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Review Article

Progress of post-harvest preservation technology of edible mushroom

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Abstract: Edible mushrooms are esteemed worldwide for their significant contributions to food, medicine, and economy. Post-harvest edible mushrooms are vulnerable to mechanical damage, microbial infection, and discoloration due to inadequate preservation techniques. This review aims to systematically examine the current state of postharvest preservation techniques for edible mushrooms. Firstly, this review presents an overview of the physiological changes that occur in edible mushrooms after harvesting, encompassing water loss, weight loss, morphological and color alterations, nutrient and flavor depletion, and microbial susceptibility. Subsequently, this review outlines common postharvest preservation techniques for edible mushrooms, including low-temperature storage, air-conditioned storage, radiation, plasma treatment, and coatings, with brief descriptions of their application cases. Lastly, the future direction of development for postharvest preservation technologies for edible mushrooms is envisioned. This review seeks to serve as a reference for the edible mushroom industry and to stimulate further development and application of postharvest preservation technologies for edible mushrooms.

Keywords: edible mushroom; post-harvest preservation; quality; shelf life

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1 Introduction

Edible mushrooms, renowned for their substantial nutritional and medicinal properties, encompass over 6,000 species in nature, of which more than 2,000 are recognized as suitable for consumption[1,2]. China boasts abundant edible mushroom resources and plays a pivotal role as a major producer and consumer. Notably, 30 species of edible mushrooms, including shiitake, black fungus, and enoki mushrooms, have been commercially cultivated[3]. Edible mushrooms are highly esteemed in gastronomy for their distinct flavors and nutritional profiles, frequently enhancing culinary dishes. Research indicates that edible mushrooms are abundant sources of nutrients such as protein[4], dietary fiber[5], and minerals, as well as various biologically active compound[6-8]. These compounds exhibit the potential to enhance human immunity[9], lower blood pressure and blood sugar levels[10], demonstrate anti-tumor properties[11], and help prevent diabete[12]. Long-term mushroom consumption may also boost metabolis[13], improve physical fitness, and regulate immune function[14], leading to their classification as 'health food' and garnering considerable interest.

Edible mushrooms have a limited shelf life post-harvest, primarily due to their high moisture content and lack of a protective outer layer[15]. The delicate structure of edible mushrooms makes them susceptible to physical damage, microbial contamination, browning, and lignification[16-18]. Nevertheless, despite their limited shelf life of 3–4 days at room temperature and approximately 8–9 days under refrigeration[19], adopting scientifically validated post-harvest preservation techniques is now imperative. These strategies aim to enhance the economic value and marketability of edible mushrooms, while also meeting consumer demand for fresh, safe, and nutritious food options.

Recent advancements in food science and technology have greatly enhanced postharvest preservation techniques for edible mushrooms. These include low-temperature storage, air-conditioned storage, radiation, plasma treatment, and coating, as depicted in Fig. 1. It is important to note that postharvest preservation requirements and responses vary significantly among different species of edible mushrooms, necessitating further thorough investigation and optimization. This study outlines the postharvest physiological changes in edible mushrooms and meticulously evaluates the advantages and disadvantages of various preservation methods, along with their practical suitability. These findings establish a foundation for the development of sustainable preservation strategies for edible mushrooms, thereby fostering their continuous advancement and wider acceptance in postharvest preservation methods.

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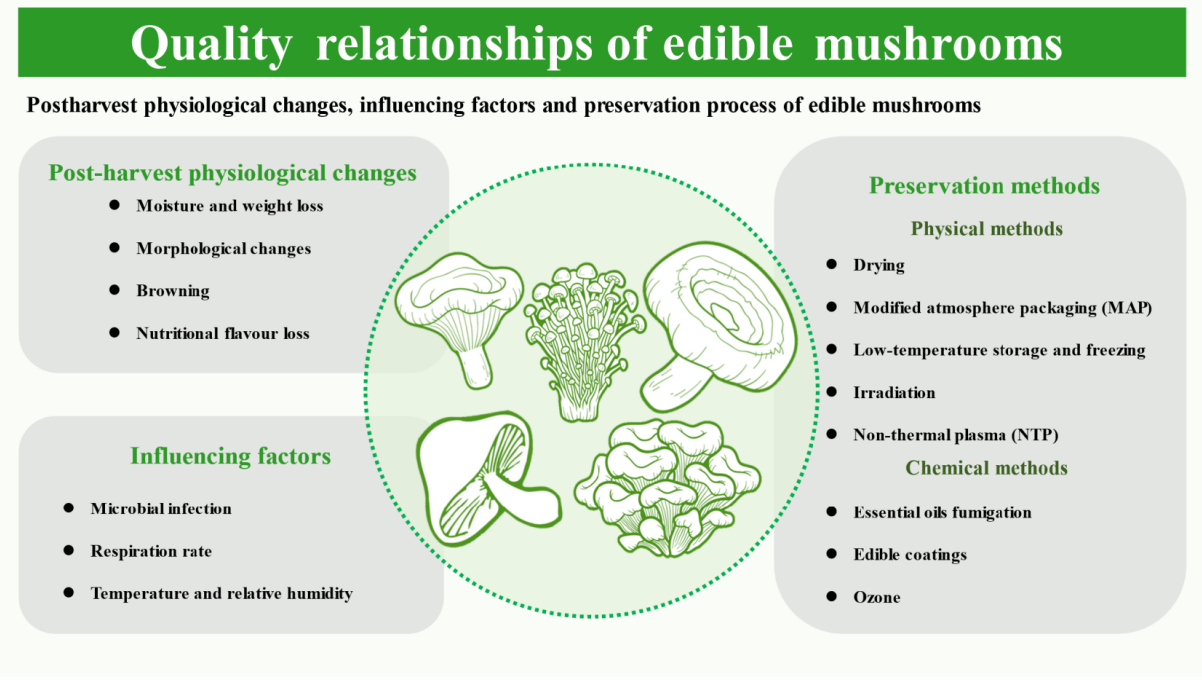


Figure 1 Post-harvest quality deterioration of edible mushrooms and its influencing factors about the storage process.

