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Review

Emerging Technologies for Extracting Antioxidant Compounds from Edible and Medicinal Mushrooms: An Efficient and Sustainable Approach

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Abstract

Edible mushrooms are well-known for their culinary and nutritional values. Additionally, they serve as a natural source of polyphenols, a group of bioactive compounds that significantly treat diseases associated with oxidative stress. The polyphenolic profile of mushrooms mainly consists of phenolic acids and flavonoids, whose chemical properties have attracted the attention of both the food and pharmaceutical industries. Consequently, methods for extracting polyphenols from mushrooms encompass conventional techniques (maceration and Soxhlet extraction) as well as innovative or green methods (ultrasound-assisted extraction, microwave-assisted extraction, pressurized liquid extraction, supercritical fluid extraction, enzyme-assisted extraction, and pulsed electric field extraction). Nonetheless, extraction with pressurized liquids and supercritical fluids is considered the most suitable method, as they function in a gentle and selective manner, preserving the integrity of the phenolic compounds. The use of mushroom-derived phenolic compounds in food and pharmaceutical formulations continues to face challenges concerning the safety of these extracts, as they might contain unwanted substances. Future applications should incorporate purification systems to yield highly pure extracts, thereby creating safe polyphenol carriers (for food and pharmaceutical products) for consumers.

Keywords: extraction; edible mushrooms; phenolic compounds; emerging technologies

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1. Introduction

Edible mushrooms have been used as food and traditional medicine in various countries [1]. Although there are around 1600 species of mushrooms, only 100 species have been recognized as suitable for human consumption [2]. However, only 33 species are cultivated worldwide, among which the white mushroom (*Agaricus bisporus*), the oyster mushroom (*Pleurotus ostreatus*), and the rice straw mushroom (*Volvariella volvacea*) stand out [3,4]. These mushrooms are an excellent source of protein, fiber, vitamins, and minerals, as well as containing polyphenols with important bioactive properties [5,6], which have gained the

interest of the pharmaceutical and food industries [7]. These compounds can be employed in the formulation of nutraceutical foods and the development of pharmaceuticals with targeted bioactive properties [8].

Phenolic compounds are secondary metabolites whose chemical structure presents at least one aromatic group, which must always be hydroxylated [9]. These compounds have various chemical structures, from monomers to high-molecular-weight polymers between 200 Da and 3500 kDa [10,11]. The polyphenol content ranges from 1.6 to ~105 mg GAE/g dry weight. However, this content may vary depending on the agronomic conditions and the type of mushroom grown [12,13]. Furthermore, the polyphenols present in mushrooms can be grouped into different specific families, such as phenolic acids, flavanols, flavonols, and flavones [14]. For the food industry, gallic acid inhibits lipid oxidation and microbial growth in meat products, prolonging their shelf life [15]. For the pharmaceutical industry, flavonols, such as quercetin, regulate blood glucose levels and insulin sensitivity [16]. Meanwhile, flavanols such as catechin and epicatechin have antibacterial and antioxidant properties [17]. However, despite the potential of edible mushrooms as an important source of phenolic compounds, selecting appropriate extraction techniques and parameters for their recovery remains a matter of discussion.

Different extraction techniques have been developed to recover phenolic compounds from edible mushrooms [18,19]. Conventional techniques such as maceration, shaking, and Soxhlet extraction are widely used due to their easy operation and scale-up [12,20]. However, these techniques require long extraction times (>4 h), large quantities of toxic solvents such as methanol, acetone, and hexane, and high temperatures (>40 °C) [21]. These conditions can degrade and/or oxidize the polyphenols present in the different species of mushrooms [22]. Contrary, alternative, or environmentally friendly technologies such as pressurized liquid extraction (PLE), ultrasonic-assisted extraction (UAE), supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), enzyme extraction (EAE), and pulsed electric field extraction (PEF) have shown that they can not only preserve polyphenols but are also more selective in extracting compounds of interest [23]. These techniques require shorter process times (5–30 min) and smaller amounts of solvent, and they are useful for recovering higher contents of phenolic compounds than conventional methods [19,24–26].

In addition, the extracts obtained through these technologies can be used to formulate nutraceutical, pharmaceutical, and functional food products [27]. Despite advances in this field, a significant gap remains in knowledge regarding the comprehensive comparison of different extraction techniques in terms of the efficiency, sustainability, quality, and food applications of the phenolic compounds obtained. Thus, this review provides an analysis of the current techniques employed for extracting polyphenols from edible mushrooms, with a focus on the advantages associated with alternative technologies. Furthermore, it addresses the prospective challenges related to the safe and effective application of these extracts within the food and pharmaceutical industries.

2. General Characteristics of Edible Mushrooms

Edible mushrooms are very popular in the preparation of various dishes such as soups, stews, salads, and sauces, as well as in the preparation of burgers and sausages due to their meat-like flavor and texture [28–30]. The structure of mushrooms comprises a scaly textured cap or pileus, whose function is to protect the gills or lamellae. Meanwhile, the stipe or stem connects the pileus to the mycelial threads through which nutrients are transferred (Figure 1) [31]. However, the shape, color, and chemical composition of mushrooms vary depending on the species and agronomic characteristics of the crop [32].

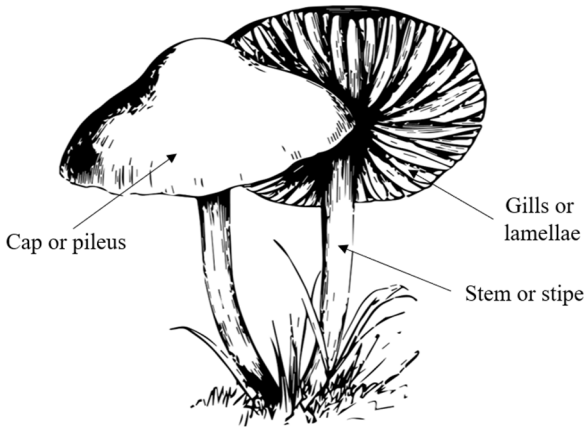


Figure 1. Structure of the edible mushroom.

The production of edible mushrooms worldwide reaches 44.97 million tons annually [33]. China is the main producer of cultivated mushrooms (~44.13 million tons), followed by Japan, the United States, and Poland with ~5.2, ~4.4, and ~2.8 million tons, respectively [34–36]. In Latin America, Mexico is the largest producer of edible mushrooms with 80.8% of the region's total production, followed by Brazil and Colombia with 7.7% and 5.2%, respectively [37]. The most cultivated mushroom species are shiitake (*Lentinus edodes*), oyster mushroom (*Pleurotus ostreatus*), rice straw mushroom (*Volvariella volvacea*), portobello (*Agaricus bisporus* and *Agaricus brunnescens*), and enoki (*Flammulina* sp.) [38]. Although edible mushrooms are a natural source of protein (120–350 mg/kg ds), dietary fiber (8–10 mg/kg ds), vitamins (12–29.9 mg/kg ds), and minerals (1.8–2.3 g/kg ds), the presence of bioactive compounds is interesting for the food and pharmaceutical industries [39,40].

3. Bioactive Compounds in Edible Mushrooms

Edible mushrooms present different types of bioactive compounds such as terpenoids, sterols, and polyphenols, which are secondary metabolites related to the prevention and treatment of chronic diseases [41]. Although terpenoids and sterols possess anti-inflammatory and anticancer properties [42,43], polyphenols are present in higher concentrations, whose antioxidant properties neutralize free radicals, protecting cells from oxidative stress [44].

3.1. Phenolic Compounds in Edible Mushrooms

In edible mushrooms, phenolic compounds can be classified according to the type of chemical structure, the number of benzene rings, and molecular weight as flavonoids and non-flavonoids [45]. In particular, non-flavonoid compounds include phenolic acids (benzoic and cinnamic) [9], while flavanols, flavonols, and flavanones belong to the flavonoid group (Figure 2). Interestingly, the latter have a structure with a greater number of functional groups (OH), which increases their ability to chemically interact with other reactive molecules or free radicals (Figure 2) [46].

