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Review

Recent advances in quality preservation of postharvest mushrooms (*Agaricus bisporus*): A review

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ABSTRACT

Background: *Agaricus bisporus* is the mushroom with the highest global production yield. However, due to their natural unprotected structure, shelf-life of this kind of mushroom is quite short. During the postharvest period, mushroom experiences continuous quality degradation, presenting discolouration, moisture loss, texture changes, microbial count increasing, and nutrient and flavour loss. In order to maintain the postharvest quality and to extend the shelf-life of mushroom, postharvest preservation techniques including physical, chemical and thermal processes are essential.

Scope and approach: This review summarises quality degradation processes of mushrooms including moisture loss, discolouration, texture changes, microbial count increasing, and nutrients and flavour loss, analyses their influential factors including temperature, relative humidity, water activity, and respiration rate, and presents the preservation methods for mushrooms including drying, cooling, packaging, irradiation, washing, and coating.

Key findings and conclusions: The quality degradation process of mushrooms is complex, which is affected by both the inner factors related to mushroom itself and the outer factors related to storage conditions. For better preserving their postharvest quality, hybrid methods such as thermal techniques combined with physical or chemical techniques and novel non-thermal technologies including plasma, ultrasound and high pressure treatments are highly recommended.

1. Introduction

Agaricus bisporus mushroom is popular in the global food market, accounting for 30% of total mushroom production in the world (Royse, 2014). Immature *Agaricus bisporus* has two colours: white and brown. The white one is called common mushroom or button mushroom and the brown one is called chestnut mushroom or brown cap mushroom. Mature *Agaricus bisporus* is called Portobello mushroom. The structure of *Agaricus bisporus* mushroom is shown in Fig. 1. Each mushroom has an umbrella-shaped cap and a cylindrical stipe (Fig. 1 (a)). The caps of young mushrooms are well closed, as shown in Fig. 1 (b) and (c). With the increase of maturity, the caps open gradually. When mushrooms are fully mature, the caps open completely and the spores are released from the gills.

Agaricus bisporus is vulnerable to physical and microbial damages as there is no such a protective cuticle layer on the skin. It was reported that the shelf-life of *Agaricus bisporus* mushrooms was 1–3 days when stored at ambient temperature (20–25 °C), 5–7 days when stored at 0–2 °C, or about 8 days when stored under refrigerated conditions (Diamantopoulou & Philippoussis, 2015; Jiang, 2013; Xu, Tian, Ma, Liu, & Zhang, 2016). The short shelf-life of mushrooms is a disadvantage that limits its economic value. During the postharvest stage, mushrooms experience a series of quality degradation, for example, moisture loss, discolouration, texture changes, off flavour and nutrition loss (Ding et al., 2016). Fresh mushrooms have a high moisture content of 85%–95% (Kumar, Singh, & Singh, 2013). Such a high moisture level is ideal for microbial growth, therefore, mushrooms should be stored at low temperatures to minimize microorganisms contamination. During the postharvest period, the moisture content of mushrooms decreases gradually, resulting in continuous weight loss. The colour of postharvest mushrooms shows a browning trend due to water loss and enzymes activities, which affects consumers' purchasing behaviour.

Several factors have an impact on mushrooms' quality during postharvest. These factors can be divided into two categories: the internal factors related to mushroom itself (i.e., water activity, respiration rate, and microbial activity) and the external factors related to storage conditions (storage temperature, relative humidity). Fig. 2 shows what quality attributes are affected by these factors and how preservation

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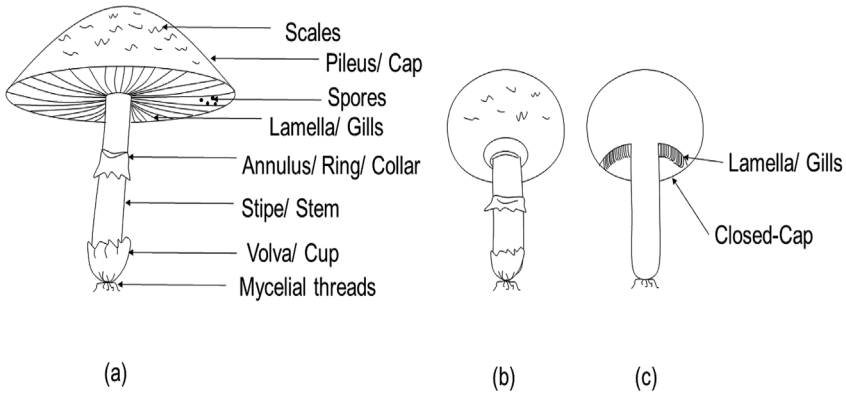

Fig. 1. Morphology of *Agaricus bisporus* mushrooms at different maturity stages. (a) mature mushroom; (b) immature mushroom with a closed cap; (c) longitudinal slice of immature mushroom.

