Impact of postharvest preservation methods on nutritional value and bioactive properties of mushrooms

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ABSTRACT

Background: Mushrooms are a good source of protein, dietary fibre, vitamins, minerals and phenolic compounds. However, mushrooms are a very perishable food and the implementation of preservation methods is essential to extend their shelf-life. The preservation methods for mushrooms can be classified into three categories: thermal (drying/freezing), chemical (edible coatings, films and washing solutions) and physical (packing, irradiation, pulsed electric field and ultrasound) processes. These processes can change the nutritional value and bioactive properties of this commodity.

Scope and approach: The goal of this review is to critically update and discuss the existing information about the effect of postharvest preservation methods on the nutritional value and bioactive properties of edible mushrooms.

Key findings and conclusions: Drying, especially when high temperatures are applied, can cause the degradation of polysaccharides, proteins and flavour compounds. Freezing is one of the best methods to extend mushrooms’ shelf life but cause the loss of vitamins. Edible coatings and films improve the total sugar, ascorbic acid and bioactive compounds preservation during the storage period. Washing solutions decrease amino acids content. Gamma and electron-beam irradiation decrease the unsaturated fatty acid content, whereas UV-B irradiation significantly increases the vitamin D content. However, there is still limited information about the impact of chemical processes, packaging, pulsed electric field and ultrasound on the nutritional composition and bioactive properties of mushrooms, opening research opportunities for future. This review presents technological and economic alternatives that may support the mushroom processing industries to obtain value-added edible mushrooms and related products.

1. Introduction

Mushrooms are macro-fungi with distinctive fruiting bodies, which are large enough to be seen with the naked eye and to be picked by hand (Chang & Miles, 1992). According to what mushrooms represent in humans’ diet and health, they can be grouped into four categories: edible, medicinal, poisonous and other mushrooms, whose properties are not yet well defined (Cheung, 2010). Some edible mushrooms also have medicinal properties and, therefore, simultaneously belong to the edible and medicinal groups (Guillamón et al., 2010).

Due to their organoleptic, nutritional and medicinal properties, fresh and preserved mushrooms are very appreciated by humans since ancient times (Wani, Bodha, & Wani, 2010). In the last years, the consumer demand for mushrooms, as well as their production, increased significantly. In 18 years of the new century (2000 up to 2018) the worldwide mushroom production increased from 4,19 to 8,99 million tons/year (FAOSTAT, 2018). Nowadays, more than 20 mushrooms species are commercially cultivated (Kalač, 2013; Rathore, Prasad, & Sharma, 2017). The most cultivated species are Agaricus bisporus (button mushroom, white or brown, or portobello, representing about 40% of worldwide production), Lentinula edodes (shiitake, representing about 25% of worldwide production), Pleurotus spp. (mostly P. ostreatus, oyster
mushroom, shiratuki) and Flammulina velutipes (golden needle mushroom, enokitake) (Duan, Xing, Shao, & Zhao, 2010; Jiang, Luo, Chen, Shen, & Ying, 2010). Aside from the cultivated ones, about 200 wild mushrooms species, collected in various parts of the world, are also commercialized (Kalac, 2013). However, there are more than 14,000 known species in nature, of which 3,000 are edible (El Sheikh & Hu, 2018). It is expected that the total mushroom production, the number of commercialized species and the importance of mushrooms on the human diet will keep increasing in the following years (Cheung, 2010; El Sheikh & Hu, 2018). Besides its organoleptic, nutritional and medicinal value, mushrooms are considered a sustainable food product: they increase the soil fertility and contribute to the removal of soil pollutants; the extracts where they are cultivated can be made of agro-industrial solid organic wastes, and they are a sustainable source of protein. Compared with meat and other animal protein sources, mushrooms need less area and time to produce the same amount of protein (El Sheikh & Hu, 2018; Wani et al., 2010).

However, the commercialization of fresh mushrooms has a major challenge: they are a very perishable food product and tend to lose quality immediately after being harvested. For example, A. bisporus shelf life is 1–3 days, at room temperature, and 8 days, under refrigerated conditions (Zhang, Pu, & Sun, 2018). Mushrooms have some characteristics that promote their fast degradation, namely, high moisture content, neutral pH, high respiration rate, high level of enzymatic activity, presence of microflora and absence of protective cuticle layer on the skin (Fernandes, Antonio, Oliveira, Martins, & Ferreira, 2012b; Zhang et al., 2018). The mushrooms quality degradation results in moisture, flavour and nutrients losses, discolouration, texture changes, cap opening, and stipe elongation (Fernandes, Antonio, Oliveira, et al., 2012; Zhang et al., 2018). In its turn, the moisture loss causes changes in texture and weight mushroom decrease and, consequently, reduces their economic value. According to Zhang et al. (2018), when moisture loss is higher than 5% of mushrooms’ fresh weight, they present no commercial value. On the other hand, the appearance of mushrooms is one of the qualitative factors that most influences consumers’ purchase behaviour (Nasiri, Barzegar,afari, & Niakousari, 2018). During the storage period, mushrooms tend to acquire brown spots due to conversion of phenolic compounds into quinones, which, in its turn, are converted into melanin (brown pigment). The enzymes involved in these reactions are polyphenol oxidase and, to a lesser extent, phenol peroxidase. Usually, the browning process occurs due to a disruption of mushrooms cellular membrane integrity that enables the contact between phenolic compounds and enzymes. The disruption of membrane integrity can be caused by rough handling, low relative humidity, ageing and presence of pathogenic microorganisms. Pseudomonas taiensis is the main bacterial pathogen of mushrooms. Pathogenic form of P. taiensis produces extracellular toxins, named taisains, with capacity to disrupt mushroom membrane. Besides P. taiensis, other species of microorganisms have been associated with mushrooms’ discoloration, for instance, Pseudomonas costantinii and Pseudomonas reactans (Lin & Sun, 2019).

The development and implementation of preservation methods are, therefore, essential to extend mushrooms’ shelf-life. However, some of the preservation methods change the chemical composition of mushrooms and, consequently, have effect on their nutritional value, bioactive properties and organoleptic characteristics. This paper aims to critically update and discuss the existing information about the effect of postharvest preservation methods on nutritional value and bioactive properties of edible mushrooms. It was given preference to publications within the last five years.

2. Nutritional value of mushrooms

Mushrooms have a high nutritional value. They are a good source of proteins, dietary fibres, vitamins, minerals and phenolic compounds with antioxidant activity. Furthermore, mushrooms have a low-fat content (composed mostly by unsaturated fatty acids) and a low energetic density (Cheung, 2010; Guillamón et al., 2010; Kalac, 2013; Valverde, Hernández-Pérez, & Paredes-López, 2015).

The mushrooms chemical composition varies considerably among and within species (Valverde et al., 2015). The variability within species is higher in cultivated than in wild mushrooms (Kalac, 2013). Possibly, this occurs due to the great variability of substrate composition. Hoa, Wang, and Wang (2015) demonstrated that there is a negative correlation between high protein content of mushrooms and low C/N ratio of the substrate. Besides substrate composition, the cultivation method and stage of harvesting also have an impact on mushrooms chemical composition (Valverde et al., 2015).

Fresh mushrooms are composed mostly of water. According to Kalac (2013), the dry matter of mushrooms varies between 8 and 14%. carbohydrates represent between 50 and 65% of mushrooms’ dry matter and comprise sugars and polysaccharides (Rathore et al., 2017). The main sugars of mushrooms are mannitol and trehalose (Guillamón et al., 2010). According to Kalac (2013), the median values of these two sugars in mushrooms are 2.9% and 3.9% (on dry basis), respectively. Besides mannitol and trehalose, mushrooms also contain raffinose, sucrose, glucose, fructose and xylene (Kalac, 2013; Wani et al., 2010). In its turn, the main polysaccharides present in mushrooms are glycogen (a reserve multibranched polysaccharide) and chitin (a structural polysaccharide). Mushrooms also contain glucans, mannans and pectic substances (Kalac, 2013; Valverde et al., 2015; Wani et al., 2010).

As aforementioned, mushrooms are a good source of fibre. They contain 4–9% of soluble fibre and 22–30% of insoluble fibre (on dry basis) (Cheung, 2010; Kalac, 2013). According to Manzi, Marconi, Aguzzi, and Pizzoferrato (2004), β-glucans and chitin represent 4–13% and 25% of the total dietary fibre, respectively.

Mushrooms are considered as a very useful food product in vegetarian diets (Valverde et al., 2015). They contain more protein (20–25%, on dry basis) than most vegetables and its biological value is higher, since the mushrooms contain the nine essential amino acids (Kalac, 2013). The limiting amino acid is methionine and the more abundant are valine, glutamine, glutamic acid, aspartic acid and arginine (Rathore et al., 2017; Valverde et al., 2015). According to Del Toro, Vega, Garín-Aguilar, and Lara (2006), the net protein utilization (NPU) of three Pleurotus spp. strains is between 84 and 87%. These values are higher than NPU of cereals like wheat (60%) and rice (82%) and are similar to eggs (87%) (Del Toro et al., 2006).