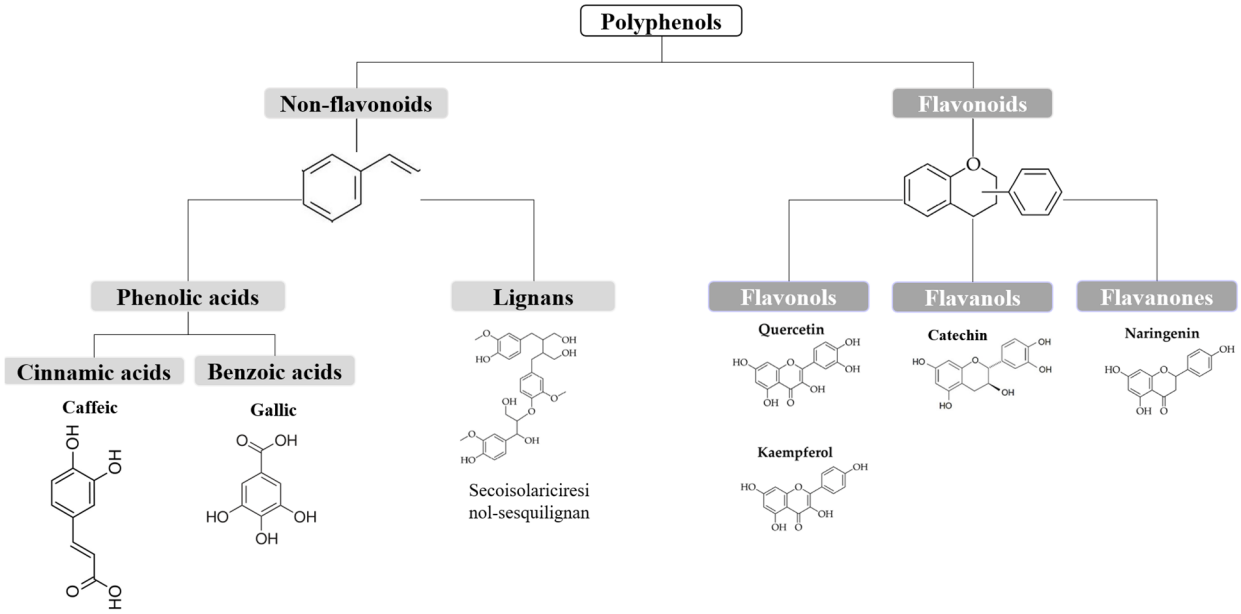
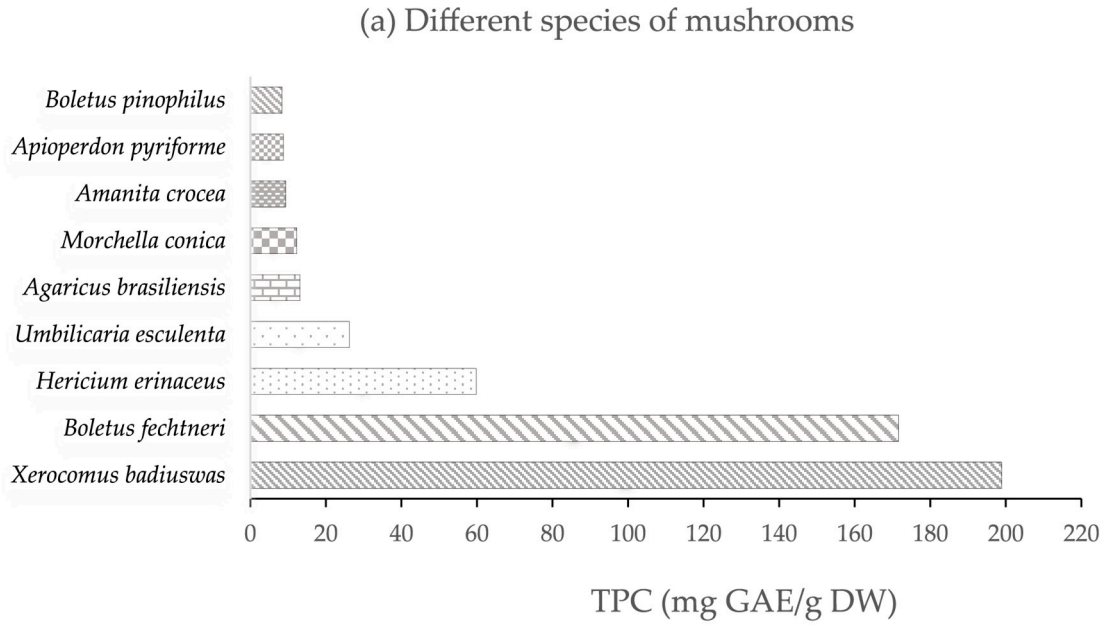


Figure 2. Classification of polyphenols reported in edible mushrooms.

The content of phenolic compounds varies considerably among different mushroom species (Figure 3a). For example, the mushroom *Xerocomus badius* was found to have ~15, ~22, ~14, ~20.3, ~7, ~23, and ~2.3 times higher total polyphenol content compared to the mushrooms *Morchella conica*, *Apioperdon pyriforme*, *Agaricus brasiliensis*, *Amanita crocea*, *Umbilicaria esculenta*, *Boletus pinophilus*, and *Hericium erinaceus*, respectively (Figure 3a) [12,47–51]. These differences are probably due to genetic, agronomic, and environmental factors [52]. Furthermore, edible mushrooms exhibit higher phenolic compound content than other plant matrices (Figure 3b). For example, the mushroom *Xerocomus badius* was found to have ~23, ~61, ~85, ~93.7, ~94, ~94.4, and ~96% higher polyphenol content compared to pistachio peel, coffee residues, orange peel, hazelnut peel, apple pomace, and cocoa shell, respectively (Figure 3b) [31,53–59]. Thus, mushrooms can be considered as a new alternative for antioxidant compounds compared to other plant matrices.



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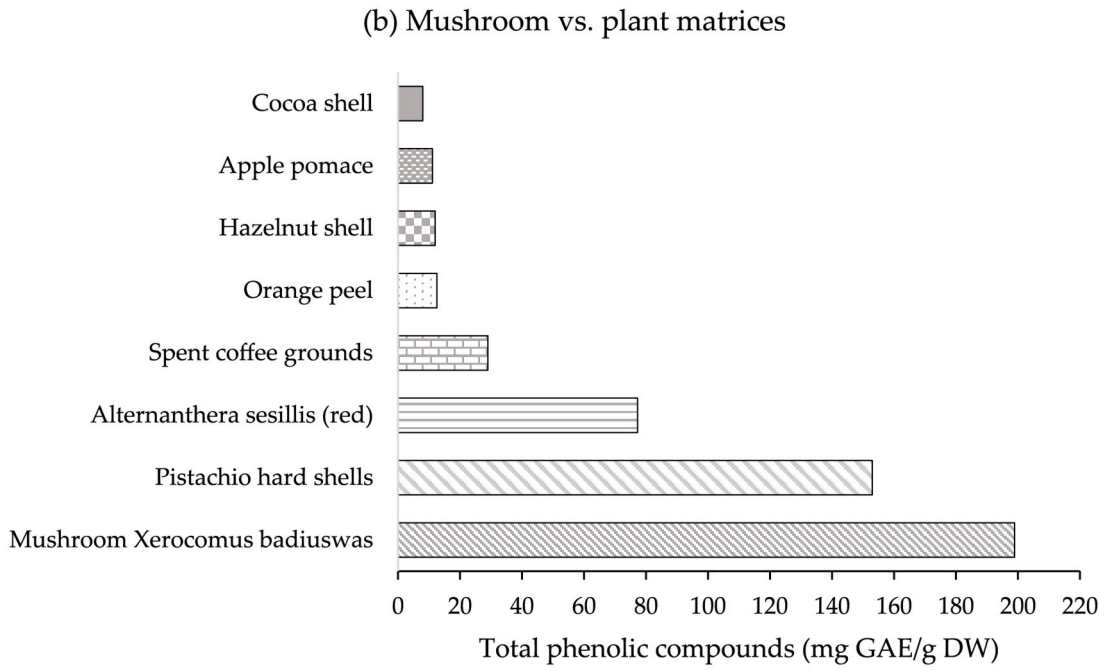

Figure 3. Comparison of total phenolic compounds between mushroom species (**a**) and Mushroom vs. plant matrices (**b**).