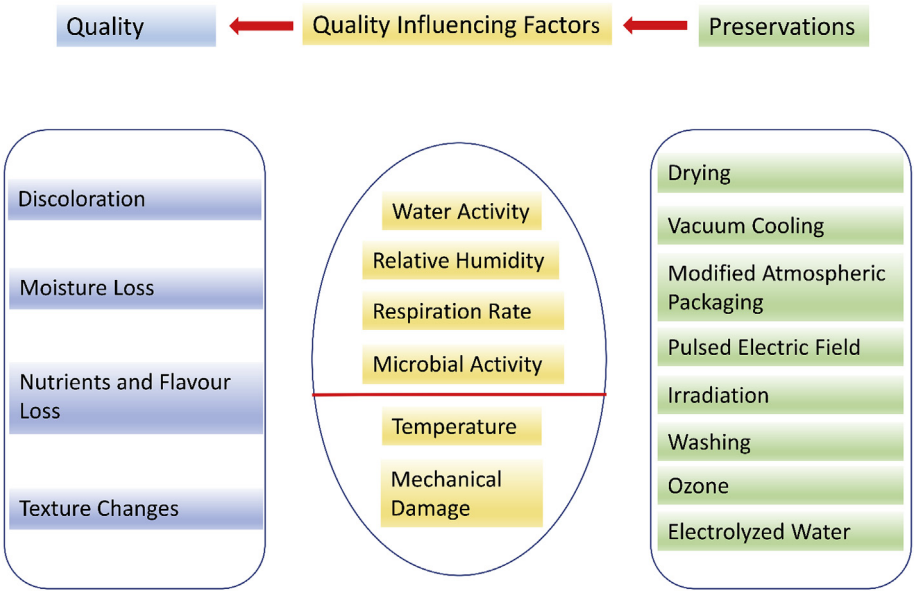

Fig. 2. The relationship between postharvest quality degradation, influential factors and preservation processes.

methods could be used to control these factors in order to maintain the quality of *Agaricus bisporus*. By controlling one or some of these quality factors, several preservation methods could effectively reduce postharvest quality deterioration and achieve shelf-life extension of mushrooms. Thermal processes (i.e., drying and cooling) are typical methods which could significantly retard mushrooms quality degradation by controlling storage temperature and water activity (Pei, Yang, et al., 2014a,b). Modified atmosphere packing (MAP) is another approach that performs well in maintaining postharvest quality of fresh mushrooms (Guillaume, Schwab, Gastaldi, & Gontard, 2010). Moreover, physical and chemical processes such as irradiation (Guan, Fan, & Yan, 2013), pulsed electric field (Dellarosa, Frontuto, Laghi, Dalla Rosa, & Lyng, 2017), washing with antimicrobial agents (Guan et al., 2013), coating (Nasiri, Barzegar, Sahari, & Niakousari, 2017), ozone (Prabha, Barma, Singh, & Madan, 2015) and electrolyzed water treatments (Aday, 2016) could effectively inactivate microbial activities and influence on physical properties such as texture, colour and weight loss.

Though a few reviews are available on the preservation techniques of edible fungi (Singh, Langowski, Wani, & Saengerlaub, 2010; Xue, Hao, Yu, & Kou, 2017), no review is currently available on detailed interrelationships among quality attributes, quality influencing factors and methods for enhancing the quality of *Agaricus bisporus*. Therefore, this review aimed to present advanced postharvest preservation methods of mushrooms from this point of view. The main quality attributes determining the shelf-life of mushrooms were first introduced, then factors influencing the quality of postharvest mushrooms were discussed and advanced preservation methods for *Agaricus bisporus* were reviewed. Finally, some future research trends were proposed.

2. Quality degradation of mushrooms

Quality degradation occurs in mushrooms during the postharvest period. The most significant quality changes are moisture loss, discolouration, texture softening, nutrients and flavour loss.

2.1. Moisture loss

The moisture content of fresh *Agaricus bisporus* mushrooms is of 85%–95% (Kumar et al., 2013). This moisture level continues to decrease during the postharvest storage due to mushrooms cell damage and internal water transfer. This physiological process speeds up mushrooms quality degradation, such as shrinkage and weight loss. Weight losses of the mushrooms stored at 4 °C for 2, 7 and 12 days were reported as 0.07%, 0.27% and 0.49%, respectively (Aday, 2016). When the water loss reaches 5% of its fresh mass, mushrooms are regarded as perished (Mahajan, Rodrigues, Motel, & Leonhard, 2008). Paudel, Boom, van Haaren, Siccama, and van der Sman (2016) reported that

water holding capacity of mushrooms was influenced by the loss in cell membrane integrity and the changes in structural polymers of the cell wall. In order to extend the shelf-life of fresh mushrooms, the water loss should be controlled at a certain low level, which can be realized by packaging (Gantner et al., 2017) or treatment by electrolyzed water (Aday, 2016).

2.2. Discolouration

Among all quality attributes of commercial *Agaricus bisporus*, appearance is the most obvious quality index that affects consumers' purchasing behaviour. The surface of white mushrooms is prone to brown due to microbial contamination or enzymatic activities. Enzyme activities are regarded as the main reason for browning occurred on fruits and vegetables (Mishra, Gautam, & Sharma, 2013). In the enzyme-catalysed reactions, phenolic substance is oxidised into quinones, which is then converted to melanin, producing the browning appearance on products (Ding et al., 2016). The activity of phenol peroxidase in the present of hydrogen perioxide and the activity of polyphenol oxidase in the present of oxygen are two responsible factors for mushrooms surface browning (Donnadieu et al., 2016; Podagatlapalli, Hamad, Sreedhar, Tewari, & Venugopal Rao, 2012). As the natural content of hydrogen peroxide in mushrooms is low, PPO is considered to be the main contributor affecting postharvest browning on *Agaricus bisporus* (Lei et al., 2018). In addition, mushrooms browning is easily triggered by mechanical injury in various processes during handling and transportation (Quevedo et al., 2016). The breakdown of cell membranes in the tissue leads to the mixing of polyphenol substrate with polyphenol peroxidases, which starts the browning reactions. Generally, the PPO catalyses the reaction of phenolic compounds in two steps: (1) hydroxylation of monophenols into diphenols, (2) oxidation of phenolic substance into quinones (Toivonen & Brummell, 2008). Among the PPO families, tyrosinase is the responsible enzyme for *Agaricus bisporus* browning because of its high content in mushrooms (Wrona, Bentayeb, & Nerín, 2015).

