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Review

Mechanisms of Action and Preservation Effects of Packaging Systems for Mushrooms: Novel Approaches to Preserve Irish Edible Mushrooms

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Abstract: Mushrooms support the Irish economy, with a farm gate value of roughly EUR 130 million in 2022 and with 80%–85% of Irish production exported to the United Kingdom. In order to apply cutting edge technologies and offer creative solutions to increase the shelf life of mushrooms, it is essential to understand the mechanisms of action and preservation effects of the current trends in edible mushroom packaging systems. This review summarises the mechanisms of action for nanopackaging, biodegradable packaging, edible coatings, modified atmosphere packaging (MAP), and active packaging in terms of their enzyme activity, antimicrobial activity, antioxidant activity, and rate of respiration along with the changes in texture, colour, nutritional value, and shelf life of mushrooms reflected in the preservation effects of these packaging systems. SWOT analysis highlights the strengths, weaknesses, and threats of these packaging systems and provides potential opportunities for trialing innovative packaging materials for fresh edible mushrooms in Ireland.

Keywords: mushrooms; nanopackaging; biodegradable packaging; edible coatings; MAP; active packaging; tyrosinase inhibitors; SWOT analysis

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1. Introduction

Agaricus bisporus, *Lentinus edodes*, *Pleurotus ostreatus*, *Flammulina velutipes*, and *Pleurotus eryngii* are common edible mushroom species found in mainstream foods [1]. Because of its great flavor and nutritional value, *Agaricus bisporus*, commonly referred to as "white button mushroom", is the most widely grown and consumed edible mushroom in the world, making up 30% of all mushroom production [2]. It is a rich source of nutrients including protein, amino acids, and dietary fiber [3–5], antioxidants [5,6], terpenoids [7], lectins [8], phenolic compounds [5,9], polysaccharides [5,10], and ergosterols [11,12].

Edible mushroom production and trade are expanding globally, with a significant positive impact on human living standards [13]. According to the Global Mushroom Market (2023–2030) research report, the compound annual growth rate (CAGR) of the mushroom market increased globally by 9.2% from USD 57.18 billion in 2022 to USD 62.44 billion in 2023. At a CAGR of 9.8%, the mushroom market is projected to reach USD 90.88 billion in 2027. Teagasc Fact sheet Horticulture reported that around 68,000 tonnes of *Agaricus bisporus* are produced annually in Ireland, nearly all of which are exported to the UK, with 20% used to supply the domestic market [14]. The fact sheet states that the mushroom industry contributes to the Irish economy with a production value of approximately EUR 130 million in 2022. However, exporting to continental Europe is not feasible due to the short shelf life of mushrooms, as they typically only last three days at ambient conditions and five to eight days in a cold storage system [15], as well as to the narrow margins that the industry faces.

The main contributing factors to the short shelf life of mushrooms are their high moisture content and enzyme activity coupled with their lack of a cuticle [16], which aggravates the respiratory and metabolic rates of the seeds' tender tissues. Additionally, these factors make mushrooms more vulnerable to mechanical damage and microbial contamination, which can result in browning and a decline in quality [17–19]. These effects involve physicochemical quality degradation, including cap opening, loss of essential phenolic compounds, proteins, and vitamins, water loss, cell membrane deterioration, loss of firmness, and increased microbial activity in the process of storage and transportation [20,21], in turn leading to loss of nutritional value, flavor, market acceptability value, and shelf life. Recent findings have reported a wide range of preservation techniques for fresh mushrooms, including irradiation [22], ultrasonication [22], pulsed eclectic field treatment [23,24], [25,26], 1-methylcyclopropene treatment [27], modified atmosphere packaging, active packaging, edible coatings and nanopackaging [1,15,28–31], and biodegradable packaging made from materials such as dextran/chitosan [32].

More specifically, edible coatings and biodegradable packaging are safe and environmentally friendly packaging systems; they are made from natural substances such as pectin, chitosan, or sodium alginate to maintain quality and extend the shelf life of mushrooms [32–36], and are mostly composed of active ingredients with antibacterial and antioxidant activities [37,38]. Studies have shown that the incorporation of essential oils, active ingredients, and nanoparticles in edible coatings and biodegradable film packaging can improve the techno-functional properties of the packaging materials [39]. Furthermore, tyrosine inhibitors such as plant extracts, fungus and bacterial extracts, and synthetic and natural phenolic compounds are utilized to control mushroom browning [40–43].

This review focuses on the mechanisms of action of modified atmosphere packaging, active packaging, edible coatings, nanopackaging, and biodegradable packaging systems in terms of respiration and energy metabolism, antimicrobial activity, antioxidant activity, polyphenol oxidase, and tyrosinase inhibition, whereas the preservation effects are demonstrated in terms of changes in the quality and shelf life of mushrooms. Most importantly, the SWOT analysis presented here could potentially serve as a reference for novel strategies in the development of innovative packaging materials for the preservation of edible mushrooms as well as for the establishment of a closed loop system in the Irish mushroom sector.

2. Mechanisms of Action and Preservation Effects

Desirable techno-functional properties of packaging materials such as permeability and mechanical and thermal properties [44] play a key role in maintaining quality by preventing off-flavour development, contamination, browning, and softening, thereby extending the shelf life of mushrooms [29,45]. Studies have shown that modified atmosphere packaging (MAP) stands first in terms of frequency of use for edible mushrooms, followed by active packaging, biodegradable film packaging, and nanopackaging systems based on a review of 235 articles on mushroom preservation techniques published between 2010 and 2021 [29] (Figure 1).