2 Physiological changes in edible fungi after harvest

Postharvest physiological changes in edible mushrooms markedly undermine their commercial viability and impede the advancement of the edible mushroom industry. These changes lead to a decline in sensory and nutritional qualities, arising from a blend of internal and external factors. Current research on the physiological changes in edible mushrooms primarily concentrates on factors including water loss, weight reduction, postharvest morphological alterations, changes in texture and color, nutritional and flavor degradation, and susceptibility to microbial infections.

2.1 Moisture and weight loss

Moisture is a critical factor in determining the quality of fresh edible mushrooms. Typically, fresh edible mushrooms have a moisture content between 85% and 95%, which decreases during post-harvest storage due to cellular degradation, facilitating internal moisture movement[20]. However, the loss of moisture during storage leads to weight reduction, significantly affecting the overall quality of fresh edible mushrooms[21]. Edible mushroom growth is intricately linked to humidity levels: optimal humidity promotes robust growth, while excessively low or high levels adversely affect both growth rate and quality.

During the initial growth stages, edible mushrooms absorb a substantial amount of water, leading to rapid weight gain. Effective moisture management during this phase is essential for achieving optimal yield and quality. Following harvesting, delayed handling or storage of mushrooms can rapidly lead to water loss, thereby reducing quality. Typically, within a few hours of harvesting, mushrooms experience considerable water loss through evaporation, resulting in immediate weight reduction. Furthermore, unfavorable storage conditions, such as high temperatures or inadequate ventilation, exacerbate the rate of water loss. The temperature and humidity levels in the storage environment profoundly impact the preservation of edible mushroom quality. Improper storage conditions perpetuate water loss and accelerate the decay process, ultimately leading to weight reduction and quality deterioration[22].

Dehydration is commonly used to inhibit microbial growth in fresh edible mushrooms and decrease their moisture content. However, this process can alter the texture of certain mushrooms, thereby affecting consumer perception. Zhong *et al.*[23] examined moisture distribution, migration, and tissue structure changes in irradiated samples using low-field nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). They examined the samples under microscopy, identifying cytoplasm and vesicles as the primary moisture components in the monkey mushroom matrix. Over the storage period, vesicle damage resulted in the transfer of water to the cytoplasm, thereby increasing fixed water mobility and decreasing free water mobility.

2.2 Morphological changes

Edible mushrooms undergo significant changes in appearance during extended storage, including cap opening, stipe elongation, and spore release. These changes impact both the visual appeal of mushroom products and accelerate quality degradation, leading to consumer aversion[24,25]. During the maturation phase, edible mushroom caps gradually unfurl, potentially expanding post-harvest due to internal cell growth and dynamic water circulation. Cap opening alters mushroom appearance and increases surface area, facilitating spore release. Additionally, the expansion of cap stalks in edible fungi may result from morphogens dispersing from concentrated sources via diffusion through concentration gradients[26].

After harvest, the stipe continues to absorb water and nutrients, leading to further expansion. Subsequently, the cap extends outward before flipping upward to release spores. Cap opening facilitates spore dispersion from the internal structure of the edible fungus into the surrounding environment, through wind or other external forces, thereby promoting the potential growth of new edible mushrooms[27]. Additionally, edible mushrooms undergo cell membrane damage via peroxidation of membrane lipids, leading to senescence and softening[28]. This phenomenon may be

attributed to the active expression of carbohydrate-active enzymes, such as laccase, chitinase, and β-glucanase, directly contributing to mushroom softening[29].

2.3 Browning

Browning significantly impacts the shelf-life quality of edible mushrooms. It typically occurs during their growth, storage, or processing, resulting in a color change from the original hue to brown. This occurrence can be attributed to oxidative reactions or enzymatic processes[30-32]. Browning in stored edible mushrooms primarily results from the accumulation of reactive oxygen species (ROS), such as superoxide anion radicals and hydroxyl radicals[33]. ROS accumulation can compromise cell membrane integrity, leading to the release of phenolic compounds from vesicles. These compounds are then exposed to polyphenol oxidases (PPOs) released from plastids, initiating mushroom browning[34]. PPOs are ubiquitous enzymes found in plant, animal, bacterial, and fungal cells. They catalyze the hydroxylation of mono phenolic compounds to produce catechols and oxidize catechols to form dimers, thereby inducing melanin production[35]. Moreover, when polyphenols act as hydrogen donors, peroxidase (POD) can catalyze enzymatic browning. The evaluation of mushroom browning commonly employs the luminance difference (L^*) value to measure color changes; a higher L^* value indicates reduced browning and superior quality[36]. Therefore, precautions must be implemented to prevent browning during cultivation, harvesting, storage, and processing.

2.4 Loss of nutritional flavour

Edible mushrooms offer substantial nutritional benefits, containing high-quality proteins, dietary fiber, multivitamins, minerals, and antioxidant phenolic compounds. They also contain small amounts of unsaturated fatty acids, making them a nutritious choice[37]. Sugars and soluble proteins in mushrooms play a crucial role in sustaining postharvest metabolic activity. Reduced levels of protein or sugar indicate spoilage [38]. Extended storage leads to increased production of ROS in mushrooms, causing a decline in reducing sugars. Mushrooms consistently metabolize their nutrients during storage to maintain metabolic functions.

