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Review

Green Synthesis of Nanoparticles by Mushrooms: A Crucial Dimension for Sustainable Soil Management

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Abstract: Soil is the main component in the agroecosystem besides water, microbial communities, and cultivated plants. Several problems face soil, including soil pollution, erosion, salinization, and degradation on a global level. Many approaches have been applied to overcome these issues, such as phyto-, bio-, and nanoremediation through different soil management tools. Mushrooms can play a vital role in the soil through bio-nanoremediation, especially under the biological synthesis of nanoparticles, which could be used in the bioremediation process. This review focuses on the green synthesis of nanoparticles using mushrooms and the potential of bio-nanoremediation for polluted soils. The distinguished roles of mushrooms of soil improvement are considered a crucial dimension for sustainable soil management, which may include controlling soil erosion, improving soil aggregates, increasing soil organic matter content, enhancing the bioavailability of soil nutrients, and resorting to damaged and/or polluted soils. The field of bio-nanoremediation using mushrooms still requires further investigation, particularly regarding the sustainable management of soils.

Keywords: nanoparticles; biosynthesis; salinization; desertification; pollution; myco-nanomanagement; myco-nanoremediation

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1. Introduction

Soil is a complex, dynamic, and open system, in which several macro- and micro-organisms live, especially bacteria, fungi, and actinomycetes. The soil biota and/or fauna are responses to the biological attributes of soil and its agroecosystems [1]. Soil has vital functions and provides many ecosystem services such as (1) the cleaning of water, storage and its supply [2], (2) the production of biomass including bio-based energy, foods, fodder, and fiber [3], (3) climate gas fluxes including carbon dioxide, methane, and nitrous oxide [3], (4) the foundation for constructions and the supply of construction materials [4], and (5) providing "aesthetic environments" for the inspiration and recreation of people [5]. Several problems face soil, including soil pollution [6,7], salinization [8,9], degradation or deteriorations [10–12], desertification [13], erosion [14,15], waterlogging [16], and climate changes [15], and great effort is required worldwide to manage and conserve this soil. Combined and/or multiple problematic cases can be found all over the world, such as soil salinity and climate change [17], flooding and climate change [18], soil erosion and climate change [15,19], desertification and climate change [20], and soil biodiversity and global changes [21,22].

Sustainable soil management requires the use of the sustainable solutions to overcome a variety of problems, which may improve the safety of environment and human health. Nanotechnology has proven essential for solving a lot of environmental issues, especially green nanoparticles using plants [23], algae [24], actinomycetes [25], fungi [26], mushrooms [27], and bacteria [28], as well as plant extracts [29] such as corncob [30], Citrus limetta peel [31], Aloevera [32], and *Conocarpus lancifolius* fruits [33]. The green synthesis of nanoparticles is considered a by-product of sustainable development and can meet the needs of future generations. These nanoparticles could be prepared by using enzymes, flavonoids, phenolics, proteins, and sugars as stabilizing and reducing agents during the green production of nanoparticles [25]. Prepared nanoparticles from green synthesis process have many applications, including several fields such as agriculture [34], biomedicine [26,35], cosmetics [36], electronics [37], textiles [38], and environmental issues [24,25,39].

Therefore, this review discusses bio-nanoremediation and its potential, especially in the field of soil science, as well as the role of mushroom in this concern. The sustainable management of soil problems will also be highlighted, including soil pollution, degradation, and erosion. The green synthesis of nanoparticles using mushrooms will be reported as a crucial approach in sustaining soil and its management depending on myco-nanoremediation and soil nanoimprovement.

2. Soil and Its Sustainable Management

It is well-known that soil has great importance for humans and animals, as well as the entire environment. Due to it being the main source of our foods, feed of animals, fiber, and fuel, soils should protect from any deterioration, pollution, and any harmful activity. Definitely, there is no development without soil security and conversion. The Sustainable Development Goals (SDGs), which were announced by the United Nations, cannot be achieved without directly and/or indirectly managing soil functions [5], as presented in Table 1. These goals may address diverse issues inherently linked to soil and/or land, including clean water, as listed in SDG 6 [40], food security in SDG 2 [41], life on land in SDG 15 [42], the climate and its action in SDG 13 [43], and sustaining resources, as listed in SDG 12 [44]. Therefore, both the persistence and quality of soil functions and their achievement for the SDGs largely rely on the health of soil [45,46]. There is a need for the continued support of soil ecosystem services, in line with the goals of sustainable development [5].

Table 1. The main Sustainable Development Goals (SDGs), which launched by the United Nations and the expected role of soil. Soils may have a significant contribution meeting directly and/or indirectly almost all United Nation's sustainable development goals (*).

The Goal (SDG)	The Expected Role of Soil	The Goal (SDG)	The Expected Role of Soil
SDG 1	Indirect role of soil, which may can support reducing the poverty if this soil well be perfect used (*)	**SDG 9**	Direct and indirect role of soil in the industry. Soil has direct role for the infrastructure and fostering innovation is needed (*)
SDG 2	Indirect and/or direct role of soil, which is the main source for our foods. Healthy soil provides us with healthy food to reduce malnutrition (*)	**SDG 10**	Without caring for soil and its conservation, the income of several populations will be not able to grow faster, especially for farmers
SDG 3	Indirect and/or direct role of soil, the nutritional status of which is the main control for our health, including the positive and negative sides (*)	**SDG 11**	Indirect role of soil for sustaining life in rural and urban areas. Soil or land is a guarantee for affordable and safe housing (*)

Table 1. *Cont.*

The Goal (SDG)	The Expected Role of Soil	The Goal (SDG)	The Expected Role of Soil
SDG 4	Indirect role of soil, which needs more interest and to be added to inclusive, equitable quality education	**SDG 12**	Soil has direct and indirect impacts on the environment by the self-management of the global wastes and their recycling in an eco-friendly way (*)
SDG 5	For soil and its handling, everyone should respect and conserve soils. Soils does not differ between man and woman, and all can support it	**SDG 13**	Soil has an indirect impact on climate and its changes by regulating emissions from soil and promoting renewable energy (*)
SDG 6	Direct and indirect role of soil in providing clean water. Clean water is needed for protecting people from diseases (*)	**SDG 14**	Indirect role of soil/land for conserving and sustainably using the seas, oceans, and different marine resources
SDG 7	Indirect role for soil for saving energy. By 2030, more renewable, affordable energy sources are needed (*)	**SDG 15**	For a prosperous world, soil and/or land need to stop any kind of degradation and must preserve ecosystems of forests, deserts, and mountains (*)
SDG 8	Indirect role of soil for highly sustainable economic growth. There is no successful economy without sustaining and conserving soil	**SDG 16**	Indirect impacts of soil/land on societies and their institutions. Soil/land may control the peace and justice for all people

Lal et al. [47] reported about sustainable management of soil health and its importance for achieving many SDGs including goal numbers 1 and 2 (ending poverty and hunger), 3 (good health and wellbeing), 5 (gender equality), 6 (clean water and sanitation), 7 (affordable and clean energy), 9 (industry innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action), and 15 (life on land). Some of these goals rely considerably on the production of plants and/or soil processes including heat transfer, ion exchange, water movement, sorption and physical filtration, and biophysical and biochemical transformations. Many reports also discussed the SDGs based on different points of view such as the impact of country-level institutional factors [48], the metals industry [49], the tourism industry [50], carbon capture technology [51], and COVID-19 [52]. Finally, it could be concluded that the main challenges related to soil and its management may include (1) the mitigation of the land take, (2) the reduction in and remediation of soil pollution, erosion, and degradation, (3) increasing provisions of ecosystem services and biodiversity, (4) increasing biomass production for food, fiber and energy, (5) the mitigation of and adaptation to climate changes, and (6) improving disaster control such as flooding, drought, landslide, and wildfire as main natural hazards [5].