3.2. Specific Polyphenols

Edible mushrooms contain different families of polyphenols, such as phenolic acids and flavonoids [9]. In particular, phenolic acids represent the largest proportion of phenolic compounds in mushrooms, such as gallic acid, protocatechuic acid, and cinnamic acid, whose properties relate to cancer cell inhibition (Table 1) [60]. The concentration of phenolic acids can vary among mushroom species (Table 1). For example, the mushroom *Pleurotus ostreatus* presents ~84.5 times more homogentisic acid than the mushroom *Cantharellus cibarius* (Table 1). Meanwhile, the mushroom *Pleurotus nebrodensis* contains ~93% and 98% more protocatechuic acid than *Sarcodon imbricatus* and *Morchella elata*, respectively (Table 1). Meanwhile, quercetin, catechin, rutin, kaempferol, hesperetin, naringenin, and myricetin are the most abundant flavonoids in this matrix type (Table 1) [61,62].

Table 1. Specific polyphenols of different species of edible mushrooms.

Mushroom Species	Specific Polyphenols	Reference
Morchella elata	Gallic acid (1.17 µg/g), protocatechuic acid (1.98 µg/g), catechin (10.24 µg/g), ellagic acid (0.39 µg/g), rosmarinic acid (0.04 µg/g)	[63]
Russula vinosa Lindblad	Fumaric acid (52 µg/g), gallic acid (2.5 µg/g), catechin hydrate (3.65 µg/g)	
Russula azurea Bres	Gallic acid (1.45 µg/g), fumaric acid (41.76 µg/g), ellagic acid (0.73 µg/g), rosmarinic acid (0.09 µg/g), *trans*-cinnamic acid (0.35 µg/g)	
Cantharellus cibarius	Pyrogallol (187.28 µg/g), benzoic acid (6.08 µg/g), resveratrol (1.65 µg/g), homogentisic acid (3.75 µg/g)	[64]
Agaricus bisporus (white mushroom)	Cinnamic acid (216.67 µg/g)	[65]
Pleurotus ostreatus (oyster mushroom)	Homogentisic acid (317 µg/g), cinnamic acid (131.73 µg/g), p-coumaric acid (13 µg/g)	

Table 1. *Cont.*

Mushroom Species	Specific Polyphenols	Reference
Lentinula edodes (shiitake)	Rutin (2100 μg/g) and quercetin (91 μg/g)	[66]
Ganoderma lucidum	Gallic acid (1.016 μg/g), *trans*-cinnamic acid (0.104 μg/g), quercetin (0.968 μg/g), kaempferol (0.918 μg/g), herretin (3.22 μg/g), and naringenin (2.18 μg/g)	[62]
Sarcodon imbricatus	Protocatechuic acid (7.48 μg/g), myricetin (34 μg/g), chlorogenic acid (20.7 μg/g), quercetin (65 μg/g)	[67]
Pleurotus nebrodensis	Protocatechuic acid (105 μg/g) and hesperetin and biochanin-A (12 μg/g)	[68]

4. Extraction Methods

Several studies have developed methods for extracting polyphenols from different plant matrices, such as peels, seeds, and roots [32,69,70]. However, the extraction of polyphenols from edible mushrooms represents a challenge due to the complex composition of their cell wall, predominantly consisting of chitin, β-glucans, and structural proteins, which limit the recovery of these compounds [71,72].

Conventional methods such as maceration and Soxhlet have been widely used due to their ease of use and low cost of implementation at an industrial level (Figure 4) [73]. However, these methods have limitations, such as lengthy process times, excessive solvent consumption, and potential degradation of thermally sensitive phenolic compounds [21]. Faced with this scenario, emerging or green methods have proven to be more efficient in breaking the cell wall of mushroom matrices compared to conventional methods (Figure 4) [74]. Therefore, selecting the appropriate method is pivotal for maximizing polyphenol recovery while maintaining their bioactivity.

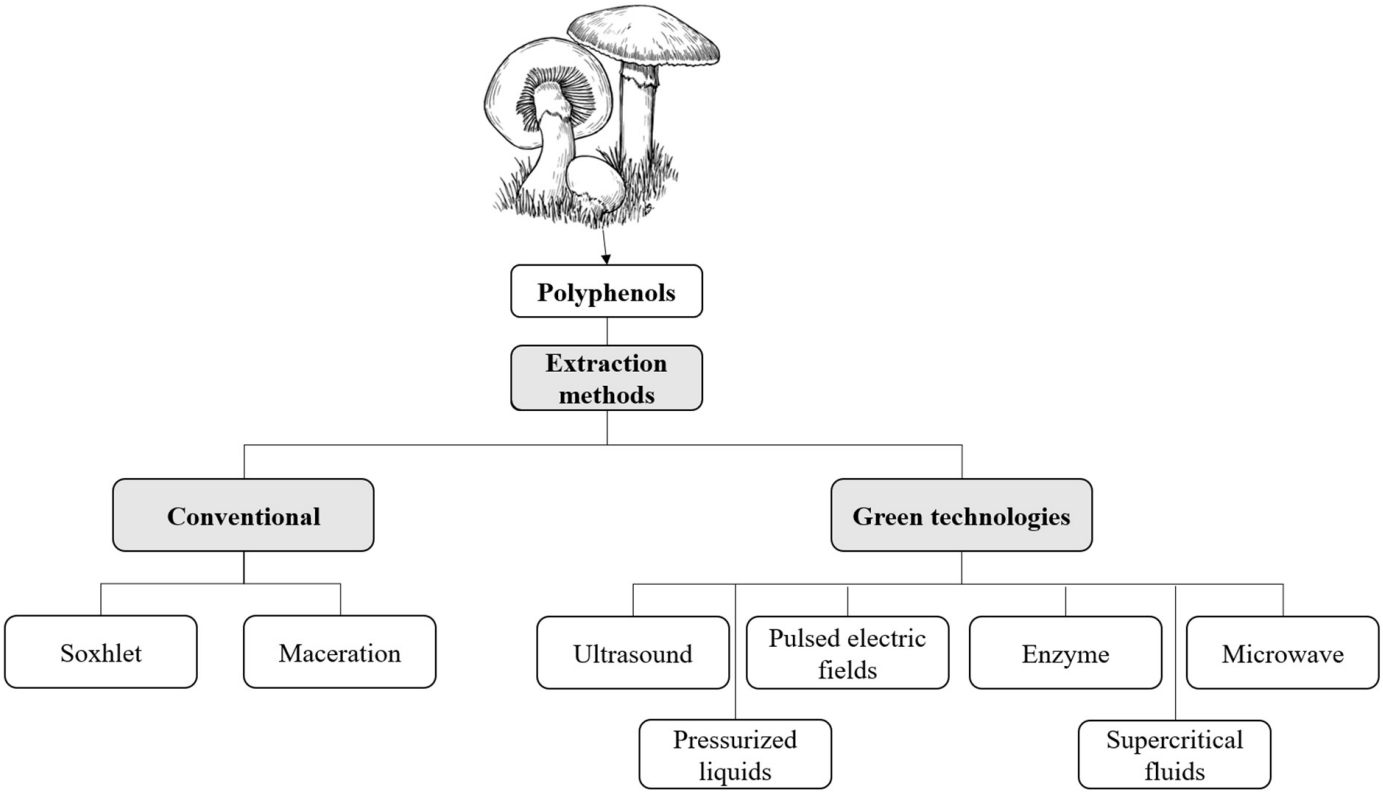

Figure 4. Methods used for the recovery of polyphenols from edible mushrooms.