2.3. Texture changes

With the progress of mushrooms senescence during the postharvest stage, the firmness of mushrooms loss rapidly, contributing to their short shelf life and the ability to microbial contamination (Gao, Feng, & Jiang, 2014). Mushrooms' postharvest texture profile is affected by water loss, wound and mechanical injury, as well as heat treatments (Pei et al., 2014a,b). For most of the fruits and vegetables, thermal processes lead to the loss of cell to cell connection in structural molecules occur, together with the membrane destruction and turgor loss, leading to tissue softening. The firmness of *Agaricus bisporus* after harvest have a rapid loss, dropping from 17.32 N to about 13 N after 16 days of cold storage at 4 °C (Gao et al., 2014). Different from other fruits and vegetables, mushrooms lack a pectin structure. The cell wall of mushrooms mainly consists of glucans, chitin and protein. During the heat treatment, the chitin and β-1, 4-acetyl-glucosamine homopolymer form a stiff microfibril structure, which enhances the strength of mushrooms cell wall (Zivanovic, Buescher, & Kim, 2003). As a result, hardness and chewiness of mushrooms increased during drying (Pei et al., 2014a,b).

2.4. Nutrients and flavour loss

Mushrooms are rich in protein in their dry matter, containing nine essential amino acids. In addition, mushrooms are low in fat and have a relatively high content of carbohydrates and fibre (Rathore, Prasad, & Sharma, 2017). The fat-soluble vitamins and ergosterol make mushrooms to be the only vegetarian source of vitamin D (Rathore et al., 2017). As reported by Valverde, Hernández-Pérez, and Paredes-López (2015), there are 14.1% protein, 2.2% fat, 9.7% ash and 74% carbohydrates in *Agaricus bisporus* (dry basis). In every 100 g fatty acids, there are 11.9 g plamitic, 3.1 g steruc, 1.1 g oleic, 77.7 g linoleic, and 0.1 g linolenic. Chitin, glycogen mannitol and trehalose are typical constituents in mushrooms carbohydrates (Fernandes, Antonio, Oliveira, Martins, & Ferreira, 2012). Total phenolics, which are major antioxidant compounds in mushrooms, in *Agaricus bisporus* decreased continuously from 500 to 400 $\times 10^{-3}$ g kg^{-1} after 48 h of storage at 4 °C with 85% relative humidity. At the same time, the content of main product of membrane lipid peroxidation (MDA) in mushroom increased approximately from 0.08 to 0.27 $\times 10^{-6}$ mol/L within 8 days of storage (Lin et al., 2017).

Special aroma and flavour are presented in mushrooms, including both volatile and non-volatile components such as soluble sugars, polyols, free amino acids, organic acids and 5′-nucleotides, and monosodium glutamate (MSG) (Pei et al., 2014a,b). Umami taste (palatable taste) is defined as an overall food flavour induced or enhanced by MSG. It is the predominant flavour provided by mushrooms that could be significantly increased by the synergistic effect of umami 5′-nucleotides and umami acids. Equivalent umami concentration is an indicator commonly used to evaluate the flavour of mushrooms by providing the information of the MSG concentration equivalent to the umami intensity given by a mixture of MSG and 5′-nucleotide (Phat, Moon, & Lee, 2016). However, mushroom flavours are affected by many processes. For example, in gamma irradiation, the amount of total volatile compounds in food products was affected by the dose applied (Kong et al., 2017).

3. Influential factors on mushrooms quality

During the postharvest period, mushrooms quality is highly related to internal factors (water activity, respiration rate and microbial activity) and external factors (storage temperature, relative humidity and mechanical damage). Understanding their effects provide information for preserving the mushroom quality.

3.1. Internal factors

3.1.1. Water activity

Water activity (a_w) is defined as the ratio of the equilibrium water vapour pressure (P_w, kPa) of a foodstuff to the saturated vapour pressure (P_{wo}, kPa) of pure water at the same temperature. It is an important factor that influences mushrooms quality (Jaworska, Pogoń, Bernaś, & Skrzypczak, 2014). As a_w depends on the content of free water, this parameter is commonly used as a responsible factor for quality deterioration reactions, such as lipid oxidation, microbial stability, enzymatic and non-enzymatic activities, and texture profile changes. A nature high a_w of fresh mushroom can provide ideal environment for microbial growth (Olotu et al., 2015). However drying methods, pre-treatment processes and blanching process can effectively influence mushroom a_w. As reported by Jaworska et al. (2014), the water activities in air dried unblanched mushrooms, air dried blanched mushrooms, freeze dried unblanched mushrooms and freeze dried blanched mushrooms were 0.228 ± 0.004, 0.298 ± 0.001, 0.029 ± 0.003 and 0.041 ± 0.002, respectively. Anshu and Anju (2018) also reported that the water activities in cabinet dried (at 50 °C) oyster mushrooms were also influenced by different pre-treatment (washing) processes. Mushrooms pre-treated by 1% glycerol had the lowest a_w, compared with the mushrooms pre-treated with 0.1% potassium metabisulphite, 0.2% potassium metabisulphite, 1% $CaCl_2$, 2% $CaCl_2$ and 0.5% glycerol. Meanwhile, mushrooms with the lowest a_w also performed the best in mushroom colour retention, microbial count control, dehydration ration enhancement, rehydration ratio improvement, and crude fat preservation.