Mushrooms contain a low amount of fat (2–3% on a dry basis) and are mostly composed of unsaturated fatty acids (Kalac, 2013). According to Kalac (2013), linoleic (C18:2c,n-6) and oleic acids (C18:1c,n-9) represent more than two-thirds of the weight of all fatty acids found in mushrooms.

Mushrooms are a good source of vitamin B complex. They have high levels of niacin (B3), folates (B9) and riboflavin (B2), while thiamine (B1) and cobalamin (B12) are present in trace amounts. They also contain vitamin C and fat-soluble vitamins (A, E and D). Mushrooms are the only non-animal source of vitamin D (Guillamón et al., 2010; Rathore et al., 2017; Valverde et al., 2015). The main minerals present in mushrooms are potassium and phosphorus or magnesium, depending on the species (Guillamón et al., 2010). They also contain, in lower levels, calcium, iron, copper, zinc, manganese, selenium and sodium (Guillamón et al., 2010). The high and low contents of potassium and sodium, respectively, make mushrooms a very interesting food product in the prevention and dietary treatment of hypertension (Kalac, 2013).

The only problem that may arise from mushrooms consumption is the eventual presence of heavy metals in some substrates where mushrooms could grow, because of its capacity to accumulate them in their tissues (Guillamón et al., 2010). However, currently, the substrates for mushroom cultivation are highly controlled, as well as mushroom safety. So, nowadays, this hazard in controlled production is restrained.
3. Bioactive properties of mushrooms

Mushrooms are important sources of several bioactive compounds with an enormous variety of chemical structures (Sande et al., 2019; Taofiq, Martins, Barreiro, & Ferreira, 2016). These bioactive compounds have been classified as important contributors to the different therapeutic properties, namely antitumor, anti-inflammatory, anti-diabetic, antiallergic, immunomodulating, cardiovascular protector, anti-cholesterolemic, detoxification, hepatoprotective, antimicrobial, antioxidant and prebiotic activities (Barros, Cruz, Baptista, Estevinho, & Ferreira, 2008; Fernandes, Antonio, Barreira, et al., 2012; Heleno, Martins, Queiroz, & Ferreira, 2015; Valverde et al., 2015). The history of the mushroom collection and consumption dates back to ancient times and most of their claimed therapeutic effects were largely based on traditional and empirical knowledge of the local communities, as evidenced by findings from several ethnomycological surveys and data (Lau & Abdullah, 2017; Liu et al., 2018). Because of their potential beneficial effects on human health, they have become increasingly attractive as functional foods and this has been translated in the increase in commercial cultivation of several edible mushrooms. The global mushroom market was worth around 35 billion USD in 2015 and it is expected to reach up to 60 billion USD by 2021, with a compound annual growth rate (CAGR) of 9.2% (Mingyi, Belwal, Devkota, Li, & Luo, 2019).

Beside their consumption due to their bioactive properties, the demand from the food industry for novel functional ingredients or bioactive compounds to be widely applied in the development of functional food formulation has also increased the interest in several mushroom species. Numerous bioactive compounds exist in mushrooms include polysaccharides such as β-glucans, proteins, polyphenols, steroids, terpenes, hydrolytic and oxidative enzymes, among others (Taofiq et al., 2016). Some of the common high (e.g. polysaccharide) and low (e.g. terpenes and polyphenols) molecular weight compounds found in mushrooms are shown in Fig. 1.

Most research studies conducted on the pharmacological potential of mushrooms are mainly focused on crude extracts. Nevertheless, it is also important to identify the bioactive compounds responsible for each of the ascribed bioactivities. Extraction and isolation of these bioactive compounds from mushrooms are well-established processes and some of the most conventional methods used include maceration, hydrodistillation, pressing, infusion, percolation, and Soxhlet extraction, that are time-consuming and require a large amount of solvents (Taofiq et al., 2019). Several novel and more efficient extraction techniques, such as microwave assisted extraction (MAE), ultrasound assisted extraction (UAE), supercritical fluid extraction (SFE) and subcritical water extraction (SWE) are now being applied, offering faster and efficient extraction with environmentally friendly properties (Oludemi et al., 2018; Pinela et al., 2018). Advancement in biomolecular tools such as mass spectrometry (MS), nuclear magnetic resonance (NMR) spectroscopy, chromatography, use of animal and cell-based models, and clinical trials have made the market for pharmacological formulations derived from mushrooms grow tremendously over the last couple of years.

Many studies have demonstrated the potential of mushroom extracts and their individual metabolites as anticancer agents, mainly based on their ability to inhibit cancer cells growth in vitro. Some preliminary findings are available, but the nature of cytotoxic component in

![Fig. 1. Selected chemical structure of common bioactive metabolites present in mushrooms.](image-url)
mushrooms and the underlying mechanism of action are still yet to be fully elucidated. Most polysaccharides have been reported to present antitumor activity against various cancer cells by either directly inhibiting the growth of tumour cells, inducing apoptosis and autophagy, changing causes in cell cycle and increase expression of tumour suppressor genes (Chakraborty et al., 2019; Mingyi et al., 2019). Most recent advancement in the use of bioactive metabolites from mushroom, with anticancer properties, was reported by Shimizu et al. (2016): Agarol, an ergosterol derivative from Agaricus blazei, was found to induce caspase-independent apoptosis in human cancer cells. A low molecular weight polysaccharide isolated from Agaricus blazei was also found to suppress the expression of tumour necrosis factor α (TNF-α) stimulated E-selectin protein, making it a promising therapeutic agent against E-selectin-mediated neoplasms metastasis (Yue et al., 2012). A novel polysaccharide from Ganoderma arum exerts antitumor activity by activating mitochondria-mediated apoptotic pathway; mainly by enhancing mitochondrial cytochrome c release and intracellular reactive oxygen species (ROS) production, elevation of p53 and Bax expression, downregulation of Bcl-2, and the activation of caspase-9 and -3 (Zhang, Nie, Huang, Feng, & Xie, 2014).

Mushrooms have also been highlighted as alternative sources of anti-inflammatory biomolecules mainly assessed by the nitric oxide assay, TNF-α inhibition in lipopolysaccharide (LPS) activated macrophage cells, measurement of inhibition of expression of inducible nitric oxide synthase (iNOS), cyclooxygenase-2 (COX-2) and other pro-inflammatory mediator using cytokine enzyme linked immunosorbent assay (ELISA) kit and cyclooxygenase-1 (COX-1) and COX-2 catalysed prostaglandin biosynthesis assay (Taoqiq et al., 2016). These biomolecules mainly present anti-inflammatory activity by inhibiting NF-kB and cyclooxygenase pathways related with the expression of many inflammatory mediators. Mushrooms extracts and their individual metabolites have been shown to activate the macrophage, splenocyte, and thymocyte, in vitro, and these observations pointed to their potential immunomodulatory effect, which, nevertheless, requires further validation in animal models.

Phenolic compounds, terpenoids, tocopherol, and carotenoids have been identified to be the most important contributors to the radical scavenging activity extensively studied and documented for mushroom species belonging to the Pleurotus, Agaricus, Ganoderma and Lentinula genus. They are also good lipid peroxidation inhibitors, hydroxyl radical scavengers, and nitric oxide inhibitors (Rathore et al., 2017). Mushrooms, like other organisms, secrete antimicrobial biomolecules in order to thrive and survive in the environment. These mushrooms have been exploited as sources of bioactive compounds displaying broad-spectrum antimicrobial activities against Gram-positive, Gram-negative bacteria and fungal strains (Alves et al., 2013; Reis, Martins, Vasconcelos, Moraes, & Ferreira, 2017). Edible mushrooms are also applied in the prevention of atherosclerosis due to their low-fat content and are important sources of biomolecules such as ergosterol, eritadenine and β-glucans that are inhibitors of β-Hydroxy β-methylglutaryl-CoA (HMG-CoA) reductase. This is the rate-limiting enzyme in the endogenous cholesterol biosynthesis pathway; therefore, mushrooms present a cholesterol lowering potential (Roncero-Ramos & Delgado-Andrade, 2017). Many studies have demonstrated the potential beneficial effect of biomolecules obtained from mushrooms in preventing or delaying the course of diseases caused by oxidative stress, making them a therapeutically stronger nutraceutical ingredient for combating and suppressing the severity of several degenerative diseases. At present, several scientific data on the nutritional attributes, bioactive composition, biological properties, and toxicity of several mushrooms have been well elaborated. Herein, we sought (i) to identify the impact of several postharvest preservation treatments on mushroom nutritional profile and bioactive properties (ii) identify gaps in the present research trends, and, finally, to propose ideas for further research.

