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Postharvest Innovations in Mushroom Shelf-life Enhancement

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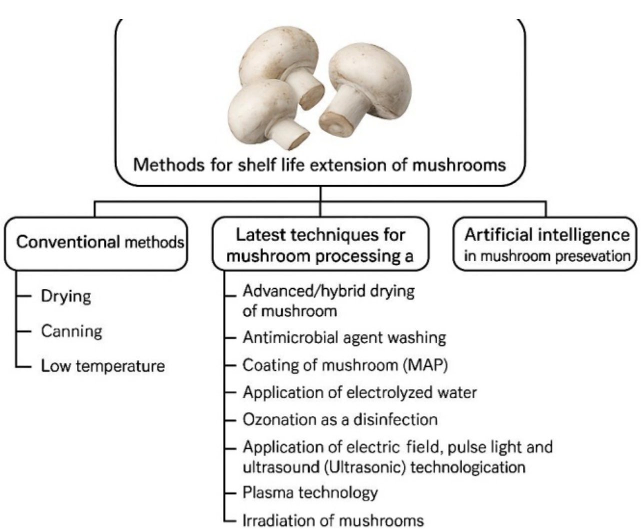
Abstract
Mushrooms are highly perishable commodities due to their high moisture content and enzymatic activity, necessitating efficient postharvest preservation strategies. This study comprehensively evaluates traditional methods such as drying, canning, and refrigeration alongside contemporary technologies, including ultrasound-assisted immersion freezing, non-thermal plasma treatment, antimicrobial surface decontamination, and advanced packaging systems. Additionally, the antioxidant ergothioneine (EGT) was explored for its cytoprotective and anti-browning properties. Button mushrooms (Agaricus bisporus) were subjected to ultrasound treatments at different power intensities and stored under modified atmosphere packaging (MAP). Quality metrics such as weight loss, texture, pH, soluble solids, and color changes were analyzed. Application of EGT significantly reduced browning and improved postharvest stability. Integrating multiple preservation technologies demonstrated synergistic effects in prolonging mushroom shelf life under commercial conditions.

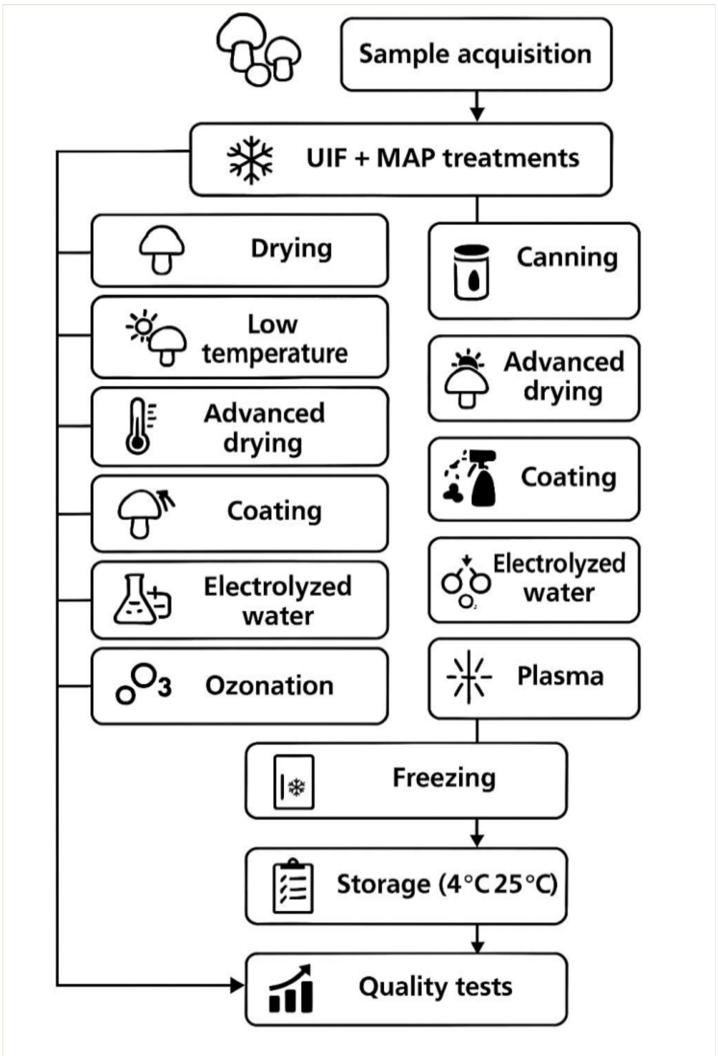
Keywords: *Postharvest technology, Mushroom preservation, Shelf-life extension, Edible fungi storage and Modified atmosphere packaging (MAP)*



