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Review Article

Edible mushroom bioactive compounds in green nanotechnology: Applications in biomedical and environmental remediation

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Abstract

The application of green chemistry to synthesize nanoparticles has led to numerous cutting-edge innovations in nanotechnology over the last few years. Of late, edible mushrooms have emerged as one of the most promising biological resources, with rich biochemical profiles that could pave greener routes for nanoparticle synthesis. This review examines the existing literature on edible mushroom extracts for the green bio-fabrication of metallic nanoparticles and their uses in the biomedicine field and environmental remediation. Mushroom-derived bioactive compounds, such as polysaccharides, proteins, phenolics, and terpenoids, have been reported to possess bio-reducing and capping properties in the synthesis of nanoparticles. Some of these nanoparticles produced by mushroom-mediated synthesis demonstrate excellent antimicrobial, anticancer, and catalytic properties that have found applications in drug delivery, imaging, and therapy. This review also includes the environmental aspects where nanoparticles are applicable, such as wastewater treatment, pollutant degradation, and biosensing, as well as challenges and future perspectives.

1. Introduction

The consumption and usage of mushrooms virtually in all ethnicities has existed for many centuries, beyond their traditional and ethno-botanical usage. Mushrooms, especially edible ones, contain many bioactive compounds that differentiate them from other fungi [1]. Fungi can be described as fruiting bodies of the orders *Ascomycetes* and *Basidiomycetes*. They also play crucial roles in ecosystem management through the bioremediation of complex biomolecules and recycling of nutrients. According to Assemie and Abaya [1] approximately 1.5 million fungi have been accounted for, of which 14,000 species have been studied to have fruiting bodies large enough to be regarded as mushrooms, and roughly 2000 species have been reported to be edible [2]. Mushrooms contain bioactive compounds such as polysaccharides, proteins, phenolics, flavonoids and terpenoids, which can act as reducing and stabilizing agents during nanoparticle formation [3]. Edible mushrooms are of great importance in research and the economy due to the following moieties: they are mass-produced and marketed, their biomass production takes a relatively short time and is less polluting to the environment, they have a wide variety of metabolites with redox

Table 1. Bioactive compounds available from edible mushrooms and their role in the nanoparticle synthesis.

Bioactive compounds	Properties	Mushroom	Ref.
Polysaccharides	Water-soluble polysaccharides, e.g. β-glucans, with many hydroxyl groups are present for the bio-reduction of metal ions and capping of nanoparticles.	*Lentinula edodes*, *Pleurotus ostreatus* (Oyster mushroom), and *Ganoderma lucidum*	[3-6]
Proteins and Peptides	Amino acids with sulfur-containing side chains, such as cysteine and methionine are known to serve as both bio-reducing and capping agents.	*Lentinula edodes*, *Pleurotus ostreatus* (Oyster mushroom), and *Ganoderma lucidum*	[3-6]
Phenolic Compounds	Free radical scavenging phenolic compounds, e.g. flavonoids and acids, hydroxyl groups attached to these compounds could further assist in metal ion reduction into nanoparticles	*Lentinula edodes*, *Pleurotus ostreatus* (Oyster mushroom), and *Ganoderma lucidum*	[3-6]
Terpenoids	These compounds have an oxidizable functional group that participates in the bio-reduction of the metal ions	*Ganoderma* spp	[3-6]
Vitamins	Water-soluble vitamins: mainly vitamin C of ascorbic acid, are found in some edible mushrooms and are strong reducing agents in nanoparticle synthesis	*Lentinula edodes*, *Pleurotus ostreatus* (Oyster mushroom), and *Ganoderma lucidum*	[3-6]

potential, their extracts can be prepared with rather simple procedures and human use profiles exist for over 50% of edible mushroom species [3]. Edible mushrooms are potential prolific sources of bioactive compounds that are strong reagents for nanoparticle synthesis. These bioactive compounds are classified into broad categories, as shown in Table 1.

Nanotechnology is the science of manipulating matter at the atomic level (1-100 nanometer). Most conventional methods of synthesizing nanoparticles entail the use of chemical reagents that are not only harmful to the environment but also produce toxic by-products [3, 6]. The green nanotechnology approach describes a paradigm shift that insists on being environmentally friendly in its methods of bulk production and application of nanomaterials [7]. Plants, algae, microorganisms, and fungi have attracted the interest of researchers as potential candidates for the green synthesis of nanoparticles. Edible mushrooms are a promising biological factory for nanoparticle synthesis [3, 7].