4. Preservation methods

According to the literature, mushrooms preservation methods can be classified into three categories: thermal (drying and freezing), chemical (washing solutions, edible coatings and films) and physical (packing, irradiation, pulsed electric field and ultrasound) processes (Zhang et al., 2018).

4.1. Thermal processes

4.1.1. Drying

Drying is a frequent and the first preservation method used on mushrooms (Fernandes, Barros, et al., 2013; Zhang et al., 2018). The goal of this process is to reduce the moisture content (until, normally, around 13%), which prevents: microbial growth; enzymatic or non-enzymatic reactions; and physiological and morphological damages (Piskov et al., 2020; Shishir et al., 2019; Xu et al., 2019).

In general, the quality of the dried mushrooms is evaluated by several factors, such as colour, rehydration rate, texture, flavour and the nutrition quality, which is mainly assessed regarding the protein and total sugar content (Xu et al., 2019). There are several techniques for drying edible mushrooms including: natural air drying, solar drying, hot air drying (HAD), thin layer drying, vacuum drying (VD), freeze-drying (FD), microwave drying (MD) or a combination of various technologies to improve the drying efficiency and product quality (Hu, Feng, Huang, Ibrahim, & Liu, 2020; Zhang et al., 2018). Dried mushrooms have a more intense flavour comparing to fresh ones, however, their nutrients and bioactive compounds can be easily altered during drying (Fan, Li, Deng, & Ai, 2012; Hu et al., 2020; Pei et al., 2016).

The most used drying method is HAD, though its disadvantages are the high temperatures and high dehydration times (Wu et al., 2015). Moreover, these disadvantages frequently cause heat damage, leading to products with textural changes (increased hardness and chewing and decreased cohesion and elasticity), browning, an unsatisfactory flavour, and a loss of nutritional value (Qi, Zhang, Mujumdar, Meng, & Chen, 2014; K.; Zhang et al., 2018). The main effects of different drying techniques on nutrients and bioactive compounds of edible mushrooms are summarized in Table 1.

The use of high temperatures during drying of mushrooms generally changes the profile of phenolic and organic acids and decrease the polysaccharides content (Gasecka et al., 2020). This is due to the conversion of polysaccharides into oligosaccharides and to the Maillard reactions. Besides, the high temperature may promote proteolysis, which, consequently, increases the level of free amino acids. However, Tian, Zhao, Huang, Zeng, and Zheng (2016) reported that the decrease in protein and uronic acid content did not vary significantly between fresh and L. edodes mushrooms dried by HAD, VD and MVD (microwave vacuum drying). Techniques such as VD and MVD, where lower temperatures are used, may avoid protein denaturation and the vacuum may inhibit oxidation of uronic acid (Tian et al., 2016).

According to Tian et al. (2016) the content of vitamin B12 in L. edodes mushrooms dried by VD, HAD and MVD increased in comparison to fresh ones. However, the mechanism that causes this increase is not yet understood. On the other hand, MD caused a loss of vitamin B12 content and it was reported that microwave heating deteriorated vitamin B12 molecules (Tian et al., 2016). Concerning vitamin D, Tian et al. (2016) reported that the content of this micronutrient in L. edodes mushrooms dried by MVD, VD, HAD and MD were 15.11%, 18.24%, 24.75% and 32.62% lower than in fresh samples, respectively. On the other hand, Sławińska et al. (2016) found that HAD did not cause statistically significant changes in vitamin D content of A. bisporus, P. ostreatus and L. edodes mushrooms, previously subjected to UVB irradiation. In this context, more studies are required to clarify the effect of drying on vitamin D content. In dried mushrooms, the increase of vitamin D content through UVB irradiation could be performed before or after the drying process (HAD or FD) (Sławińska et al., 2016). The same
Table 1
Main effects reported on some studies about drying treatment on mushrooms’ nutrition value, bioactive compounds and bioactive properties.

<table>
<thead>
<tr>
<th>Mushrooms species</th>
<th>Drying systems</th>
<th>Nutrients</th>
<th>Bioactive compounds</th>
<th>Bioactive properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. bisporus</td>
<td>Freeze drying (40 °C, for 5 h) and freeze drying combined with microwave vacuum drying (60 W/g, for 9 min)</td>
<td>–</td>
<td>FD and FMVD processes changed mushrooms’ volatile profile and consequently their flavour.</td>
<td>–</td>
<td>Pei et al. (2016)</td>
</tr>
<tr>
<td>Ganoedera lucidum</td>
<td>Hot air drying (60 °C), vacuum drying (60 °C) and freeze drying (~30 °C)</td>
<td>–</td>
<td>–</td>
<td>FD and VD samples had higher scavenging effects on hydroxyl radicals, superoxide radicals and DPPH free radical, and stronger reducing power than HAD samples. FD sample showed a stronger antioxidant capacity than VD and HAD samples in FRAP system.</td>
<td>Fan et al. (2012)</td>
</tr>
<tr>
<td>Hypsizygus marmoreus</td>
<td>Hot air drying (60 °C, for 13 h), vacuum drying (60 °C, for 11 h), microwave vacuum drying (1000 W, for 5 min) and freeze drying (~45 °C, for 9 h)</td>
<td>MVD process showed the highest retention of total sugar content.</td>
<td>FD was the treatment that showed better preservation of organic acids compounds and flavour nucleotides, which had the values most like fresh. VD and FD are interesting drying methods for obtaining a higher retention rate of non-volatile taste components.</td>
<td>–</td>
<td>Wu et al. (2015)</td>
</tr>
<tr>
<td>Lecinum scabrum (Bull.) Gray</td>
<td>Hot air drying (20 °C, for 48 h; 40 °C, for 12 h; 70 °C, for 7 h)</td>
<td>HAD at 70 °C reduced the content of Ca, K, Mg, Na and P.</td>
<td>HAD decreased the total phenolic compounds, ergosterol and organic acids contents. Reductions were higher in HAD at 70 °C. For instance, HAD at 70 °C reduced the total phenolic content by 40%. MVD got the highest retention of polysaccharides content. MD had the lowest soluble polysaccharide content because high microwave power alone caused a severe increase in product temperature. Drying increased the total number and amount of sulphur and volatile compounds in mushroom.</td>
<td>The DPHH and ABTS scavenging activity was lower in dried mushroom.</td>
<td>Gąscek et al. (2020)</td>
</tr>
<tr>
<td>L. edodes</td>
<td>Hot air drying (70 °C), vacuum drying (539 W, for 18 min), vacuum drying (60 °C, for 15 h), and microwave vacuum drying (15 W/g, for 13 min)</td>
<td>During drying treatments, protein and uronic acid contents did not vary significantly. Regarding vitamins, drying treatments caused a loss of vitamin D value compared with fresh mushrooms, but HAD and VD methods increased Vitamin B12 content. Drying treatments increased the free amino acids content with greater rise in MVD process.</td>
<td>–</td>
<td>–</td>
<td>Tian et al. (2016)</td>
</tr>
<tr>
<td>P. ostreatus</td>
<td>Hot air drying (pre-drying: 45, 55, 65 or 75 °C, for 30 min, followed by drying at 45 °C, for 4.5 h)</td>
<td>–</td>
<td>HAD-pre-dried mushrooms at 75 °C had the highest content of aroma components.</td>
<td>HAD-pre-dried samples showed higher levels of enzyme activities (γ-glutamyl transferase and cysteine sulfoxide lyase) and at 75 °C had the high content of aroma components. Treated mushrooms exhibited better preserving of antioxidant activity compared to the control. The ferric reducing ability and ABTS scavenging activity were better in VD, instead of the DPPH scavenging capacity was better in FD. Regarding in vitro gastrointestinal digestion as a measure of bioaccessibility index, VD mushrooms performed better. The ferric reducing ability, reducing power activity and ABTS scavenging activity was better in MD. The total antioxidant capacity by the electrochemical method scavenging activity was better in HAD. Besides, FD and SD mushrooms had relatively high angiotensin-converting enzyme inhibitory activity.</td>
<td>Xu et al. (2019)</td>
</tr>
</tbody>
</table>
authors also showed that the content of vitamin D in dried mushrooms (A. bisporus, P. ostreatus and L. edodes) decreased significantly during storage (in sealed plastic bags, at room temperature, in darkness). After 18 months, the vitamin D content in A. bisporus, P. ostreatus and L. edodes dried mushrooms was 2.07, 1.49 and 1.46 times lower than the respective values obtained immediately after drying. However, the amount of this compound compared to other products is still high, suggesting that the dried mushroom could be a good source of vitamin D (Sławińska et al., 2016).

Regarding the effect of drying on mushrooms fatty acids composition, Fernandes, Barreira, et al. (2013) reported that dried Macrolepiota procera mushrooms (HAD in an oven at 30 °C) increased the total saturated fatty acids. Moreover, compared with fresh mushrooms, dried samples had higher total tocopherol content mainly due to increase of α-tocopherol and β-tocopherol (Fernandes, Barreira, et al., 2013).