3. Soil and Mushrooms: A Vital Relationship

Soil is the main growing media for several macro- and micro-organisms such as mushrooms. Mushrooms are important plant fungi and have distinguished attributes making them crucial for medicinal, industrial, and agricultural activities. There are several species of mushrooms that belong to the kingdom of fungi and Phylum of Basidiomycota, in addition to several classes such as Agaricomycetes, many orders such as the Order of Agaricales, including many families such as Agaricaceae, Pleurotaceae, and Omphalotaceae. Table 2 shows a comparison of three well-known mushrooms including champignon (*Agaricus linnaeus* L.), oyster (*Pleurotus ostreatus* L.), and shiitake mushrooms (*Lentinula edodes* L.). The anatomy of a mushroom includes the stem of the mushroom, which is called the stipe or stalk, the cap (pileus), and the gills, which are called its lamellae (or lamella), on the underside of the cap. Mushrooms are fungal species that typically grow above/on soil and are fleshy, spore-bearing macrofungal fruiting bodies [53]. There has been growing concern about mushrooms regarding their consumption and cultivation for human health during the last 3 decades [54]. Several mushroom species have nutritional and medicinal properties that are crucial to human health [55–59].

Table 2. A comparison of three species of mushrooms, their family, and common species.

Item	Champignon	Oyster Mushrooms	Shiitake Mushrooms
Kingdom	Fungi	Fungi	Fungi
Phylum	Basidiomycota	Basidiomycota	Basidiomycota
Class	Agaricomycetes	Agaricomycetes	Agaricomycetes
Order	Agaricales	Agaricales	Agaricales
Family	Agaricaceae	Pleurotaceae	Omphalotaceae
Genus	*Agaricus* (200 species)	*Pleurotus* (202 species)	*Lentinula* (9 species)
Example	*Agaricus Linnaeus* L.	*Pleurotus ostreatus* L.	*Lentinula edodes* L.

		
Agaricus campestris	*Pleurotus ostreatus*	*Lentinula edodes*
Some common mushroom species of the family		
Agaricus abruptibulbus Peck 1905	*Pleurotus calyptratus* Sacc. 1887	*Lentinula edodes* (Berk.) Pegler (1976)
Agaricus amicosus Kerrigan 1989	*P. citrinopileatus* Singer 1942	*Lentinula edodes* (Beck.) Sing. (1941)
Agaricus arvensis Schaeff. 1774	*P. cornucopiae* (Paulet) Rolland 1910	*Lentinula aciculospora* J.L. Mata & R.H. Petersen (2000)
Agaricus augustus Fr. 1838	*P. columbinus* Quél. 1881	*Lentinula boryana* (Berk. & Mont.) Pegler (1976)
A. bitorquis (Quél.) Sacc. 1887	*P. cystidiosus* O.K. Mill. 1969 (edible)	*Lentinula guarapiensis* (Speg.) Pegler (1983)
A. bisporus (Lange) Imbach 1946	*P. dryinus* (Pers.) P.Kumm. 1871	*Lentinula lateritia* (Berk.) Pegler (1983)
Agaricus blazei Murrill 1945	*P. djamor* (Rumph. ex Fr.) Boedijn 1959	*Lentinula raphanica* (Murrill) Mata & R.H. Petersen (2001)
Agaricus campestris L. 1753	*P. eryngii* (DC.) Quél. 1872	*Lentinula reticeps* (Mont.) Murrill (1915)
A. columellatus (Long) R. Chapm., V.S. Evenson, and S.T. Bates 2016	*P. opuntiae* (Durieu and Lév.) Sacc. 1887	*Lentinula novae-zelandiae* (G.Stev.) Pegler (1983)

Table 2. *Cont.*

Item	Champignon	Oyster Mushrooms	Shiitake Mushrooms
	A. cupreobrunneus (Jul. Schäff. and Steer) Pilát 1951	*P. pulmonarius* (Fr.) Quél. 1872	
	Agaricus sylvaticus Schaeff. 1774	*Pleurotus radicosus* Pat. 1917	

Source of photos: for *Pleurotus ostreatus* L. (by Gréta Törős, Debrecen Uni., Hungary). For *Agaricus campestris*, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1710232 (accessed on 3 March 2022); For *Lentinula edodes*, By Frankenstoen from Portland, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=7304024 (accessed on 3 March 2022).

Mushrooms, like other fungi, have a strong impact on soil, both positive and negative. The compost that forms from spent mushroom substrate could be applied to soil as an organic fertilizer, which could increase soil microbial activity and the content of amino acid metabolites in studied orchard [60]. Mushroom also could be used as a bioindicator for soil pollution, such as soil polluted with heavy metals [61,62], toxic elements [63,64], organic pollutants [65], radioactives, or isotopes [66–70], as well as for health risk indices [71–73]. It is found that wood-grown mushrooms can adsorb major and trace elements in the wild, growing aboveground mushrooms like *Meripilus giganteus*. Thus, wood-grown mushrooms can play a crucial role in forest ecosystems due to their symbiosis with trees and/or their ability as saprotrophic organisms in decomposing the dead organic matter [74]. Several mushrooms are also abundant for exploitation in agro-wastes or agro-industrial wastes such as winery and olive mill wastes, producing many beneficial materials such as bioethanol or biofertilizers [75]. A relationship between mushrooms and their role in soil could be noticed in Figure 1. Several human activities, especially urbanization-based anthropogenic pollution, have led to the production of polluted soil- and tree-growing mushroom species [76]. Mushroom residues can also be applied to cultivated crops under a continuous cropping regime, which increase the productivity of cucumber by regulating the soil microbial communities [77]. More roles of mushrooms in the soil will be discussed in detail in the next sections, including soil myco-nanomanagement, soil myco-nanoremediation, and the role of mushrooms for soil improvement.

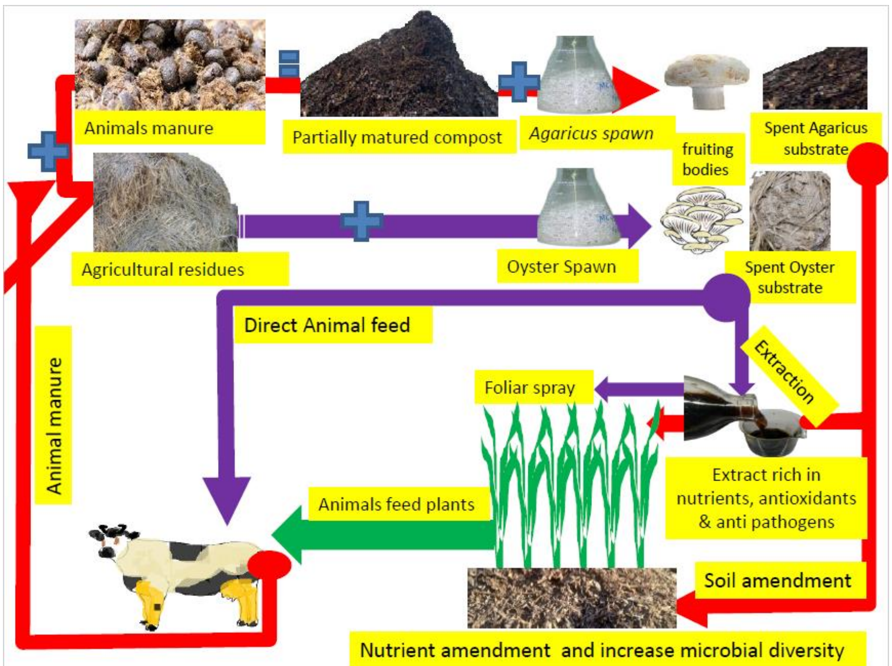

Figure 1. The relationship between mushroom and soil is very important due to the vital roles of mushroom in improving soil beside many other benefits, which include using the wastes of mushroom substrate as organic fertilizer and in feeding the animals.