3.1.2. Respiration rate

Respiration is a metabolic process, during which the plant consumes

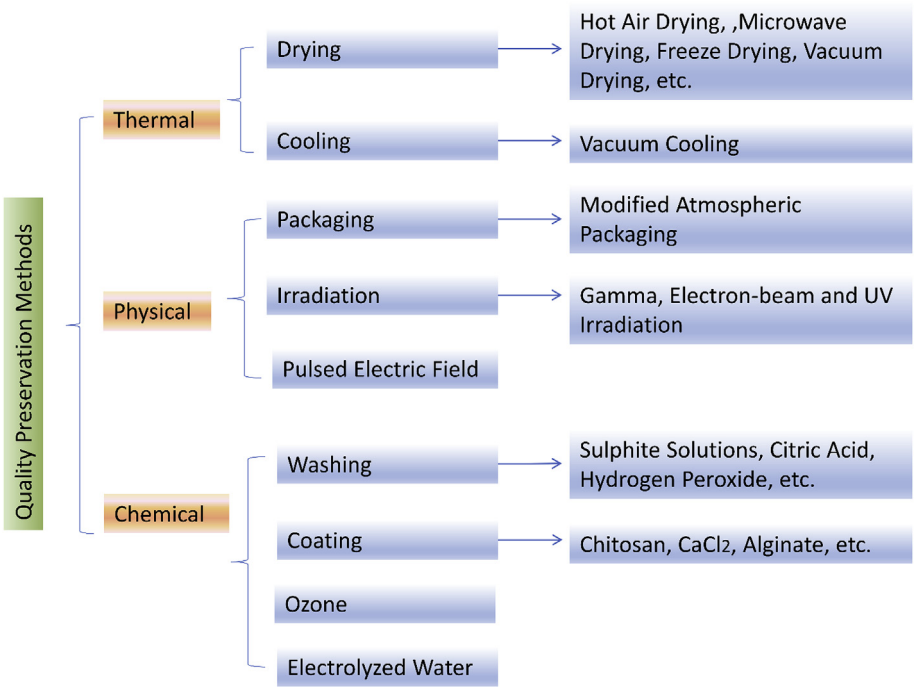

Fig. 3. Preservation methods of postharvest *Agaricus bisporus*.

oxygen and releases carbon dioxide. Respiration is a good indicator for potential physiological aging process of fresh mushrooms, depending on the maturity of the sporophore (Belay, Caleb, & Opara, 2017). The peak of the respiration rate corresponds with the phase of rapid gill development for immature mushroom. During mushrooms aerobic respiration procedure, various substrates such as carbohydrate, lipids and organic acids in mushrooms was broken down to simple molecules, like CO_2 and water. The respiration rate in mushroom (about 200–500 mg kg^{-1} h^{-1} at 20 ± 1 °C) was relatively higher when compared with other plants, such as cherry tomatoes and peaches (0.3–0.48 and 0.66–1.26 mg kg^{-1} h^{-1}, respectively at 23 ± 0.5 °C with relative humidity of 50 ± 5%) (Mistriotis, Briassoulis, Giannoulis, & D'Aquino, 2016; Singh et al., 2010; Wei et al., 2017). Mushroom respiration rate ise affected by storage temperature, storage time and whether the mushrooms are cut into slices (Azevedo, Cunha, & Fonseca, 2015). A higher storage temperature leads to a higher mushroom respiration rate during postharvest. As reported by Xu et al. (2016), the respiration rate (based on CO_2 production) of the *Agaricus bisporus* (immersed in sterile distilled water for 15 min) stored at 4 °C with 90% relative humidity was about 2.5 mg kg^{-1} h^{-1}, which increased to about 4.7 mg kg^{-1} h^{-1} after 3 days of storage at 20 ± 2 °C with 70 ± 5% relative humidity. Result showed that mushroom weight decreased while the respiration rate increased during storage.

3.1.3. Microbial activity

Commercially, the technique used for cultivation of *Agaricus bisporus* relys on composting. Therefore, mushrooms are likely to expose to various microorganism, having a high possibility of being contaminated (Mleczek et al., 2016). On commercial white *Agaricus bisporus*, the total culturable microbial load are in the range of 5.2–12.4 log CFU per g (Rossouw & Korsten, 2017). High water content and a neutral pH in mushrooms provide an ideal medium for microbial growth. The quality degradation rate in postharvest mushrooms can be affected by their initial microbial loads. A large microbial population significantly disrupts mushrooms quality by causing browning, blotchy and deterioration (Singh et al., 2010).

3.2. External factors

3.2.1. Temperature

Storage temperature is one of the most important factors that influence mushrooms postharvest quality, as most of the quality deterioration reactions in physical, biochemical and microbiological processes are highly related to temperature, such as respiration, colour and ripening (Qué, Nicolaï, & Verlinden, 2017). Generally, increasing the storage temperature accelerates mushrooms' senescence, browning, weight loss as well as texture softening. As reported by Guillaume et al. (2010), one-day storage at ambient temperature (20–25 °C) might induce mushrooms quality lost, such as cap opening, discolouration, stem elongation, and texture softening. The study of Azevedo, Cunha, Oliveira, Mahajan, and Fonseca (2017) showed that when the storage temperature increased from 2 to 18 °C, the transpiration rate of fresh oyster mushrooms increased from 1.82 (± 0.20) to 3.88 (± 0.41) g kg^{-1} at 86% relative humidity. Low and constant temperature (above 0 °C) was recommended for mushroom postharvest storage, as chilling injury would occur if the storage temperature below 0 °C (Singh et al., 2010).

3.2.2. Relative humidity and mechanical damage

Relative humidity (RH) has a significant effect on mushrooms transpiration rate (an indicator for products' water loss). A higher RH used in the storage conditions helps to minimize the mass loss in mushroom during postharvest. A high relative humidity level (85%–95%) should be maintained in any case (Diamantopoulou & Philippoussis, 2015). As reported by Azevedo et al. (2017), oyster mushrooms had the least mass loss of 8.35% fresh weight when storage under vapour saturated conditions at 2 °C for 136 h.

Due to the unprotected structure, *Agaricus bisporus* is prone to mechanical damages during postharvest transportation or processing. Mechanical damage can induce surface bruise, cap colour changes and texture softening, leading to shelf life reduction of mushrooms (Gao et al., 2015; Rojas-Moraleda et al., 2017).

4. Preservation methods

In recent years, research advances have been made in preservation of *Agaricus bisporus*, which can be classified into three categories, as shown in Fig. 3. Drying and cooling are two effective thermal processes for mushrooms postharvest quality management. Physical-based preservation methods refer to modified atmosphere packaging, irradiation and pulsed electric field. Washing with antimicrobial agents, ozone, electrolyzed water and coating treatments are chemical methods.