2.1. Changes in Quality of Fresh Mushrooms

Fresh mushrooms are flavorful, have a moisture content ranging from 81.8% to 94.8%, and are rich sources of nutrients such as carbohydrates (50%–65%), protein (19%–35%), fat (2%–6%), minerals, dietary fiber, phenolic compounds, and vitamins [46]. A wide range of studies have shown change in quality of fresh mushrooms during storage, including texture [47–49], color [16,50–52], nutrients, and flavor [17,47,49,53–55]. These quality changes in mushrooms are attributed to the cumulative effects of respiratory, energy, membrane lipids, and reactive oxygen species metabolic reactions due to changes in enzymatic activity and microbial activity in response to intrinsic factors and the atmosphere surrounding the product. For example, the transport of electrons in mitochondria cells results in excessive reactive oxygen species accumulation such as H_2O_2 and O_2^- in mushroom [56]. These processes can lead to oxidative damage to nutrients such as membrane lipids, nucleic acids, and proteins as well as enzyme activity inhibition, leakage of electrolytes, and increased electrical conductivity, ultimately causing tissue aging, nutritional quality loss, and reduced shelf life of mushrooms [48,57].

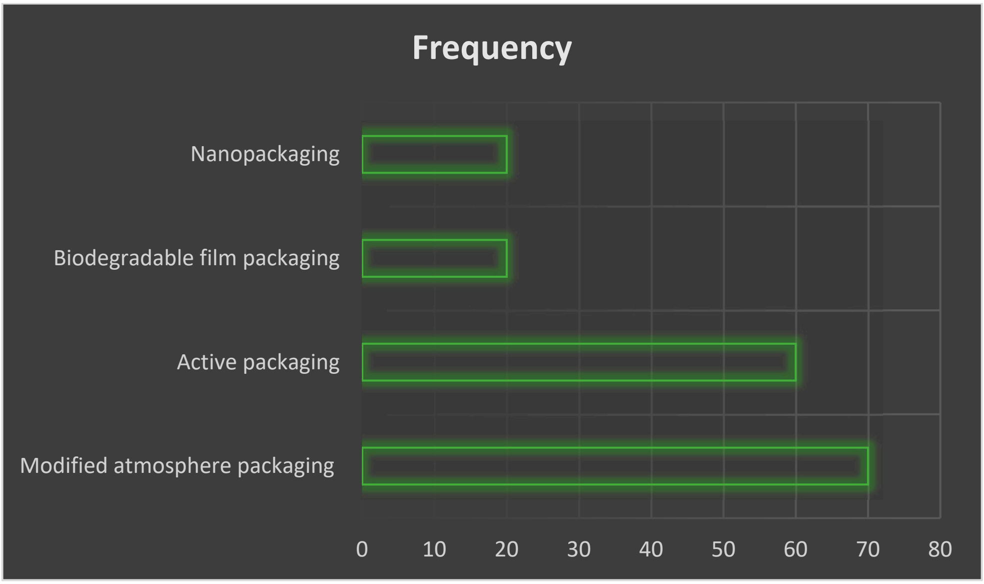

Figure 1. The research frequency of four packaging technologies for preservation of edible mushrooms according to a review of 235 articles published between 2010 and 2021.

Figure 2 provides an overview of changes in mushroom quality along with the mechanisms of action and preservation effects of five major packaging systems for the preservation of fresh edible mushrooms: edible coatings, modified atmosphere packaging, active packaging, biodegradable packaging, and nanopackaging. For instance, edible coatings and biodegradable packaging made with active ingredients can successfully delay or minimize browning reactions by inhibiting tyrosinase and polyphenol oxidase activities in fresh mushrooms [58–61].

Nanopackaging minimizes tissue aging, electrical conductivity, and the accumulation of reactive oxygen species (ROS) by controlling the energy metabolism and enzymatic activity of mushrooms [29]. MAP lowers the rate of respiratory metabolism, thereby reducing the loss of cell wall components and cell swelling [62]. By regulating metabolic enzyme activity, oxygen concentration, and energy metabolism, active packaging can lessen membrane lipid metabolism and microbial growth, thereby preventing loss of nutrients and flavor from mushrooms [30,63]. The mechanisms of action of packaging systems can be explained by enzymatic, (such as tyrosinase and polyphenol oxidase activity), antimicrobial, antioxidant, and respiration activity [44,61,64]. The following sections highlight the mechanisms of action and preservation effects of edible coatings, MAP, active packaging, biodegradable packaging, and nanopackaging.

2.2. Edible Coatings, Essential Oils, and Tyrosinase Inhibitors

Edible coatings have moderate to excellent barrier, preservative, cosmetic, and aesthetic qualities, are biocompatible and environmentally friendly, and can usually be consumed with food [17]. Edible coatings combined with active ingredients can supply bioactive compounds to enhance the quality of edible mushrooms or prolong their shelf life, in addition to superior qualities of high air permeability and moisture permeability [65]. Chitosan, guar gum, sodium alginate, aloe vera, leek powder, pectin, carboxymethyl, and cellulose are commonly used as edible coating materials for edible mushrooms; they are based on natural biopolymers with essential oils, nanoparticles, and active ingredients such as cinnamon (Table 1). For example, the mixture of chitosan with guar gum can significantly increase antimicrobial activity, reduce cell wall and membrane destructive symptoms, and maintain higher firmness, protein, and ascorbic acid while increasing total soluble solids and reducing sugars of *Lentinus edodes* mushrooms [66]. Edible coatings made from a cinnamon nanoemulsion active ingredient in polymeric matrixes of alginate and glycerol significantly decreased the respiration rate, PPO activity, pseudomonas count, and weight loss while increasing antioxidant activity and maintaining firmness, color, and total polyphenols of *Agaricus bisporus* mushrooms [67].

Table 1. Mechanism of actions and preservation effects of edible coatings of fresh edible mushrooms.