4. Mushrooms for Soil Improvement

As mentioned earlier, mushrooms have many uses, and the global mushroom-growing industry plays a major role in addressing critical issues and positive contributions to humankind. These applications include foods, cosmeceuticals, tonics, medicines, and natural biocontrol agents in plant protection with insecticidal, fungicidal, bactericidal, herbicidal, nematocidal, and anti-phyto-viral activities [53]. The cultivation of mushrooms can pilot a so-called "*white agricultural revolution*" in developing countries and all over the world [53]. Several studies have focused on using spent mushroom substrates as soil amendments and in removing pollutants from soil (e.g., [78–82], few published reports about impacts of mushroom cultivation on improving soil quality [83]). The main fields in which mushroom cultivation could improve soil quality may include (1) soil erosion control, (2) improving soil aggregates, (3) increasing soil organic matter, (4) enhancing soil nutrition, (5) promoting C, and NPK cycling, and (6) the bioremediation of polluted soils. More details concerning the role of mushroom in improving soil will be explained in the next subsections.

4.1. Controlling Soil Erosion

Soil erosion is considered an important key factor leading to poor soil health and the productivity loss of crops, particularly under heavy rainfall conditions. To control soil erosion, the biological approach may be a crucial route, which represents the promotion of the intensive growth of mushroom mycelium in agricultural soils [83,84]. Growing mushrooms in agricultural soils has direct and indirect benefits on eroded soil, which may include the binding of mushroom mycelia of soil particles, establishing strong cord-forming mycelial networks, and forming soil aggregates as a direct mechanism, whereas the indirect mechanism may include exudating the fungal hyphae with some extracellular compounds such as the hydro-phobin group (e.g., glomalin) and polysaccharides into soils, which boost soil organic matter [85]. Forming hydrophobicity and adhesion exopolymers of fungal mycelium is the proposed mechanism for enhancing soil erosion resistance by mushrooms [84]. Therefore, mushrooms can control and limit soil erosion through forming a net from soil aggregate clumps and fungal hyphae, which contain organic matter, lipids, protein, water, nutrients, and minerals [83,86]. This net may result from the interaction between plants and mushrooms or microbes (from one side) and the mineral particles and soil microbes (from the other side), which plays a major role in forming the soil. Soil fungi are well-known by their production of a non-water soluble called glomalin as a highly persistent glycol-protein (e.g., mushrooms or mycorrhizae), which can maintain the structure of soil and its fertility [86].

4.2. Improving Soil Aggregates

The life cycle of a mushroom starts with a spore (i.e., a diameter of a few microns). This spore swells, germinates, and elongates to form filamentous cells in humid and nutrient-rich environments, called a "hypha". After growing the hypha, they elongate and form a network of interconnected hyphal threads called a "mycelium" [87]. The cultivation of mushroom species is useful for soil and its quality (e.g., the good soil aggregation), because mushrooms are considered saprobic fungi living on organic matter that exist in soil and/or the compost layers [83]. Forming the "*cord-forming mycelial network*" occurs during the cultivation process of mushrooms, when mushroom mycelium grows in compost, seeking nutrients. Mycelia grow in the soil layers after the complete forming of the fungal mycelial network and once it has fully colonized the compost layers. So, mushrooms have a very strong relationship with soil; mushrooms can obtain nutrients and carbon from the soil, and the soil can receive many release-fungal-based organic compounds from the mushrooms [87].

The fungal hyphae can penetrate the soil layers and support the formation of soil aggregates by their hyphal networks, which can chemically and/or physically bind soil particles [88,89]. Thus, mushrooms can improve the overall soil quality by forming networks of cored-forming mycelia, which enhance soil aggregations through the increasing abundance of mushroom-hyphae in soils [83]. Hence, forming soil aggregates not only reduces the erosion of soil, but also increases the movement of gases within the soil (mainly O_2 and CO_2), improving the ability of roots to penetrate different soil systems [90]. Moreover, several microbial dynamic processes in soil could be supported by aggregates, including microbial evolutionary [91], soil carbon sequestration [92], nutrient turnover [93], and gas emissions [83,94]. Regarding applied spent mushroom wastes to soils, they can increase larger stable aggregates (i.e., >2.0 mm), as reported by Udom et al. [95].

4.3. Increasing Soil Organic Matter Content

Soil organic matter content is a key mechanism for mitigating several soil processes and functions including soil fertility, biota biomass, soil aeration, soil structure, the formation of aggregation, soil erosion, water-storage capacity, and the biodiversity of soil ecosystems [83]. Soils with high organic matter can preserve excellent protection against erosion [96]. Soil organic matter binds their particles with increasing soil moisture content, which prevents soil particles drying out during strong winds or heavy rain events [97]. Mushroom cultivation in soils is an effective approach for promoting soil organic matter content in two main ways: (1) applying fungal-based organic materials (i.e., hyphal exudates and mycelium) and/or (2) applying compost and spent mushroom substrates to the soils [83]. Several studies on the application of the compost of the substrate of mushrooms to soil have confirmed many benefits of organic matter derived from mushrooms to soil and its quality (e.g., [98,99]). More details on the role of applied compost or substrate derived from mushrooms and their impact on soil and cultivated crops can be found in Table 3.

Table 3. List of some published articles concerning applied spent mushroom substrates (SMS) to cultivated or non-cultivated soil under different purposes.

Cultivated Plant or Used Mushroom for SMS	Soil Properties or Used Substrate	Main Purpose of the Application	Refs.
I. Applied SMS under cultivated soils			
Paddy rice (*Oryza sativa* L.)	Silty loam, pH (5.58), SOM (1.2 g kg^{-1}), and Cd (72.87 mg kg^{-1})	SMS of both *P. eryngii* and *A. bisporus* decreased soil content of Cd by 99% and increased rice yield by 38.8%	[100]
Roselle (*Hibiscus sabdarifa* L.)	Loamy sand, pH (7.98), SOM (0.25%)	Applied SMS to improve plant growth, soil fertility, and its quality as a biofertilizer	[101]
Cucumber (*Cucumis sativus* L.)	Silty, pH (6.12), TOC (11.1 g kg^{-1})	SMS enhanced soil microbial diversity and the activity of enzymes for long-term cultivated cucumber in greenhouse	[102]
Barely (*Hordeum vulgare* L.)	Clayey, pH (5.40), initial soil 60 kg N ha^{-1} and fertilized up to 200 kg N ha^{-1}	Applied SMS (50%) caused a strong shift in soil-rhizosphere microbiota due to release enzymes as root exudates, depending on the kind of applied organic fertilizers	[103]
Pumpkin (*Cucurbita pepo* ssp.)	Sandy loam, pH (8.0), N (6.0 mg kg^{-1})	Applied SMS as organic fertilizer is promising under organic farming	[104]
Tomato (*Solanum lycopersicum* L.)	Modified paddy straw as substrate	Paddy straw based-silica rich SMS of *P. ostreatus* is effective for plant disease and nutrient management	[105]
Lettuce (*Lactuca sativa* L.)	Composted SMS, vermiculite, coir, and perlite at (3:1:1:1)	Microbial agents can inhibit potentially pathogenic microbes of plants and increase the efficient utilization of SMS	[106]
Cherry tomato (*Solanum lycopersicum* Mill.)	Soil (dystro-ferric red latosol)	Co-cultivation at the same bucket tomato and *A. bisporus* reduced by 60 days and continuous producing mushroom prolonged by 120 days	[107]

Table 3. *Cont.*

Cultivated Plant or Used Mushroom for SMS	Soil Properties or Used Substrate	Main Purpose of the Application	Refs.
II. Applied SMS under non-cultivated soils			
SMS provided by Xiangfang edible fungi factory, Harbin, China	Sandy, pH (6.83), SOM (38.64 g kg^{-1})	SMS was compared to biochar and lime on reducing Cd-bioavailability by 66.47% and increased soil enzyme activities	[108]
Organic amendment (SMS and its biochar)	Soil pH (6.83), SOM (38.64 g kg^{-1}), ava. N (115.7 mg kg^{-1})	Applied amendment alleviated Cd and N damage on soil, by increasing microbial biomass and enzyme activities in the soil	[109]
SMS-derived biochar	Soil pH (4.62), TOC and TN (57.2 and 3.9 g kg^{-1}, resp.)	Spent mushroom substrate derived biochar was pyrolyzed at 450 °C can mitigate greenhouse gas emissions	[110]
Applied SMS, bacteria of *Paracoccus* sp., and humic acid	PAHs in soil was 1.97 mg kg^{-1}, soil pH (6.71)	Bio-degradation of PAHs by humic acid and SMS via soil laccase activity as bioremediation	[111]

Abbreviations: soil organic matter (SOM), total organic carbon (TOC), polycyclic aromatic hydrocarbons (PAHs), cadmium (Cd), nitrogen (N), soil acidity (soil pH).