4.1. Thermal processes

4.1.1. Drying

Drying (Ma, Sun, Qu, & Pu, 2017; Pu & Sun, 2016; Pu & Sun, 2017; Qu, Sun, Cheng, Pu, & Hongbin, 2017; Sun & Woods, 1993; Sun & Woods, 1994a, 1994b, 1994c; Yang, Sun, & Cheng, 2017) is a common preservation method for agri-food products. Conventionally, mushrooms are dried by solar drying and hot air drying. However, the heat transfer from food surface to the centre is slow during solar drying and hot air drying. Thus, a long dehydration time is required, leading to quality degradation of final dried products. Several advanced and combined drying techniques have been explored to improve drying efficiency and product quality of mushrooms. Microwave drying is an advanced drying technique with the use of electromagnetic waves in the frequency range from 300 MHz to 300 GHz (Sun, 2012). Water molecules in food absorb the microwave energy in a short time, the microwave energy was transferred to heat that leads to water to be evaporated rapidly. Compared to hot air drying, microwave drying can significantly reduce the drying time (Sun, 2012). Freeze drying (FD) could produce high-quality products based on water sublimation, water is removed from the solid phase to vapour phase directly during the drying process. Freeze drying takes place at a low temperature, heat-sensitive properties of products such as vitamins could be maintained without heat damage (Pei et al., 2014a,b). Due to the sublimation of ice crystals, freeze-dried products have a porous structure. One of the main disadvantages of FD was the high capital cost and high energy consumption for the vacuum system and refrigeration system, with a small throughput and a low drying rate (Huang, Zhang, Wang, Mujumdar, & Sun, 2012). As reported, different drying methods have different effects on mushrooms' volatile compounds content, total free amino acids content, nutrient retention, colour maintain as well as water holding capacity (Paudel, Boom, & van der Sman 2015; Tian, Zhao, Huang, Zeng, and Zheng (2016)). Compared with hot air, vacuum, microwave and microwave vacuum drying, microwave vacuum drying helped to produce more uniform dried products with a larger amount of taste-active amino acids residual (Tian et al., 2016). Recent applications of different drying techniques in mushrooms preservation are shown in Table 1.

4.1.2. Cooling

Cooling (Desmond, Kenny, Ward, & Sun, 2000; Hu & Sun,2000; McDonald & Sun, 2001; McDonald, Sun, & Kenny, 2001; Sun & Eames,1996) is an essential process to extend the storage life of agri-food products. At 0 °C, mushrooms respiration rate is three times lower than that at 10 °C, immediate field heat removal from mushrooms after harvest can slow down their deterioration, increasing their shelf life for up to 9 days (Diamantopoulou & Philippoussis, 2015). There are various cooling techniques available, among them, vacuum cooling is a rapid cooling technique based on moisture evaporation of product under vacuum conditions. The porous structure and high moisture content of mushrooms make them suitable to be vacuum-cooled (Drummond, Zheng, & Sun, 2015, pp. 477–494). Compared to conventional cooling methods, vacuum cooling can reduce the mushroom cooling time significantly and can lower the microbial growth rate (Ozturk, Ozturk, & Koçar, 2017). However, weight loss is a major disadvantage in vacuum cooling of mushrooms. Based on Ozturk et al. (2017), the mass loss rate was about 5% in vacuum cooling and 9% in conventional cooling. . In addition, as a common agri-food preservation technique, freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Cheng, Sun, Pu, & Wei, 2018; Kiani, Sun, Delgado, & Zhang, 2012; Ma et al., 2015; Pu, Sun, Ma, & Cheng, 2015; Qu et al., 2017; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016), especially freeze drying, can also be used for the storage of mushroom.

4.2. Physical processes

4.2.1. Packaging

Modified atmosphere packaging (MAP) is a popular packaging method in the food industry, which has been used to effectively preserve a variety of fruits and vegetables (Caleb, Mahajan, Al-Said, & Opara, 2013). It uses a modification of atmosphere within the food packages to extend the shelf-life of products. Fruits and vegetables absorb O_2 and release CO_2 during postharvest storage. The metabolic process of the agricultural products interacts with the diffusion process of the packaging materials to generate a suitable atmosphere for product preservation (Oliveira et al., 2015). The decrease in O_2 and the increase in CO_2 concentration in MAP inhibit the growth microorganisms on fresh food. For fresh mushrooms preservation, MAP is considered as an effective, simple and economical packaging technique. A number of factors, such as the properties of the packaging materials, ambient gas composition, the surface area of the sample as well as storage temperature and humidity can influence the storage effect of MAP (Belay, Caleb, & Opara, 2016; Rux et al., 2016). Recent applications of MAP on mushroom preservations are shown in Table 2.

A low O_2 concentration could reduce mushrooms respiration rate, retard cap opening and diminish discolouration. Early study of Roy, Anantheswaran, and Beelman (1995) showed that the optimum in-package O_2 concentration that could reduce cap opening of mushrooms was 6%. When the O_2 concentration in the package was lower than 2%, the growth of some anaerobic microorganisms (i.e., *Clostridium botulinum* and *Staphylococcus aureus*) could be increased. The material of packaging films is another quality influencing factor for MAP products. Guillaume et al. (2010) investigated the effect of different packaging films on the quality of mushrooms by packaging fresh mushrooms with stretchable polyvinylchloride (PVC) films, paper, and paper coated with wheat gluten solution. Results showed that dark brown blotches appeared on mushrooms packed by stretchable PVC films with one-day storage, and about 30% of mushrooms had open veils. However, the mushrooms packaged by paper coated with wheat gluten solution had better preservation results in terms of colour, veil-opening and texture properties during the 3-day storage. In addition, the effect of film thickness with different initial gas compositions was also investigated (Gantner et al., 2017). Two types of polyethylene films with a thickness of 39 and 54 μm were used for fresh mushrooms preservation (14 days storage at 4 ± 1 °C) in high oxygen packaging (100% O_2), medium oxygen packaging (50% O_2 and 50% N_2), and low oxygen packaging (5% O_2, 5% CO_2 and 90% N_2). Results showed that the colour and weight loss of mushrooms were significantly influenced by the film thickness and initial gas compositions, while the texture of mushrooms was related to the gas compositions alone. The medium oxygen level and film with higher permeability (with 39 μm thickness) were found to be the optimum MAP condition to prolong mushrooms shelf-life.