Edible Coating	Applicable	Mechanism of Actions [a]	Preservation Effects [b]	Reference
Chitosan-guar gum	*Lentinus edodes*	Significantly reduced cell wall and membrane destructive symptoms Increased antimicrobial activity	Maintained higher firmness, protein, and ascorbic acid Increased total soluble solids and reducing sugars	[66]
Alginate-glycerol-cinnamon nanoemulsions	*Agaricus bisporus*	Decreased respiration rate Reduced polyphenol oxidase activity Reduced Pseudomonas counts Increased antioxidant activity	Decreased weight loss Maintained firmness Maintained colour and total polyphenols	[67]
Pectin-chitosan-sodium alginate- carboxymethyl cellulose- N-acetyl cysteine	*Agaricus bisporus*	Controlled lipid peroxidation Increased antioxidant activity	Delayed weight loss and cap opening	[68]
Aloe vera-basil essential oil	*Agaricus bisporus*	Reduced polyphenol oxidase, respiration, and electrolyte leakage rate Increased phenylalanine ammonia-lyase and antioxidant activity	Reduced weight loss and softening Increased total phenolic contents Delayed browning and colour change	[69]
Leek powder sunflower oil-guar gum	*Agaricus bisporus*	Reduced the rate of respiration	Reduced weight loss Maintained colour	[70]
Alginate-nanoAg-Silver nitrate-sodium Borohydride-polyvinylpyrrolidone	*Lentinus edodes*	Reduced the rate of respiration and physiological activity	Extended shelf life Reduced weight loss softening, browning, and microbial counts. Increased total soluble solids	[71]

[a] respiration and energy metabolism, antimicrobial activity, antioxidant activity; [b] nutritional value, shelf life, and sensory quality.

Table 2 shows the effects incorporation of different sources of essential oils in edible coatings on the shelf life of fresh mushroom. A recent study showed that an edible coating with cajuput (*Melaleuca cajuputi* Powell.) essential oil extract minimized weight loss and respiration rate while maintaining firmness, color, and fungal antioxidant metabolites, and had a shelf life of 12 days [28]. Furthermore, edible coatings of mushroom with *Citrus aurantium* essential oil provided 20 days of shelf life [72], and Eucalyptus leaf essential oil provided 12 days of shelf life [63,73].

Table 2. The effects of different sources of essential oils in edible coatings on the shelf life of fresh mushrooms.

Essential Oils	Shelf Life	References
Eucalyptus leaf	12	[63,73]
Lemon	12	[47]
Cinnamon	5	[74,75]
Tocopherol with zein	12	[76]
Cinnamaldehyde	12	[67]
Satureja khuzistanica	16	[77]
Citrus aurantium peel	20	[78]
Cumin seed	20	[78]
Cuminum cyminum	20	[78]
Citrus aurantium	20	[72]
Melaleuca cajuputi Powell.	12	[28]

Steroids, alkaloids, and phenolic compounds make up the majority of the diverse range of tyrosinase inhibitors isolated from plant sources and fungi, and are frequently incorporated in polymeric matrixes of edible coatings. Phenolic compounds, which can range in size from simple to large and complex tannins and derived polyphenols, display strong tyrosinase inhibition because of their molecular weight and quantity of aromatic rings [42,58,61]. To identify new sources of anti-tyrosinase compounds, research has been performed on the tyrosinase inhibitory activity of several plant extracts [61,79], and all significantly inhibited tyrosinase activity.

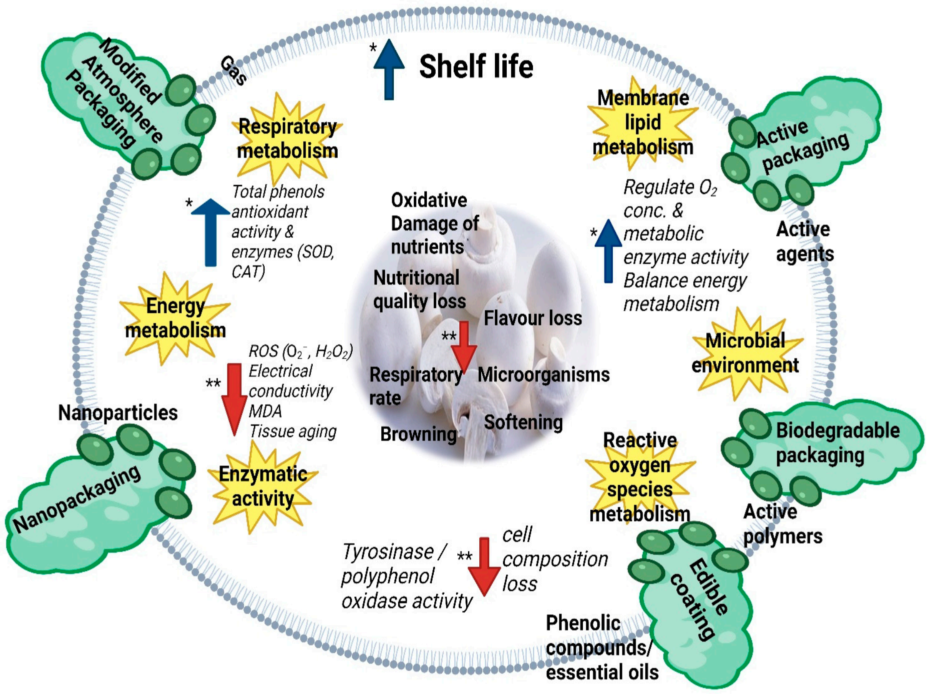

Figure 2. Mechanisms of action and preservation effects of active packaging, edible coating, biodegradable packaging, modified atmosphere packaging, and nanopackaging for the preservation of fresh edible mushrooms. CAT—catalase, H_2O_2—hydrogen peroxide, MDA—malondialdehyde, $O_2{}^-$—superoxide radical, ROS—reactive oxygen species, SOD—superoxide dismutase, * an increase, ** a decrease.

A smaller class of alkaloids and polyphenols found in fungi, including *Aspergillus* sp., *Paecilomyces* sp., *Trichoderma* sp., *Phellinus linteus*, *Daedalea dickinsii*, and *Dictyophora indusiata*, have been reported to selectively block the enzyme and are a source of novel tyrosinase inhibitors [40,41]. Studies have shown that four distinct strains of lactic acid bacteria isolated from cow faeces exhibit tyrosinase inhibitory activity [80]. For instance, the most active compounds within the group of natural flavones, flavanols, isoflavones, and flavanones inhibited mushroom tyrosinase with an IC_{50} of 44–500 µM, while natural anthocyanidins, aurones, and chalcones had an IC_{50} ranging from 18 to 106.7 µM, which was in comparison to kojic acid (a potent inhibitor of tyrosinase) with a tyrosinase inhibitory activity of IC_{50} of 59–318 µM (Table 3).