4.4. Enhancing Bioavailability of Soil Nutrients

A huge amount of wastes or spent mushroom substrates (SMS) result from mushroom cultivation; about 5–6 kg of SMS for production of every kg of fresh mushroom [83]. These substrates contain different nutrients (e.g., NPK) and various organic compounds such as crude protein, carbohydrate, cellulose, lignin, hemicelluloses, and neutral and acid detergent fibers [112]. Dumping or incineration is the current disposing of the majority of spent mushroom substrates [113]; however, many innovative techniques can be applied for the valorization of these wastes, including composting, the production of animal feeds and enzymes, energy production (bioethanol), the cultivation of new mushroom species, packing, and construction materials [112]. On the field scale of mushroom cultivation, SMS can be disposed through composting for biofertilizer, which uses and/or amends the degraded soil in situ [114].

The SMS could be utilized as a biofertilizer because it contains many essential nutrients, besides it being a resource for microbial biomass. Thus, the SMS can enhance the bioavailability of nutrients in the soil as a biofertilizer; consequently, SMS may promote the growth of seedlings and the growing of other mushroom varieties [115,116]. The aged compost of SMS has high macro-nutrient contents (if its age is more than 6 months) compared to a fresh one. This compost could be used as an alternative source of some components of growth media such as peat or perlite, and it is reported to be 30% mixable with SMS compost (and 70% for SMS). This mixture has led to an increase in the germination rate and the morphology of cultivated pepper seedlings [115]. The role of SMS compost was confirmed by many researchers in mitigating stress from Pb or Mn or Zn on *Paulownia fortunei* seedlings [117,118], Pb-Zn-stress on *Macleaya cordata* [119], or drought stress on *Althaea rosea* [120]. For obtaining a healthy SMS compost, biocontrol agents such as *Bacillus subtilis* and *Trichoderma harzianum* may need to be added during the compositing process [121].

4.5. Resorting of Damaged and Polluted Soils

The restoration of damaged soil or the environment through mushroom mycelium has been reported by some investigators due to its strong ability to decompose or degrade many pollutants and wastes. The mode of action of this biodegradation by mushroom mycelium may revert to the formation of complex extracellular enzyme groups [53]. The mycelia of mushroom also have a crucial role in restoring damaged environments in four different ways, including (1) myco-remediation [122] or bioremediation through the decontamination of a certain area by the mycelia, (2) myco-filtration, using mycelia to filter toxic wastes and microorganisms from soil or water medium [123], (3) myco-pesticides, using mycelia to control insect pests [124], and (4) myco-forestry, using mycelia to restore the forests [53]. The previous approaches represent different methods for a clean agroecosystem, which can remove damage in agro-environments after mushroom implementation. Regarding the mode of action of myco-pesticides, this mechanism could increase the biopesticide efficacy through reducing plant diseases by the mycoparasitism, direct antagonism, and induction of resistance [124]. The removal of pollutants using a network of fungal mycelium is called myco-filtration. It is an eco-friendly technology that treats contaminated water/wastewater by calculating the removal efficiency [125]. Myco-forestry is considered a crucial system, which could enhance plant communities and forest ecosystems through different species of mushrooms as an ecological forest management system. A myco-forestry system also can restore the environment through myco-remediation and myco-filtration activities, which clean up toxins in the environment.

Concerning myco-remediation, it is a sustainable approach for the bioremediation of polluted environments using the fungi of mushrooms to remove toxic pollutants through biosorption, bioaccumulation, and bioconversion [126]. This approach could be applied using live and dead mushrooms to myco-mediate the polluted soil [127,128], wastewater [129,130], and lignocellulosic biorefinery sludge [131]. It found that the fungal mycelia act as bio-sorbents to remove polluted metals from industrial wastewaters [130] or through the production of many lignocellulolytic enzymes, removing 90% of organic contaminants [131].

5. Green Synthesis of Nanoparticles by Mushrooms

It is well-known that nanoparticles (converted to atomic or molecular scales ranging from 1 and 100 nm) could be produced by three main methods, including physical (using mechanical tools such as for grinding or milling), chemical (using some chemicals as deducting agents), and biological tools (using organisms such as plants, bacteria, fungi, actinomycetes, and algae). The production process or the synthesis of stable nanoparticles (NPs) through biological routes could be referred to as green nano-biotechnology [25]. The green chemistry of nanotechnology has mainly 12 principles, including (1) minimizing the production of wastes and reducing pollution, (2) the manufacturing of products in safer manner, (3) lowering toxicity due to less hazardous chemical synthesis, (4) using renewable feedstocks, (5) utilizing effective catalysts, (6) reducing unnecessary derivatives, (7) producing economically greener products, (8) controlling and reducing pollution, (9) increasing the efficiency of used energy, (10) using safer solvents for safer reaction conditions, (11) using degradable and recyclable materials, and (12) minimizing the possibility of accidents [25]. The biosynthesis of nanoparticles using fungi has been reported by several researchers, focusing on the genera of fungi used in NPs biosynthesis, the bio-activity of this biosynthesis, and the main applications resulting from this biosynthesis (Figure 2), as adapted from Al-Bahrani et al. [132].

Concerning the fungal genera used for NPs-biosynthesis, there are several genera of fungi like *Aspergillus* (27%), *Fusarium* (21%), *Verticillium* (9%), *Trichoderma*, *Rhizopus* and *Penicillium* about 7% and some other mushrooms like *Pleurotus* about 1% [133]. Several species of cultivated and wild mushrooms have been successfully used for the green- or bio- or myco-synthesis of many kinds of nanoparticles particularly gold (Au) [134–136], silver (Ag) [137–140], magnesium oxide (MgO) [141], titanium oxide (TiO_2) [142], copper (Cu) [143], zinc (Zn) [144,145], and cadmium sulfide (CdS) [133]. The mechanism of nanoparticle myco-synthesis by mushrooms seems to be simple, but many factors control the stability, and biocompatibility of produced nanoparticles. These factors mainly include temperature (up to 40 °C for *Trichoderma harzianum*, or 90 °C for *Aspergillus oryzae*), pH of the reaction medium (a higher pH is preferable), the used amount of fungal biomass, and the medium composition [133]. The mechanism may return to various types of enzymes, mainly reductases, that can direct the intracellular or extracellular reduction and stabilization of NPs by the fungal exudates of biomolecules [146] and [27,147]. These biomolecules may contain amino acids, alkaloids, carboxylic acids, enzymes, flavonoids, peptides, phenols, polysaccharides, saponins, steroids, tannins, vitamins, and other secondary metabolites [133,139,148–152]. Biosynthesis of many metal or metal oxide-NPs using mushrooms like *Pleurotus* sp. and *Pleurotus sajorcaju* was reported (Table 4). However, the specific mode of action behind NP-myco-synthesis based on biological materials needs to be fully elucidated [27].