4.2.2. Irradiation

Food irradiation is regarded as a breakthrough after pasteurization. During the process, food is exposed to ionizing radiation to eliminate microorganisms or insects, as a result, sensory and nutritional properties of food products are preserved. Radiation sources such as gamma irradiation, UV irradiation and electron-beam were used to preserve mushrooms quality (Roberts, 2014).

Gamma irradiation has been proved to be a safe processing technique for a number of food products by the United States Food and Drug

Table 1
Application of different dehydration methods on mushroom postharvest preservation.

Drying systems	Process parameters	Results	References
Solar assisted heat pump drying	Temperature: 45–55 °C Air flow rate: 310 kg/h	Less energy input with high coefficients of performance compared with heat pump system separately	(Şevik, Aktaş, Doğan, & Koçak, 2013)
Infrared-hot air drying	Infrared lamp power: 150, 250 and 375 W Hot air temperature: 50, 60 and 70 °C Hot air rate: 1, 2 and 3 m/s	With increasing hot air temperature from 50 to 70 °C, and flow rate from 1 to s m/s, weight loss increased by 10.3% and 13.9%, respectively	(Salehi, Kashaninejad, Mahoonak, & Ziaiifar, 2017)
Microwave Drying (MD)	Pre-treatment: ABOUT 100G OF mushroom slices were immersed in a solution of 0.25% potassium meta-bisulfite and 0.1% citric acid for 5 min at room temperature Microwave power: 120 W Air temperature: 60 °C	The optimum treatment time of MD was found to be 20 ± 3 min so as to have better quality attributes and minimum drying time. The optimum thickness of the mushroom was suggested as 2.5 mm to meet the commercial quality standards for dried mushroom	(Das & Arora, 2017)
Hot air drying (HAD), Microwave drying (MD), Vacuum drying (VD), Microwave vacuum drying (MVD)	HAD: Temperature: 60, 70 °C Air flow velocity: 1.0 ± 0.03 m/s MD: Microwave Power: 539 W Frequency: 2455 MHz Treatment Time: 18 min VD: Vacuum degree: −90 kPa Temperature:60° Treatment Time: 15 h MVD: Vacuum degree: −80 kPa Microwave density: 15 W/g Treatment Time:13 min	A significant increase of the total free amino acids and the relative content of sulphur compounds were found in all dried products. MVD helps keep larger amount of taste-active amino acids, and maintain better nutrient and colour attributes	(Tian et al., 2016)
Combined drying of hot air and microwave vacuum drying	Hot air temperature: 60 °C Air velocity: 0.9 m/s Microwave power: 1200 W Frequency: 2450 MHz	Better dried product quality (based on colour, texture, density, porosity and rehydration characteristics of dried mushrooms)	(Argyropoulos, Heindl, & Müller, 2011)
Freeze drying (FD), freeze drying combined with hot air drying (FD + AD), freeze-drying combined with vacuum drying (FD + VD), freeze drying combined with microwave vacuum drying (FD + MVD)	Chamber pressure: 108 ± 5 Pa, Cold collector temperature: −83 ± 1 °C, Power of microwave vacuum dryer: 0–1 kW. FD: Frozen temperature: 30 ± 2 °C, process temperature: 40 °C FD + VD/FD + MVD: Vacuum pressure: −90 kPa	Compared with FD samples, no remarkable changes in colour, average density and hardness were observed on FD + VD and FD + MVD samples, FD + MVD reduced drying time by 35.63% FD + MVD products generally had better nutrient retention than FD + AD products	(Pei et al., 2014a,b)

Table 2
Comparison of different packaging techniques on mushrooms postharvest preservation.

Film material	Process parameters	Results	Reference
Perforation mediated Low density Polyethylene film	Film Thickness: 95 μm Diameter of the perforation: 0.45 mm Number of perforations on package (175 mm × 110 mm): 0, 20, 40 and 60 Storage temperature: 12 (± 1) °C Pre-treatment: half of the samples were treated by 0.5% $CaCl_2$	Perforation mediated MAP increased the shelf life of mushroom to 6 days. The firmness of mushroom was better preserved by 20 and 40 perforation packs. There is no significant different of the total l protein content between the mushroom samples packed in 20 and 40 perforation packages, but in terms of total phenolic, antioxidants, and bacterial count, the pre-treated samples storage in 40 perforation packs performed the best.	(Dhalsamant, Dash, Bal, & Panda, 2015)
Biorientated polypropylene bags	Pretreatments: dipping in different concentrations of bisethanamine (DETANO) for 10 min Storage temperature: 4 °C	Treatment with 1 mM DETANO maintained a high level of firmness, delayed browning and cap opening, DETANO in combination with MAP extended storage life for up to 12 days	(Jiang et al., 2011)
Poly lactic acid (PLA) and Poly ε -caprolactone (PCL) blend films with different cinnamaldehyde contents	Storage temperature: 4 ± 1 °C	The highest weight loss of mushrooms packed by PLA and PCL was found to be 3.08% at the end of storage. The CO_2 level inside of the PLA and PCL films with cinnamaldehyde was lower than the PLA and PCL without cinnamaldehyde, but the O_2 level in these two kinds of films are similar.	(Qin et al., 2015)
Paraffin-based thermo regulating material (TRM) microencapsulated in melamine powder (MMP))	Mean particle size of melamine-based microencapsulated powder: 5.11 μm Melting point of the paraffin-wax-based TRM: 5 °C Heat capacity of TRM: 216 J/g	MMP containing corrugated package had a sufficient thermal buffering capacity to maintain the internal temperature of the package at 5 °C when the package was held at ambient temperature for 30–60 min.	(Singh, Gaikwad, Lee, & Lee, 2018)
Low density polyethylene	Film thickness: 0.04 mm Storage temperature: 4 °C Relative humidity: 84%	High CO_2 reduced mushroom browning index and increased total phenolic content and total antioxidant activity, extending the shelf life of button mushroom	(Lin et al., 2017)