For instance, the soluble protein content of enoki mushrooms decreased by 28.7% (from 5.501 mg/g) after storage in ordinary polyethylene (PE) packaging at 4 °C and 90%–95% relative humidity for 14 days. This reduction signifies a substantial nutrient loss during postharvest storage[24]. Furthermore, the fat content of edible mushrooms progressively declines with extended storage due to the hydrolysis of stored fats by lipase, resulting in the formation of fatty acids and glycerol, which are subsequently oxidized in other tissues[36]. Although research on flavor has concentrated on compositional changes, there is a notable deficiency of studies that elucidate the mechanisms underlying nutritional flavor loss in postharvest edible mushrooms[39]. Therefore, further investigation is essential to comprehend the metabolic mechanisms that drive nutritional flavor loss in postharvest edible mushrooms.

3 Factors affecting postharvest physiological changes in edible mushrooms

3.1 Mechanical damage

Mechanical damage to edible mushrooms after harvesting can lead to quality deterioration or accelerated spoilage. To optimize the quality of edible mushrooms, it is crucial to minimize mechanical damage during harvesting, particularly by refraining from using sharp tools or rough handling. Furthermore, immediate storage or handling of edible mushrooms after harvesting is essential to minimize exposure to the external environment, thereby prolonging freshness and preserving taste.

3.2 Microbiological infections

Edible mushrooms are vulnerable to microbial contamination post-harvest. Improper handling and storage of mushrooms after picking can lead to contamination by various microorganisms present in the air, soil, or environment. Such microorganisms can cause spoilage or deterioration of mushrooms, posing potential health risks to consumers. To mitigate microbial contamination of edible mushrooms, prompt handling and packaging immediately after harvesting are essential. Freshly harvested edible mushrooms facilitate microbial colonization due to their high water content, lack of cuticle protection, and the abundance of microorganisms on their surfaces[40-42]. Microorganisms initiate spoilage of fresh edibles by degrading the cellular matrix and diminishing the central vesicle, resulting in partial cellular collapse. This process hastens spoilage and reduces shelf life[43]. Additionally, the generation of unpleasant odors and changes in color in edible mushrooms are closely linked to microbial spoilage and anaerobic respiration[44]. For example, almond abalone mushrooms are often affected by the toxin produced by *Pseudomonas torulosa*, resulting in the development of brown spots and yellow to dark brown lesions on the fungal cap[45, 46]. Moreover, other bacteria, such as *Pseudomonas aeruginosa*, *Pseudomonas brucei*, and *Ewingia americana*, have been documented to induce decay in edible mushrooms. Therefore, improving the efficacy of respiratory and water-permeable barriers can mitigate lipid peroxidation and microbial proliferation. This, in turn, can manage microbial contamination, extend the shelf life of edible mushrooms, and preserve their physicochemical attributes[24, 47, 48].

3.3 Respiratory action

Edible mushrooms continue to respire post-harvest because they require energy to maintain metabolic processes. During respiration, mushrooms utilize stored carbohydrates and produce CO_2.

The respiration rate and energy status significantly affect the postharvest senescence of edible mushrooms. At a storage temperature of 25 °C, the respiratory intensity of freshly cut edible mushrooms notably increased over time, reaching 1,382 CO_2 mg/(kg·h) at 12 h and 3,526 CO_2 mg/(kg·h) at 72 h. Simultaneously, over 50% of the surface of the edible mushrooms underwent browning, rendering them essentially devoid of their nutritional value[21]. Furthermore, some edible mushrooms possess a thin epidermal structure that cannot effectively prevent rapid dehydration, thereby accelerating their respiration rate compared to other vegetables. This increased respiration results in elevated water loss, inevitably reducing the nutritional value and flavor of the mushrooms. To extend the shelf life of edible mushrooms, storing them in a cool and appropriately humid environment reduces respiratory activity, thereby prolonging their freshness and shelf life.

3.4 Temperature and relative humidity

Temperature and relative humidity are critical factors that influence microbial growth, thereby affecting the presence and

composition of fresh flavor components in edible mushrooms. Temperature directly influences the respiration of edible mushrooms, enzyme activity, and the growth rate of microorganisms. Typically, the optimal storage temperature for most edible mushrooms after harvesting ranges from 0 °C to 4 °C. This temperature range effectively inhibits the respiration of edible mushrooms, thereby slowing down the loss of freshness and quality deterioration. Additionally, suitable relative humidity helps maintain the moisture balance and texture of edible mushrooms. The optimal relative humidity range for most edible mushrooms during post-harvest storage is between 85% and 95%. Within this range, edible mushrooms experience slower moisture loss, preserving their appearance and texture. These factors influence a variety of nutrients such as polysaccharides, aldehydes, and phenolic compounds, as well as quality attributes and microbial colonization in specific edible mushrooms. During storage, temperature fluctuations activate various oxidative enzymes, enhance physiological processes, and regulate respiration and transpiration, thereby prolonging the post-storage ripening period. Consequently, extending the shelf life of edible mushrooms often requires reducing storage temperature and increasing environmental humidity.