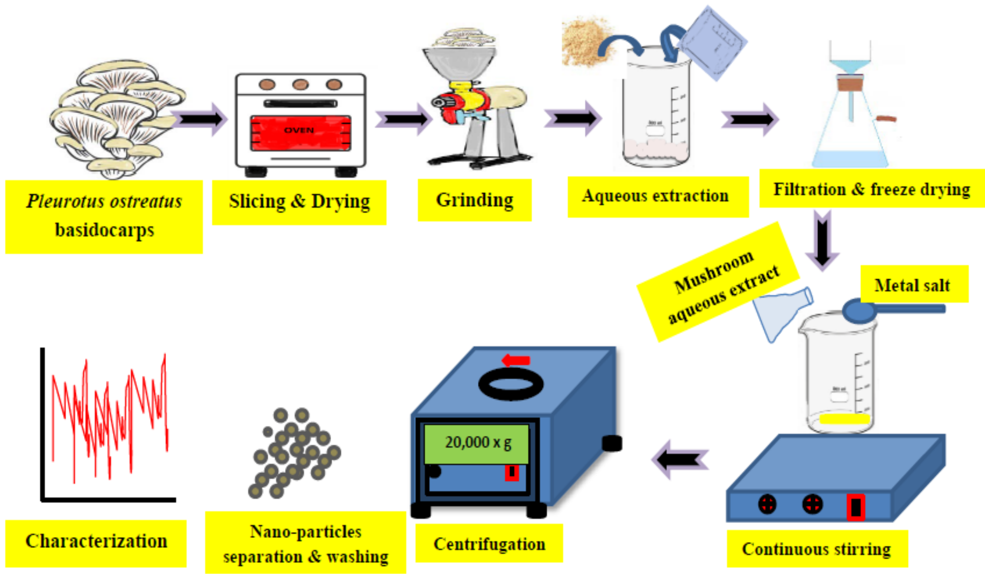

Figure 2. Graphical illustration for the green synthesis of metal nanoparticles using aqueous extract of the fresh basidiocarps of *Pleurotus ostreatus*. The steps include grinding the collected mushrooms, boiling within aqueous extraction, and then after filtration, the aqueous extraction is added to metal salt, which is needed to produce its nanoparticles (such as Ag, Zn, Cu, etc.).

Table 4. Green synthesis of some nanoparticles by fundi or mushrooms and their bioactivity.

Mushroom Species	Nanoparticle Kind and Its Size (nm)	Bioactivity or the Reaction	Reference
Agaricus bisporus	Ag-NPs (80–100)	Antibacterial activities	[153]
Amanita muscaria	Ag-NPs (5–25)	Anticancer activity	[153]
Pleurotus ostreatus	Ag-NPs (35)	Antioxidant properties	[154]
Pleurotus giganteus	Ag-NPs (5–25)	Antimicrobial activity	[155]
Ganoderma applanatum	Ag-NPs (20–5)	Antioxidant; Antibacterial	[156]
Ganoderma lucidum	Ag-NPs (15–22)	Antimicrobial activity	[148]
Pleurotus giganteus	Ag-NPs (2–20)	Antibacterial activity	[155]
Lentinus tuber-regium	Ag-NPs (5–35)	Antimicrobial activity	[157]
Pleurotus ostreatus	Ag-NPs (15–45)	Antimicrobial activity	[158]
Pichia pastoris	Ag-NPs (6.63)	Antioxidant and antimicrobial	[159]
Inonotus hispidus	Ag-NPs (69.24)	Antibacterial and antifungal	[150]
Ramaria botrytis	Ag@AuNPs (200)	Antioxidant and antibacterial	[149]
Flammulina velutipes	Ag-NPs (22)	Antibacterial activities	[160]
Boletus edulis *Coriolus versicolor*	Ag-NPs (87.7) Ag-NPs (86.0)	Anticancer of breast, colon; liver, and antimicrobial	[137]
Pleurotus ostreatus *Pleurotus djamor*	Ag-NPs (28.44) Ag-NPs (55.76)	Antioxidant activities and antimicrobial agent	[152]

Table 4. *Cont.*

Mushroom Species	Nanoparticle Kind and Its Size (nm)	Bioactivity or the Reaction	Reference
Agaricus arvensis	Ag-NPs (20)	Anticancer, Antimicrobial	[138]
Ganoderma lucidum	Ag-NPs (50)	Antibacterial activities	[140]
Agaricus bisporus	Ag-NPs (50.44)	Antibacterial activity	[139]
Pleurotus sajor-caju	Au-NPs (16–18)	Cancer cell inhibition	[135]
Ganoderma applanatum	Au-NPs (18.7)	Dye decolorization	[161]
Lentinula edodes	Au-NPs (5–15)	Anticancer activity	[162]
Ganoderma lucidium	Au-NPs (5–15)	Anticancer activity	[162]
Agaricus bisporus	Cu-NPs (10)	Antibactericidal activity	[143]
Pleurotus tuber-regium	Se-NPs (50)	Anticancer activity	[163]
Pleurotus djamor	TiO_2-NPs (31)	Antilarval properties	[142]
Pleurotuss ostreatu	ZnS-NPs (2–5)	Biomedical; food packaging	[164]
Agaricus bisporus	Zn-NPs (12–17)	Antirenal cancer	[165]
Candida albicans	ZnO-NPs (10.2)	Antimicrobial activities	[145]
Pleurotus floridanus	ZnO-NPs (34.98)	Biomedical applications	[144]
Pleurotus djamor	ZnO-NPs (38.73)	Antibacterial and anticancer	[166]
Agarius bisporus	ZnO-NPs (20)	Antibacterial activity	[167]

6. Soil Nanomanagement and Mushrooms

The cultivation of mushrooms is known to have been performed since 600, 1100, and 1650 AD, for the species *Auricularia auricula-judae*, *Lentinula edodes*, and *Agaricus bisporus*, respectively [53]. Mushrooms as fungi can play different roles in soil, including promoting soil fertility, biodegrading agrowastes, or removing pollutants from soil, as mentioned in the previous section. According to their main source of carbon for nutrition, the most cultivated mushrooms in the soil are considered saprophyte and heterotrophic fungi. Mushrooms can biosynthesize their own foods from the agroresidues of different crops by converting these by-products and wastes and preventing the accumulation of them as health hazards. Mushrooms cannot synthesize their food through photosynthesis because they are devoid of chlorophylls [53]. The vascular xylem and phloem are also absent in mushrooms, but they can absorb O_2 and release CO_2 [53].

The quality of cultivated mushrooms may depend on the concertation of pollutants such as heavy metals and their accumulation in the fruit bodies of mushrooms, which may migrate from the growing substrates [168]. The selected proper substrate for mushroom cultivation is considered a limiting factor, which depends on the price and lignocellulosic compounds in used agrowastes [169]. Although the use of spent mushroom substrate as raw materials remains a formidable challenge, it could produce complexes of chitin-cellulose nanofiber, which promote plant growth through increasing plant disease resistance [170]. An increased concern on the manufacture of nanomaterials derived from mushrooms recently has been noticed (Table 5). These nanomaterials include chitin-cellulose nanofiber from *Lentinula edodes* substrate [170] and chitin nanopaper from *Lentinula edodes*, *Flammulina velutipes*, and *Pleurotus ostreatus* [171]. Mushrooms are useful for soil when their wastes from cultivation could be used as fodder for livestock, as a soil conditioner, as organic fertilizers, and/or for environmental bioremediation, as discussed in the next sections.

Table 5. List of some important materials-derived from mushrooms and their applications.