INTRODUCTION

Button mushrooms (*Agaricus bisporus)* are among the most widely cultivated and consumed mushrooms worldwide due to their culinary versatility and rich nutritional profile. They are a source of essential nutrients, such as B vitamins, dietary fiber, minerals, and bioactive compounds like ergothioneine (EGT), which have been linked to numerous health benefits [1-2]. Despite their popularity, mushrooms exhibit a short postharvest shelf life due to their high respiration rate, delicate tissue structure, and susceptibility to enzymatic browning and microbial spoilage [3-4]. Traditional preservation approaches, such as drying, canning, and cold storage, have been widely used to extend the shelf life of mushrooms. These methods can reduce microbial growth and moisture content but often compromise mushrooms' sensory and nutritional qualities [5-6]. While effective in slowing deterioration, these methods alone are insufficient to preserve the fresh-like attributes over extended periods. Therefore, there is a growing demand for advanced preservation strategies that are efficient, cost-effective, and capable of maintaining product integrity. Emerging non-thermal technologies, including ultrasound-assisted freezing, pulsed electric fields, plasma treatment, and modified atmosphere packaging (MAP), have gained attention in recent years for their potential in postharvest applications [9-11]. Ultrasound-assisted freezing can enhance the freezing rate, resulting in smaller ice crystals and less cellular damage, while MAP can regulate oxygen and carbon dioxide levels to reduce respiration and oxidative browning. These technologies, when combined, offer promising solutions for enhancing the postharvest stability of mushrooms [12-13]. Ergothioneine, a unique thiol-containing antioxidant naturally synthesized by fungi and bacteria, is highly stable under oxidative conditions and offers protective effects against oxidative stress and cell damage [14-15].

Although it has been studied in the context of meat and seafood products, its application in mushroom preservation is relatively new. Recent evidence suggests that EGT treatment can inhibit polyphenol oxidase activity, reduce browning, and maintain textural and color quality in postharvest mushrooms [16-17]. This review explores the synergistic use of EGT, MAP, and ultrasound freezing to develop an integrated strategy for shelf-life extension in button mushrooms.



2. Materials and Methods

2.1 Sample Procurement and Preparation: Uniform-sized, healthy button mushrooms were sourced from Mallard Mushroom Cultivation and Industry (Karaj, Iran) and Fungorobica Srl (Cenate Sotto, Italy). The mushrooms, selected from the second flush with 40–50 mm cap diameter, were stored at 4 °C and 75 ± 2% relative humidity for 24 hours before analysis.

2.2 Ultrasound-Assisted Freezing Protocol: A 24 kHz ultrasonic processor (UPT400, FAPAN, Iran) was used for UIF. Mushrooms were immersed in 97% ethanol, maintained at −20 °C with 2 L/min coolant flow. A K-type thermocouple monitored internal temperatures recorded every 10 seconds. Samples underwent UIF at 50–400 W (FDC and HDC) and were frozen until −15 °C, then stored at −18 °C.

2.3 Modified Atmosphere Packaging: MAP samples were sealed using a tabletop vacuum machine (E100) fitted with a MAP mix 9001 gas mixer. Optimal gas composition was 15% O2, 5% CO2, and 80% N2. Packages were analyzed every two days using a Hewlett-Packard 5890 gas chromatograph with a TCD detector. Packaging material consisted of multilayer PET/coating/LLDPE film with a 0.5 μm oxygen barrier layer laminated with linear low-density polyethylene (Metalvuoto Spa, Italy).

2.4 Temperature Variation Studies: Mushrooms stored at 25 °C showed deterioration within four days across all techniques. Visual defects included color changes, textural degradation, and microbial spoilage. Samples stored at 4 °C retained marketable quality for over a week, especially those treated with UIF and MAP.

2.5 Quality Evaluation Parameters: Post-treatment evaluations included:
- **Weight Loss (%):** Mass change before and after thawing.
- **Texture Profile Analysis:** Hardness, chewiness, gumminess, and fracturability using texture analyzer.
- **pH and TSS:** Measured via calibrated pH meter and refractometer.
- **Color Metrics:** Total color difference (ΔE), whiteness index (WI), yellowness index (YI), and browning index (BI) were quantified using a colorimeter. Photographs were taken before and after thawing to aid color evaluation. Each treatment was conducted in five replicates for statistical reliability.

