

Heated Wood-Based Ethylene Scavenger for Active Packaging to Prevent Browning of *Lentinula edodes*

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Most mushrooms are sensitive to ethylene, and exposure leads to degradation in mushroom quality, particularly in appearance and organoleptic properties. This study investigated the feasibility of using heated wood for ethylene removal. The hypothesis was that ethylene accumulation can be limited by using heated wood-based ethylene scavengers in mushroom packaging. The applicability and benefits of heated wood-based ethylene scavengers in mushroom home delivery are discussed. The heated wood-based ethylene remover used in the courier maintained the color of *Lentinula edodes* during transportation. These results were supported by quantitative analysis, in which the ethylene concentration in packaging headspace was significantly reduced ($p < 0.05$) by the wood-based scavenger, and rate of weight change also showed significant improvement ($p < 0.05$) compared to the control. Overall, this heated wood-based ethylene scavenger has potential in terms of mushroom packaging and food shelf-life extension.

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Keywords: *Lentinula edodes*; Delivery; Heating; Shelf life; Ethylene scavenger

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INTRODUCTION

Ethylene scavenger packaging changes the state of the packaged food and adds sustainability, thus longer retention periods and food shape (Gaikwad *et al.* 2020a). Ethylene (C₂H₄) controls mechanisms, growth regulation, and aging aspects of foods, including mushrooms (Thomas and Diehl 1988). In addition to the aging of mushrooms and fruit, they are mainly caused by ethylene-induced ripening processes and contamination with microorganisms (Mariah *et al.* 2022).

An effective way to control ethylene production inside packaging is to use ethylene scavengers, also known as ethylene removers (Sadeghi *et al.* 2021). Standard packaging forms for ethylene scavengers are pouches and films (Kumar *et al.* 2024a). The scavenger reduces the concentration of ethylene in the air through a physicochemical adsorption process (Gunes 2024). Ethylene absorbers are used in fresh food packaging to extend shelf life (Ebrahimi *et al.* 2022a).

Heated wood chip is a structured, amorphous, porous, non-crystalline form of carbon obtained from the pyrolysis of carbonaceous materials (Amalina *et al.* 2022a). Heating of wood is a process in which biomass is heated at atmospheric pressure without oxygen using a fixed bed reactor and a thermochemical treatment process to improve its properties (Zhang *et al.* 2010). Heated wood has advantages such as hydrophobicity, high surface area, and relatively low production costs (Ghafurian *et al.* 2020).

Kumar *et al.* (2024b) summarized the use of layered silicates and montmorillonite clays modified with transition metals and their roles in ethylene adsorption, showing promise as eco-friendly materials for active packaging. Amalina *et al.* (2022b) and Jiao *et al.* (2024) emphasized that biomass-derived porous carbonaceous materials—such as biochar from agricultural and forestry waste—exhibit high surface area, tunable pore structures, and cost-effective production, making them viable ethylene scavengers. Keller *et al.* (2013a) proposed using photocatalytic oxidation methods (*e.g.*, TiO₂-based systems) as sustainable methods for ethylene removal under light exposure, albeit with limitations for packaging applications. Although still emerging, enzymatic systems that degrade ethylene enzymatically (*e.g.*, ACC oxidase mimetics) and microbial strains engineered to consume ethylene have been reported in niche applications (Ebrahimi *et al.* 2022b). Gaikwad *et al.* (2020b) reviewed packaging films incorporated with natural zeolites, activated carbon, and biopolymers loaded with scavengers, allowing for direct integration into food packaging environments. To clearly position this study within this landscape, it was clarified that heated wood-based scavengers function through a physicochemical adsorption mechanism, are derived from renewable biomass (wood waste), and require no chemical activation or additive—making them a low-cost, biodegradable, and scalable alternative to KMnO₄ systems. Despite considerable interest and progress in the topic of ethylene scavenger applications (Scariot *et al.* 2014), there has been relatively little consideration of ethylene scavengers for mushroom freshness preservation. This paper proposes and evaluates a heated wood-based ethylene scavenger for mushroom packaging and delivery systems.