Mushroom Species	Potential Materials	The Main Application/Main Findings	Refs.
Agaricus bisporus	Nanoencapsulation of rutin in β-glucan matrix	Encapsulation by green technology for nutraceutical activities	[147]
Lentinula edodes	Chitin/cellulose nanofiber	Growth promotion and disease resistance	[170]
Lentinula edodes, Pleurotus ostreatus	Chitin nanopaper derived from mushroom	Extraction of chitin from the mushrooms to produce nanopaper	[171]
Pleurotus ostreatus	Chitin–glucan complex	Producing eco-friendly polymers	[172]
Agaricus bisporus, *Pleurotus ostreatus*	Biocompatible fluorescent carbon-based nanomaterials	Producing live cells by fluorescent carbon quantum dot derived from mushrooms	[173]
Lentinus edodes	Nanoemulsion	Nanoemulsion derived from mushroom polysaccharide for the antitumor activity	[174]
Agaricus bisporus	Chitin nanopaper derived from mushroom	Production of chitin nanopaper from an extract of mushrooms	[175]
Agaricus bisporus	Fraction of chitin/glucan	Producing glycosidases (e.g., chitinases), which immobilize on nanoparticles and spray for biocontrol of insect pests	[176]
Lactarius volemus	Modified chitosan with nano-Fe_3O_4 nanoparticles	Purification of phytase enzymes and their potential in cereal industries	[177]
Lentinus edodes	Cellulose nanofibers	The highest yield of the film was produced using 0.18 g NaClO per 1.0 g of waste mushroom bed (71% cellulose)	[178]

7. Soil Nanoremediation and Mushrooms

Soil pollution is a serious challenge facing the global community. This pollution is a direct and/or indirect harmful deterioration, which penetrates all aspects of our life, especially human health. Therefore, there is an urgent need to repair, remove, or decompose these pollutants according to various approaches. Depending on the kind of pollutants and their concentration in the soil and other environmental compartments, the types of remediation could be selected for bioremediation by microorganisms, phytoremediation by plants, nanoremediation by nanomaterials, nano-bioremediation by both microorganisms and nanomaterials, and nano-phytoremediation by both plants and nanomaterials [179]. Concerning the nanoremediation of soil, several recent published review articles have discussed this global issue as reported below in this section.

Many traditional materials have applications in soil and water remediation, but many advanced materials could be used, such as nanomaterials, particularly nano-zero valent iron, which can be applied to soil and water polluted with heavy metals [180,181]. Different nanoremediation strategies could be used to treat polluted soil, water, and air, including both in situ and ex situ strategies. Several nanoparticles (NPs) could be applied to diminish environmental hazards from pollutants such as TiO_2-NPs, Fe-based NPs, and nanomaterials of silica and carbon [182]. Concerning these strategies, in situ strategies could be remediated using many approaches such as phytoremediation, bio-slurping, bioventing, bio-sparging, and permeable reactive barrier, whereas ex situ strategies may include bio-pile, bioreactors, windrows, and land farming [182].

In general, global polluted soils with toxic elements require three important points for their remediation strategies, including (1) using geographical coordinate maps, (2) using suitable soil indices for investigating soil quality, and (3) collecting data on polluted soils, which is crucial for choosing the best treatment strategy, including nanomaterials and others [6]. The accumulation of organic pollutants on coastal soils and their sediments due to the rapid growth in both population and economy in these areas is considered a serious environmental issue. These organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), could be remediated using many strategies including chemical oxidation, physical repair, bioremediation, and integrated approaches such as reversible surfactants, micro-nano bubble, and biochar [183]. Using nano-biochar in remediating polluted soils with heavy metals is a promising approach due to their unique properties for soil remediation, which include a high specific surface area and hydrodynamic dispersivity. The main mechanism of nano-biochar may include high efficacy for the immobilization of non-degradable heavy-metal pollutants in soil rhizosphere [184].

The reuse of soil polluted for agricultural production after its remediation from petroleum hydrocarbons could be achieved using physical, chemical, and biological methods, bio-electrochemical system, and nanomaterials like biogenic iron oxide depending on the internal and external factors [185]. Many approaches could be applied for remediating soil from textile mill effluents, which may include dyes, metal pollutants, and organic pollutants from printing, softening, and heat stabilizing. These approaches may include biosurfactants derived from microorganisms, oxidation–reduction, electrokinetic processes, phytoremediation, and nanoremediation using nano-zero valence iron oxide [186].

Concerning the relationship between soil nanoremediation and its mushrooms, this process can be called nano myco-remediation. The mechanism of this kind of remediation depends mainly on the enzymatic system of mushroom species and is involved in the bioremediation of organic environmental pollutants (Figure 3). Many species of mushrooms have the ability to remediate soil pollutants and could be cultivated in agricultural soil or grown on the compost of crop residues (e.g., animal manure, cobs, straw, and sugarcane bagasse) or agro-industrial wastes such as *Agaricus bisporus*, *A. subrufescens*, *Phallus impudicus*, *Pleurotus ostreatus*, and *Volvariella volvacea* [83]. The mechanism mainly depends on the enzymes and their types (e.g., cellulase, laccase, manganese peroxidase, and xylanase). Mushroom hyphae can biodegrade crop residues or wastes by converting them into compounds of carbohydrates, fatty acids, and proteins [83]. Details of these enzymatic reactions are shown in Figure 3.

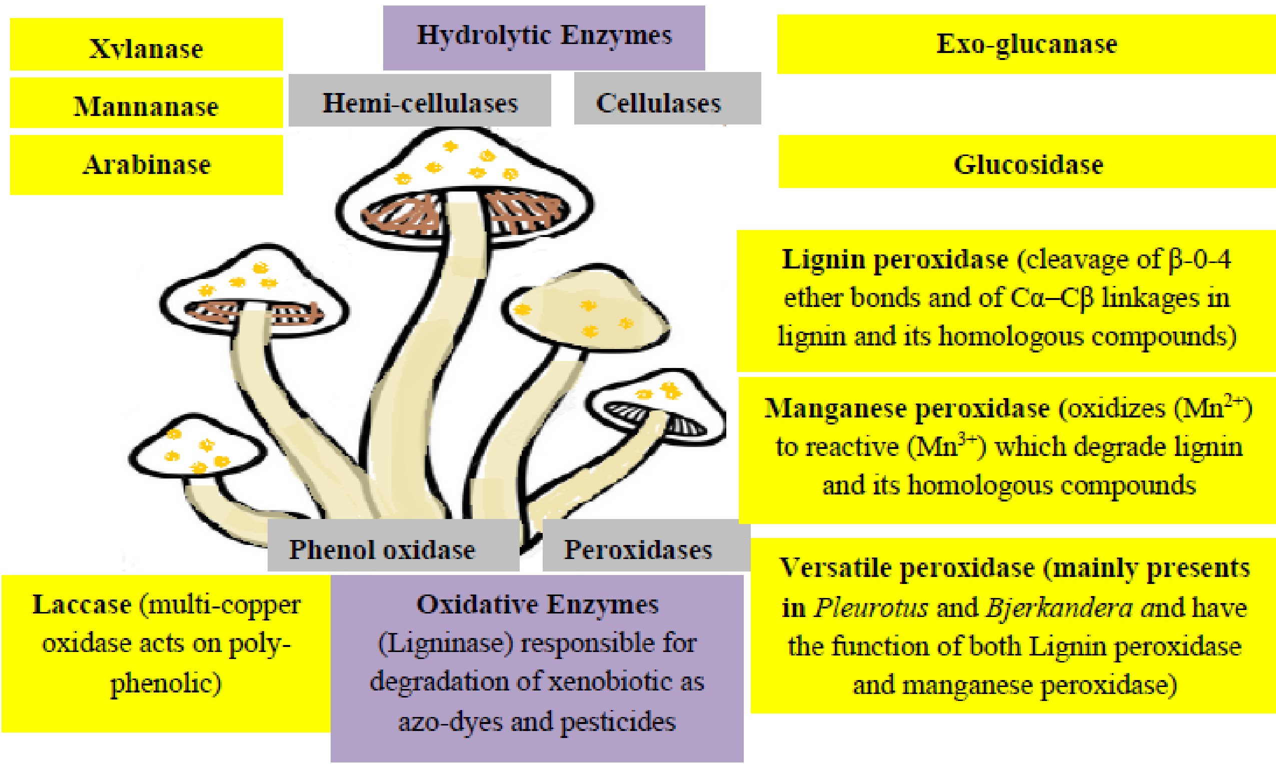

Figure 3. The main enzymatic system in mushroom species responsible for the bioremediation of organic environmental pollutants. Boxes with violet color refer to enzyme category; grey boxes refer

to enzyme class while small yellow boxes refer to enzyme name, whereas the big yellow boxes explain the mechanisms of enzymes. Hydrolytic enzymes include hemi-cellulases and cellulases, whereas oxidative enzymes include peroxidases and phenol oxidases, and each enzyme class includes a number of enzymes.