3. Results and Discussion

3.1 EGT as a Natural Preservative: Ergothioneine, synthesized by certain fungi, offers significant antioxidant and cytoprotective activity by scavenging singlet oxygen and chelating transition metals. Compared to conventional antioxidants like ascorbic acid and cysteine, EGT demonstrates greater stability under oxidative stress. Studies have highlighted EGT's efficacy in preserving meat color and reducing melanosis in seafood. However, its application in mushroom preservation is novel. Treatment with 0.12 mmol

L^{-1} EGT successfully delayed browning and maintained post

harvest quality in button mushrooms.

3.2 Ultrasound-Enhanced Freezing: High ultrasound intensities (300–400 W) accelerated freezing and preserved mushroom microstructure. UC300 maintained textural integrity, confirming uniform crystallization. Post-Thaw Weight Loss in Mushrooms subjected to ultrasonication exhibited significantly lower weight loss compared to control samples. Enhanced nucleation and uniform ice crystallization contributed with minimal internal cellular damage.

Textural Integrity explore gumminess and chewiness were markedly higher in UC300 and UP300 samples. The non-invasive nature of ultrasonic waves helps maintain intracellular turgor, reducing post-thaw softening. Color Stability factor showed the lowest ΔE and BI values were observed in UC300-treated mushrooms, indicating minimal enzymatic browning. Enhanced water mobility and inhibited polyphenol oxidase activity likely contributed to improved visual quality.

3.2 MAP Impact on Storage Stability: MAP maintained mushroom quality at 4 °C with minimal oxidative browning and microbial decay. At 25 °C, shelf life was limited to four days despite packaging, suggesting temperature dependency (Singh et al., 2023). The multilayer film prevented oxygen ingress and preserved visual quality.

3.3 Comparative Quality Assessment: UIF treatments reduced weight loss and better retained chewiness and gumminess, particularly UP200. Color retention was optimal in UC300, showing low ΔE and BI values.

3.4 Multimodal Approach Benefits: Integration of UIF with MAP and novel coatings (e.g., chitosan, aloe-vera essential oil) improved shelf life. Electrolyzed water and ozonation enhanced surface decontamination [18].

3.4 Combined Preservation Strategies: Ultrasound-assisted freezing combined with EGT and MAP treatment synergistically extended shelf life beyond 10 days. Such multimodal approaches outperform individual preservation technologies, especially under refrigerated conditions.

3.5 Drying Techniques and Advanced Packaging: Drying methods such as microwave-assisted and vacuum drying significantly reduce moisture content while preserving aroma and color. Osmatic pre-treatments further improve drying efficiency. Table 1 summarizes drying methods and outcomes.

3.6 Innovative Packaging and Coating Technologies: Chitosan-dextran films, nanoparticle coatings, and gelatin layers inhibit enzymatic browning and microbial contamination. Certain coatings extended shelf life to 28 days under refrigerated storage. These materials also help retain mushroom respiration rate and antioxidant activity.

3.7 Comparison with Conventional Techniques: Conventional methods such as drying and canning significantly alter the physicochemical properties of mushrooms. In contrast, advanced techniques such as UIF, ozone treatment, and plasma exposure offer superior preservation with minimal nutrient degradation. Studies such as Zhou et al. (2022) and Esua et al. (2021) confirm the synergistic effects of ultrasonication and cold preservation in mitigating spoilage.

3.8 Future Innovations: Artificial intelligence (AI) systems can monitor gas concentrations and spoilage indicators in real-time, enabling smart packaging applications [19].