4 Post-harvest preservation techniques for edible mushrooms

4.1 Drying

Drying is a widely utilized method for preserving food products by reducing their moisture content, which prevents microbial growth and ensures physicochemical stability. This technique has been employed for many years to extend the shelf life of food items[49,50]. Various drying techniques are employed for edible mushrooms, including solar drying, hot air drying (HAD), vacuum drying (VD), freeze-drying (FD), and microwave drying (MD). Sun drying involves spreading cleaned edible mushrooms in a sunny location to allow for natural drying. Although this method is straightforward to implement, it is constrained by weather conditions. HAD is commonly used for drying mushrooms, such as matsutake[51], apricot mushrooms[52], and delicata porcini[53]. Yang *et al.*[54] investigated the flavor of shiitake mushrooms processed using HAD and FD. The total free amino acid content was found to be higher in HAD samples processed at 60 °C compared to other drying methods. The levels of glutamic acid (Glu), citric acid, and succinic acid increased during the drying process as the temperature was elevated from 50 °C to 70 °C. This suggests that new flavor compounds were formed during the HAD process. The results indicated that different drying treatments led to variations in the physicochemical properties and nutrient composition of shiitake mushrooms. MD can alter the microstructure of the product, thereby affecting drying characteristics, water content, and migration[55]. Su *et al.*[56] found that optimal pretreatment with MD significantly enhanced the quality indices of apricot mushrooms, including color, water content, and polysaccharide content. This improvement can be attributed to increased resistance to free water migration and a reduced pore structure. Different drying methods serve various purposes, and the selection of the most appropriate method depends on the characteristics of the end product, the complexity of the process, drying time, energy consumption, and cost[50].

4.2 Modified atmosphere packaging (MAP)

Gas-conditioned packaging is a technology utilized to extend the shelf life of edible mushrooms by manipulating the gaseous environment. This method slows down the metabolism and microbial proliferation of edible mushrooms by regulating gas composition, typically focusing on O_2 and CO_2 concentrations. MAP can be categorized as active or passive. Active MAP achieves equilibrium more rapidly by directly introducing desired gas components into the packaging, while passive MAP relies on the natural interactions between the product's respiration and gas permeation through the package[57]. MAP serves to manage nitrogen, O_2, carbon dioxide, and ethylene ratios in gases, while also regulating humidity, temperature (maintained above freezing thresholds), and barometric pressure within gas-conditioned chambers. These measures suppress cellular respiration, reduce metabolic rates, and maintain mushrooms in a quasi-dormant state, facilitating long-term preservation[58].

In the preservation of edible mushrooms under controlled atmospheres, selecting appropriate O_2 and CO_2 concentrations emerges as a crucial factor determining the effectiveness of MAP. Decreasing the O_2 concentration helps mitigate quality degradation by preventing phenomena such as oxidation and browning. Conversely, increasing the CO_2 concentration inhibits bacterial and fungal proliferation, thereby extending the shelf life of edible mushrooms. This method typically involves packaging mushrooms in specially designed bags, infusing them with precise gas ratios, and subsequently sealing the containers to maintain an optimal gas environment. Such a technique effectively extends freshness and preserves the quality of edible mushrooms. Conventionally, storing edible mushrooms in environments with high CO_2 and low O_2 levels impedes physiological processes such as mouth opening and stalk elongation, while also hindering the germination and proliferation of certain bacterial and fungal spores. Consequently, this leads to diminished synthesis of post-ripening reactions and decreased enzyme activity, resulting in reduced production of volatiles like ethylene, which in turn slows the deterioration of edible mushroom quality[59]. For instance, shiitake mushrooms exhibit greater respiratory intensity and CO_2 sensitivity compared to other mushroom varieties. CO_2 concentrations exceeding 9% can lead to the deterioration of organoleptic characteristics and reduced shelf life[60]. Wan-Mohtar *et al.*[61] showed that high CO_2 packaging (HCP) containing 20% CO_2 and 15% O_2 effectively preserves apricot mushroom quality. Park *et al.*[62] studied the effects of argon and nitrogen treatments on the quality of white mushrooms. Samples underwent treatment with five different gases at 4 °C. Argon-treated samples showed lower CO_2 production levels compared to those treated with both argon and nitrogen. White mushrooms exposed to 90% argon (90AR) experienced less weight loss than other samples by the end of the storage period. The researchers concluded that conditions with 90AR more effectively prevented the deterioration of white mushroom quality (Fig. 2A). However, research on the flavor and nutritional changes caused by metabolites during gas-conditioned preservation of edible mushrooms, which are crucial for consumer acceptance, remains insufficient. Therefore, comprehensive research on the transcriptome, proteome, metabolome, and multi-omics of gas-conditioned edible mushrooms, including varieties such as shiitake mushrooms, is needed to provide a stronger theoretical basis for the mechanism of gas-conditioned preservation.

4.3 Low-temperature storage and freezing

Post-harvest cold storage is a commonly employed method to preserve the freshness and quality of edible mushrooms. Edible