It is worth mentioning that the relationship between mushrooms and nanoparticles (NPs) during the biosynthesis of nanoparticles by mushrooms should be clear and the produced NPs of metals or metal oxides (especially NP-Ag) have been successfully used in different biomedical activities. The main role of mushrooms in this process is as bio-reducing agents. On the other hand, many applications of mushrooms' spent substrate have been reported, such as removing environmental pollutants in the absence of applied nanomaterials [187] or in the presence of nanomaterials such as nanoscale ferroferric-oxide-coated biochar derived from wastes of mushroom to remove Cr(VI) [148]. More studies concerning this approach can be listed in Table 6, such as [149–151] in presence of nanomaterials or [152–156] in the absent of nanomaterials.

What is the difference between myco-remediation and green-synthesis of NPs by mushrooms? A brief answer is found in Figure 4, and more details are given in the following section. Soil myco-remediation or bioremediation is considered an innovative and emerging practice, which shows crucial potential as an effective approach in using natural processes to remove pollutants from soil systems [83]. The bioremediation of pollutants using mushrooms is presented in Table 6 under different conditions including the presence/absence of nanomaterials. It could use mushrooms in live or dead form in myco-remediation. Soil bioremediation could be achieved using spent mushroom substrate (SMS), which helps in the biodegradation of different pollutants (e.g., heavy metals, pesticides, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons, petroleum, and related products). Many studies have reported the use of spent mushroom substrate in the bioremediation of different polluted environments as green adsorbents, which can remove up to 90% of pollutants from soil [188] or from groundwater [189], such as simulated acid mine drainage [190], biopesticide development [191], zero waste management [192], the production of xylo-oligosaccharides as feed ingredient and functional food [193], and polluted soils [100,109,194,195]. The SMS also can promote plant disease resistance [170], whereas the cultivation of mushrooms (like *Agaricus subrufescens*) is considered a promising remediator agent under the "circular food-to-waste-to-food system" [125]. More information about SMS applications and their challenges for "sustainable development of the global mushroom industry" is emphasized in the distinguished review article of Leong et al. [196] and the book chapter of Rajavata et al. [197].

Table 6. Some published studies on the nano-bioremediation of polluted environments using fungi (mainly the mushrooms) in the presence and absence of applied nanomaterials.

Bio-Source	Applied Material	Pollutant	Mechanism or Main Findings	Refs.
	I. In presence of nanomaterials			
Lentinula edodes	Biochar nano Fe_3O_4 (LBC)	Cr(VI) (200 mg L^{-1})	Max. removing rate of Cr(VI) by LBC-Fe_3O_4 was 99.44% in aqueous media	[198]
Lentinula edodes *Agrocybe cylindracea*	Nano Fe_3O_4 at 2, 4, 6–22, 24 g L^{-1}	Cr(VI) at 200 mg L^{-1}	Removing Cr(VI) up to 73.88 at 240 min, 40 °C, pH 3 from 200 mg L^{-1} liquid by combined adsorption and redox	[199]

Table 6. *Cont.*

Bio-Source	Applied Material	Pollutant	Mechanism or Main Findings	Refs.
Saccharomyces cerevisiae (Desm.) Meyen	Pd-NPs (32 nm)	Azo dye direct blue 71	Pd-NPs degraded 98% of direct blue 71 dye photochemically within 60 min under UV light in an aqueous medium	[200]
Tricholoma crissum Sacc.	CuO-NPs	Thorium (Th^{4+})	An indicator for detecting Th^{4+} in aqueous medium	[201]
II. In absent of nanomaterials				
Pleurotus ostreatus *Pleurotus eryngii*	Fresh SMS at rate of 4:1 (soil: SMS)	PAHs (2.63 mg kg^{-1}) in soil	Effective remediating due to activity of laccase and manganese peroxidase in the treatment of fresh *P. eryngii* SMS	[81]
Agaricus bisporus *Pleurotus eryngii*	Soil amended by 5% SMS (*w/w*)	Total Cd in soil 72.87 mg kg^{-1}	Applied SMS of both mushrooms improved rice production by 38.8%; decreased Cd in soil by about 99%	[100]
Pleurotus ostreatus	Soil amended by dried SMS (3–12 g kg^{-1})	Soil Co was 8.53 mg kg^{-1}	Maximum pakchoi biomass recorded at applied SMS up to 9.51 g kg^{-1} and Co phytoavailability in soil was minimum	[111]
Mushroom residues	Soil amended by 10% of residues	Pb/Zn slag: 3.1 and 4.6 g kg^{-1}, res.	Mushroom residue enhances phyto-remediation of *Paulownia fortunei* in Pb-Zn slag; alleviates their toxicity to plants	[117]
Pleurotus ostreatus	Mine polluted soil mixed with the spawn of *P. ostreatus*	Cr and Mn: 1.5 and 8.8 g kg^{-1}, res.	Studied mushroom is a bio-accumulator of toxic metals (Cr, Mn, Ni, Co) from polluted soil, but not recommended to harvest/eat mushroom from polluted soil	[202]
Auricularia auricular and *Sarcomyxa edulis*	SMS mixed with polluted soil	PAH-polluted soil	Humic acid and SMS enhanced bioremediation by bacteria through laccase activity via biodegradation	[195]
Ganoderma lucidum, *Pleurotus ostreatus*, *Auricularia polytricha*	SMS (25 g) put into the mold	Formaldehyde free bio-board	The produced bio-board material from SMS of *G. lucidum* recorded the highest strength (2.51 mPa); high resistance to both fire and water	[203]
Discarded sticks of mushrooms	MnO_2-modifed biochar	Antimony, Sb 100 mg L^{-1} in aqueous solution	MnO_2-modified biochar produced from discarded sticks of mushrooms was excellent adsorbent; adsorption capacity 64.12 mg g^{-1}	[204]

Abbreviations: nanoscale zero-valent iron (nZVI), palladium nanoparticles (Pd-NPs), Polycyclic aromatic hydrocarbons (PAHs), Spent mushroom substrate (SMS), weight/weight (*w/w*).