Table 1. Summary of Advanced Drying Techniques for Mushrooms

Drying process	Process parameters	Results	References
Alternative microwave and convective process	Optimal Mushroom Thickness = 2.5 mm. MW was applied 20 min	Optimally dried mushroom with superior quality in 72 min of convective drying. While the optimum period for the microwave process was 20 ± 3 min, based on the shortest drying time and improved quality features.	[20]
Combined infrared and vaccum drying	Mushroom thickness = 5 mm	The drying time of the mushroom sample was 110,90 and 60 min for the power consumed	[21]
Combined infrared and vaccum drying	The power of infrared used was 150, 250, 375 W	With an increase in power, the color of the mushroom was degraded	[22]
Fluidized bed drying	Drying temperature 30°C . Air velocity of 3 m/s	High energy efficiency and superior-quality mushroom. The values for water loss and solid gain were 57% and 5.0%, respectively.	[23]
Osmatic pre-treatment before drying	Dipping the slices in 5%-10% salt solution concentration. After that use of sun, solar, and oven-dying techniques were used	Pre-treatment reduced the protein, fat, and fiber content in mushrooms whereas the content of mushrooms was increased	[24]
Ultrasonically assisted atmospheric freeze-drying	Use of ultrasound during freeze-drying	Reduction of time Similar rehydration, low luminosity,high red tones	[25]
Ultrasonically assisted atmospheric freeze-drying	The mushroom slices were dried with (24.6 and 12.3 kW/m³; 21.9 KHz)	Diffusivity was increased by 280% and drying time was reduced by 74%.	[26]
Solar-assisted heat pump drying system	Mushroom dried at 45°C and 55°C and the mass flow rate of the system is 310 kg/h	Mushrooms were dried from 13.24 to 0.07 water/g of dry matter with less energy input. The values of specific moisture extraction rate varied from 0.26 to 0.92 kg/kW h.	[27]
Hot air drying (HAD), vaccum drying (MD), microwave drying (MD), microwave vaccum drying (MVD)	HAD temperature is 60°C . MD power is 539 W and frequency of 2455 MHz.	The sulfur content of the mushrooms was increased because of the drying	[28]
Hot air drying (HAD), vaccum drying (MD), microwave drying (MD), microwave vaccum drying (MVD)	vaccum pressure and temperature is -90 kPa and 60°C and treatment was done for 15 h	Better retention of nutrients and color was seen in MVD	[29]
Hot air drying (HAD), vaccum drying (MD), microwave drying (MD), microwave vaccum drying (MVD)	MVD: Vaccum was maintained at -80 kPa with MW intensity at 15 W/g	Better retention of nutrients and color was seen in MVD	[30]

Oven drying	Temperature -40,50, and 60°C and time -5 h	Edible bolete had the most protein, fiber, and antioxidants of eryngium, shiitake, and oyster mushrooms. Bacteria count did not change after 6 months of hoover storage. ¼th of total phenolics and antioxidant activity remained after 5 h of drying at 60°C.	[31]
Freeze-drying and Cabinet-drying	Freeze drying conditions = -80°C, 5 m Torr pressure for 24 h Mushroom drying = -50°C	After drying, button mushroom physiochemistry changed little or not at all. Consumers liked freeze-drying button mushrooms because it affected their colorless. Freeze-dried samples were than cabinet drying in quality and nutrition. More antioxidant compounds were maintained after freeze-drying than cabinet drying. The best drying method preserves nutritional value and bioactive elements.	[32]

Table 2. Advanced Preservation Techniques with Mushroom Varieties

Variety of mushrooms	Preservation technique	Aspects	Result	References
Button mushroom and Oyster mushroom	Agar and gelatine coatings	Extending shelf life and preventing weight loss.	The shelf life of coated mushrooms was 14 days compared to the normal of 4-5 days. The weight loss in normal was 48% but 30% in coated mushroom.	[33]
Oyster mushroom	Chitosan-dextran packaging film	Delay spoilage	28 days of shelf life at 4°C	[34]
Oyster mushroom	Chitosan gallic acid packaging film	Reducing browning	The respiration rate and polyphenol oxidase activity were the lowest.	[35]
Shiitake mushroom	Storage temperature	Extending shelf life	8 days under refrigeration, 5-7 days at 0-2°C, and 1-3 days at ambient temperature	[36]
Oyster mushroom	Chitosan nanoparticle film	Preserving the quality of mushroom	Preserving antioxidant capacity, reducing microbial load, improving firmness of tissue, and minimising brown spot development	[37]
Oyster mushroom	Treated with aloe vera - basil essential oil	Prevent softening	Lowered respiration rate, polyphenol oxidase activity, and electrolyte leakage	[38]
Oyster mushroom	Treated with O3+NA and low-temperature storage	Prevent softening	The shelf-life of mushrooms at low temperatures by 6-9 days	[39]
White button mushrooms	Modified atmosphere packaging	Prevent browning	Retained mushrooms quality, postponed browning, and increased postharvest life by 16 days	[40]
White button mushrooms	Low-density polyethylene modified atmosphere packaging	Prevent browning	After 15 days of storage very minor browning.	[41]

4. Conclusion

This study demonstrates that ultrasound-assisted immersion freezing is an effective method for enhancing the shelf life of button mushrooms. UIF at 200–300 W improves textural stability, inhibits enzymatic browning, and minimizes moisture loss compared to conventional freezing. Further integration with packaging technologies like chitosan-based films and AI-assisted spoilage prediction could redefine mushroom preservation. Future research should explore combined effects of non-thermal technologies and biopolymer coatings under commercial conditions to validate scalability and consumer acceptance.

Artificial Intelligence Disclaimer

The author(s) hereby declare that no generative artificial intelligence (AI) tools, including but not limited to large language models (e.g., ChatGPT, Copilot) or AI-based image generation software, were used in the writing, editing, data analysis, or figure creation of this manuscript. All content is the original work of the authors.

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