EXPERIMENTAL

Preparation of Heated Wood

The wood chips were pre-dried at 105 °C for over 24 h. The pre-drying step ensures complete moisture removal from the wood chips, which is essential for two reasons. It prevents steam formation during torrefaction, which can interfere with heat transfer and promote uncontrolled reactions. In addition, it aligns with standard drying protocols in biomass pretreatment studies to achieve consistent and reproducible thermal behavior. According to ASTM D4442 and similar biomass protocols, drying at 105 °C for 24 h is widely adopted to reduce moisture content to below 2 to 3% (McKendry 2002; Zhang *et al.* 2010). This ensures uniform thermal decomposition during heating. The high-temperature supported scavenger-based heated wood was prepared under oxygen-blocked conditions. Briefly, 5 cm x 5 cm wood chips (0.2 cm thick) were treated at 330 °C for 15 min. Previous studies have shown that at 330 °C, hemicellulose degradation is maximized, while cellulose partially carbonizes, yielding microporous char with high CO/OH group availability (Phanphanich and Mani 2011). Short durations (10 to 20 min) in this temperature range balance structural integrity and functional surface development, avoiding over-carbonization or brittleness (Chen *et al.* 2015). Therefore, 330 °C for 15 min was selected as an optimal balance between carbonization efficiency and material stability for packaging use. The product was ground until it reached a size of 4 mm after heating. The obtained heated wood powder was stored in a desiccator until use next experiment.

Preparation for Ethylene Scavenging

Active pouches containing C₂H₄ scavenger (positive control; Sungel Co., Ltd.) and/or heated wood powder (at various doses as described in Table 1 and Fig. 1) were prepared. Each pouch is constructed of a nonwoven, breathable fabric (comparable to medical-grade spunbond polypropylene) that allows for effective gas exchange while containing the powder or granulated scavenger safely. The dimensions of each pouch were approximately 7 × 4 cm, and one of the pouches was placed inside each packaging container, as per manufacturer recommendation. These sachets are functionally analogous to activated absorbent tea bags and are commonly used in commercial ethylene absorber systems for fresh produce storage. The commercially effective KMnO₄-based C₂H₄ scavenger was acquired as it is one of the most effective scavengers on the market.

Table 1. Components in the Treatment Scavenger with Heated Wood

No.	Heated Wood Powder (g)	Commercially Available KMnO ₄ -based C ₂ H ₄ scavenger (g)	Nomenclature
1	0	4	4C
2	0	7	7C
3	0	14	14C
4	1	3	1T3C
5	2	5	2T5C
6	4	10	4T10C
7	2	2	2T2C
8	3.5	3.5	3.5T3.5C
9	7	7	7T7C
10	3	1	3T1C
11	5	2	5T2C
12	10	4	10T4C
13	4	0	4T
14	7	0	7T
15	14	0	14T

Nomenclature: The nomenclature is based on the weight of Heated Wood Powder (g) and Commercially Available KMnO₄-based C₂H₄ scavenger (g) in the scavenger. Specifically, the weight of Heated Wood Powder is denoted by "T" and the weight of Commercially Available KMnO₄-based C₂H₄ is denoted by "C".