4.1. Conventional Extraction Methods

4.1.1. Soxhlet

Soxhlet extraction is commonly used for lipid recovery; it can also be used to recover polyphenols from edible mushrooms [20,75]. This system heats the solvent, which evaporates, condenses, and falls onto the sample contained in a cartridge. The solvent then percolates through the solid matrix and extracts the phenolic compounds, returning to the flask by siphon. This process is repeated continuously for several hours until all of the compound of interest is recovered [76]. However, Soxhlet extraction requires large amounts of sample (10–20 g), lengthy extraction times (2–11 h), and substantial amounts of solvent (100–400 mL), also resulting in excessive thermal energy loss (Table 2). For example, Sevindik et al. [12] reported that the optimal extraction time to recover 59.75 mg GAE/g of phenolic compounds from *Hericium erinaceus* was 7.83 h. However, prolonged times represent a significant operational feasibility and energy efficiency limitation.

4.1.2. Maceration

Maceration is a solid–liquid extraction method that enables the extraction of polyphenols using organic solvents at room temperature or moderately high temperatures below their boiling point [77]. Additionally, agitation during the maceration process facilitates the transfer of phenolic compounds from the cells of the fungal matrix to the extraction solvent [78–80]. Similar to the Soxhlet method, a prolonged extraction time has a positive impact on the yield of polyphenols from edible mushrooms when using maceration (Table 2) [62,78,81]. Furthermore, a higher solid–liquid ratio enhances the extraction of polyphenols (Table 2) [49,82]. An increase in the volume of liquid relative to the solid likely reduces the medium's viscosity, improving the solvent's diffusivity within the cells and increasing the mass transfer of phenolic compounds to the solvent [83]. However, a higher solid–liquid ratio requires a greater volume of solvent, negatively impacting the process costs of obtaining these phenolic compounds.

Table 2. Conventional extraction techniques for the recovery of phenolic compounds from edible mushrooms.

Edible Mushroom	Conventional Extraction Method	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Hericium erinaceus	Soxhlet	Temperature: 40–70 °C Extraction time: 3–9 h Solid–solvent ratio: 0.5–2 mg/mL	60.67 °C, 7.83 h, 1.98 mg/mL, and ethanol as extraction solvent	59.75 ± 1.82 mg GAE/g	[12]
Pleutorus abalonus, *Auriculata auricula-judae*, and *Pleutorus sajor-caju*	Soxhlet	–	20 g with 400 mL of absolute ethanol for 11 h	*Pleurotus sajorcaju*: 12.21 ± 0.14 mg GAE/g	[84]
Pleurotus ostreatus and *Pleurotus djamor*	Soxhlet and maceration	In the Soxhlet procedure, 10 g of sample in 100 mL of the solvent was boiled for 2 h For the maceration method, 10 g of sample was mixed in 100 mL of solvent and kept under stirring at 110 rpm and 25 °C for 48 h Ethanol/water ratios: 100/0, 80/20, 50/50, 20/0, and 0/100 (*v*/*v*) Mushroom conditions: fresh, oven-dried, and sun-dried	*Pleurotus ostreatus*: maceration using pure water and fresh samples *Pleurotus djamar*: maceration using pure water and fresh samples	*Pleurotus ostreatus* fresco: 41.6 mg GAE/g *Pleurotus djamar* fresco: 11.02 mg GAE/g	[20]
Agaricus bisporus (white), *Agaricus bisporus* (brown), *Lentinula edodes*, *Pholiota nameko*, *Pleurotus eryngii*, and *Pleurotus ostreatus*.	Maceration		80% (*v*/*v*) ethanol at 50 °C, 160 RPM, and solid–solvent ratio of 1:30 g/mL	Stem of *P. ostreatus*: 1.09 ± 0.09 mg QE/g Stem of white *A. bisporus*: 4.02 ± 0.20 mg QE/g	[82]
Boletus edulis and *Cantharellus cibarius*	Maceration	Acid water (10% CH3COOH); ethanol/water/acetic acid (15:76.5:8.5, *v*/*v*/*v*), hexane, and diethyl ether	5 g of mushroom in 150 mL of 10% acidic water	*B. edulis*: 3.72 mg GAE/g *C. cibarius*: 0.79 mg GAE/g	[6]
Neolentinus lepideus	Maceration		The sample (1 g) was macerated for two days in 10 mL of 80% methanol	1.648 mg GAE/g	[85]

Table 2. *Cont.*

Edible Mushroom	Conventional Extraction Method	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Agaricus bisporus (mushroom), *Agaricus bisporus* (Portobello), *Agaricus brasiliensis*, *F. velutipes*, and *Lentinus edodes*	Maceration	Temperature: 25–55 °C Solvent–solid ratio: 30–70 mL Ethanol concentration: 25–75%	*A. bisporus* (mushroom): 50 °C/70 mL/g/75% ethanol *A. bisporus* (Portobello): 55 °C/70 mL/g/75% ethanol *A. brasiliensis*: 55 °C/ 70 mL/g/75% ethanol *F. Velutipes*: 25 °C/ 60.34 mL/g/25% ethanol *L. edodes*: 25 °C/ 59 mL/g/25% ethanol	*A. bisporus* (mushroom): 9.53 ± 0.16 mg GAE/g *A. bisporus* (Portobello): 9.97 ± 0.21 mg GAE/g *A. brasiliensis*: 13.16 ± 0.06 mg GAE/g *F. Velutipes*: 8.38 ± 0.13 mg GAE/g *L. edodes*: 5.66 ± 0.10 mg GAE/g	[49]
Melanoleuca cognata and *Melanoleuca stridula*	Maceration	Extraction solvents: ethyl acetate, methanol, and pure water	5 g of mushroom powder in 100 mL of pure water (solvent) for 48 h	*M. cognata*: 43.38 ± 1.36 mg GAE/g *M. stridula*: 34.02 ± 1.19 mg GAE/g	[61]
Ganoderma lucidum	Maceration	Extraction time (days): 1, 15, and 30 Particle size (mm): 10 and 0.13	40 g of mushroom was extracted with 60% ethanol (1000 mL), 25 °C, 1 day, and 0.13 mm particle size	0.013971.77 ± 0.3 mg GAE/g	[62]
Pleurotus djamor	Maceration	Water (100%) and methanol (100%)	10 g of mushroom in 100 mL of water (100%) for 2 h	5.95 mg GAE/g	[79]
Lentinus edodes, *Volvariella volvácea*, *Pleurotus eous*, *Pleurotus sajor-caju*, and *Auricularia auricular*	Maceration	Extraction solvents: water, 50% (*v*/*v*) ethanol, and diethyl ether, and 1.5 h	*Volvariella volvácea*: 50% (*v*/*v*) ethanol For the mushrooms *Lentinus edodes*, *Pleurotus eous*, *Pleurotus sajor-caju Auricularia auricula*: pure water	*Lentinus edodes*: 36.19 ± 0.59 mg GAE/g *Volvariella volvácea*: 27.89 ± 0.23 mg GAE/g *Pleurotus eous*: 20.31 ± 0.56 mg GAE/g *Pleurotus sajor-caju*: 16.46 ± 0.67 mg GAE/g *Auricularia auricula*: 2.90 ± 0.40 mg GAE/g	[86]

Table 2. *Cont.*

Edible Mushroom	Conventional Extraction Method	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Pleurotus ostreatus, *Pleurotus pulmonarius*, *Schizophyllum commune*, *Volvariella volvácea*, and *Lentinus edodes*	Maceration	Methanol: 10 g of each mushroom powder in 100 mL of methanol at 150 rpm for 1 h at room temperature Hot water: 10 g of each mushroom powder with 100 mL of boiling water (100 °C) and stirring at 150 rpm for 30 min	*Volvariella volvácea* presented the highest content of phenolic compounds in both cases	14.56 mg GAE/g	[80]
Pleurotus citrinopileatus	Maceration with a bath	With cold water for 24 h Hot water: 1 or 2 h	5 g of mushroom in 100 mL of cold water for 24 h	27.5 mg GAE/g	[81]
Pleurotus ostreatus (gray mushroom)	Maceration with a bath	Extraction time: 240–420 min Temperature: 40–60 °C	5 g of sample in 50 mL, 347.6 min at 49.7 °C	8.26 mg GAE/g	[78]

QE: quercetin equivalent.