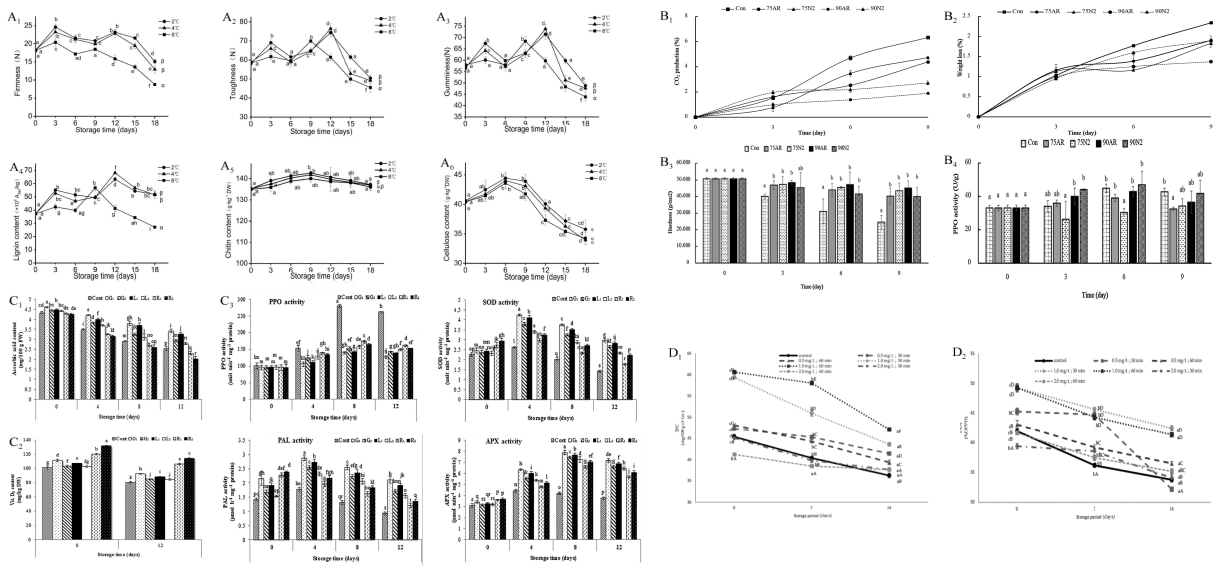


Figure 2 (A) Edible mushrooms air-conditioned packaging, hardness, toughness, gelatinousness, lignin, chitin and cellulose content of mushroom stalk tissue (A_1, A_2, A_3, A_4, A_5 and A_6)[62]. (B) Edible mushrooms cryogenic storage, changes in carbon dioxide production by white mushrooms during 9 days of storage at 4 °C under five different gas compositions (B_1), weight loss of white mushrooms during 9 days of storage at 4 °C in the presence of 5 different gas compositions (n = 3) (B_2), Changes in mushroom hardness during storage of white mushrooms at 4 °C for 9 days in the presence of five different gas compositions (n = 5) (B_3), changes in PPO activity of white mushrooms during 9 days of storage at 4 °C in the presence of five different gas components (n = 3) (B_4)[67]. (C) Edible mushrooms essential oil fumigation for preservation, effect of gamma irradiation and essential oil treatment on ascorbic acid content (mg/100 g FW) of mushrooms during storage (C_1), Effect of gamma-rays and essential oil treatments on vitamin D_2 content (mg/kg DW) of fresh mushrooms during storage time (C_2), effect of gamma irradiation and essential oil treatments on enzymes activity (PPO, SOD, PAL and APX) of mushroom during storage time (C_3)[114]. (D) Ozone preservation, effect of ozone dose, time of ozonization, and storage time on total phenolic content of *A. bisporus* measured on 0, 7, and 14 days of storage at 2 °C (D_1), effect of ozone dose, time of ozonization, and storage time on total antioxidant activity of *A. bisporus* measured on 0, 7, and 14 days of storage at 2 °C (D_2)[117].

mushrooms should be promptly stored post-harvest in a refrigerated environment, ideally ranging from 0 °C to 4 °C, to reduce metabolic rates and postpone spoilage. The application of low temperatures inhibits enzyme activity, decreases physiological metabolism rates, minimizes respiration intensity, and impedes the growth and reproduction of microorganisms. Freezing is an effective technique to prevent microbial growth and maintain the texture and nutritional content of mushrooms. Extended freezing periods, whether rapid or gradual, are recommended for preserving edible mushrooms[63]. Research by Bernaś *et al.*[64] revealed that freezing significantly reduces the levels of various vitamins in *Agaricus bisporus* mushrooms, such as B1, B2, B6, ascorbic acid, α-tocopherol, β-carotene, and lycopene while having minimal impact on the levels of total carbohydrates, proteins, fats, and ash. The storage durations of 0, 6, and 12 months at −20 or −30 °C had minimal impact on the changes in these nutrients. Long-term freezing, whether conducted rapidly or slowly, is a suitable approach for the extended preservation of edible mushrooms. Jiang *et al.*[65] evaluated the substrate metabolite content to clarify the variations in the nutrient composition of apricot mushrooms under short-term, slow-freezing conditions. Additionally, Kim *et al.*[66] showed that the concentrations of beneficial compounds in shiitake mushrooms were affected by storage temperature, suggesting that control over storage parameters could facilitate the manipulation of specific bioactive compounds. Li *et al.*[67] noted the toughening of apricot abalone mushrooms in all experimental groups after three days of storage at different cryogenic temperatures, highlighting a significant link between toughening and lignification. Toughening could directly or indirectly affect the postharvest quality of almond abalone mushrooms (Fig. 2B). Consequently, the nutritional quality and bioactivity of edible mushrooms are influenced by multiple factors during cryopreservation, such as initial pre-treatment processes (e.g. blanching), freezing techniques, frozen storage parameters (e.g. temperature and humidity), and storage duration.

4.4 Irradiation

Irradiation is used in post-harvest technologies such as food irradiation to enhance the value of commodities and extend their storage duration, with the technology widely commercialized[68,69]. Low-dose irradiation treatments ensure the hygienic safety of fresh produce and significantly improve post-harvest storage by affecting various physiological processes, such as enzyme activity and respiration[70,71]. This preservation method helps to maintain the flavor, color, nutritional content, and texture of edible mushrooms without leaving behind any residual toxicity. However, the effect of irradiation on the nutrient composition of edible mushrooms may vary depending on factors such as the type of mushroom, the secondary preservation method used, the dose of irradiation, and the type of irradiation source. For example, Hou *et al.*[72] discovered that γ-ray irradiation at 0.8 kGy slowed down the weight loss and softening process of straw mushrooms. Dong *et al.*[73] found that the hardness of mushrooms in the treated group significantly exceeded that of other groups after E-beam irradiation with a low dose of 1 kGy. In addition, Wang *et al.*[74] observed that the hardness of flat mushrooms treated with UV-C irradiation during storage increased significantly when the phenylalanine deaminase (PAL) content was relatively high, except on day 0. These results suggest that optimal radiation doses can reduce the activity of relevant enzymes and promote the accumulation of phenolic compounds in irradiated edible mushroom varieties, in line with the specific irradiation conditions outlined in Table 1. The recommended dose for extending the shelf life of fresh edibles varies by country, typically ranging from 1 kGy to 3 kGy. For decontaminating dried edibles used as flavorings, including those in food additives, the