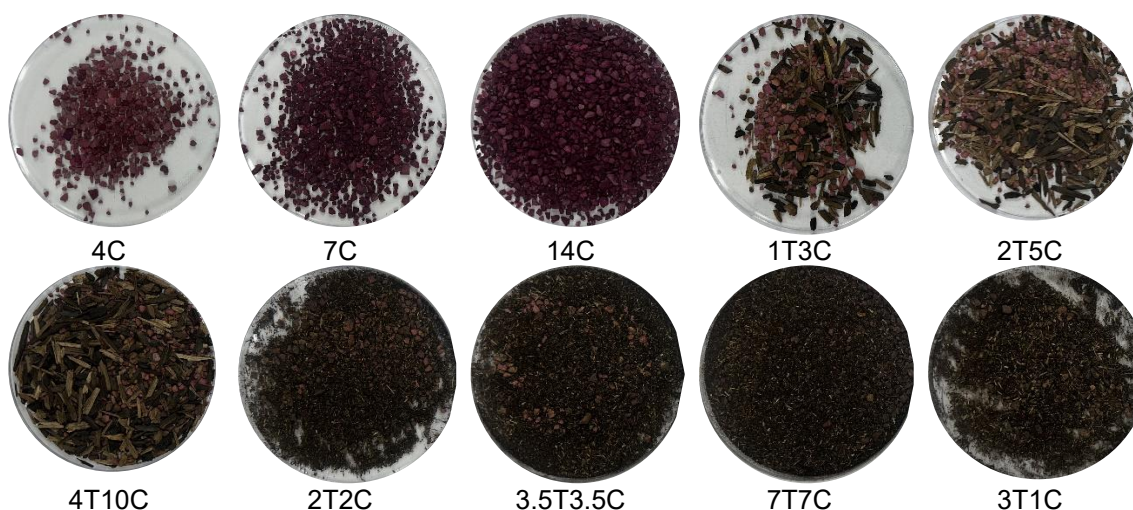




Fig. 1. Active sachets with heated wood and commercial scavenger

Mushroom Preparation

Lentinula edodes (*L. edodes*) was grown under greenhouse conditions in South Korea (54, Jinhwanggyeong-ro 105beon-gil, Sicheon-myeon, Sancheong-gun, Gyeongsangnam-do, South Korea; Gyeongsang National University Academic Forest) according to integrated pest management cultivation methods. *L. edodes* were harvested in the early morning of October at the ripening stage. The mushrooms were selected to be free of defects and similar in size and pericarp color. They were then stored in a cold room at 4 °C until used in the experiment.

Effect of the heated wood-based scavenger on L. edodes quality during postharvest in the Lab scale

Lentinula edodes was placed in sealed flasks containing each of the scavenger in Table 1. The flasks were left at room temperature (approximately 25 °C) under continuous light and room temperature (approximately 25 °C), which are unfavorable conditions for shelf life, for up to 28 days. Experiments were replicated three times per treatment, and after 28 days, ammonia, volatile organic compounds, and ethylene concentrations were measured using a composite gas meter.

Lentinula edodes packaging applications and shipping test of heated wood-based scavenger

The impact of ethylene scavengers containing heated wood was tested in the packaging environment of fresh *L. edodes*. The weight of *L. edodes* in each test group was approximately 100 g. The test groups were stacked vertically in a box. Samples of *L. edodes* from different test groups (Table 1) were delivered to three cities with different environmental conditions (Table 2). The cardboard box in which the mushrooms were packaged has a certain air permeability that allows the mushrooms to maintain their normal physiological activity, but does not allow a large amount of air to enter the box.

Table 2. Information of Addressee for Parcel Test

Classification	Latitude	Longitude	Temperature of the parcel start date	Temperature of the parcel end date	Parcel period, day
Sender-GyeongSang National University	35.153072	128.095859	32	-	-
Addressee- A	35.165432	128.109448	32	26	3
Addressee- B	35.156200	128.171786	32	26	3
Addressee- C	35.153238	128.106420	32	26	3
Average temperature, maximum temperature, minimum temperature during the three days, respectively: 25.6 °C, 30.0 °C, and 21.7 °C					

Ethylene gas analysis

Ethylene gas was measured with a multi-gas meter (SKY2000, SAFEGAS, Korea). Ethylene gas was measured at 25 °C, 50% RH, immediately after receiving the courier.

Visual changes of *L. edodes*

The visual imaging of *L. edodes* was performed with a digital camera. The *L. edodes* samples were packaged in the developed packaging of the scavenger containing heated wood. The analysis was performed either before or after parceling.

Colorimetric analysis of *L. edodes*

The mushroom photo was taken with the camera set at a height of 15 cm and an angle of 45°. The obtained photos were processed using the Adobe Photoshop 2024 program. The white areas of the photo were selected, and the background of the mushroom was not taken into account in the subsequent color analysis, using Eq. 1.

$$L^* = (L/255) \times 100\% \quad (1)$$

In this study, the L^* parameter (lightness, ranging from 0 = black to 100 = white) was selected as the primary indicator of color change because surface browning in mushrooms is predominantly perceived and quantified as a loss of brightness (*i.e.*, darkening), rather than shifts in chromaticity (a^* or b^*). This is particularly relevant for *L. edodes*, which has a naturally light or whitish cap surface in its fresh state. According to Mahajan *et al.* (2008) and Gómez *et al.* (2016), browning in mushrooms during storage or ethylene exposure is primarily due to enzymatic oxidation (*e.g.*, polyphenol oxidase) leading to melanin formation, which results in a decrease in L^* values. These authors also noted that a^* (red-green axis) and b^* (yellow-blue axis) values often show less pronounced or inconsistent variation in mushrooms compared to L^* , such that L^* tends to be a more sensitive and representative indicator of freshness and visual quality degradation.