Administration (USFDA). As reported by Fernandes et al. (2013), gamma irradiation (up to 1 KGy) is a useful alternative for quality maintain and shelf life extension of *Lactarius deliciosus* L. wild edible mushroom. It have an effect on diminishing enzymatic browning by retarding the polyphenol oxidase activities in mushrooms (Donnadieu et al., 2016). However, the use of gamma irradiation could cause variation in chemical composition of mushrooms (Fernandes et al., 2017).

For ultraviolet-C (UV−C) treatment, Guan et al. (2013) investigated the effect of UV-C on microbial loads of fresh button mushrooms during 21 days of storage at 4 °C. A dose of 0.45–3.15 kJ m^{-2} UV-C irradiation resulted in 0.46–1.13 log CFU/g reduction of *E. coli* 0157:H7 and 0.63–0.89 log CFU/g reduction of total aerobic plate counts on the cap of mushrooms. For electron-beam treatment, irradiation level of 1 kGy have a positive effect on shelf-life extension of mushroom slices, by reducing aerobic and psychrotrophic populations (Yurttas, Moreira, & Castell-Perez, 2014).

4.2.3. Pulsed electric field and ultrasound

Pulsed electric field (PEF) is a non-thermal processing method to preserve the natural quality of food products. The use of short pulses of electricity in PEF treatment can inactivate microorganisms and enhance the mass transfer process. In PEF, the electric field strength creates transient pores in biological membranes, leading to irreversible cell disruption (Roselló-Soto et al., 2017), which helps to kill the microorganisms as well as assist total polyphenols extraction processes of mushroom (Parniakov, Lebovka, Van Hecke, & Vorobiev, 2014).

Ultrasound is an alternative technique to increase the mass transfer for various processes by affecting physical properties of the mushroom tissue. Ultrasound treatment takes the advantages of cavitation effect, in which the gas bubbles are induced by the ultrasound collapse, generating high energy shock waves and intensive shear forces (Guerrero, Ferrario, Schenk, & Carrillo, 2017). For example, ultrasound assisted hot air drying can achieve high drying efficiency by enhancing water transportation in fruits and vegetables (Ortuno, Perez-Munuera, Puig, Riera, & Garcia-Perez, 2010). A combination of low-concentration acidic electrolyzed water and ultrasound are proved as an effective method for retarding enzymatic browning and firmness maintenance in fresh mushroom slices (Wu et al., 2018).

Dellarosa et al. (2017) compared the effect of PEF and ultrasound on the water distribution in mushrooms. PEF and ultrasound were applied on mushrooms individually and in combination at low and high temperature, results showed that the two treatments could redistribute inter-cellular water to extracellular spaces in mushrooms' stalk tissue.

4.3. Chemical processing

4.3.1. Washing with antimicrobial agents

Washing is an essential treatment to remove attached casing soil and microorganisms from mushrooms surface to inhibit microbial spoilage. However, the washed mushrooms generally have a higher moisture content, which is even more vulnerable to microorganisms when compared to unwashed mushrooms. Therefore, chemicals such as antimicrobial agents are generally added to the washing water to remove casing soil and to diminish mushrooms quality deterioration (Lagnika, Zhang, Nsor-Atindana, & Bashari, 2014).

Early in the 20th century, sulphite solutions such as sodium metabisulphite, sodium chloride and sodium hypochlorite were used as washing agents to remove unwanted casing particles so as to enhance the whiteness of mushrooms (Sapers, Miller, Miller, Cooke, & Chio, 1994). However, the use of sulphite has been reduced and replaced by stabilized chlorine dioxide in the Irish mushrooms processing, as washing with 1 g L^{-1} of sodium metabisulphite showed a negative

effect on mushrooms quality (Brennan, Le Port, & Gormley, 2000). Gupta and Bhat (2016) studied the effect of different washing solutions on mushroom postharvest preservation by dipping whole fresh *Agaricus bisporus* into H_2O_2 solutions (with concentration of 1.5%, 2.5% and 3.5%), citric acid solutions (with concentration of 0.5%, 1.5% and 2.5%), and EDTA solutions (with concentration of 2%, 4%, 6%) for 10 min, followed by a refrigeration storage for 12 days. Results showed that 2.5% citric acid was the most effective solution for mushroom quality preservation, in term of controlling weight loss, postharvest maturity index and microbial growth. Guan et al. (2013) also investigated the use of different washing treatments (i.e., water washing, H_2O_2 washing) before UV-C light (254 nm, 0.45 kJ m^{-2}) irradiation to mushrooms during14 days storage at 4 °C. Result showed that the water washed mushrooms followed by UV-C light treatment led to a 0.77 log CFU/g reduction in *E. coli* 0157:H7. The use of 3% H_2O_2 as a washing agent on mushrooms before UV-C irradiation could achieve a microbial reduction of up to 0.85 log CFU/g and showed the best performance in inhibiting mushrooms lesion and browning.