Table 3. Natural and synthetic phenolic compounds at half-maximal inhibitory concentration (IC_{50}) values against white button mushroom tyrosinase.

Compound Name	Tyrosinase Inhibition (IC_{50} Values (mM))	References
Natural anthocyanidins	18–78	[81,82]
Natural aurones	31.7–98.5	[82]
Synthetic aurones	31–100	[83]
Natural chalcones	23–106.7	[60]
Synthetic chalcones	29.3–114.4	[58,84]
Natural flavones	110	[58–61]
Natural flavanols	55–300	[58,59]
Natural isoflavones	52–500	[61]
Natural flavanones	44–500	[81,82]
Synthetic flavonols	53–182	[82]
Kojic acid	59–318	[58–61,85]

2.3. Biodegradable/Compostable Food Contact/Packaging

Biodegradable/compostable food contact films are primarily used for packaging purposes, as opposed to edible films, which are normally sprayed or liquid-impregnated on food surfaces and are typically consumed with the food [21,76]. Table 4 shows the mechanism of action and preservation effects of compostable/biodegradable packaging for fresh edible mushroom. Common compostable food contact films or biodegradable packaging materials for edible mushrooms include starch, chitosan, soybean protein, cellulose, zein, and polylactic acid (PLA) [86–90]. Because polysaccharides have poor mechanical stability, solubility, and barrier, the most common technique to improve the techno-functional properties of polysaccharide films is to pour polymer into a solution containing protein [91,92] and active ingredients [93]. Studies have shown that the ideal ratio for chitosan and zein film mixtures is 1:1 [94], as these combinations have superior structural and mechanical qualities compared to either material alone. Per the authors' findings, the packaging impeded the activities of mushroom peroxidase and polyphenol oxidase activities while decreasing the rate of respiration, weight loss, and relative electrolyte leakage rates of fresh edible mushrooms.

Table 4. Mechanisms of action and preservation effects of compostable/biodegradable packaging for fresh edible mushrooms.

Biodegradable Packaging	Applicable	Mechanism of Actions [a]	Preservation Effects [b]	Reference
Chitosan-0.0 to 4.0% *w/v* dextran film	*Agaricus bisporus*	Highest tensile and elastic strength, water vapour permeability attained with 0.5% *w/v* dextran dispersion in chitosan	Delayed spoilage Shelf life of 28 days at 4 °C	[32]
Chitosan-gallic acid film	*Agaricus bisporus*	Increased the activities of superoxide dismutase and catalase The lowest respiration rate and polyphenol oxidase activity recorded	Maintained mushroom quality by reducing browning degree, O_2^-, malondialdehyde content, H_2O_2, and rate of electrolyte leakage	[93]

Table 4. *Cont.*

Biodegradable Packaging	Applicable	Mechanism of Actions [a]	Preservation Effects [b]	Reference
PLA-polybutylene adipate film	*Lentinus edodes*	Effectively reduced the respiration rate Lowered microbial count and CO_2 level Prevented water vapour condensation inside the package	Inhibited cap opening Improved phenolic contents Maintained firmness Delayed senescence Shelf life of 14 days	[95]
Chitosan-zein-lemon essential oil film	*Agaricus bisporus*	Significantly inhibited microbial, PPO, and POD activities Decreased respiratory rate Increased antioxidant and antibacterial activities	Delayed browning Inhibited microbial growth Maintained textural properties	[96]
Chitosan-zein film		Reduced electrolyte leakage and respiration rate Significantly inhibited PPO and POD activities Lowered physiology activity	Lowered weight loss Maintained colour	[94]
Chitosan-zein/α-tocopherol film	*Agaricus bisporus*	Reduced respiration rate, electrolyte leakage rate, polyphenol oxidase and peroxidase activity Increased CAT, SOD, POD, and antioxidant activities	Reduced browning index and weight loss Maintained colour, firmness, and overall quality of mushrooms	[86]

[a] respiration and energy metabolism, antimicrobial activity, antioxidant activity; [b] nutritional value, shelf life, and sensory quality. CAT—catalase, H_2O_2—hydrogen peroxide, POD—peroxidase, O_2^-—superoxide radical, PPO—polyphenol oxidase, SOD—superoxide dismutase.

Additionally, one of the most efficient ways to create new materials with the desired properties is to combine compostable polymers with active agents such as antioxidants and antimicrobials as carriers to improve the barrier and mechanical properties of the polymers [97,98]. Studies have shown that antibacterial agents (lactobacillin), essential oils, gallic acid, cinnamic aldehyde, ascorbic acid, vitamins, and tea polyphenols incorporated with biodegradable polymers can improve the techno-functionality of compostable packaging materials for edible mushrooms [53,93,99–103]. For example, a mixtures of chitosan, zein, and lemon essential oil biodegradable packaging film significantly inhibited PPO, POD, and microbial activities, decreased the respiratory rate, increased antioxidant and antibacterial activity, delayed browning, and maintained the textural properties of *Agaricus bisporus* mushrooms [96]. In another study, composite biodegradable packaging made from chitosan with 0.5% w/v dextran dispersion significantly improved tensile strength, elasticity, and water vapour permeability while delaying spoilage and extending the shelf life of *Agaricus bisporus* mushrooms at 4 °C to 28 days [32].

2.4. Active Packaging

Active packaging with built-in active ingredients permits the release or absorption of substances into and from packaged food or the surrounding environment, allowing products to extend their shelf life [104]. Thus, there are two types of active packaging systems: scavenging systems and release systems [105,106]. In scavenging systems, keeping the food and packaging material apart prevents food spoilage by absorbing gases such as oxygen. In release systems, the food or the package's headspace is exposed to active agents. Numerous active packaging systems have been developed to date, including ethylene scavenger packaging, water-controlled packaging, antioxidant packaging, antibacterial packaging, CO_2 generation systems, O_2 scavenger packaging, and odour-absorbent packaging [107–110].