Furthermore, previous ethylene scavenger-related packaging studies (Jiang and Fu 1998; Ares *et al.* 2007) focused on L^* as the core index of postharvest mushroom browning, particularly under modified or active atmosphere conditions. Based on these precedents, and to minimize complexity and redundancy in visual quality assessment, L^* was selected as the primary quantitative index of browning severity.

Fresh weight variable of *L. edodes*

The percentage of variable of fresh weight was calculated as follows,

$$\% \text{ Percentage of variable of fresh weight} = (W_b - W_a) / W_b \times 100 \quad (2)$$

where % Percentage of variable of fresh weight is the weight loss percentage, W_b is the measured weight before shipping, and W_a is the sample weight after shipping.

pH determination of *L. edodes*

The pH of the mushroom was measured at a 1:5 mushroom:water (w/v) ratio. Three measurements were taken for each sample.

Statistical Analysis

All experiments were performed in triplicate. Significance tests were performed using ANOVA analysis in the SAS program, with a *p*-value of 0.05.

RESULTS AND DISCUSSION

Effects of the Heated Wood-Based Scavenger on Ethylene Absorption in the Lab Scale

Figure 2 shows the ethylene adsorption efficiency of heated wood and commercial scavenger composites with different additions of activated carbon.

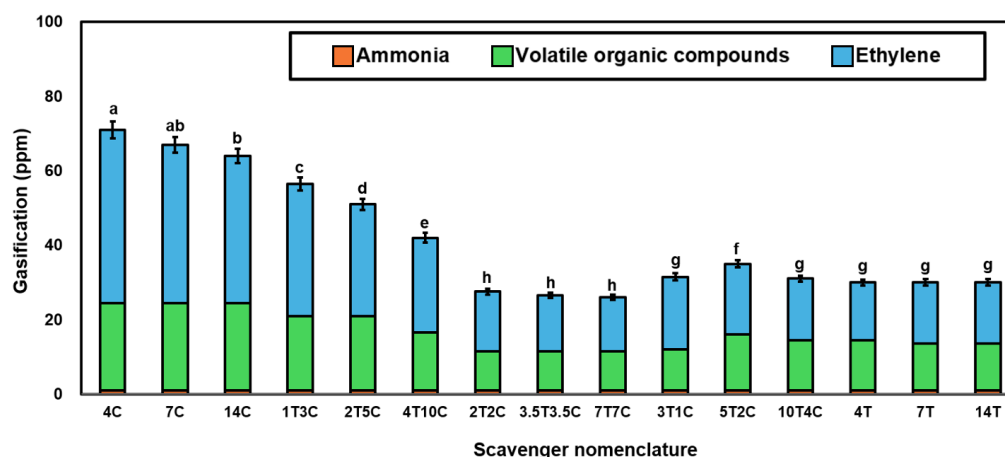


Fig. 2. Gasification within active sachets containing the sachet as described. Different small letters between test samples and control indicated significant differences at a *p*-value 0.05 level.

The ethylene adsorption capacity of the heated wood-based scavenger was evaluated in a laboratory environment for 28 days to measure concentration. The ethylene that passed through the system over the 28 days was detected at approximately 14 to 47 ppm. The heated wood composites for ethylene adsorption showed very good efficiency, especially the composite containing 50% 4 mm heated wood had a very high ethylene adsorption yield.

The composite containing 70% KMnO₄-based C₂H₄ scavenger (a commercial scavenger) showed favorable results, *i.e.*, the composite containing KMnO₄-based C₂H₄ scavenger absorbed ethylene gas, but lower than the expected results. Therefore, KMnO₄-based C₂H₄ scavengers are less suitable for preparing ethylene scavenger composites for the freshness of *L. edodes* than heated wood.

Effects of the Heated Wood-Based Scavenger on Ethylene Absorption after Shipping

Relative to the blank and commercial scavenger-only sachets, the 2T2C and 7T7C sachets reduced ethylene levels by over 70%. The empty box served as a baseline to evaluate the efficacy of the heated wood-based scavengers. All samples showed a sharp decrease in ethylene concentration, emphasizing their high adsorption rates. 4C commercial scavenger showed the lowest adsorption capacity, followed by 7C without heated wood. 2T2C, 3.5T3.5C, and 7T7C showed increasingly larger capacities. These

results suggest that incorporating heated wood not only enhances ethylene adsorption in commercial scavengers but also that the effectiveness of this enhancement depends on the weight of heated wood input.