Table 1 Irradiated edible fungal species and irradiation conditions

Radiation Source	Species	Origin	Sample	Doses	Reference
γ radiation	*Lentinula edodes*	China	Fresh	1.0 and 2.0 kGy	[76]
γ radiation	*L. edodes*	China	Fresh	1.0 kGy	[70]
γ radiation	*A. bisporus*	Iran	Fresh	1 and 2 kGy	[77]
γ radiation	*Volvariella volvacea*	China	Fresh	0.2, 0.4, 0.6, 0.8 and 1.0 kGy	[72]
γ and E-beam radiation	*A. bisporus*	Bragança	Fresh	1.0, 2.0 and 5.0 kGy	[69]
γ and E-beam radiation	*A. bisporus*	Portugal	Dried (oven)	1.0, 2.0, 5.0 and 10.0 kGy	[78]
Electron-beam-generated X-ray irradiation	*Hericium erinaceus*	China	Fresh	0, 1.0, 1.5 and 2.0 kGy	[79]
Electron-beam-generated X-ray irradiation	*A. bisporus*	China	Fresh	0, 0.5, 1.0, 1.5 and 2.0 kGy	[73]
UV-C	*Pleurotus eryngii*	China	Fresh	2, 4 and 6 kJ/m^2	[80]
UV-C	*A. bisporus*	China	Fresh	1.0 kJ/m^2	[81]
UV-C	*Pleurotus ostreatus*	China	Fresh	4.0 kJ/m^2	[82]
UV-B	*L. edodes*	India	Air-dried	0.5, 1, 1.5, 2 and 2.5 h	[83]

recommended dose is higher, typically between 10 and 50 kGy[75]. In general, using irradiation as a food processing method is crucial for ensuring food safety and extending shelf life. However, more research and evaluation of the effects of different foods and specific irradiation doses are essential to avoid any negative impacts on the nutritional quality of food products.

4.5 Non-thermal plasma (NTP)

NTP is an innovative technique for microbial inactivation in the edible mushroom industry. It preserves mushroom freshness by exposing them to ionizing radiation like charged particles, electric fields, ultraviolet (UV) photons, or reactive substances[57]. Typically, NTP employs high-temperature plasma to eradicate microorganisms, eliminate contaminants, and prolong the shelf-life of food products. Within the edible mushroom sector, plasma treatment serves as a method of sterilization and preservation, aiming to prolong shelf life, minimize wastage, and enhance quality. This treatment is widely recognized as an effective food safety measure, preserving the freshness and nutritional value of edible mushrooms. Advances in NTP technologies, including plasma-activated water (PAW)[42], dielectric barrier discharge[84], negative air ions[85], and surface dielectric barrier discharge plasma[86], have been observed to influence mitochondrial function, decrease membrane potential, and enhance energy utilization in edible mushrooms. Consequently, these technologies slow the aging process during storage. For example, Minh *et al.*[87] examined the effect of corona discharge plasma power (120, 150, 180, and 210 W) on enoki mushrooms stored at room temperature for 10 days. Their findings showed that corona discharge plasma pretreatment efficiently maintained the physicochemical properties of enoki mushrooms and suppressed microbial growth during fermentation. However, the application of plasma entails relatively high costs, requiring additional efforts to attain industrial feasibility.

4.6 Edible coatings

Recent advancements in coating products have offered new possibilities for extending the shelf life of edible mushrooms. Various types of edible coatings have been thoroughly researched and utilized for post-harvest storage[88]. Edible coating technologies reduce flavor loss and minimize moisture loss by limiting O_2 absorption from the surrounding environment[89]. Currently, preservation techniques involving coatings include surface coating methods and various coatings intended to protect food from environmental elements such as light, O_2, and microorganisms. Chitosan (CS), a naturally occurring biodegradable polymer, has been used as an edible coating to reduce quality deterioration during the storage of edible mushrooms[90]. Fu *et al.*[91] demonstrated the successful preparation of cinnamaldehyde tannic acid nanoemulsions (CIN-TA-NEs) using tannic acid (TA) as an emulsifier. TA is a natural, environmentally friendly, edible extract known for its exceptional antioxidant and UV-resistant properties. CS was doped with CIN-TA-NEs, and subsequently, CIN-TA-NEs/CS (CSCT) films were successfully synthesized to extend the shelf life of *A. bisporus* mushrooms. In their study, Liu *et al.*[92] formulated a solution of protocatechuic acid grafted onto chitosan (PA-g-CS), demonstrating antioxidant properties. This solution was then utilized in the post-harvest preservation of apricot mushrooms, with results suggesting the potential of PA-g-CS III as a preservative for almond and abalone mushrooms. Besides CS, the incorporation of various natural polymeric materials and antimicrobial agents notably enhanced the coating efficacy, thereby delaying the postharvest senescence of edible mushrooms. These materials encompass konjac glucan, carrageenan, antimicrobial peptide microspheres, streptococcal lactobiontin, thymol, polysaccharides, among others. Despite the prevalent use of edible coating films for preserving edible mushrooms, there exists a necessity to broaden the application of edible coating solutions derived from natural plant sources. Table 2 provides an inventory of innovative coating materials.