4.2. Alternative Methods (Green Technologies)

4.2.1. Pressurized Liquid Extraction

Pressurized liquid extraction (PLE) is a term applied to several systems that use the same principle, such as accelerated solvent extraction (ASE), high-pressure solvent extraction (HPSE), subcritical water extraction, or high-pressure hot water extraction (PHWE) [87]. In PLE, the solvent interacts with the solid matrix, which is subjected to temperatures between 50 and 200 °C, 4 to 10 MPa pressures, and short extraction times (5–20 min) [88–90]. Under these conditions, the solvent remains in a liquid state, favoring the rupture of the matrix and mass transfers [91,92].

During PLE, high temperatures (>100 °C) favor the recovery of phenolic compounds from edible mushrooms (Table 3). For example, Sakdasri et al. [19] found that using water at 140 °C improved the recovery of polyphenols by 25.5% compared to 100 °C from *Pleurotus sajor-caju* (Fr.) Singer. Similarly, Krümmel et al. [88] observed that using aqueous ethanol at 80 °C increased the extraction of polyphenols by ~27% compared to 40 °C from *Pleurotus sajor-caju*. In this regard, increasing temperatures enhance the kinetic energy of the solvent, favoring matrix breakdown and interactions between phenolic compounds and other compounds such as protein, polysaccharides, and fibers; consequently, the solubility of these compounds increases [90,92]. Furthermore, high temperatures (>100 °C) combined with high pressures (>4 MPa) favor the reduction in the viscosity and surface tension of the solvent, maintaining its liquid state and avoiding the oxidation and hydrolysis of phenolic compounds [89].

4.2.2. Microwave-Assisted Extraction

The microwave-assisted extraction (MAE) method utilizes the interaction of microwave electromagnetic radiation with the polyphenol-rich botanical matrix. The radiation produces dielectric heating of the solvent and the intrinsic moisture of the sample, where the polar molecules, primarily the solvent, vibrate and rotate rapidly, generating heat through molecular friction. This phenomenon ruptures cell walls and membranes, releasing the polyphenols.

In general, for the extraction of phenolic compounds from edible mushrooms, powers between 100 and 800 W, irradiation times of 1 to 30 min, temperatures ranging from 40 to 140 °C, and solid–liquid ratios of 1:10 to 1:70 (g/mL) are used [66,93]. During this process, the polyphenols are separated from the active sites of the matrix (proteins and carbohydrates). The solvent then diffuses through the matrix, and the polyphenols are released into the extraction solvent [94]. The efficiency of MAE extraction depends primarily on the microwave energy, treatment time, and temperature. Furthermore, the rapid heating of the system reduces thermal gradients, improving the stability and yield of the polyphenols (Table 3) [66,95]. For example, Latif et al. [96] reported that using 58% ethanol combined with 16 min allowed the highest polyphenol yields (14.82 mg GAE/g) from *Agaricus busporus*. Meanwhile, Maeng et al. [97] found that 40% ethanol and 3.8 min were the optimal conditions for extracting polyphenols (4.70 mg GAE/g) from *Coriolus versicolor*. On the other hand, independent of the temperature and process time, particle size reduction also significantly impacts polyphenol extraction efficiency (Table 2). For example, Xiaokang et al. [66] observed that smaller particle sizes (1.75 mm) recovered 36% more polyphenol content compared to 4.75 mm particles from *Lentinula edodes*. Thus, the smaller the particle size, the greater the surface area in contact with the solvent, improving mass transfer [98].

4.2.3. Ultrasound-Assisted Extraction

This method employs ultrasonic waves that induce acoustic cavitation to encourage the formation, growth, and explosive collapse of small bubbles, disrupting the biological matrix. As a result, phenolic compounds are released [99–101]. The UAE process generally uses either an ultrasonic bath or an ultrasonic probe. In an ultrasonic bath, the solid sample is placed in a beaker, flask, or test tube, which is immersed in the liquid medium contained in a stainless-steel tank connected to a transducer. An ultrasonic probe, on the other hand, consists of a probe connected to a transducer, which is immersed directly in the extraction medium [102,103].

During UAE, the most commonly used parameters are short extraction times (5–30 min), low temperatures < 70 °C, and water–ethanol mixtures. Furthermore, in this type of system, the working power is regulated by adjusting the amplitude (20–60%) (Table 3) [71,104,105]. For example, Dong-Bao et al. [27] reported that the use of 42% ethanol favors the extraction of polyphenols by 86% compared to the use of 80% ethanol from the mushroom *Boletus bicolor.* The authors of [106] found that using 40% ethanol allows for the extraction of 2.2 times more polyphenol content than pure water from *Pleurotus ostreatus*. Ethanol reduces the dielectric constant, viscosity, and density of the aqueous solvent, increasing the diffusion of polyphenols into the extraction solvent [107,108].

While some studies report higher polyphenol recovery at high temperatures (Table 3), Gogoi et al. [74] reported an opposite effect where a low temperature of 39 °C favored 14% polyphenol yields from *Pleurotus citrinopileatus* compared to 60 °C. Similarly, Xu et al. [104] reported that a moderate temperature (40 °C) recovered 23% more phenolic compound content than 80 °C from *Thelephora ganbajun*. During the UAE process, high temperatures cause an increase in the vapor pressure of the solvent, which decreases the implosion intensity of the bubbles formed. Consequently, a lower proportion of polyphenols is released [69].

Table 3. Emerging methods for the recovery of phenolic compounds from edible mushrooms.

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Pressurized Liquid Extraction	*Inonotus obliquus*	Subcritical water extraction (SWE)	Temperature: 120 and 200 °C	Solid–liquid ratio (1:10 g/mL), 20 min extraction at 200 °C	89.94 ± 1.58 mg GAE/g	[18]
	Gray oyster mushroom (*Pleurotus sajor-caju* (Fr.) Singer)	Pressurized hot water (PHW)	Temperature (°C): 100, 120, and 140 Pressure (bar): 4, 7, and 10 Time (min): 20, 40, and 60	10 g of mushroom in 300 mL at 140 °C, 9.2 bar, and 20 min	8.49 ± 0.66 mg GAE/100 g DW	[19]
	Lentinula edodes	Accelerated solvent extraction (ASE)	Temperature: 40 to 160 °C Ethanol concentration: 0 to 100%	3 g of mushroom in 100 mL of 23% ethanol at 160 °C	5.78 mg GAE/g DW	[105]
	Pleurotus sajur cajur		Temperature: 40 and 80 °C Mode: dynamic and static Time: 25 min for the static mode and 45 min in a dynamic mode	6 g of mushroom, pure ethanol (99.8%), 10 MPa pressure for 45 min at 80 °C	14.1 ± 04 mg GAE/g	[88]
	Chaga mushroom (*Inonotus obliquus*)	Accelerated solvent extraction (ASE)	Ionized water at different pH values: 2.5, 7.0, 9.5, and 11.5 Temperature: 60 and 100 °C	Extraction solvent at pH 11.5 at 100 °C	82.53 ± 0.66 mg QE/g	[21]
Microwave-Assisted Extraction	White mushrooms (*Agaricus bisporus*)	-	Ethanol concentration: 10–90% Time: 1–30 min Solvent–solid ratio: 5, 8, 13, 17, and 20 mL in 0.2 g	58% ethanol, 16 min, and 12.9 mL/0.2 g	14.82 mg GAE/g	[96]
	Lentinula edodes (shiitake)	-	Particle size: 1.75, 3.35, and 4.75 mm Solid to liquid ratio: 1/40, 1/50, 1/60, and 1/70 g/mL Microwave power: 200, 300, 400, 500, and 600 W Time: 2.5, 5, 10, 15, and 17.5 min	1.75 mm, 1/40 g/mL, 600 W, and 15 min	11.23 ± 1.05 mg GAE/g	[66]