Table 3. Effects of Active Sachets Containing the Sachet as Described on Ethylene Adsorption Efficiency

Nomenclature	Ethylene Adsorption (%)
Blank	0.0 ± 0.0
4C	47.1 ± 0.2
7C	52.9 ± 1.7
14C	63.4 ± 1.2
1T3C	55.5 ± 0.5
2T5C	60.2 ± 1.1
4T10C	62.8 ± 1.2
2T2C	77.0 ± 1.2
3.5T3.5C	78.0 ± 1.7
7T7C	79.1 ± 1.5
3T1C	68.1 ± 1.2
5T2C	73.3 ± 0.7
10T4C	75.4 ± 0.5
4T	62.8 ± 0.8
7T	71.7 ± 1.1
14T	73.8 ± 1.1

Effects of the Heated Wood-Based Scavenger on Visual Change of *L. edodes* after Shipping

Photo analysis of the mushrooms (Fig. 3) showed that the test pouch containing the blank sample (no scavenger) was completely decayed after vesiculation, showing brown color and stains. Care was taken to ensure that the mushrooms were arranged in a sufficiently dense and uniform layer such that the entire background was fully covered during image capture. This was done to prevent interference from underlying surfaces and to ensure that only the surface color of the *L. edodes* samples was assessed. The mushrooms packaged with 2T2C and 7T7C remained white during vesiculation. However, white or yellowish were observed on the surface edges of some *L. edodes*, indicating the importance of the role of scavengers in the transportation of mushroom parcels. The 2T2C scavenger was determined to be suitable for courier transportation of *L. edodes*, and as a result, the *L. edodes* remained white during vesiculation without turning yellowish. Therefore, 2T2C was suitable for fresh *L. edodes* packaging vehicles.

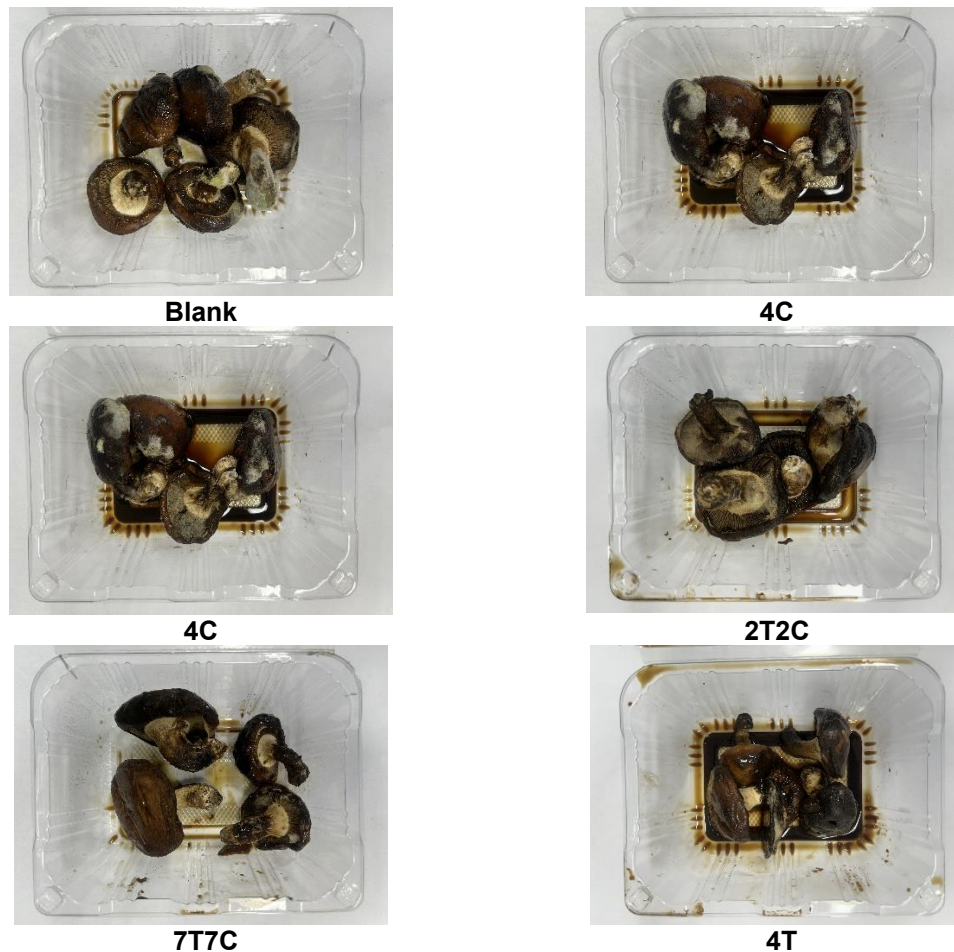


Fig. 3. Visual of *L. edodes* after shipping

Effects of the Heated Wood-Based Scavenger on Color Change of *L. edodes* after Shipping