4.7 Essential oils fumigation

Essential oils (EOs) are aromatic compounds derived from various plant parts, including flowers, buds, leaves, roots, seeds, twigs, bark, herbs, wood, fruits, and other botanical components, each possessing distinct plant-specific aromas[104-106]. EOs exhibit antioxidant, antifungal, antimicrobial, and anticancer properties, making them valuable as natural food preservatives and meeting consumer demands for post-harvest treatment of perishable goods[107-109]. Their high volatility, ability to be used at low concentrations, and biodegradability make EOs suitable for fumigation applications[110]. EOs influence the biochemical processes in edible mushrooms by either inhibiting or enhancing the concentration of enzymes and secondary metabolites crucial for preservation[111]. Commonly used EOs for fumigating edible mushrooms include clove, cinnamaldehyde (CIN), and thyme. Fumigation treatments prolong the shelf life of edible mushrooms, maintain their sensory characteristics, and enhance their antioxidant properties. Among various treatments, fumigation

Table 2 New coating and film materials

Species	Materials	Process parameters	Results	Reference
Flammulina velutipes	Soy protein isolate, nano-silica	4 °C, 10 days	The application of SPI/nano-SiO_2 films resulted in a significant reduction in weight loss and browning ($P < 0.05$), along with mitigation of the loss in total soluble solids and soluble protein content	[59]
Pholiota nameko	Sodium alginate, 1% (*V*/*V*) thyme essential oil, 0.3 g/L *L*-cysteine, and 0.4 g/L nisin	4 °C	The content of soluble sugars, ascorbic acid, and soluble proteins was effectively maintained	[93]
A. bisporus	Protocatechuic acid-$CaCl_2$-NaCl-pullulan, the protocatechuic acid (118 mg/L)-$CaCl_2$ (0.83%)-NaCl (0.55%)-pullulan (0.30%)	(4 ± 1) °C, 12 days	It increased soluble protein content, decreased nucleic acid and free amino acid content, delayed the increase of 3-octanol and benzaldehyde content, and prevented the loss of flavor such as 3-octane, while inhibiting the increase of alkane content in enoki mushrooms	[94]
A. bisporus	Oregano essential oil (OEO) and mesoporous nano-silica (MNS)	(4 ± 1) °C, 12 days	Effective in reducing weight loss, respiration rate, relative leakage rate, PPO and POD activity as well as malondialdehyde and microbial content	[95]
A. bisporus	Gallic acid grafted CS	4 °C	Compared to mushrooms packaged with CS film and commercially utilized PE film, mushrooms enclosed in GA-g-CS film exhibited significantly reduced respiration rate, browning degree, malondialdehyde content, electrolyte leakage rate, superoxide anion production rate, and hydrogen peroxide content	[96]
A. bisporus	Cinnamaldehyde-tannic acid nano-emulsion/CS	4 °C, 4 days	Improved film densification, reduced permeability to water vapor and oxygen, and improved water resistance of the composite film	[91]
L. edodes	γ-Polyglutamic acid hydrogel	4 °C, 30 days	Coating treatments with γ-PGA hydrogel improved the storage life and quality of shiitake mushrooms. Meanwhile, it also obviously suppressed the polyphenol oxidase (PPO) activity, consequently inhibited the browning of shiitake mushrooms during storage	[97]
L. edodes	Oudemansiella Eradicate polysaccharide (ORWP)	4 °C, 18 days	Enhances flavor and nutrient retention, reduces production, increases antioxidant enzyme activity, improves tissue structure, and delays softening	[98]
A. bisporus	CS/zein film lemon essential oil	4 °C, 12 days	Reduces PPO and POD activity, inhibits microbial growth, and reduces browning	[99]
A. bisporus	Nano coating nisin 1%	4 °C, 12 days	Delays aging, reduces weight loss, maintains color and hardness, significantly reduces PPO activity, and reduces yeast	[100]
A. bisporus	Gellan gum-based Coating cellulose nanocrystals (CNCs)	4 °C	Reduces respiration intensity and browning	[101]
A. bisporus	CS/zein films-tocopherol	4 °C, 12 days	Decreases respiratory intensity, weight loss, relative leakage rate, browning, PPO, POD activity, and malondialdehyde content Increases hardness, CAT, SOD activity, and total phenolic content	[102]
A. bisporus	Agar, gum, egg white protein, sodium alginate, lecithin coating	4 °C, 15 days, 90%–95% relative humidity	Sodium alginate and gum were more effective in preventing weight loss, coloration, and browning Agar and lecithin coatings were more effective in inhibiting respiration rate and ethylene production	[103]

with CIN essential oil has proven to be the most effective[112]. Shao *et al.*[113] pioneered the development of bioactive paper to preserve edible mushrooms by incorporating microcapsules of cinnamon essential oil (CEO) into the paper matrix. Their findings demonstrated the successful integration and adherence of CEO microcapsules to paper fibers via starch, facilitating the sustained release of CEO onto the paper surface. This innovative approach presents a promising packaging solution to extend the shelf-life of edible mushrooms. Aly *et al.*[114] conducted a comprehensive investigation on the impact of γ-irradiation (at doses of 1.5 and 2.0 kGy) and fumigation with EOs on the nutrient composition of mushrooms. Their study revealed that the post-harvest application of EOs, particularly geranium (60 μL/L) and lemongrass (40 μL/L), exhibited superior efficacy in mitigating the browning and senescence of frozen mushrooms compared to gamma irradiation. The evaporation of EOs not only mitigated cell membrane damage and bolstered antioxidant activity but also preserved optimal levels of total phenols, total flavonoids, soluble proteins, and vitamins C and D compared to the control group. Furthermore, the antioxidants activated by EOs effectively suppressed the enzymatic activities of superoxide dismutase (SOD), phenylalanine ammonialyase (PAL), ascorbate peroxidase (APX), and PPO throughout the storage period, thereby retarding the aging and browning processes in mushrooms. Consequently, these natural substances hold promise for extending the post-harvest shelf-life of *A. bisporus* mushrooms while preserving their quality attributes (Fig. 2C).