Fernandes, Barros, et al. (2013) also reported that dried M. procera, when compared with other different processing methods (freezing and gamma irradiation), had higher antioxidant capacity (measured by DPPH scavenging activity and β-carotene bleaching inhibition) and also presented the highest phenolic value. The heat applied during the drying process may have inactivated endogenous oxidative enzymes, which explains the increase of antioxidant activity in dried mushrooms (Fernandes, Barreira, et al., 2013).

The mushroom flavour is highly impacted by changes in the composition of amino acid and volatile compounds, where eight-carbon (C8) volatiles compounds are the major contributor to the characteristic flavour. The drying process decreases the amount of C8 volatile compounds, however, it increases the contents of sulphur and nitrogen groups compounds and, consequently, the total amount of volatile compounds, which could interfere with the mushroom flavour (Pei et al., 2016). In this way, Tian et al. (2016) reported that the MVD could be a promising method for obtaining high-quality dried mushrooms, once it helped taste-active amino acids, including aspartic acid and glutamic acid, and improved nutrient retention. Apart from MVD, FD could produce high-quality products, regarding both the nutritional value and organoleptic parameters. However, FD technique requires a high-energy consumption and high-operation cost (Wu et al., 2015; Zhang et al., 2018).

A novel laboratory-scale freeze-drying apparatus with an infrared lamp was developed by Wu, Zhang, and Bhandari (2019) and was applied for the FD of Cordyceps militaris. Results showed that drying at 40, 50 and 60 °C resulted in higher retention of cordycepin and adenosine content, leading to an increase in the total phenolics, hydroxyl radical scavenging activity, and the reducing power capacity. The technology was also able to achieve faster and efficient drying when compared to conventional FD (7.21–17.78% less drying time and 11.88–18.37% reduced energy consumption), without compromising the quality and bioactive composition of the dried product (Wu, Zhang, and Bhandari 2019). The effect on C. militaris quality of a microwave assisted pulse fluidized bed freeze-drying (MPFFD), which uses microwaves in a pulsed fluidized mode to obtain rapid heating, was evaluated (sensory parameters, volatile compounds, and antioxidant activities) and the effect was compared with FD and HAD. The FD and MPFFD samples had similar hardness and crispness, but it was higher than in HAD dried samples. Comparatively, the relative contents of ketones were 51.5%, 41.4% and 11.7% for FD, MPFFD and HAD samples respectively. Similarly, regarding the radical scavenging effect, FD and MPFFD samples had a better activity in the following order: FD (90.4%) > MPFFD (85.7%) > HAD (66.8%) (Wu, Zhang, Bhandari, and Li, 2019).

In fact, the choice of the most suitable drying method will depend on the final product properties, the complexity of the process, drying time, energy consumption and, consequently, the cost (Piskov et al., 2020).

4.1.2. Freezing

Freezing is one of the best methods to extend mushrooms shelf life and preserve their nutritional value during the storage period. Moreover, compared with drying, freezing allows better preservation of the mushrooms colour, aroma, texture and taste (Bernas & Jaworska, 2016; Fernandes, Barreira, et al., 2013).

Regarding the effect of the freezing process on mushrooms nutritional composition, Fernandes, Barros, et al. (2013) showed that frozen M. procera kept the ash and protein contents, but had a lower amount of carbohydrates, fat, total sugars, tocopherols and phenolic compounds than fresh ones. The reduction of fat content occurred due to decrease of monounsaturated and saturated fatty acids (Fernandes, Barreira, et al., 2013), Bernas and Jaworska (2016) reported that freezing process significantly decreased the vitamins B1, B2, B6, ascorbic acid, α-tocopherol, β-carotene and lycopene contents of A. bisporus.

Concerning the effect of freezing on preservation of mushroom nutritional composition during storage, Jaworska, Bernas, and Mickowska (2011) found that, after 12 months, frozen samples (~25 °C) of P. ostreatus had less dry matter, protein and total amino acids than initial fresh samples. Conceivably, the total amino acids reduction occurred due to Maillard reactions. On the other hand, Bernas and Jaworska (2016) reported that, in frozen A. bisporus, the length of storage (0, 6 and 12 months, at ~20 °C or ~30 °C) did not cause marked changes in the amount of total carbohydrates, protein, fat and ash. However, the same study showed that the amount of vitamins B1, B2, B6, ascorbic acid, α-tocopherol, β-carotene and lycopene decreased significantly during frozen storage. The losses were higher in the last six months. Overall, the storage temperature (~20 °C or ~30 °C) did not have a significative effect on the reduction of vitamins (Bernas & Jaworska, 2016).

The nutritional quality and bioactivity of frozen mushrooms are affected by the pre-treatment applied (e.g., blanching), method of freezing, frozen storage conditions, namely temperature and relative humidity, and length of storage (Bernas & Jaworska, 2016).

4.2. Chemical processes

4.2.1. Washing solutions

Washing A. bisporus mushrooms is necessary to remove casing soil particles. However, this process increases the mushrooms’ moisture due to uptake of water, which consequently promotes their microbial deterioration. In this sense, washing A. bisporus mushrooms with antimicrobial and anti-browning solutions is common practice within the mushroom industry (Zhang et al., 2018). Thus far, the effect of various washing solutions on mushrooms postharvest preservation was studied, namely sodium metabisulfitite, hydrogen peroxide, potassium sorbate, sodium salts of benzoate, ethylendiaminetetraacetic acid (EDTA), citric acid and phosphoric acids (Lagnika, Zhang, Nsor-Atindana, & Bashari, 2014), Lagnika et al. (2014) reported that citric acid and hydrogen peroxide washing solutions decreased the respiration rate, weight loss, discoloration, firmness loss and improved the A. bisporus mushrooms microbial quality. Moreover, these results were improved when the washing solutions were combined with an ultrasound treatment (Lagnika et al., 2014).

There are only a few recent studies regarding the impact of washing solutions on mushrooms nutritional value. Sapers, Miller, Choi, and Cooke (1999) reported that hydrogen peroxide washing solution, combined with sodium erythorbate solution, did not change marked carbohydrate, protein, fat, ash and vitamin contents, and preserved the phenolic compounds of A. bisporus mushrooms. However, this treatment caused a loss of 19% of free amino acids. Conceivably, this loss occurred due to leaching phenomena during washing (Sapers et al., 1999). Citric acid and hydrogen peroxide washing solutions combined with

Abbreviations: FD: Freeze Drying; FMVD: Freeze Drying combined with Microwave Vacuum Drying (FMVD); VD: Vacuum drying; HAD: Hot air drying; MVD: Microwave Vacuum Drying; MD: Microwave drying; CPHAD Cold Plasma Hot Air Drying; SD: Sun Drying; NAD: Natural air drying; VFD: Vacuum freeze drying.
ultrasound treatment improved the phenolic compounds and flavonoids preservation of *A. bisporus* mushrooms. However, the sole use of the solution, without the ultrasound treatment, did not have a significant effect on these bioactive compounds’ preservation (Lagnika et al., 2014). Sodium metabisulphite solution also preserved the phenolic compounds and ascorbic acid of *A. bisporus* mushrooms. However, the preservation was higher in samples coated by tragacanth gum enriched with essential oils (Nasiri, Barzegar, Sahari, & Niakousari, 2017). Coccukner and Oxdemir (2000) studied the effect of citric acid and EDTA blanching on *A. bisporus* mushroom mineral composition and concluded that citric acid blanching slightly decreased Fe, Cu, Mn and Zn, but these reductions were not statistically significant. Conversely, EDTA blanching significantly decreased Fe and Cu contents.

4.2.2. Edible coatings and films

Edible coatings and films are thin layers of organic compounds applied on food products to extend their self-life through protection against physical, chemical and biological deterioration. The main feature that differentiates films and coatings is the presence or absence of self-supporting structures (e.g., film packaging), respectively. In the past years, the number of publications regarding edible coatings and films increased significantly. Compared with traditional packaging, this preservation method has a high environmental advantage: they do not contribute to the accumulation of residues, because coatings and films are biodegradable and, most of the times they are consumed with food. Besides, consumers are increasingly more interested in natural preservatives instead of artificial ones. Edible coating and films composition comprise biopolymers (polysaccharides and proteins), lipids, food-grade solvents (e.g., water and ethanol), plasticizers (sorbitol or glycerol) and additives with antioxidant and antimicrobial activity, which can be from natural sources (Salgado, Ortiz, Musso, Di Giorgio, & Mauri, 2015).

In the previous 5 years, the effect of edible coatings and, to a less extent, of edible films on mushrooms preservation has been investigated by several researchers (Huang, Qian, Jiang, & Zheng, 2019; Liu et al., 2019, 2020; Mirshekari, Madani, & Golding, 2019; Nasiri et al., 2017, 2018; Ogđa, Sgroppo, Martin-Belloso, & Soliva-Fortuny, 2019; Zalewska, Marcinkowska-Lesiak, & Onopink, 2018; Zhang, Liu, Sun, Wang, &

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**Table 2**

Effects of edible coatings and films on mushrooms’ nutritional value, bioactive compounds and bioactive properties.