Mushrooms undergo browning in some areas during the courier transportation process, and these color changes can be used to objectify the quality of the mushrooms. The L^* values of *L. edodes* courier-transported with heated wood-based scavengers used in different proportions are shown in Fig. 4. The blank without scavengers was standardized to 100% and compared to the scavenger for each condition. The test scavengers containing 2T2C and 7T7C had the highest average L^* values for *L. edodes*. *L. edodes* using the heated wood-based scavengers had higher L^* values on average than the blank. Figure 4 shows that the combined heated wood provided a better effect than the blank. The quantified CIE L^* values derived from RGB color analysis using Adobe Photoshop are described in the following sentence. These L^* values reflect the whiteness of mushroom caps and provide a continuous numerical indicator of browning severity. In particular, mushrooms treated with 2T2C and 7T7C maintained high L^* values (77.0 and 79.1, respectively), whereas control and commercial-only groups showed significantly lower values (e.g., 4C: 62.8). The L^* values for each of the tested scavengers are as follows: 4C 62.8 ± 0.8 , 7T7C 79.1 ± 1.5 , 2T2C 77.0 ± 1.2 , 4T10C 62.8 ± 1.2 , and 10T4C 75.4 ± 0.5 . These results clearly demonstrate that *L. edodes* packaged with 2T2C and 7T7C maintained significantly higher L^* values, confirming superior visual freshness (whiteness) relative to the blank or commercial-only scavengers.

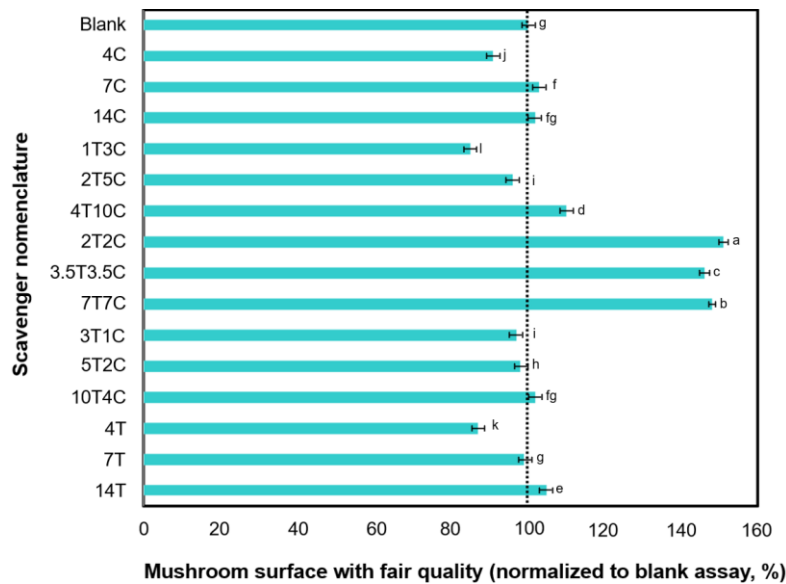


Fig. 4. Whiteness changes of *L. edodes* after parcel delivery in different scavengers with or without heated wood. Different small letters between test samples and blank indicated significant differences at a p -value 0.05 level.

Effects of the Heated Wood-based Scavenger on Fresh Weight of *L. edodes* after Shipping

Figure 5 shows the effect of different scavengers on physiological weight change. Samples shipped with only commercial scavenger showed significantly higher weight change compared to the mixed heated wood-based scavengers. After delivery, the maximum weight change for the commercial scavenger samples with treatment alone was 52%. *L. edodes* vesicle scavenger, in combination with heated wood, strongly suggested that no noticeable loss in quality and value of *L. edodes* was identified in samples with less than 30% weight change.