When using EOs for food preservation, it is crucial to ensure sufficient concentration and appropriate application methods to avoid any adverse effects on food quality or flavor alteration. Additionally, sufficient ventilation is necessary during food sealing or fumigation to prevent excessive absorption of essential oil vapor, which could lead to adverse reactions or compromise food quality.

4.8 Ozone

During mushroom production, contamination with various

microorganisms can occur, increasing the microbial load during storage and hastening post-harvest spoilage. Ozone, or triatomic O_2, demonstrates potent antimicrobial properties due to its strong oxidizing effects. Used in fumigation without producing harmful by-products or residues, ozone effectively controls bacteria, yeasts, and spores. Regulatory agencies have approved ozone fumigation as safe, ensuring the preservation of post-harvest edible mushroom quality. In a study by Liu *et al.*[115], ozone's impact on shiitake mushrooms' physicochemical properties and enzymatic activities was examined using intermittent ozone treatment (IOT), revealing that an optimal ozone concentration of 3.21 mg/m³ significantly delayed browning. Similarly, Wang *et al.*[116] maintained the freshness of *A. bisporus* through ozone fumigation combined with nano-film packaging. Zalewska *et al.*[117] utilized ozone treatment on *A. bisporus* mushrooms for durations of 30–60 min, followed by a 14-day storage period at 2 °C. Their findings suggested that ozone accelerated the external browning process of *A. bisporus* mushrooms while simultaneously slowing the internal browning rate. The study suggests that ozonation can be an additional technology for preserving the quality and physical attributes of fresh *A. bisporus* mushrooms with minimal alterations. The integration of ozone in food production facilitated the establishment of its safety and environmental friendliness (Fig. 2D). However, improper use of ozone may lead to nutrient degradation, surface discoloration, and flavor deterioration in edible mushrooms, due to increased phenolic compounds and moisture content. Thus, further research is necessary to assess the impact of ozone treatment on the postharvest preservation of edible mushrooms, considering their nutritional, organoleptic, and bioactive properties.

4.9 Multi-technology integrated applications

In addition to the aforementioned single freshness application, several researchers have employed a variety of technologies for the preservation of edible mushrooms. For instance, Fu *et al.*[91] combined CS coatings with nanoemulsions for the preservation of shiitake mushrooms, successfully preparing CSCT films. These films significantly enhanced the utilization rate of CIN and imparted a range of functional properties. It has been demonstrated that the CSCT composite film effectively prolonged the freshness preservation period of shiitake mushrooms by more than four days compared to PE film. This research developed a multifunctional composite film with promising applications for extending the shelf-life of mushrooms. Additionally, Lyn *et al.*[118] integrated MAP with double-layer active packaging to enhance the shelf-life of mushrooms, achieving superior overall acceptability compared to MAP alone. Chang *et al.*[119] utilized collagen combined with plasma modification to effectively mitigate the deterioration of edible mushroom quality, thereby extending their shelf-life. The integration of multiple preservation technologies significantly enhances the ability to maintain the freshness of edible mushrooms, presenting substantial potential for future applications.

5 Conclusions and prospects

Significant advancements have been made in investigating post-harvest physiological alterations and preservation methodologies for edible mushrooms. Combining these alterations and methodologies can efficiently extend the shelf life of edible mushrooms, enhancing their market competitiveness. Previous studies show that appropriate treatment methods and packaging techniques can slow down the respiration rate of edible mushrooms, thereby delaying the aging process and extending their freshness. Additionally, regulating environmental factors such as storage temperature and humidity is crucial in preservation technology. Freezing is considered one of the most effective methods for preserving the nutritional value of mushrooms during storage; however, frozen edibles may lose nutrients with prolonged storage. The effects of irradiation on edible mushrooms vary considerably, influenced by factors such as mushroom strain, auxiliary preservation methods, irradiation doses, and types of radiation sources. The flavor and nutritional changes induced by metabolites in edible mushrooms under MAP remain underexplored. Deriving the optimal preservation method for edible mushrooms from existing research findings proves challenging due to the varying suitability of preservation methods for different mushroom types.

However, several challenges remain in practical applications. For example, it is crucial to develop technologies tailored for the post-harvest preservation of various edible mushroom species. Moreover, enhancing the environmental sustainability and cost-effectiveness of these methods is essential. Future research should focus on developing customized preservation technologies that meet the specific needs of different edible mushroom species to improve preservation efficacy. Secondly, integrating ecological principles into environmental conservation and exploring the use of biocontrol technology and natural preservatives in mushroom preservation can mitigate environmental chemical pollution. Additionally, fostering collaboration with enterprises in the edible mushroom industry is crucial to enhance the industrial implementation of preservation technology and promote sustainable development in the sector. Research on post-harvest physiological changes and preservation technologies in edible mushrooms will further the development of the industry and contribute significantly to enhancing the quality and market competitiveness of mushroom products. Continued exploration and concerted efforts are expected to bring new developmental opportunities and broader prospects for the edible mushroom industry through advances in postharvest preservation technology.

In conclusion, research on the post-harvest physiological changes and preservation technology of edible mushrooms has significantly contributed to the development of the industry. Future studies will focus on enhancing preservation effectiveness, reducing costs, ensuring environmental sustainability, and fostering industrial application. Amidst the rapid expansion of the global edible mushroom industry, ongoing research on the post-harvest physiological changes and preservation technology of edible mushrooms is expected to lead to novel breakthroughs and foster the sustainable development of the sector.

Conflicts of interest

The authors declare that there are no conflicts of interest in this work.

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