<table>
<thead>
<tr>
<th>Mushrooms species</th>
<th>Coating or film</th>
<th>Nutrients</th>
<th>Bioactive compounds</th>
<th>Bioactive properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. bisporus</em> was stored at 4°C, for 16 days</td>
<td>Tragacanth coating enriched with <em>Satureja</em> khasitaniaca essential oil</td>
<td>Coating treatment improved the preservation of ascorbic acid during storage.</td>
<td>Coating treatment improved the preservation of phenolic compounds during storage.</td>
<td>–</td>
<td>Nasiri et al. (2018)</td>
</tr>
<tr>
<td><em>A. bisporus</em> was stored at 4°C, for 15 days</td>
<td>Aloe vera gel coating</td>
<td>–</td>
<td>Coated mushrooms showed the highest total phenolic content, during all storage period.</td>
<td>Superoxide dismutase showed a higher activity in coated mushrooms than in controls.</td>
<td>Mirshekari et al. (2019)</td>
</tr>
<tr>
<td><em>A. bisporus</em> was cut in slices and stored at 5°C, for 16 days</td>
<td>Coating containing acid ascorbic-loaded chitosan/tripolyphosphate nanosaggregates</td>
<td>Coating treatment increased the ascorbic acid content and improved their preservation during storage.</td>
<td>Coating treatment increased the initial concentration of phenolic compounds. However, at the end of storage, the concentration of total phenolic compounds in coated mushrooms and controls was similar.</td>
<td>Coating treatment increased mushrooms’ antioxidant capacity and improved their preservation during storage.</td>
<td>Ujeda et al. (2019)</td>
</tr>
<tr>
<td><em>A. bisporus</em> was stored at 2°C, for 14 days</td>
<td>Chitosan coatings: 0.1% chitosan in 1% citric acid; 0.5% chitosan in 1% citric acid or 0.5% chitosan in 1% acetic acid</td>
<td>–</td>
<td>Coating treatments worsened phenolic compounds preservation during storage.</td>
<td>Coating treatment with acetic acid worsened the mushrooms’ antioxidant capacity, while the other coatings did not cause significant changes.</td>
<td>Zalewska et al. (2018)</td>
</tr>
<tr>
<td><em>A. bisporus</em> was stored at 4°C, for 12 days</td>
<td>Chitosan and zein film enriched with α-tocopherol</td>
<td>–</td>
<td>Film-treated mushrooms showed a higher amount of phenolic compounds at the first 9 days.</td>
<td>Active film packaging increased the activity of antioxidant enzymes (superoxide dismutase and catalase) and improved the preservation of mushrooms’ antioxidant activity.</td>
<td>Zhang et al. (2020)</td>
</tr>
<tr>
<td><em>A. bisporus</em> was stored at 4°C, for 15 days</td>
<td>Gallic acid grafted chitosan film</td>
<td>–</td>
<td>Film-treated mushrooms showed a higher amount of phenolic compounds during all storage period.</td>
<td>The activity of antioxidant enzymes (superoxide dismutase and catalase) was higher in films-treated mushrooms.</td>
<td>Liu et al. (2019)</td>
</tr>
<tr>
<td><em>L. edodes</em> was stored at 4°C, for 16 days</td>
<td>Chitosan and guar gum coating</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Huang et al. (2019)</td>
</tr>
<tr>
<td><em>P. ostreatus</em> was stored at 4°C, for 15 days</td>
<td>Water-soluble polysaccharide from <em>Oudemansiella radicata</em> coating</td>
<td>Coating treatment improved the preservation of soluble protein and ascorbic acid.</td>
<td>Coating treatment increased the amount of total phenolic compounds and improved their preservation during storage.</td>
<td>Antioxidant enzymes (superoxide dismutase and catalase) kept a higher activity in coated mushrooms than in controls. Coating treatment improved the preservation of mushrooms’ antioxidant activity.</td>
<td>Liu et al. (2020)</td>
</tr>
<tr>
<td>Pholiota nameko was stored at 20°C, for 9 days</td>
<td>Sodium alginate coating enriched with thyme essential oil, l-cysteine and nisin</td>
<td>Coating treatment improved the preservation of soluble protein, soluble sugar and ascorbic acid.</td>
<td>The sodium alginate-based coatings effectively reduced total soluble phenol content relative to those of the untreated control group.</td>
<td>Antioxidant enzymes (superoxide dismutase and catalase) kept a higher activity in coated mushrooms than in controls.</td>
<td>Zhu et al. (2019)</td>
</tr>
</tbody>
</table>

– not reported.
coatings on mushrooms nutritional composition and bioactive compounds, the major findings are the preservation of soluble protein, total sugar, ascorbic acid and total phenolic compounds (Huang et al., 2019; Liu et al., 2019, 2020; Mirshekari et al., 2019; Nasiri et al., 2017, 2018; Ojeda et al., 2019; Zhang et al., 2020; Zhu et al., 2019). Concerning the effect of edible coatings and films on mushrooms microbial quality. Akata et al. (2015) reported a reduction of 31% and 33% in ascorbic acid and total phenolic retention, respectively, in A. bisporus samples coated with tragacanth gum enriched with essential oils. The main studies developed on the effects of edible coatings and films on mushroom preservation, including an analysis of nutrients and bioactive compounds preservation, are summarized in Table 2. As far as we know, there are no studies about the effect of edible coatings and films on fatty acids profile, minerals, dietary fibre and vitamins (except vitamin C) preservation, during mushrooms storage.

Moreover, gallic acid grafted chitosan (GA-g-CS) film was utilized as a novel active packaging material for the preservation of A. bisporus (Liu et al., 2019). When compared to mushrooms packaged with chitosan and commercially used polyethylene film, mushrooms packaged with GA-g-CS film showed significantly lower respiration rate, browning degree, malondialdehyde content, electrolyte leakage rate, superoxide anion production rate and hydrogen peroxide content. The results suggested that GA-g-CS film packaging could increase the antioxidant status of A. bisporus, which in turn maintained the postharvest quality of mushrooms (Liu et al., 2019). Concerning the effects of most edible coatings and films on mushrooms bioactive properties (Table 2), most studies reported an enhancement in the antioxidant defence system of the coated mushroom and a higher bacteriostatic activity (Liu et al., 2019, 2020; Mirshekari et al., 2019; Nasiri et al., 2017, 2018; Ojeda et al., 2019; Zhang et al., 2020; Zhu et al., 2019).

4.2.3. Ozone

During their production, mushrooms are exposed to a wide range of microbial contaminations. When no antimicrobial treatment is applied, mushrooms microbial load continues to increase, during the storage period, which accelerates the postharvest mushroom deterioration. Ozone, also called triatomic oxygen, has a high antimicrobial activity due to its oxidant power (Akata, Torlak, & Erci, 2015). Until now, few studies have been conducted on the effects of ozone on the improvement of mushrooms microbial quality. Akata et al. (2015) reported a reduction of the total microbial load and three foodborne pathogens (Salmonella enterica Typhimurium, Listeria monocytogenes, Escherichia coli O157: H7) in A. bisporus mushroom exposed to gaseous ozone (2.8 mg/L or 5.3 mg/L, 1 h). On the other hand, Yuk, Yoo, Yoon, Marshall, and Oh (2007) reported that combined treatment of 3 ppm ozone with 1% citric acid did not significantly decrease the growth of Listeria monocytogenes and Escherichia coli O157: H7 in sliced F. velutipes stored at 15 °C for 10 days. Compared with other antimicrobial treatments, ozone has the advantage of leaving no toxic residues in the food product because it is rapidly degraded in oxygen. However, more studies are needed to evaluate the impact of ozone treatment on mushrooms postharvest preservation as well on their nutritional, sensorial and bioactive properties (Akata et al., 2015).

4.2.4. Electrolyzed water

Electrolyzed water (EW) is produced through electrolysis of a salt solution with chlorine and it is used in the food industry as a disinfectant. Just as ozone, EW has the advantage of leaving no toxic residues on food products where it is applied. When EW is diluted with tap water, it is converted into ordinary water (Aday, 2016; Wu et al., 2018). The effect of EW on edible mushrooms preservation was investigated by Aday (2016), Ding, Rahman, and Oh (2011) and Wu et al. (2018). These studies reported that the application of EW reduced the natural microflora of mushrooms (A. bisporus and P. ostreatus) and decreased the cell count of foodborne pathogens (Salmonella enterica Typhimurium, Listeria monocytogenes, Escherichia coli O157: H7 and Bacillus cereus) (Aday, 2016; Ding, et al., 2011; Wu et al., 2018). Moreover, results reported by Aday (2016) and Wu et al. (2018) indicated that EW treatment combined with passive atmosphere or ultrasound preserved the colour, pH, texture, total phenolic compounds and soluble protein, during storage.