Multilayer active packaging systems with high absorbency and ion-exchange capacity coatings such as zeolites as active coatings of low-density polyethylene (LDPE) or high-density polyethylene (HDPE) films can be used for extending the shelf life of fruits and vegetables [111]. For instance, in *Agaricus bisporus*, zeolites combined with açai extract active coating in an active MAP packaging system (5% CO_2, 80% O_2, and 15% N_2) decreased water loss and browning while increasing the bioactive compounds and ascorbic acid content of the mushrooms, thereby extended shelf life to 28 days [112]. Studies have shown that a mixture of 0.5% collagen and 1% carboxymethyl cellulose active coatings accompanied by plasma modification of LDPE can significantly inhibit polyphenol oxidase and β-1,3-glucanase activity, reduce the respiration rate, and increase catalase activity to inhibit browning while maintaining the structural integrity of *Agaricus bisporus* mushrooms and extending their shelf life from 7 days to 21 days [113]. Furthermore, a bilayer active packaging of gelatin with pomegranate peel powder coated on polyethylene film combined with MAP showed increased antibacterial activity and extended the shelf life of *Pleurotus ostreatus* mushrooms by 9 days compared to the conventional packaging system [114].

Additionally, active packaging systems can involve the incorporation of active ingredients such as bioactive plant extracts, antioxidants, antimicrobials, O_2 and ethylene scavengers, and CO_2 emitters/generators in a polymeric matrix of edible coatings or biodegradable packaging materials [54,106,115–117]. Specifically, antibacterial and antioxidant active packaging system have been reported to be the most frequently utilized for edible mushrooms [76,87,99]. Numerous edible mushrooms, including *Agaricus bisporus* [99,118], *Pleurotus ostreatus* [119], and shitake mushroom [120], have been packaged in this format on a large scale. For example, studies have shown that the incorporation of active ingredients in biodegradable [100] and edible coating [93] polymeric matrixes improved the mechanism of action and preservation effects of the packaging materials (Table 5). For instance, the incorporation of 0.5% nisin antimicrobial polypeptide in PLA significantly reduced PPO activity and total bacteria count, maintained quality by reducing changes in texture and sensory attributes, and extended the shelf life of *Boletus edulis* mushrooms to 18 days [100].

Table 5. Mechanisms of action and preservation effects of active packaging systems for fresh edible mushrooms.

Active Packaging	Applicable	Mechanism of Actions [a]	Preservation Effects [b]	Reference
Active coatings/films in a multilayer active packaging systems				
Bilayer active packaging + MAP: gelatin with pomegranate peel powder coated on the polyethylene film	*Pleurotus ostreatus*	Increased antibacterial activity	Increased the shelf-life of mushroom by 9 days compared to the control Inhibited bacterial growth Lowered weight loss Improved overall acceptability	[114]
Collagen and carboxymethyl cellulose active coatings with plasma modification of LDPE	*Agaricus bisporus*	0.5% Collagen and 1.0% carboxymethyl cellulose Effectively inhibited polyphenol oxidase and β-1,3-glucanase activity Modified the gas composition in the package (carbon dioxide: 10%–15% and oxygen: 8%–15%) Increase catalase activity Reduced respiration rate	Inhibited browning Maintained structural integrity Extended shelf life from 7 to 21 days	[113]
Zeolite açai extract coating with MAP (5% CO_2, 80% O_2, 15% N_2)	*Agaricus bisporus*	Significantly increased antioxidant activity Inhibited the deterioration of mushroom quality	slowed water loss, and slowed the browning process Increased bioactive compounds and ascorbic acid content Extended shelf life to 28 days	[112]

Table 5. *Cont.*

Active Packaging	Applicable	Mechanism of Actions [a]	Preservation Effects [b]	Reference
Active ingredients in a biodegradable polyemeric matrix				
PLA/PCL-antimicrobial	*Agaricus bisporus*	Significantly decreased the CO_2 concentration and microbial counts	Preserved firmness, colour, overall quality, and market acceptability of mushrooms for a 12-day storage period	[99]
PLA-0.5% nisin antimicrobial polypeptide	*Boletus edulis*	Reduced polyphenol oxidase activity and total bacteria count	Maintained quality by reducing changes in texture and sensory attributes Shelf life of 18 days with 7.5 and 15 wt.% plasticizer PLA film	[100]
Chitosan-baicalin-liposomes-polyvinyl alcohol	*Agaricus bisporus*	Exhibited high antibacterial activity on *Escherichia coli* and *Staphylococcus aureus*	Inhibited weight loss Reduced browning and rancidity Minimized bacterial growth Maintained nutrients of mushrooms	[103]
Glutenin-tamarind gum-melatonin	*Agaricus bisporus*	Improved mechanical, barrier and thermal properties Decreased polyphenol oxidase activity, respiratory rate, H_2O_2, and O_2^- levels Maintained high antioxidant enzyme activities	Maintained colour and hardness Increased ascorbic acid and glutathione content Maintained quality Delayed senescence	[121]
Active ingredients in edible coatings polymeric matrix				
Gallic acid-chitosan	*Agaricus bisporus*	Increased the activities of superoxide dismutase and catalase Reduced respiration rate and polyphenol oxidase activity	Maintained mushroom quality by reducing the browning degree, O_2^-, malondialdehyde content, H_2O_2, and rate of electrolyte leakage	[93]
Chitosan-tripolyphosphate nanoaggregates	*Agaricus bisporus*	Exhibited a significant reduction in polyphenol oxidase activity Increased the antioxidant capacity	Reduced the browning index Preserved ascorbic acid and firmness Increased phenolic compounds	[101]

[a] respiration and energy metabolism, antimicrobial activity, antioxidant activity; [b] nutritional value, shelf life, and sensory quality. PLA—Polylactic acid, H_2O_2—hydrogen peroxide, O_2^-—superoxide radical.