Table 3. *Cont.*

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Microwave-Assisted Extraction	Wild edible mushrooms (*Terfezia boudieri* Chatin, *Boletus edulis*, *Lactarius volemus*)	-	Methanol/water: 100, 80, 50, 20, and 0% Time: 5–25 min Temperature: 20–140 °C Microwave power: 0–1500 W	Dry sample (0.2 g) in 20 mL (80% methanol) at 80 °C, 1500 W, and 5 min extraction	*Terfezia boudieri*: 45.60 mg TR/g *Boletus edulis*: 89.53 mg TR/g and *Lactarius volemus*: 57.62 mg TR/g	[109]
	Coriolus versicolor	-	Extraction time: 1–5 min Ethanol concentration: 0–100% Microwave power: 0–200 W	2 g of mushroom in 20 mL of 40% ethanol, 125 W and 3.8 min	4.70 mg GAE/g	[97]
	White oyster mushrooms (*Pleurotus ostreatus* var. Florida and *Pleurotus ostreatus* (Jacq.) P. Kumm); gray oyster mushrooms *(Pleurotus sajor-caju)*; pink oyster mushrooms (*Pleurotus flabellatus*); brown oyster mushrooms (*Pleurotus cystidiosus*); *Pleurotus eryngii* and *Pleurotus pulmonarius* from Indonesia; *Pleurotus ostreatus* samples from Spain and Germany and *Pleurotus eryngii* from Portugal	-	Solvent composition (0–30% methanol in water), solvent to sample ratio (10:1–20:1 mL/g), and temperature (40–70 °C)	Pure water as solvent, a 17.5:1 mL/g, and a 44 °C, with a 10 min extraction time	*Pleurotus pulmonarius* exhibiting the highest level of gallic acid at 0.43 ± 0.007 mg/g and *Pleurotus ostreatus* var. Florida showing the highest concentration of ρ-hydroxybenzaldehyde at 0.199 ± 0.001 mg/g	[93]

Table 3. *Cont.*

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Ultrasound-Assisted Extraction	*Suillus bovinus*	Ultrasonic bath	% MeOH (50–100%), temperature (10–60 °C), amplitude (10–40%), cycle (0.2–1 s–1), and solid–solvent ratio (0.25 g:10 mL–0.25 g:20 mL)	0.2 g of sample extracted with 15.3 mL of solvent (93.6% MeOH) at 60 °C for 5 min and using 16.86% amplitude and 0.71 s−1 cycles	11.33 mg GAE/g	[22]
	Agaricus biphorus	Ultrasonic bath	Influence of different ultrasound frequencies: 25, 33, and 45 kHz	A frequency of 25 kHz		[110]
	Pleurotus. ostreatus (PeruMyc2412 and PeruMyc2475)	Ultrasonic bath	Solvent (% water in ethanol): 0–50% Solvent–solid ratio (mL/g): 10, 35, and 60 Time (min): 10, 35, and 60 Temperature (°C): 3, 45, and 60	60 °C for 10 min with a solvent–solid ratio of 60 mL/g and 50% ethanol	4.24 mg GAE/g	[106]
	Pleurotus citrinopileatus	Ultrasonic bath	Temperature of 30–55 °C; treatment time: 8–20 min; and solvent–solid 20–50 mL/g	For the aqueous extract: 44 °C, 14 min, 20 mL/g For the ethanolic extract: 39 °C, 13 min, and 20 mL/g	For the aqueous extract: 6.87 mg GAE/g For the ethanolic extract: 9.9 mg GAE/g	[74]
	Agaricus bisporus and *Pleurotus ostreatus*	Ultrasonic bath	Extraction solvents: ethanol, methanol, and acetone Mushrooms dried in a conventional oven (60, 70, and 80 °C) or in a microwave oven (180, 360, and 600 W)	1 g of *Agaricus bisporus*, methanol (80%), conventional drying at 80 °C *Pleurotus ostreatus*: conventional drying at 80 °C using methanol (80%)	*Agaricus bisporus*: 31.680 mg GAE/g *Pleurotus ostreatus*: 30.58 mg GAE/g	[103]

Table 3. *Cont.*

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Ultrasound-Assisted Extraction	*Thelephora ganbajun*	Ultrasonic bath	Ethanol concentration: 10–80%; solvent–solid ratio: 10–80 mL/g Extraction time: 0–30 min Extraction temperature: 30–80 °C Ultrasonic power: 300–800 W	57.38% ethanol, 70.15 mL/g, 10.58 min at 40 °C, and 500 W ultrasound power	91.51 ± 4.38 mg GAE/g	[104]
	Ganoderma lucidum, *Morchella esculenta*, *Lentinula edodes*, and *Hericium erinaceus*	Ultrasonic bath	10 g of dried mushrooms in 70 mL of methanol at 60 °C for 3 h	The *Ganoderma lucidum* mushroom was shown to have the highest content of phenolic compounds	26.40 ± 0.33 mg GAE/g	[111]
	Pleurotus pulmonarius (Fr.)	Probe ultrasound	Extraction power and time: E0 (300 W, 40 min), E1 (460 W, 30 min), E2 (140 W, 50 min), E3 (140 W, 30 min), and E4 (460 W, 50 min) The sample-to-solvent ratio (1:10 g/mL)	E0: 40 min and 300 W	11.07 mg GAE/g	[102]
	Stalks of *Agaricus bisporus*	Probe ultrasound	Ethanol: 70% and 96% Time: 2, 4, 6, 8, 10, 12, 15, 20, 25, 30, and 60 min	The solid–solvent ratio was 1:5 (*w*/*v*, g/mL), 30 min using 70% ethanol at 25 °C	6.00 ± 0.43 mg GAE/g	[73]
	Inonotus hispidus	Probe ultrasound	Extraction solvent: 80% methanol and 40% ethanol (*v*/*v*) Time: 20 to 68.28 min Solvent-to-solid ratio (mL/g): 14.64 to 85.36	Ethanol at 40% (*v*/*v*), 75 mL/g DW, during 20 min of sonication	104.68 mg GAE/g DW	[101]
	Ganoderma lucidum	Probe ultrasound	Time: 20, 40, 60, and 80 min	Ultrasonic power of 600 W for 1 h of extraction; 10 g of mushroom was mixed with 250 mL of distilled water	9.14 ± 0.002 mg GAE/g	[99]