4.3. Physical processes

4.3.1. Packaging

Appropriate packaging is one of the essential methods for preserving the quality and extending the shelf life of mushrooms. Modified atmosphere packaging (MAP) is a simple and economical packaging method to control physiological effects and microbial growth in mushrooms (Gholami, Ahmadi, & Farris, 2017; Zhang et al., 2018). MAP consists of the change of the atmosphere inside the package influenced by the respiration rate of the product and the transfer of gases through the packaging material (Oliveira et al., 2015). The storage effect of MAP can be influenced by some factors, such as the packaging materials, gas composition, storage temperature and humidity and the surface area of the packaged sample (Zhang et al., 2018).

A low O₂ concentration can potentially reduce the mushroom respiration rate controlling physiological effects, such as colour and texture changes and microbial growth (Gholami et al., 2017). Some authors recommend an atmosphere with low O₂ content (between 2% and 10%) and limited CO₂ content (5% maximum). On the other hand, high O₂ concentration (80%) was also tested for button mushrooms and it was shown that mushrooms under these conditions showed, among other factors, a lower lipid peroxidation rate and a lower production of reactive oxygen species (Gholami et al., 2017; Joshi et al., 2018; Zhang et al., 2018). A good selection of packaging material is essential to keep the quality of packaged products. Different materials can be selected depending on the storage conditions (refrigerated or room temperature), type of mushroom presentation (sliced or whole) and packaging technology (with or without MAP, type of MAP) (Gholami et al., 2017). For example, MAP accompanied by low-temperature storage is effective in improving the shelf life of fresh mushrooms. Additionally, microperforated packaging films are commonly used to prevent the accumulation of CO₂, depletion of O₂, the condensation of water and high humidity levels, which accelerates microbial growth and browning (Joshi et al., 2018). Mushrooms are usually packaged in plastic films (e.g., polyethylene terephthalate, PET or polyvinyl chloride, PVC), wrapped with PVC film or other stretchable films. Nevertheless, other materials have emerged, such as the use of PET with different degrees of perforation and materials obtained from renewable resources such as poly(lactic acid)/poly(e-caprolactone) blend films and wheat gluten (WG) coated paper (Gholami et al., 2017; Zhang et al., 2018). It was reported that WG coated paper was the most effective to improve the shelf-life of mushrooms when compared with a stretchable PVC film, commonly used to over-wrap mushrooms (Zhang et al., 2018). There are few publications about the effects of packaging on nutritional composition during mushroom’s storage period. Dongli, Wenjian, Muinde, Xinxin, and Qiubui (2016) analysed the effect of nano-composite packaging material (Nano-PM) on the physicochemical characteristics and antioxidant capacity of F. velutipes mushrooms during 21 days of postharvest storage, at 4 °C. The results showed that...
Nanoparticle-microbial packaging (Nano-PM) inhibited the weight loss, respiration rate and improved the preservation of mushroom nutrients in comparison to those packaged with the normal packaging material (Normal-PM). Besides, Nano-PM improved retention of total soluble solids and soluble protein; superoxide dismutase, catalase and peroxidase activities and decrease the levels of ROS, which contribute to the maintenance of the integrity of the mushroom biological membrane (Donglu et al., 2016). In addition, Nano-PM also inhibited the deterioration of the quality of *A. bisporus* by reducing the oxidation of lipids and proteins, contributing to the maintenance of the structure and function of the mitochondrion (Wu, Hu, et al., 2019). This approach could be an alternative to preserve the quality of postharvest mushrooms successfully.

### 4.3.2. Irradiation

The irradiation is a non-thermal physical process that is useful to eliminate insects, microorganisms and toxins present in food products (Fernandes, Antonio, Barreira, et al., 2012). It is considered a safe, environmentally clean and energy-efficient mushroom preservation method (Fernandes et al., 2014c). Besides that, from a global point of view, irradiation preserves flavour, colour, nutrients and the taste of mushrooms, without leaving any toxic residues. Notwithstanding, irradiation might affect the mushrooms nutrients on different degrees, according to the mushroom species, complementary preservation methods used, irradiation dose and type of irradiation source (Mami, Peyvast, Ziaie, Ghasemnezhad, & Salmanpour, 2014). The sources of irradiation can be gamma-irradiation, electron beam and UV radiation (Fernandes, Antonio, Barreira, et al., 2012). Radiation doses between 1 and 2 kGy eliminate insects, but to eliminate microorganisms, radiations up to 10 kGy might be necessary (Fernandes et al., 2014c). Any food product irradiated with doses up to 10 kGy is considered to be safe by the World Health Organization (WHO) (Mami et al., 2014). However, consumers are still poorly receptive to consume irradiated food products.

#### 4.3.2.1. Gamma irradiation

Gamma irradiation extends the postharvest mushrooms shelf-life through inhibition of cap opening, stalk elongation, browning and weight loss; and improvement of microbial quality (Fernandes, Antonio, Barreira, et al., 2012).

In 2012, Fernandes, Antonio, Oliveira, et al. (2012) reviewed the effect of gamma and electron beam irradiation on mushrooms chemical composition. The main studies regarding the impact of gamma irradiation on mushrooms nutritional composition, bioactive compounds and bioactive properties, published after 2012, are summarized in Table 3.

Concerning the effect of gamma irradiation on mushrooms macro-nutrients, the main reported disadvantage was the reduction of polyunsaturated fatty acids (Cardoso et al., 2014b, 2016, 2017; Fernandes, Barros, et al., 2013). For instance, Fernandes, Barreira, et al. (2013) reported a decrease in protein content in wild *Boletus edulis* and *Hydnum repandum* mushrooms irradiated with 1 and 2 kGy, while Fernandes, Antonio, Barreira, et al.

### Table 3

<table>
<thead>
<tr>
<th>Mushrooms species</th>
<th>Irradiation doses</th>
<th>Nutrients</th>
<th>Bioactive compounds</th>
<th>Bioactive properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. bisporus</em> was stored at 5 °C for 8 days</td>
<td>1, 2 and 5 kGy</td>
<td>Overall, irradiation did not cause marked changes in protein, ash, total sugars and tocopherol contents. Regarding fatty acids profile, it was observed that irradiation increased the saturated fatty acid content and decreased the amount of polyunsaturated fatty acids.</td>
<td>1 and 2 kGy irradiation increased the ergosterol content and did not cause marked changes in total organic acid content.</td>
<td>–</td>
<td>Cardoso et al. (2019)</td>
</tr>
<tr>
<td>β-D-glucan extracted from <em>A. bisporus</em></td>
<td>5, 10, 20, 30 and 50 kGy</td>
<td>–</td>
<td>–</td>
<td>There was a significant increase in the antioxidant activity as the irradiation dose increased from 5 to 50 kGy. Irradiation also increased the fat binding and bile acid-binding capacity.</td>
<td>Khan et al. (2015)</td>
</tr>
<tr>
<td>Wild <em>B. pinophilus</em> and wild <em>Clitocybe subconnexa</em></td>
<td>2 kGy</td>
<td>Irradiation treatment decreased total sugar and tocopherol. On the other hand, this treatment increased protein and ash contents.</td>
<td>Irradiation treatment did not change markedly phenolic compounds and organic acids.</td>
<td>Overall, irradiation treatment increased the mushrooms’ antioxidant activity.</td>
<td>Fernandes et al. (2016)</td>
</tr>
<tr>
<td>Wild dried <em>B. edulis</em> was stored for 12 months</td>
<td>2; 6 and 10 kGy</td>
<td>Irradiation treatments improved the fat, protein and ash preservation. However, they were not effective regarding the total sugar preservation. Concerning tocopherol content, irradiation treatment increased their total amount but did not avoid their decrease during the storage period.</td>
<td>–</td>
<td>Irradiation treatment increased the mushrooms’ antioxidant activity.</td>
<td>Fernandes et al. (2017)</td>
</tr>
<tr>
<td>Wild <em>B. edulis</em> and <em>H. repandum</em></td>
<td>1 and 2 kGy</td>
<td>Irradiation treatment decreased the protein, total sugar content and unsaturated fatty acids. On the other hand, they increased the ash and total tocopherols.</td>
<td>Overall, irradiation increased the amount of organic acids.</td>
<td>Irradiated samples showed lower scavenging activity and reducing power, but higher lipid peroxidation inhibition capacity.</td>
<td>Fernandes, Barreira, et al. (2013)</td>
</tr>
<tr>
<td>Wild <em>L. deliciosus</em> was stored at 5 °C for 8 days</td>
<td>0.5 and 1 kGy</td>
<td>Irradiation treatments decreased ash, tocopherols and polyunsaturated fatty acids. On the other hand, they increased the protein content.</td>
<td>0.5 kGy irradiation increased the amount of phenolic compounds while 1 kGy irradiation decreased it.</td>
<td>Irradiated samples showed higher DPPH radical-scavenging capacity.</td>
<td>Fernandes, Antonio, Barreira, et al. (2012)</td>
</tr>
<tr>
<td>Wild <em>M. procera</em></td>
<td>0.5 and 1 kGy</td>
<td>Irradiation treatment did not cause marked changes in mushrooms’ nutritional composition (except a slight decrease of ash content and an increase in total tocopherol).</td>
<td>1 kGy irradiation increased the amount of phenolic compounds.</td>
<td>Irradiation treatment did not cause marked changes in mushrooms’ antioxidant activity.</td>
<td>Fernandes et al. (2014b)</td>
</tr>
</tbody>
</table>

– not reported.
Antonio, Barreira, et al. (2012) reported an increase in this nutrient in *Lactarius deliciosus* irradiated with 0.5 and 1 kGy.