2.5. Nanopackaging

Nanopackaging is the process of incorporating nano-scale sizes and structures ranging from 1–100 nm [122,123]. Nanoparticles such as zinc oxide, starch, carbon nanotubes, silver nanoparticles, titanium dioxide, chitosan nanoparticles, nanoclay, antimicrobial nanomaterials, and silver are widely used and have huge potential in food packaging. Recent studies have classified nanomaterials into two separate categories with respect to their material and shape. The material group includes metallics, carbon, organics, boron nitride, minerals, and silicon, while the shape group involves quantum dots, nanowires, nanofibers, aerogels, nanorods, nanosheets, and nanotubes [123,124]. Nanoscale fillers in polymeric matrixes can improve the mechanisms of action of packaging materials, including their enzymatic activity, antimicrobial properties, antioxidant activity [125], mechanical strength, thermal stability, and barrier qualities [88,126], and as such offer the best packaging for maintaining quality and extending the shelf life of various types of mushrooms [28,95,127,128]. For example, metal and metal oxide nanoparticles such as gold, silver, titanium dioxide, zinc oxide, and copper oxide have antimicrobial properties for food preservation [122].

The application of nanomaterials to conventional synthetic plastics (adding new properties) or biopolymers (helping to improve mechanical and barrier properties) that form mushroom packaging is currently the subject of growing research [129–135]. Table 6 highlights the mechanisms of action and preservation effects of nanopackaging for mushrooms from a wide range of recent studies.

Table 6. Mechanisms of action and preservation effects of nanopackaging for edible mushrooms.

Nano Packaging	Applicable	Mechanism of Action [a]	Preservation Effects [b]	References
PE/PP-Ag nanoparticles	*Agaricus bisporus*	Delayed respiration rate Inhibited bacterial growth Inhibited ROS accumulation Increased SOD and CAT activity Reduced reactive oxygen species	Maintained sensory quality and firmness Reduced weight loss and browning Extended shelf-life from 8 to 10 days	[53]
PE- Nano masterbatch composite	*Flammulina velutipes*	Delayed ATP content decline Inhibited carbohydrate metabolism Reduced energy metabolism	Maintained post-harvest quality	[127]
PVA-Nano-SiO_2:nano-TiO_2	*Agaricus bisporus*	Reduced the rate of respiration Decreased bacteria counts Increased antimicrobial activity Effectively controlled the level of O_2 and CO_2	Maintained pH, colour, total phenol content, and ascorbic acid content	[132]
PE- Nano Ag:TiO_2	*Agaricus bisporus*	Inhibited glutathione activity Reduced bacterial counts and rate of respiration	Maintained ascorbic acid content	[130]
PE- Nano Ag:TiO_2:attapulgite:SiO_2	*Flammulina velutipes*	Significantly reduced bacterial count Increased SOD, CAT, and POD activities Decreased MDA and tyrosinase activity	Nanoparticles enhanced the umami flavour Increased accumulation of phenolic compounds	[127,135–137]
Chitosan nanoparticle -Cajuput essential oil	*Agaricus bisporus*	Decreased respiration rate Increased antioxidant activity	Maintained firmness and colour Extended shelf life	[28]
Chitosan-nano-SiO_2:1% nisin	*Agaricus bisporus*	Increased antimicrobial activity Reduced polyphenol oxidase activity	Reduced weight loss Maintained colour, pH, and total soluble solids	[138]
1-MCP: nano-packaging, 4 °C, RH 90%–95%	*Pleurotus eryngii*	Decreased respiration rateEnhanced antioxidant activity Increased PPO, SOD, and CAT activities	Maintained texture Improved soluble proteins	[27]
Chitosan-acetic acid: glycerol: SiO_2 nanoparticles	*Agaricus bisporus*	Reduced peroxidase activity Increased superoxide dismutase and catalase activities Increased antioxidant activity Reduced respiration rate	Prolonged shelf life to 12 days. Increased total phenol content Maintained overall quality	[139]
PLA-nanoTiO_2	*Lentinus edodes* *Agaricus bisporus*	Inhibited microbial activity Reduced respiratory rate	Decreased reducing sugars Reduced vitamin C content	[140]

[a] respiration and energy metabolism, antimicrobial activity, antioxidant activity; [b] nutritional value, shelf life, and sensory quality. CAT—catalase, H_2O_2—hydrogen peroxide, POD—peroxidase, O_2^{-}—superoxide radical, PPO—polyphenol oxidase, SOD—superoxide dismutase, MDA—malondialdehyde, ROS—reactive oxygen species.

Nanoparticles incorporated in films can increase the shelf life of fresh produce by regulating the exchange of gases across the films. Nanopackaging can prevent oxidative damage and aging in mushrooms by lowering the respiration rate and ethylene synthesis, thereby preserving high levels of ATP and energy metabolism in cells [29,53]. Studies have shown that nanocomposite packaging materials containing nanoparticles of silver, titanium, and silicon can effectively postpone the degradation of membrane lipids, decrease POD activity, tyrosinase activity, and reactive oxygen in mushrooms [53,130,141]. For example, a nanocomposite film of polyethylene with a mixture of nanosilver and nanotitania significantly inhibited glutathione activity, reduced the rate of respiration and bacterial counts, and maintained the ascorbic acid content of *Agaricus bisporus* mushrooms [130]. On the other hand, a mixture of chitosan with nanosilica and 1% nisin nanocomposite film increased antimicrobial activity, reduced polyphenol oxidase activity and weight loss, and maintained the color, pH, and total soluble solids of *Agaricus bisporus* mushroom [138].

2.6. Modified Atmosphere Packaging (MAP)

MAP increases the shelf life of mushrooms by lowering the amount of reactive oxygen species, thereby blocking microbial activity and respiratory metabolism. Studies have shown that MAP is regarded as an efficient, straightforward, and relatively inexpensive packaging technique for fresh mushrooms [21]. To create a passive modified atmosphere, packaging bags, film covering the tray, or a tray with microporous material are directly perforated [142,143], contributing to preservation by controlling the amount and makeup of gases. Table 7 provides an overview of the mechanisms of action and preservation effects of modified atmosphere packaging for mushroom. According to studies, fresh mushrooms are preserved better in environments with low O_2 levels (between 2% and 10%) and limited CO_2 levels (up to 5%).

Table 7. Mechanisms of action and preservation effects of modified atmosphere packaging for mushrooms.