4.3.2. Coating

Alginate is a kind of edible coating substrate extracted from brown algae. Jiang (2013) dipped mushrooms with 2% alginate for 2 min then stored the coated mushrooms in jars that were ventilated with 100% oxygen. This treatment helped to maintain the firmness of mushrooms, to delay discolouration and cap opening, and to inhibit the loss of soluble solids concentration, total sugars and ascorbic acid of mushrooms. The shelf-life of mushrooms was successfully extended to 16 days. Chitosan is an alternative coating material for a wide range of food products for it is a biodegradable and biocompatible polysaccharide extracted from natural resources (Elsabee & Abdou, 2013). As reported by Jiang, Feng, and Li (2012), treatment with chitosan-glucose complex coating maintained tissue firmness, reduced microbial counts and inhibited increase of respiration rate in mushroom (*lentinus edodes*) within 16 days of storage at 4 °C. The effects of aloe vera, gum tragacanth, and the combination of both edible coatings on postharvest quality preservation of *Agaricus bisporus* were also investigated (Mohebbi, Ansarifar, Hasanpour, & Amiryousefi, 2012). Within 13 days of cold storage at 4 °C, the combination of these two coatings was the most effective approach in minimize mushroom weight loss, colour changes and texture softening. Tragacanth gum combined with *Zataria multiflora* Boiss. essential oil helped to maintain 93.47% of mushrooms tissue firmness, reduced microbial counts and decrease browning index of fresh mushrooms after 16 days of storage at 4 °C (Nasiri et al., 2017).

4.3.3. Ozone

Ozone, also called triatomic oxygen, is a powerful antimicrobial agent to extend shelf-life of food. Due to the strong oxidation capacity, ozone inactivates microorganisms rapidly after reacting with intercellular enzymes and cell components (Prabha et al., 2015). Compared to aqueous solutions, ozone is less likely to change the composition of food matrices. After decontamination, ozone is quickly decomposed into oxygen, as a result, there are no undesirable residues left. Gaseous ozone has been regarded as a safe sanitizing agent by the USFDA to be directly contacted with food. Akata, Torlak, and Erci (2015) investigated the effect of gaseous ozone on the content of microflora and foodborne pathogens on *Agaricus bisporus*. Results showed that 60 min exposure to gaseous ozone with concentrations of 2.8 and 5.3 mg/L caused 2.44 and 3.07 log reduction in aerobic plate counts, respectively. The initial levels of *Salmonella, L. monocytogenes and E. coli: 157* were reduced by 3.61, 2.80 and over 3.41, respectively, by ozonation at 5.3 mg/L.

4.3.4. Electrolyzed water

Electrolyzed water (EW) is another promising disinfectant generated by electrolysis of a salt solution. The antimicrobial activity of EW is determined by the concentration of free available chlorine, which forms the hypochlorous acid (HCLO), the oxidation-reduction potential (ORP) and their combined effect (Lee et al., 2014). The use of EW on fresh food products has been approved by the USFDA with a limitation of 200 ppm of free available chlorine. Compared to other disinfectants, EW treatment has less aggressive corrosion on food quality. In addition, EW could be reverted to ordinary water by diluting with tap water. Aday (2016) studied the effect of electrolyzed water with different concentrations (5, 25, 50 and 100 mg/L) combined with a passive MAP on the quality of postharvest mushrooms. Result showed that the use of 25 mg L^{-1} EW had the best performance in maintaining mushrooms whiteness index and texture, and diminishing weight loss. Ding, Rahman, and Oh (2011) compared the bactericidal effect of low concentration EW with four other sanitizers (strong acid electrolyzed water, 1% citric acid, aqueous ozone, and sodium hypochlorite solution), results showed that no significant difference was observed between the bactericidal effect of low concentrated electrolyzed water and strong acid electrolyzed water. The low concentrated electrolyzed water had the strongest antimicrobial efficacy when compared with the other sanitizers on total aerobic bacteria counts, yeasts and moulds, and foodborne pathogens of oyster mushrooms, leading to a microbial reduction of 1.35, 1.08 and 1.90–2.16 log CFU/g after 3 min treatment at room temperature (23 ± 2 °C).

Similarly, the antimicrobial effect of electrolyzed water was investigated by Xu et al. (2016), who treated fresh *Agaricus* mushrooms by plasma-activated water followed by storage at 20 °C, results showed that the microbial counts of bacteria and fungi on mushrooms were reduced by 1.5 log and 0.5 log after 7 days of storage, respectively. Mushroom softening was retarded by the plasma-activated water.

5. Challenges and future trends

Though the preservation techniques summarized above can effectively preserve some key quality attributes of *Agaricus bisporus* mushrooms, these techniques have their own drawbacks. For example, drying can significantly extend the shelf-life of mushrooms, however, it results in texture changes and discolouration. Heat-sensitive properties of fresh mushrooms could be maintained by vacuum cooling but a high capital cost for vacuum systems is required. For irradiation method, the dose rate should be carefully controlled within a specified range. For chemical processes, washing mushrooms with antimicrobial agents or electrolyzed water increase the water activity of mushrooms immediately might increase the possibility of microbial growth.

Currently, the most effective preservation methods for mushrooms are based on thermal processing, packaging and the use of chemical agents. Applications of some non-thermal techniques such as ultrasound and cold plasma on mushrooms are limited in recent years. In future, the combination of novel techniques and conventional techniques could be applied to enhance mushrooms postharvest quality, such as cold plasma treatment followed by MAP, or a combination of ultrasound and cold plasma.

6. Conclusions

This paper reviews advances of postharvest preservation techniques for *Agaricus bisporus* mushrooms, focusing on the quality degradation, factors affecting mushrooms postharvest quality and preservation methods. Key quality parameters of mushrooms such as colour, moisture content, texture, microbial counts, nutrients and flavour could be maintained by applying appropriate postharvest preservation techniques. The above-mentioned thermal-based, physical-based and chemical-based preservation methods could effectively extend the shelf-life of *Agaricus bisporus*, however, internal quality degradation are unavoidable. The application of some novel techniques and the combination of different techniques with a low capital cost or less processing time should be encouraged to further enhance mushrooms postharvest quality.

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