Regarding bioactive compounds, namely phenolic compounds, organic acids and ergosterol, overall, gamma irradiation did not impair their content in mushrooms (Cardoso et al., 2019; Fernandes et al., 2014b, 2016; Fernandes, Antonio, Oliveira, et al., 2012). Besides that, several studies reported an improvement of antioxidant activity in gamma irradiated mushrooms (Fernandes et al., 2016; Fernandes, Antonio, Oliveira, et al., 2012; Khan et al., 2015).

### 4.3.2.2. Electron beam irradiation

Electron beam irradiation is produced through generators that accelerate electrons close to the velocity of light. Compared with gamma irradiation, electron beam irradiation is a faster process (its doses rates are higher) and can be initiated and stopped more easily. However, unlike gamma rays, electrons have a little penetrating power and, therefore, can only be used in thin packages (Fernandes et al., 2014a; Mami et al., 2014).

Electron beam irradiation extends postharvest mushrooms shelf life (Fernandes, Antonio, Barreira, et al., 2012). Irradiation doses up to 4 kGy improved the texture and colour preservation during storage (Mami et al., 2014). Regarding weight loss, the electron beam irradiation did not avoid moisture loss during storage (Duan et al., 2010; Mami et al., 2014). Regarding weight loss, the electron beam irradiation did not avoid moisture loss during storage (Duan et al., 2010; Mami et al., 2014). Mami et al. (2014) reported an increase of weight loss in *A. bisporus* irradiated with 1, 2 and 4 kGy, while Duan et al. (2010) did not detect significant differences between controls and *A. bisporus* irradiated with 1–4 kGy.

As far as we know, the effect of electron beam irradiation in edible mushrooms chemical composition and bioactive properties was only studied in fresh *A. bisporus* and wild dried mushrooms, namely, *M. procera*, *B. edulis*, *Russula delica*, *Amanita caesarea*, *A. curtipes*. The evaluated irradiation doses varied between 0.5 and 10 kGy (Cardoso et al., 2019; Fernandes et al., 2014a, 2014c; Fernandes, Antonio, Barreira, et al., 2012; Fernandes, Barreira, Antonio, Morales, et al., 2015; Fernandes, Barreira, Antonio, Rafalski, et al., 2015; Mami et al., 2014). The main studies regarding the impact of electron beam irradiation on mushrooms nutritional composition, bioactive compounds and bioactive properties, published after 2012, are summarized in Table 4.

In mushrooms, sugars are the main respiration substrate. Therefore, high reductions of total sugars during storage are, usually, a consequence of high respiration rates that, in their turn, are associated with high deterioration levels (Duan et al., 2010). Some studies reported that electron beam irradiation decreased the total sugar content (Cardoso et al., 2019; Duan et al., 2010; Fernandes et al., 2014c). Besides that, Duan et al. (2010) showed that electron beam irradiation did not improve the preservation of the total sugar of *A. bisporus* irradiated with 1–4 kGy, during storage.

Concerning protein content, Duan et al. (2010) and Mami et al. (2014) reported higher preservation of this nutrient in irradiated *A. bisporus* during storage. Several authors reported that, just like gamma irradiation, electron beam irradiation changed mushrooms fatty acid profiles (Cardoso et al., 2019; Fernandes et al., 2014a, 2014c; Fernandes et al., 2014c and Fernandes, Barreira, Antonio, Morales, et al., 2015). The decrease of polyunsaturated fatty acids can be explained by their higher susceptibility to radiolysis compared with monounsaturated and saturated fatty acids.

### Table 4

<table>
<thead>
<tr>
<th>Mushrooms species</th>
<th>Irradiation doses</th>
<th>Nutrients</th>
<th>Bioactive compounds</th>
<th>Bioactive properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. bisporus</em> stored for 8 days</td>
<td>1, 2 and 5 kGy</td>
<td>Overall, irradiation did not cause marked changes in protein, ash and tocopherols contents. However, this treatment decreased total sugars content and changed the fatty acid profile.</td>
<td>Irradiation increased the organic acids and ergosterol contents.</td>
<td>–</td>
<td>Cardoso et al. (2019)</td>
</tr>
<tr>
<td><em>A. bisporus</em> stored at 4°C for 16 days</td>
<td>0.5, 1, 2, 3 and 4 kGy</td>
<td>Irradiation increased the protein content and improved its preservation during storage. The increase was higher in samples irradiated with higher doses. On the other hand, this treatment decreased the vitamin C content.</td>
<td>Irradiation increased the amount of total phenolic compounds and improved their preservation during storage. The increase was higher in samples irradiated with higher doses.</td>
<td>Irradiation increased the DPPH radical-scavenging capacity and improved its preservation during storage.</td>
<td>Mami et al. (2014)</td>
</tr>
<tr>
<td>Wild dried <em>A. caesarea</em> and <em>A. curtipes</em></td>
<td>2, 6 and 10 kGy</td>
<td>Irradiation treatment increased the protein, ash and tocopherols contents. However, it changed fatty acids profile. Regarding total sugars, the results were different in both mushrooms. They increased in irradiated <em>A. caesarea</em> and decreased in irradiated <em>A. curtipes</em>.</td>
<td>–</td>
<td>Irradiation increased the mushrooms’ antioxidant activity (DPPH radical-scavenging capacity, reducing power, TBARS formation inhibition and β-carotene bleaching inhibition capacities).</td>
<td>Fernandes, Barreira, Antonio, Rafalski, et al. (2015)</td>
</tr>
<tr>
<td>Wild dried <em>B. edulis</em> and <em>R. delica</em></td>
<td>2, 6 and 10 kGy</td>
<td>Irradiation decreased the protein, total sugar and ash content. Besides that, irradiation changed the fatty acids profile and increased tocopherols content.</td>
<td>Irradiation increased phenolic compounds but decreased the amount of organic acids.</td>
<td>–</td>
<td>Fernandes et al. (2014c)</td>
</tr>
<tr>
<td>Wild dried <em>M. procera</em> was stored for 12 months</td>
<td>0.5, 1 and 6 kGy</td>
<td>Overall, irradiation did not cause marked changes in carbohydrates, total sugar, protein and ash. However, this treatment changed the fatty acids profile and decreased the tocopherols content.</td>
<td>–</td>
<td>Irradiation decreased the mushrooms’ antioxidant activity (DPPH radical-scavenging capacity, reducing power and lipid peroxidation inhibition capacity).</td>
<td>Fernandes et al. (2014a)</td>
</tr>
<tr>
<td>Wild dried <em>B. edulis</em></td>
<td>2, 6 and 10 kGy</td>
<td>10 kGy irradiation decreased the insoluble and total fiber contents of <em>B. edulis</em>. Regarding <em>M. procera</em>, all irradiation doses decreased the insoluble and total fiber contents. The increases were higher in samples irradiated with higher doses.</td>
<td>–</td>
<td>–</td>
<td>Fernandes, Barreira, Antonio, Morales, et al. (2015)</td>
</tr>
</tbody>
</table>

- not reported.
4.3.3. Pulsed electric field and ultrasound

Regarding bioactive compounds, the main advantage of electron beam irradiation was the increase of phenolic compounds (Fernandes et al., 2014a, 2014c; Fernandes, Barreira, Antonio, Rafalski, et al., 2015; Mami et al., 2014). However, according to Fernandes et al. (2014c) and Fernandes, Barreira, Antonio, Rafalski, et al. (2015), wild dried mushrooms submitted to electron beam irradiation treatment had lesser organic acids content than non-irradiated controls. Overall, the electron beam irradiation increased the antioxidant activity of mushrooms (Fernandes et al., 2014c; Fernandes, Barreira, Antonio, Rafalski, et al., 2015; Mami et al., 2014).