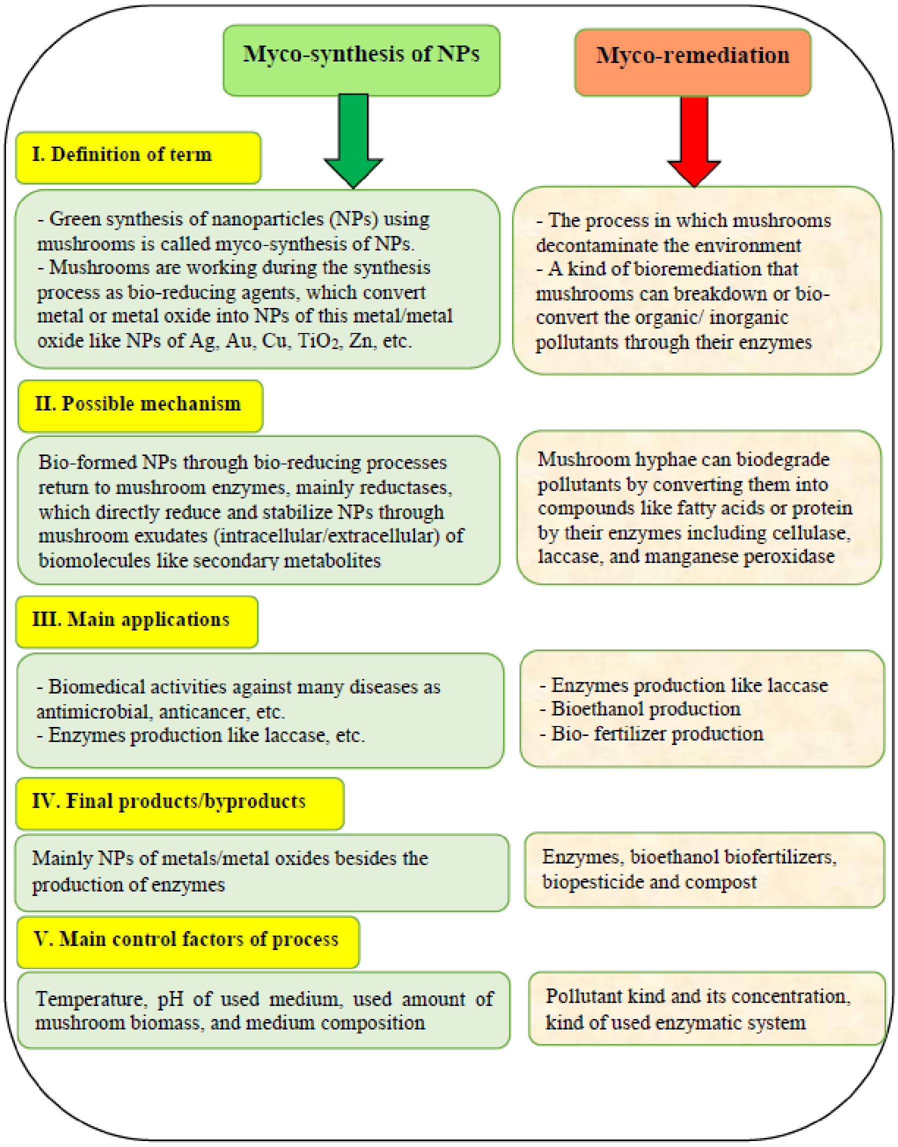

Figure 4. A comparison between myco-remediation and green synthesis of nanoparticles by mushrooms, including the definition of each process, their applications, their control factors, and the final products.

8. General Discussion

This review discussed soil and its importance in our lives as a main source of our food, fodders for our animals, and fiber for our clothes, as well as for the production of energy. Soil needs to be conserved for the sake of all living organisms, and it should be maintained to avoid degradation and deterioration. Several approaches have been used in soil management, including sustainable and non-sustainable methods. The use of green or phytoremediation is considered an eco-friendly tool for the management of soil pollution. Green synthesis, using plant-based nanoparticles, is also a promising approach that could be applied in several fields in our lives, such as agriculture and biomedicine. Many kind of microorganisms have been used in the biosynthesis of nanoparticles of many metals/metal oxides such as algae [24], actinomycetes [25], fungi [26], mushrooms [27], and bacteria [27,205–207], as mentioned before. Recently, many published reviews have focused on sustainable management using the green synthesis of nanoparticles, especially for biotechnological applications such as in [27,133]. The main mechanism of producing nanoparticles (NPs) with mushrooms relies on the exudates of many enzymes (mainly reductases), which can directly bio-reduce the used metals into nanosize materials and then stabilize the formed NPs [27].

The main question that needs to be answered in this review is whether mushrooms have the ability to biosynthesize nanoparticles. If yes, how can we use these nanoparticles of different metal/metal oxides in managing many soil problems? This answer has been confirmed by the ability of many mushroom species to produce nanoparticles by green or biosynthesis, which could be applied for polluted environments and for biomedical applications. Therefore, many species of mushrooms could be used in producing nanoparticles (such as Ag, Au, and Zn) and/or using these mushrooms for myco-remediation and producing bioethanol [208,209]. Like any scientific theme, this review opens many questions that need to be answered. Is there any possibility of using poisonous mushrooms in myco-remediation? What are the limitations and/or advantages for this process? What are the necessary regulations and/or legislations for mushroom utilization as efficient remediation tools?

Finally, we can summarize this review in the following diagram (Figure 5). This figure includes the main ideas in this review, which were divided into two groups: the advantages (benefits) and disadvantages of mushrooms.

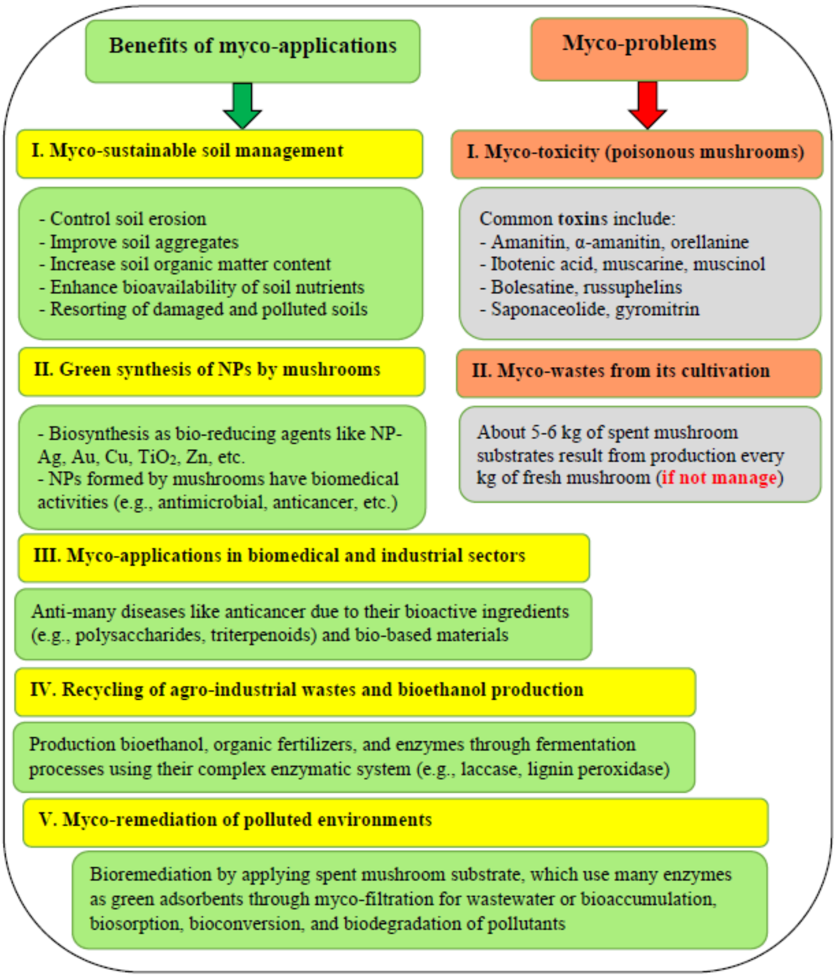

Figure 5. A comparison between the cons and pros or the benefits and problems of mushrooms. These items could be caused after cultivation of mushrooms or wild poisonous mushrooms, which cause several human diseases (for more details concerning the toxins and more, please refer to [208]).

9. Conclusions

The field of nanotechnology is of great interest in all areas of our life. Several methods have been used to produce nanoparticles, including physical, chemical, and biological or green approaches. The green or biological production of nanoparticles by plants such as mushrooms has become a crucial route, especially concerning sustainable solutions for soil management under different global issues such as soil pollution, soil erosion, soil carbon sequestration, the decline of soil fertility, the restoration of damaged or polluted soils, etc. Several studies confirm the sustainable management of soil problems using green nanotechnology, based on the fact that soil is the main source of our living needs (food, feed, fiber, and fuel). The role of mushrooms in soil management has also been confirmed by many researchers, focusing on used spent mushroom substrate (SMS) as a by-product of mushroom production. These substrates could be recycled into a new cycle of mushroom cultivation, as bio-control agents, biofertilizers, and soil amendments, as alternative feeds for insects, pigs, poultry, and ruminant, as raw materials for biofuel production, and as a bioremediation agent for pollutants. Under the dual challenging global problems of pollution and climate change loads, there is an urgent need for a bio-nanoremediation approach for the global safety of natural resources and for a healthy agroecosystem. Key questions remain concerning bio-nanoremediation by mushrooms and its expected relationship to nano-biofortification and other global issues.

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