Modified Atmosphere Packaging	Applicable	Mechanism of Action [a]	Preservation Effects [b]	Reference
PE/PA-calcium chloride-citric acid/10% O_2, 5%CO_2/ 5%O_2, 10% CO_2	*Pleurotus florida*	Significantly decreased respiration rate Increased radical scavenging activity	10% O_2 and 5% CO_2: retained quality, received higher sensory ratings and storage life of 25 days Lowered the changes in weight, pH and TSS, and total polyphenol contents	[143]
Polyvinyl chloride-polyethylene-silicon window	*Pine-mushrooms*	Lowered respiratory rate Increased CAT activity	Delayed texture and flavour changes, reduced browning and weight loss, delayed senescence Decreased ammonia content	[144]
Biorientated polypropylene-gamma irradiation	*Lentinula edodes*	Decreased respiratory rate Significantly decreased microbial count Increased antioxidant ability Reduced microbial activity	Increased total sugar content Lowered the accumulation levels of malondialdehyde Promoted phenolic compounds	[145]

Table 7. *Cont.*

Modified Atmosphere Packaging	Applicable	Mechanism of Action [a]	Preservation Effects [b]	Reference
High CO_2 (20% CO_2 + 15% O_2) **Low CO_2 (30% O_2 + 2% CO_2)** **High N_2 (85% N_2, 15% O_2)** **Low O_2 (2% O_2 + 30% CO_2), at 4 °C, 95% RH**	*Pleurotus eryngii*	Optimised rate of respiration attained with 20% CO_2 + 15% O_2	High total phenolic content Reduced browning Shelf life of 10 days	[146]
Cellophane film-CO_2 scavenger	*Agaricus bisporus*	Equilibrium gas composition of 3.6% O_2 and 11.5% CO_2 attained	Maintained weight loss, pH, firmness and colour	[142]
50% CO_2:50% N_2 **70% CO_2:30% O_2** **50% CO_2:50% O_2, at 4 °C**	*Crassostrea plicatula*	Improved beneficial bacterial diversity Optimized condition CO_2:O_2 (70%:30%)	Reduced microbial growth	[147]
Chitosan-nanopackaging-10% O_2 10% CO_2	*Agaricus bisporus*	Reduced respiration rate	Minimized changes in quality	[148]
CO_2:20% O_2 (applied at 2 h; 12 h and 22 h)	*Agaricus bisporus* *Pleurotus ostreatus*	Optimized process attained at 12 h CO_2 treatment Inhibited physiological processes	Maintained quality	[149]
Alginate coating-high O_2	*Lentinus edodes*	Alginate coating (2%) + 100% O_2: Reduced microbial count Inhibited the activity of PPO and POD	Maintained firmness Delayed browning, cap opening, changes in soluble solids, total sugars, and ascorbic acid Shelf life of 16 days	[150]

[a] respiration and energy metabolism, antimicrobial activity, antioxidant activity; [b] nutritional value, shelf life, and sensory quality. CAT—catalase, POD—peroxidase, PPO—polyphenol oxidase.

The effects of multiple initial gas components (ranging from low 3% to high 100% of O_2 content) on the nutrient components (polysaccharides, total phenols, and free amino acids) of fresh *Lentinula edodes* mushroom were studied [151,152]. According to the authors, high-O_2 packaging (more than 50% O_2) can enhance the umami amino acid content while preventing the synthesis of ethanol and electrolyte leakage. MAP packaging involving PE/PA, calcium chloride, and citric acid with 10% O_2 and 5% CO_2 significantly decreased the respiration rate, increased radical scavenging activity, retained quality, received higher sensory ratings, lowered the changes in weight, pH and TSS, and total polyphenol contents, and extended the storage life of *Pleurotus florida* mushroom to 25 days [143].

3. SWOT Analysis

3.1. Strength

Regardless of the type of packaging system, they all play an important role in maintaining or improving the quality of mushrooms and extending their shelf life [29]. Each packaging system has unique performance characteristics defining their strengths/benefits in terms of preserving edible mushrooms, safety, and circular economy impact.

Considering the high bioactivity of mushrooms, such as their transpiration and respiration rate, extreme values of relative humidity within the packaging system have negative effects. For example, low relative humidity can cause loss of weight and texture/hardness, whereas high relative humidity can cause water vapour to condense within the packaging and on the mushroom surface, providing free water for microbial growth and discoloration [15]. In this regard, MAP is an effective, easy, and economical mushroom packaging technology that prevents water vapor condensation by changing the gas composition and moisture transport within the packaging system.

As discussed in this review article, most recent innovative packaging technologies apply a combination of techniques whereby active ingredients or nanoparticles are incorporated in a bio-polymeric matrix, leading to functional edible coatings, biodegradable packaging, active packaging, or nanopackaging for preservation of edible mushrooms. These innovative functional packaging systems are based on biopolymers, making them environmentally friendly, biodegradable, non-toxic, renewable, and biocompatible [29,153]. This makes them the best alternative to synthetic single-use plastic packaging materials such as polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP) used in packaging in the Irish mushroom industry [154]. This can significantly contribute to a continuous cycle of resource utilization, reducing waste and creating a closed-loop system to promote a more sustainable future and transition to a circular bio-economy.

3.2. Weakness

Recycled plastic and biopolymer-based packaging materials can eliminate single-use plastics in circular packaging systems or circular economies [154]. However, in Europe fresh edible mushrooms are generally retailed in polypropylene (PP) punnets wrapped in a stretchable polyvinyl chloride (PVC) cling film, and trays are single use plastics with a label on the top [155]. This kind of film not only has high permeability to O_2 and CO_2, it uses single-use plastics subject to environmental criticism, and might be banned for food packaging in the future. The packaging film must be environmentally friendly and adapted to the O_2 and CO_2 requirements of the commodity, which largely depend on the storage temperature [153,156]. Similarly, the packaging systems used in the Irish mushroom industry represent one of the main contributing factors to the high percentage of plastic waste sent to landfills and incinerators in Ireland [154]. According to EU Packaging Regulations (SI 322/2020), Ireland must hit recycling targets of 65% of all packaging by 2025 and 70% by 2030, whereas the 2023 report of the Environmental Protection Agency (EPA) indicated that in 2021 only 28% of plastic waste was recycled in Ireland.