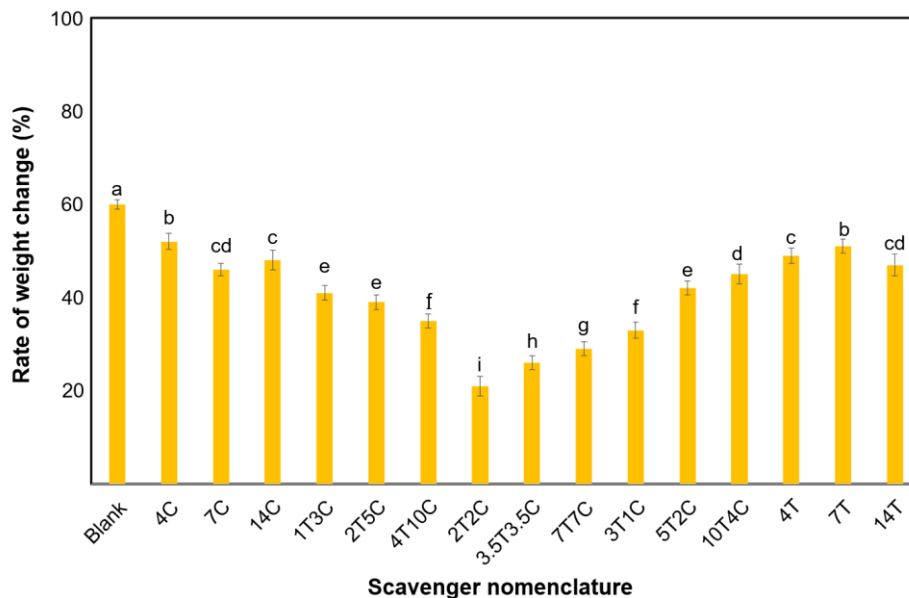


Fig. 5. Variability of fresh weight after shipping. Different small letters between test samples and control indicated significant differences at a 0.05% level of significance.

Effects of the Heated Wood-based Scavenger on pH of *L. edodes* after Shipping

A significant change in pH of *L. edodes* was observed after parcel delivery. This result is consistent with previous reports of decreased acidity during storage of mushrooms. No significant change in pH was observed for *L. edodes* with 2T2C scavenger compared to the control; the lowest pH values were 3.53 and 3.56 for the blank and 4C scavenger without scavenger, respectively. Gholami *et al.* (2024) reported that CO₂ stimulation from the use of scavengers was associated with the maintenance of pH.

Among the many benefits of heat-treated wood, its high adsorptive capacity is emerging as a potential application for ethylene gas adsorption to keep fresh food fresh (Keller *et al.* 2013b). Although wood produced from industrial carbonization furnaces is widely used, it is currently used without scientific verification of its efficacy (Assis *et al.* 2016). In this study, the feasibility of using heat-treated wood as a commercial ethylene gas adsorbent was investigated. Heat-treated wood is a material with chemical heterogeneity associated with a complex porous structure (Candelier *et al.* 2016). Their structural heterogeneity is a result of the presence of a wide pore size distribution that includes micropores, mesopores, and macropores of various sizes and shapes (Jiao *et al.* 2024). The results of the study showed that scavengers manufactured by adding heat-treated wood without compromising their mechanical properties can be used to effectively reduce the concentration of ethylene and thus increase the shelf life of mushrooms. The results obtained in this study helped to develop an innovative method for research on extending the shelf life of mushrooms during the distribution process using heat-treated wood.

Activated carbon is known to exhibit specific surface areas exceeding 800 to 1000 m²/g, making it an excellent candidate for gas adsorption. Several studies (Ioannidou and Zabaniotou 2007; Mohan *et al.* 2014) have demonstrated the feasibility of producing high-quality activated carbon from forestry residues and wood-based biomass under controlled pyrolysis and activation conditions. Therefore, future work may involve the comparative evaluation of activated carbon versus heated wood powder, examining not only ethylene removal efficiency but also cost-effectiveness, biodegradability, and packaging safety.

CONCLUSIONS

1. This study examined the feasibility of using heated wood to maintain the freshness of *Lentinula edodes* during courier transportation. This study is valuable because mushrooms are living foods that breathe, and therefore, it is difficult to maintain their freshness during courier transportation.
2. The results demonstrated that a scavenger containing heated wood was suitable for maintaining the quality of *L. edodes* during courier transportation, including color, ethylene gas adsorption, and pH.
3. Using eco-friendly and biodegradable heated wood as a scavenger to maintain the quality of mushrooms is feasible for industrial utilization.

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