Table 3. *Cont.*

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Ultrasound-Assisted Extraction	Ear mushrooms (*Auricularia auricula-judae*)	Probe ultrasound	Solvent-to-sample ratios (10:1, 20:1, 30:1 mL/g); pulse duty cycles (0.2, 0.6, 1.0 s−1) and temperatures (10, 40, 70 °C)	1 g sample was 18 mL of methanol at 59 °C, with a pulse duty cycle of 0.7 s−1	0.386 mg GAE/g	[112]
	Boletus bicolor	Probe ultrasound	Ethanol at 10, 20, 30, 40, 50, 60, 70, and 80% Liquid-to-solid ratios: 10,1, 15:1, 20:1, 25:1, 30:1, 35:1, 40:1, and 45:1 mL/g Ultrasonic times: 20, 25, 30, 35, 40, and 45 min Temperatures: 30, 35, 40, 45, 50, and 55 °C	Ethanol concentration 42%; solvent to solid ratio 34:1 mL/g; ultrasonic time 41 min; and temperature 40 °C.	13.69 ± 0.13 mg GAE/g DW	[27]
	Hericium erinaceus	Probe ultrasound	Ethanol concentration: 40, 60, and 80% Time: 20, 30, and 45 min Solvent–material ratio: 10, 20, and 30 mL/g	80% ethanol, extraction time of 45 min, and solvent-to-material ratio of 1:30 (g/mL)	23.2 mg GAE/g MS	[113]
Pulsed Electric Field-Assisted Extraction	*Agaricus bisporus*		Field intensity (kV/cm): 2, 2.5, and 3 Specific energy (kJ/kg): 50, 51, 125, and 200 Time (h): 0, 3, and 6	20 g of fresh mushroom in 200 mL of distilled water, 2.5 kV/cm, 50 kJ/kg for 5 h	28.80 ± 2.86 mg GAE/g	[114]
	White mushroom (*Agaricus bisporus*)		Electric field intensity: 12.4 to 38.4 kV/cm Bipolar square pulses: 136 µs and 272 µs	38.4 kV/cm and 272 µs at 85 °C	1.6 mg GAE/g	[13]

Table 3. *Cont.*

Extraction Method	Edible Mushroom	Type	Parameters	Optimal Conditions	Yield of Phenolic Compounds	Reference
Enzyme-Assisted Extraction	Oyster mushrooms (*Pleurotus sajor-caju*)	Cellulose	pH: 4.5, 5.0, 5.5, and 6.0 Temperature: 40, 45, 50, and 55 °C Time: 4, 6, 8, and 10 h.	5 g of mushroom in 100 mL of water, 50 °C, pH 5.5, and 8 h of extraction	0.626 mg TAE/g	[115]
	Inonotus obliquus	Viscozyme L		10 g was dispersed in 400 mL water. The enzyme was added at 5% (*v*/*w*)	72.0 ± 1.2 mg GAE/g	[107]
Supercritical Fluid-Assisted Extraction	Mushroom melena of leon (*Hericium erinaceus*)		Temperature: 40 °C to 60 °C Pressure: 100 bar to 300 bar Ethanol flow rate: 0 a 1 mL/min	3 g de polvo de hongo, 46.38 °C, 100 bar, and 0.99 mL/min de caudal de EtOH.	0.816 mg GAE/g	[108]
	Pleurotus ostreatus		Pressure: 15–25 MPa Temperature: 40–60 °C Amount of co-solvent (ethanol): 100–200 mL	5 g of mushroom, 21 MPa, 48 °C, and 133 mL ethanol as co-solvent	5.48 mg de GAE/g	[116]

4.2.4. Pulsed Electric Field Extraction

Pulsed electric field (PEF) extraction involves applying high-voltage pulses (10 to 80 kV/cm) to a biological matrix for a specific time. The intensity of the generated electric field depends on the applied voltage and the distance between the electrodes [117]. When cells are exposed to this field, cell membranes can be damaged, causing the formation of temporary (reversible) or permanent (irreversible) pores. This phenomenon of cellular damage is called electroporation, which allows the release of polyphenols [118].

Although the number of PEF studies on polyphenol recovery from edible mushrooms is limited (Table 3), the results show its advantages over conventional extraction methods. For example, Calleja-Gómez et al. [114] reported that PEF allowed for the recovery of 87% more polyphenol content than a conventional method from *Agaricus bisporus* (Table 3). Furthermore, the obtained extract presented ~57% more antioxidant capacity to inhibit peroxyl radicals than the conventional extract. In particular, the PEF method exhibits greater environmental sustainability and economic efficiency due to its lower total energy consumption and lower energy requirements per unit of processed product compared to conventional methods [119].

4.2.5. Enzyme-Assisted Extraction

The enzyme-assisted extraction (EAE) method uses specific enzymes to degrade structural components of botanical cell walls, facilitating the release of bioactive compounds (polyphenols). This method is based on the enzymes' ability to hydrolyze cellulases, pectinases, or hemicellulases, releasing phenolic compounds [120]. The EAE operates under moderate pH conditions (3.5 to 7) and low temperatures (35 to 60 °C), reducing the risk of degradation of phenolic compounds [115]. Hwang et al. [107] compared emerging methods (high-pressure, ultrasound, and enzymatic) versus a conventional method (hot water) for the extraction of phenolic compounds from chaga mushroom, where EAE extracted ~4.4% and ~18% higher gallic acid and caffeic acid content compared to the conventional method, respectively. Although the high cost of enzymes represents a challenge for their development and industrial scaling, enzyme-assisted extraction is an effective strategy for recovering large amounts of phenolic compounds.

4.2.6. Supercritical Fluid Extraction

Supercritical fluid extraction (SFE) is an advanced technique that utilizes a fluid at conditions above its critical temperature (20–60 °C) and pressure (80–600 bar). The fluid is in a transition state (gas–liquid), facilitating its diffusion within the solid matrix [121]. Carbon dioxide (CO_2) is the most commonly used fluid in SFE due to its excellent mass transfer properties, density, and viscosity. Furthermore, supercritical CO_2 is a relatively inert substance, considered a GRAS solvent [122]. The main advantages of SFE over conventional techniques include the use of low temperatures, significant reduction in solvent use, higher purity of extracts, and lower energy costs [123].

Joradon et al. [108] reported that using CO_2 during SFE for 60 min favors the extraction of total polyphenols from *Hericium erinaceus*. However, the results obtained with SFE did not differ significantly from those obtained with the maceration process (60% acetone, 72 h). Interestingly, Table 3 shows that the temperatures used in supercritical fluid extraction did not exceed 60 °C. Therefore, thermal degradation would not be a problem for most phenolic compounds in edible mushrooms when using the supercritical fluid technique.

4.2.7. Green Solvents

Although alternative methods, referred to as green technologies, are more sustainable and effective for recovering polyphenols, selecting food-grade solvents such as wa-

ter, ethanol, glycerol, or isopropanol could enhance the recovery of these compounds (Tables 2 and 3) [124]. The effectiveness of these solvents in interacting with the target analytes is largely determined by their polarity [125]. Additionally, it is important to take into account the presence of both polar and non-polar functional groups in the chemical structure of the polyphenols [126].

The polarity of a solvent can be understood through its solvatochromic properties, which refer to its ability to engage in intermolecular interactions such as dipole–dipole interactions, London dispersion forces, and hydrogen bonding with the functional groups of the analytes of interest, including hydroxyl and aromatic groups [127,128]. For instance, water is a highly polar solvent (π^*: 1.09) compared to ethanol (π^*: 0.51), glycerol (π^*: 0.62), and isopropanol (π^*: 0.48) [127,129]. This higher polarity in water explains its greater capacity to form hydrogen bonds with various analytes. Contrary, solvents with low polarity are more adept at establishing intermolecular interactions like dipole–dipole interactions and London dispersion forces. Thus, when selecting a solvent, considering its polarity is crucial. However, other process parameters, such as temperature and pressure, should also be considered.

4.2.8. Economic Evaluation

Several studies have demonstrated that alternative methods for recovering phenolic compounds are both highly scalable and sustainable. For example, several companies offer polyphenol extracts with 30% and 50% polyphenol content priced at USD 32 and USD 15 per 100 g, respectively [130]. In contrast, de Aguiar et al. [131] reported that the production costs for obtaining phenolic extracts using pressurized liquid extraction (PLE) can reach up to USD 25.39 per kg. Meanwhile, Solana et al. [132] found that the process costs for polyphenol extraction using supercritical fluid extraction (SFE) can reach USD 21.90 per kg. Although these examples provide a useful baseline for assessing the economic viability of these techniques, it is crucial to continue researching methods that could further reduce time and energy consumption.