Studies have shown that the use of single or multiple perforations in MAP can pose risks due to microbial safety, moisture penetration into the product, and loss of volatile flavor compounds [157]. On the other hand, the design of MAP depends on the properties of the packaging material, gas composition in the environment, sample surface, storage temperature, and humidity [142,158]. This complicates operation and control, and requires consideration of all of the above parameters to allow for species-specific MAP design for mushrooms.

Because of these limitations of MAP, as discussed in Section 2, current studies have focused on innovative functional packaging materials such as active packaging, edible coatings, biodegradable film packaging, and nanopackaging; however, all of these have their own limitations. For example, active packaging systems are emerging with active roles as O_2/ethylene scavengers, CO_2 generation systems, antioxidants, antimicrobials, and odor absorbers. However, the main challenge is to control the release rate of active ingredients within active packaging systems during storage [29]. For this reason, there is increasing research on the need for encapsulation techniques for active ingredients in edible coatings and biodegradable packaging systems; in particular, synergistic effects are worth further investigation.

Biodegradable film packaging has poor technical and functional properties such as mechanical properties and barrier properties, which limits its industrial expansion [29,153,156]. Overall, the limitations of emerging packaging technologies such as edible coatings, biodegradable film packaging, and nanopackaging depend on the primary origin, production method, and waste management system of the biopolymer. Therefore, life cycle assessment of materials is necessary to make them into global industrial food-grade packaging materials. On top of this, nanopackaging and active packaging materials may pose migration issues threatening the safety of humans and the environment.

3.3. Opportunities

From MAP to innovative functional packaging materials such as active packaging, biodegradable packaging, edible coatings, and nanopackaging, the continued expansion of innovation in packaging technology is enabling innovation of a variety of sustainable packaging options to close the loop on plastic waste and promote a circular economy. The development of MAP using recycled materials and a combination of these packaging formats can help in reshaping the way in which mushrooms are packaged and consumed while reducing food and plastic waste.

For example, recycled polyethylene terephthalate (rPET) is a sustainable approach to move away from single-use plastics. It is a lightweight, rigid packaging material with excellent barrier properties, which can support the circular economy by using recycled materials and minimizing waste [154]. The team behind the Science Foundation of Ireland (SFI) Food Waste Challenge winner Leaf No Waste project packaging team (based in National Prepared Consumer Food Research Centre, Teagasc, Ashtown) is currently investigating and trialling the use of novel rPET for fresh produce packaging. PET mono and rPET films can be used to introduce modified atmosphere in the package to extend the shelf life of fresh produce such as mushrooms. This can support Ireland in complying with the EU Packaging Regulation (SI 322/2020). The lightweight novel rPET plastic punnets are fully recyclable compared to PP (polypropylene), which is the most used plastic packaging material in Irish mushroom packaging. If successfully used, PET monomaterials could eliminate the use of Poly-Vinyl Chloride (PVC) in fresh produce packaging in general.

Mixing biodegradable polymers with nanoparticles is one of the most effective ways to obtain novel packaging materials with desirable properties. For example, the incorporation of nanomaterials or active ingredients in biodegradable packaging, edible coatings, and MAP can improve the techno-functional properties of packaging materials and extend the shelf life of mushrooms.

In recent years, functional paper and cardboard packaging for raw mushrooms has gradually emerged as a sustainable alternative to single-use plastics [159]. Therefore, incorporating ethylene scavengers, tyrosinase inhibitors, and essential oils to develop innovative activated paper and pulp trays can help slow down respiration and softening rates while preventing weight loss and browning of Irish edible mushrooms. For instance, the SFI food waste challenge winner the Leaf No Waste project aimed to develop novel sustainable functional compostable food contact packaging materials by increasing diversification of biopolymer sources through utilization of renewable biological resources and valorization of waste, which can support the Irish bio-economy action plans and reduce plastic waste.

Interestingly, many industries around the world are now moving towards producing biopolymers-based packaging, such as WikiFoods and Loliware's edible packaging, Ecovative packaging from mushroom mycelium, Nature Works plant-based plastics, reusable packaging systems from Loop, and a number of companies producing recycled paper and cardboard. Considering the current advancements in research and industrial trends focusing on bio-based packaging technologies, there is a great opportunity for recycled plastic MAP, edible coatings, biodegradable packaging, nanopackaging, and active packaging to promote a circular economy in the Irish edible mushroom industry.

3.4. Threats

In MAP, the use of perforation techniques may involve microbial safety risks, though in biodegradable film packaging and edible coatings the use of pure biopolymers poses no threat to society or the environment [29,153,156]. However, when biopolymers are combined with nanofillers or active ingredients to improve the functionality of the packaging materials, there might be a risk that these active ingredients will enter the mushroom and cause both short-term and long-term health hazards. Additionally, nanoparticles or active ingredients might migrate into soil or water bodies during the biodegradation process; hence, there could be a risk of environmental pollution. As set out in Section 2 of this review, there is a lack of research on migration studies concerning innovative packaging materials.

4. Conclusions

This review paper offers a theoretical foundation on the mechanisms of action and preservation effects of active packaging, edible coatings, compostable/biodegradable packaging, modified atmosphere packaging, and nanopackaging for new approaches to preserve Irish edible mushrooms. In light of the characteristics of various mushroom species and packaging systems, it is best to combine different packaging techniques in order to fully utilize the advantages of each and achieve the best preservation effect. Potential migration of active ingredients or nanoparticles from packaging materials needs attention in future research to ensure food safety and regulatory compliance.

The SWOT analysis highlights the strength, weakness, and threats of these packaging systems and discusses the potential opportunity presented by these packaging systems for trialling innovative packaging materials for fresh mushroom in the Irish context. This could promote plastic waste reduction by addressing potential strategies around creating a continuous cycle of natural resource use for biopolymers, active ingredients, edible coatings, and nanopackaging in which plastic packaging materials are reused or recycled instead of being disposed of after a single use, aiding the shift towards a more sustainable and circular bio-economy.

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