2 DAT (Tables 1 and 4). The control and room-temperature treatments, including groups "b" and "c", had higher ΔE values (≥ 35), indicating a more drastic color change compared to the initial storage. This difference indicates that low-temperature treatments, especially at 10 and 5 °C, are effective in suppressing color changes, possibly by slowing down the enzymatic activity responsible for pigment degradation [47].

Table 5. Impact of different nano edible coatings, packaging, and storage temperatures on the color difference in wood ear mushroom

Treatment	Color Difference		
	2 DAT	4 DAT	6 DAT
Control	41.03 c	38.20 b	42.79 c
NSA + vacuum + ±25 °C	37.59 b	37.54 b	40.37 c
NSA + wrap + ±25 °C	42.39 c	38.55 b	41.24 c
NSA + biodegradable + ±25 °C	37.53 b	41.42 b	40.70 c
NSA + vacuum + 10 °C	30.26 a	24.22 a	26.45 a
NSA + wrap + 10 °C	29.60 a	29.06 a	33.60 b
NSA + biodegradable + 10 °C	29.13 a	30.65 a	35.93 c
NSA + vacuum + 5 °C	37.53 b	37.84 b	41.62 c
NSA + wrap + 5 °C	41.11 c	40.57 b	39.22 c
NSA + biodegradable + 5 °C	37.77 b	39.22 b	38.03 c
NAV + vacuum + ±25 °C	44.48 c	39.64 b	39.92 c
NAV + wrap + ±25 °C	35.67 b	36.19 b	32.21 b
NAV + biodegradable + ±25 °C	32.52 a	32.85 a	35.72 c
NAV + vacuum + 10 °C	39.89 c	38.01 b	34.01 b
NAV + wrap + 10 °C	36.73 b	37.55 b	35.07 b
NAV + biodegradable + 10 °C	38.02 b	36.02 b	37.86 c
NAV + vacuum + 5 °C	28.29 a	26.63 a	29.40 a
NAV + wrap + 5 °C	35.71 b	35.10 b	30.62 a
NAV + biodegradable + 5 °C	35.14 b	35.93 b	36.89 c

At 6 DAT, the difference in ΔE persisted, with group "a" still dominated by low-temperature treatments (e.g., nano aloe vera with vacuum packaging at 5 °C), while group "c" consisted of room temperature treatments such as control and nano sodium alginate with plastic wrap at ±25 °C. This strengthens the indication that cooling can maintain color stability longer because it reduces the activity of browning-related enzymes (PPO and peroxidase) [48]. High temperatures cause the Maillard reaction, which is a series of complex non-enzymatic browning reactions that occur between reducing sugars and amino acids, which produce melanoidin compounds (brown color) [49]. Polyphenol oxidase (PPO) also catalyzes the formation of o-quinones, which can then react with anthocyanins, the red pigments in wood ear mushrooms, causing their degradation [50].

4. Conclusion

The combination of nano edible coating, packaging, and storage temperature significantly affected ($p < 0.05$) the lightness, hue, and color difference of the wood ear mushroom during storage. The best treatment was obtained from nano edible coating aloe vera with vacuum packaging at a temperature of 5 °C, which resulted in low lightness and color difference values at 2, 4, and 6 DAT. This study is still limited by the scope of physical parameters, without considering microbiological or sensory aspects that also affect product quality. Further research is recommended to evaluate the combination of nano-edible coating with natural antimicrobial agents and its effect on overall shelf life. These findings have practical implications for the wood ear mushroom industry and can be used as a reference in the development of product operating standards (SOPs) for packaging fresh mushrooms based on nano-edible coatings, to improve product quality stability during storage and distribution.

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