5. Bioactivity of Specific Phenolic Compounds

The polyphenols present in edible mushrooms have bioactive properties with important applications in the food and pharmaceutical industries (Table 4). For example, gallic acid has been shown to have high antioxidant and antibacterial activity, inhibiting strains such as *Stenotrophomonas maltophilia*, and reducing brain oxidative stress induced by environmental toxins [133,134].

Protocatechuic acid stands out for inhibiting lipid oxidation, a key property in preserving fat-rich food matrices and preventing cellular damage induced by lipid peroxidation [135,136]. Quercetin also protects the pancreas against lipid oxidation and acts as a modulator of hyperglycemia [16,137]. These findings support the potential of edible mushrooms as a sustainable source of antioxidant compounds, especially when green technologies are employed for their extraction.

On the other hand, the study of the bioactive properties of phenolic compounds is a prominent research area within the scientific community, where in vitro studies are most common. However, these studies often do not consider biochemical, metabolic, or physiological parameters, among others [138]. In contrast, in vivo studies, particularly in murine models, allow for a more comprehensive evaluation of how polyphenols impact disease progression. For instance, Kaur et al. [139] reported that gallic acid has a protective effect against sodium arsenite-induced toxicity in rats. This effect was primarily attributed to gallic acid's ability to inhibit lipid peroxidation and reduce nitric oxide production, indicating significant antioxidant activity. Given the extensive scientific evidence supporting

the antioxidant, anti-inflammatory, and neuroprotective roles of specific polyphenols in preventing degenerative diseases, edible mushrooms stand out as promising candidates for developing therapeutic and preventive strategies against various degenerative conditions.

Table 4. Bioactivity of the different specific polyphenols.

	Bioactive Properties	Bioactivity	Reference
Gallic acid	Antibacterial activity	Inhibits the proliferation of bacteria such as *Stenotrophomonas maltophilia*, *Achromobacter xylosoxidans*, and *Burkholderia cenocepacia*	[133]
	Antioxidant activity	Relieves paclitaxel-induced neuropathic pain symptoms by inhibiting oxidative stress	[139]
	Antioxidant activity	Prevents oxidative damage to the brain from environmental toxins such as heavy metals, aflatoxins, and dust	[134]
	Anticancer activity	Significantly inhibits cell proliferation and induction of apoptosis in human melanoma A375S2 cells	[140]
	Neuroprotective activity	In a rat model of hypoxic–ischemic brain damage, gallic acid demonstrated neuroprotective effects by reducing neuroinflammation and neuronal loss through the inhibition of reactive oxygen species (ROS) and proinflammatory cytokines	[141]
	Antioxidant activity	In streptozotocin-induced diabetic rats, oral administration of gallic acid significantly reduced high levels of lipid peroxidation and improved reduced glutathione levels	[142]
	Cardioprotective	In rats intoxicated with sodium arsenite, administering gallic acid reduced histological damage in cardiac tissue	[143]
Protocatechuic acid	Antioxidant activity	Inhibits lipid oxidation of meat	[135]
		It attenuates liver injury induced by the intraperitoneal administration of high doses of cisplatin, as evidenced by decreased levels of AST, ALT, GGT, ALP, and bilirubin, as well as increased serum albumin	[136]
Cinnamic acid	Anti-inflammatory activity	Inhibits the production of basal levels of nitric oxide	[144]
		Inhibits the release of IL-6 at the cellular level, reducing the risk of developing acute lung injury	[145]
Fumaric acid	Functional activity in the food industry	It acts as an acidifying, preservative, and flavoring agent in food and feed	[146]
Chlorogenic acid	Anticancer activity	Inhibits the proliferation, migration, and invasion of cancer cells	[147]
	Antibacterial activity	Inhibits the growth of Gram-positive bacteria such as *Bacillus cereus*, *Bacillus subtilis*, *Enterococcus faecalis*, and *Enterococcus faecium*	[148]
	Anti-inflammatory activity	In a rat model of acute myocardial infarction, intravenous administration of extracts enriched with chlorogenic acid significantly reduced the inflammatory response, as well as inhibited the activation of NF-KappaB and JNK	[149]
Homogentisic acid	Cytoprotective activity	Counteracts the cytotoxic and genotoxic effects of the antineoplastic drug irinotecan in vitro	[150]
Ellagic acid	Antioxidant and antimutagenic activity	Protects cells from DNA damage caused by free radicals	[151]

Table 4. *Cont.*

	Bioactive Properties	Bioactivity	Reference
Kaempferol	Antioxidant activity	Reduces lipid oxidation in the human body, preventing the deterioration of organs and cellular structure and protecting their functional integrity	[152]
Quercetin	Antioxidant and antidiabetic activity	Protects the pancreas from hyperglycemia mediated by oxidative stress	[137]
	Antiglycemic activity	Regulates glucose levels and insulin sensitivity in the blood	[16]
	Antidiabetic activity	In diabetic mice, quercetin administration lowers blood glucose levels, maintains islet cell function, and increases the number of β-cells	[153]
	Antimicrobial activity	In rats, quercetin provides a protective effect against catheter-associated infections caused by Staphylococcus aureus by inhibiting coagulase activity	[154]
	Neuroprotective activity	Administering quercetin at 100 mg/kg in rats enhanced the effects of sitagliptin and improved cognitive performance and memory	[155]

6. Future Perspectives

Although various methods exist for recovering polyphenols from edible mushrooms, PLE and SFE are emerging as sustainable methods for extracting these compounds. This is due to their ability to operate under gentle and selective conditions that preserve the integrity of the phenolic compounds. Furthermore, both methods (PLE and SFE) are selective methods for recovering specific families.

Using sustainable, environmentally friendly methods will allow for producing polyphenolic extracts with potential applications in developing functional ingredients. This will enable the use of process parameters to develop future industrial systems. However, it is important to consider that the extracts contain polyphenols in the solution and unwanted compounds that could interfere with future applications, such as proteins, lipids, carbohydrates, and metals, which would limit their industrial use. Therefore, it is necessary to develop purification systems to obtain safe extracts with a high degree of purity. In this scenario, mushroom polyphenols would be incorporated as antioxidants in functional foods and as active ingredients in pharmaceutical formulations, opening new lines of high-value applications.

On the other hand, the processing of edible mushrooms generates byproducts such as discarded stems and fruiting bodies, which serve as a valuable secondary source of phenolic compounds. These compounds can be utilized as extraction materials, and the phenolic compounds recovered through pressurized liquid extraction (PLE) and supercritical fluid extraction (SFE) techniques can be reintegrated into the production chain to promote a circular and sustainable economy. Thus, future research should focus on assessing the technical and economic feasibility of PLE and SFE processes for extracting polyphenols from fungi at both pilot and industrial scales. This review provided a clearer understanding of the potential of these emerging technologies as scalable methods for the sustainable production of phenolic extracts from fungal biomass.

7. Conclusions

Edible mushrooms represent an invaluable and underappreciated natural source of phenolic compounds with significant bioactive properties, which are essential for pre-

venting and treating chronic diseases. This review of extraction methods reveals a clear evolution from conventional techniques toward more efficient and sustainable approaches. Emerging methods, such as PLE and SFE, are promising tools for improving the yield of phenolic compounds while minimizing their degradation. Future research should focus on evaluating various process parameters, such as the solvent composition, temperature, pressure, and extraction time. Additionally, it should incorporate purification techniques such as membrane filtration and the use of macroporous resins to obtain extracts with high antioxidant capacity and free from unwanted compounds.

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