4.3.3.2. UV irradiation.

Unlike gamma and electron beam irradiation, the main function of UV irradiation within the mushroom industry usually is not to extend their postharvest shelf life, but rather to increase their nutritional value, through the increase of its vitamin D content (Huang, Lin, & Tsai, 2015). Vitamin D has an impact on bone and muscle health, cancer disease, cardiovascular diseases, liver function, atopic dermatitis, obesity, depression and diabetes (Huang et al., 2015; Taofiq, Fernandes, Barros, Barreiro, & Ferreira, 2017).

Wild mushrooms are a good source of vitamin D. For example, a serving (100 g) of wild B. edulis provides enough vitamin D (58.7 μg) to achieve the recommended daily allowance (RDA) (15 μg) (Simon, Phillips, Horst, & Munro, 2011). In mushrooms, the vitamin D production occurs due to a photochemical reaction, catalysed by UV radiation from sunlight, which converts ergosterol (fungal sterol) into vitamin D3 (Taoqiq, Fernandes, Barros, Barreiro, & Ferreira, 2017). Although, when cultivated mushrooms grew in the darkness, they did not have or had negligible amount of vitamin D (Guillamón et al., 2010). Recently, UV light sources have been incorporated in mushroom production processes to simulate sunlight exposure and promote vitamin D production (Huang et al., 2015; Taoqiq et al., 2017). For instance, Simon et al. (2011) and Huang et al. (2015) reported an increase of vitamin D levels of 74.7% in A. bisporus and 438530% in Pleurotus spp. (golden oyster, oyster and pink oyster) when these were exposed to UVB irradiation (1.08 J/cm² and 0.259 J/cm², respectively).

As far as we know, there is little information about the impact of UV irradiation on other nutrients and bioactive substances present in mushrooms (Huang et al., 2015; Simon et al., 2011). Simon et al. (2011) analysed the chemical composition of A. bisporus exposed to UVB irradiation (1.08 J/cm²) and concluded that UV-B irradiation exposure did not cause significant changes in carbohydrates, fat, fatty acids profile, protein, amino acids profile, ash and water-soluble vitamin content. On the other hand, Huang et al. (2015) reported changes in soluble poly saccharides and antioxidant compounds content (phenolic compounds and flavonoids) of Pleurotus spp. (golden oyster, oyster and pink oyster irradiated with UV-B (0.259 J/cm²). It is important to emphasize that, even though UV irradiation may lead to nutritional losses (more studies are required to confirm this fact), these irradiated mushrooms provide an alternative to animal source derived vitamin D and can be an attractive option for vegans or lactose intolerant individuals, taking into account that most vitamin D fortified foods are based on dairy or related products (Huang et al., 2015). Pulsed irradiated (60 pulses) freeze-dried P. festulae mushrooms contributed to 65 μg/g dry weight of vitamin D2 and were able to increase bone density in osteoporotic mice after 23 weeks of treatment (Chen et al., 2015).

4.3.3.3. Pulsed electric field and ultrasound

Pulsed electric field (PEF) is a non-thermal technique used to preserve the quality of food. The treatment with PEF creates transient or permanent pores in the microbial cell membranes, leading to irrevers ible cell disruption, which helps to inactivate the microorganisms (Zhang et al., 2018). This phenomenon, recognized as electroperoration, induces lethal damage to cells and allows electrophoretic movement of saturated fatty acids (Fernandes, Barreira, Antonio, Rafalski, et al., 2015).

There are very few studies about PEF as a postharvest preservation method of mushrooms and its influence on the nutritional composition. Dellarosa et al. (2017) reported that polysaccharides, mainly those that constitute the mushroom cell wall, were modified by PEF process in their morphology and molecular weight.

Ultrasound is a promising technique applied in food technology for processing, preservation and extraction. It improves the food quality, reduced chemical and physical damages and keeps the characteristics of the fresh product (colour, consistency, flavour, and nutrients) (Jiang, Zhang, & Xu, 2020; Lagnika, Zhang, & Mothibe, 2013; Li et al., 2017). The application of ultrasound in the preservation process is based on an ultrasonic wave that propagates through materials, causing a rapid series of alternate compressions and rarefactions. This results in the production of numerous microscopic channels and cavitation effect (Zhao, Yi, Bi, Chen, & Zhou, 2018). The cavitation generates local heat and pressure that disintegrate biological cells and can create free radicals that neutralize enzymes such as lipoygenase, peroxidase, polyphenol oxidase (Jiang et al., 2020; Lagnika et al., 2013; Zhang et al., 2018; Z. Zhang, Liu, Liu, Li, & Jiang, 2016). The ultrasound frequency to neutralize microorganisms or enzymes ranges from 20 kHz to 10 MHz (Jiang et al., 2020; Ojha, Tiwari, & Donnell, 2018). However, this recommended frequency range can also induce physical damage to products and lead to the free radical formation (Jambrak, Mason, Paniwnyk, & Lelas, 2007).

In general, the ultrasound treatment on mushrooms slowed the respiration rate. Possibly, this observation occurs due to hydrogen peroxide formation in distilled water during the process, thus decreasing the oxygen levels (Lagnika et al., 2013, 2014; Li et al., 2017). Li et al. (2017) reported that the ultrasound treatment improved the storage life of straw mushroom (Volvariella volvacea) for 72 h, keeping a stable colour and original odour without spoilage. The ultrasound treatment also retarded the discoloration of white mushrooms. Possibly this occurs due to the lowest polyphenol oxidase and peroxidase activities and other enzymes activities involved in respiratory pathways (slowing respiratory rate) and microbial growth inhibition (Lagnika et al., 2013; Li et al., 2017; Wu et al., 2018). Furthermore, ultrasound treatment could prolong the storage of mushroom with a beneficial appearance and physicochemical characteristics by slowing the production of malondialdehyde, a marker of lipid peroxidation that can damage the integrity of cellular membranes (Li et al., 2017).

There are few studies about the effect of ultrasound treatment on mushrooms’ chemical composition. Li et al. (2017) studied the effect of ultrasound treatment on total soluble sugar and total soluble protein of straw mushroom. The total soluble sugar and protein are indicators of mushroom postharvest deterioration. After ultrasound treatment, the content of these nutrients decreased, which indicates that ultrasound caused tissue destruction (Li et al., 2017). On the other hand, Zhang et al. (2016) reported that the ultrasound application had a positive effect in preserving the nutrients of A. bisporus mushrooms, especially for vitamin C content, possibly due to its non-thermal character. In addition, it was observed that ultrasonic waves were effective in retaining the total phenolics and flavonoids content of mushroom (A. bisporus) during refrigerated storage (Lagnika et al., 2014, 2013; Wu et al., 2018).

5. Concluding remarks

To extend the shelf life, improve nutritional quality, enhance bioactive properties and chemical composition of edible mushrooms, either during postharvest preservation, transportation or commercialization, several novel and emerging preservation techniques have been...
explored. This paper summarized the more recent scientific information about the effect of several preservation methods on the nutritional value, bioactive compounds and bioactive properties of mushrooms.

Freezing is one of the best methods to preserve the mushrooms nutrition value during storage. However, after a long storage, frozen mushrooms lose amino acids and vitamins (Bernas & Jaworska, 2016; Jaworska et al., 2011). In its turn, drying causes significant changes in texture, colour and flavour of mushrooms. Furthermore, when high temperatures are used, the degradation of polysaccharides and proteins occur. Further, research is required in order to clarify the effect of drying on vitamins D and B12.

The use of edible coatings and films tend to increase due to the associated environmental advantages compared to the use of plastic packaging. From a global point of view, those solutions have proved to preserve total sugar, ascorbic acid, total phenolic compounds and flavonoids during storage. Regarding washing solutions, the main nutritional change reported is the loss of free amino acids due to the leaching effect. Gamma and electron beam irradiation might affect the mushroom nutritional composition. On the other hand, UV irradiation significantly increases the amount of vitamin D, in mushrooms.

There is scarce information about the impact of edible coatings, films, washing solutions, ozone, electrolyzed water, packaging, pulsed electric and ultrasound on mushrooms chemical composition. Compared with nutritional properties, characteristics, such as colour, texture, weight loss and microbial quality, had more influence on the consumers’ purchase behaviour. In this sense, most studies about mushrooms preservation are more focused on these properties. Regarding the effect of these post-harvest preservation methods on the bioactive properties of edible mushrooms, a significant number of reports only focused on the antioxidant activity, with merely a few studies reporting the antimicrobial properties of the treated mushrooms. Hence, there is a need for more studies using other biological assays and elucidating their mechanisms of action.

However, it was difficult to draw general conclusions about the most sustainable preservation methods to preserve mushrooms’ nutritional value and bioactive properties. Overall, the results in different published studies cannot be compared because the preservation methods were applied in different mushrooms species. Furthermore, even when different preservation methods were used on the same mushrooms species, it can be incorrect to compare the results from different studies because mushrooms’ chemical composition varies significantly within the same species. This variability may, therefore, influence preservation.

CRediT authorship contribution statement


Declaration of competing interest

The authors declare no conflicts of interest.

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