2. Materials and methods

The information was collected by searching for English keywords. Literature was sourced from various databases, including Google Scholar, Wiley Online Library, PubMed, Science Direct, and Springer Link. An updated bibliography was compiled, with a focus on covering publications from the last five years.

3. Results and discussion

3.1. Mushroom-mediated nanoparticle synthesis mechanisms

The mushroom extract-mediated approach for the green synthesis of nanoparticles comprises of three main phases: reduction nucleation and growth and stabilization (Fig. 1).

During the reduction phase, bioactive components are known to reduce metal ions to their zero-valent state.

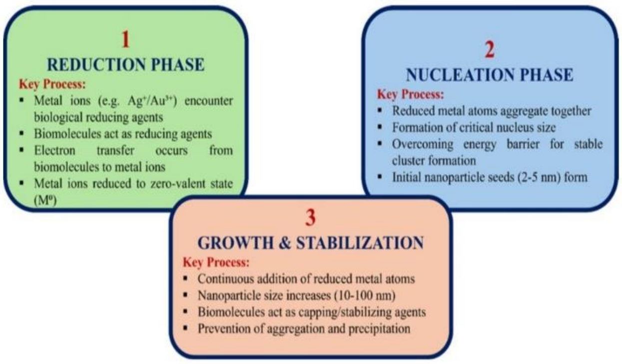

Figure 1. Nanoparticles synthesis mechanism.

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For example, in the preparation of silver nanoparticles, silver ion Ag^+ in the metallic salt (precursor) is reduced to silver (Ag^0), through the electro-donating groups present in the bioactive molecules of the mushroom, which are mainly hydroxyl, carboxylic, and amino groups [3]. In the nucleation phase, clusters of reduced metal atoms join to form small nuclei. This phase is important for determining the shape and size distribution of nanoparticles [8]. The growth of the formed nuclei lies in the presence of more reduced metal atoms during the biofabrication and stabilization of the nanoparticles. During the biofabrication process, the biomolecular capping creates a charged surface layer on the nanoparticles that generates repulsive forces between particles, preventing agglomeration or aggregation through electrostatic repulsion [3, 6].

Several edible mushroom species, including *Agaricus bisporus* (White Button Mushroom), the most widely grown edible mushroom worldwide, have shown promise in the synthesis of silver and copper nanoparticles [9-11]. *Pleurotus species* (Oyster Mushrooms) like *P. florida, P. sajor-caju* and *P. ostreatus* have been utilized for synthesizing various metallic nanoparticles with distinctive morphologies [12-14]. *Lentinula edodes* has been reported to be rich in polysaccharides such as lentinan, which has been employed in the synthesis of metallic nanoparticles with enhanced biological activities [5]. *Ganoderma lucidum* is known for its medicinal properties and has been used as a reducing and capping agents in the bio-fabrication of nanoparticles with significant antimicrobial and anticancer properties [15]. *Cantharellus cibarius* (Chanterelle) is an edible wild mushroom that has shown potential for synthesizing gold and silver nanoparticles with distinct morphologies [16]. Some non-metallic, metallic, composite and hybrid nanoparticles synthesized using edible mushroom extracts are listed in Table 2.

Experimental studies have shown that bioactive compounds in edible mushrooms facilitate the bio-fabrication of nanoparticles through biochemical pathways, the NADH-dependent nitrate reductase serves as the primary enzymatic mechanism for metal ion reduction from ionic (M^+) to neutral metallic state (M^0) [3]. Edible mushrooms such as *Agaricus bisporus*, *Ganoderma lucidum* and *Pleurotus ostreatus* have been used to mediate the synthesis of silver nanoparticles. These edible mushrooms contain secondary metabolites such as anthraquinones and hydroxyl-quinoline, which serve as additional electron donors facilitating the reduction process [4, 11, 15, 17]. Peptides serve as both reducing and stabilizing agents through electrostatic interactions, particularly via cysteine residues and negative carboxyl groups that prevent agglomeration [3, 17]. Fourier transform infrared spectroscopy and fluorescence studies have established protein capping on nanoparticle surfaces, with aromatic amino acids such as tryptophan and tyrosine, providing superior stability compared to their chemically synthesized counterparts [11, 15, 17]. Polysaccharides contribute through metal-binding functional groups and extracellular polymeric substances, with the filamentous mycelial network providing numerous nucleation sites due to its high surface area-to-mass ratio [3, 6].

The characteristics mushroom-mediated nanoparticles are mainly dependent on the species bioactive profile of the mushroom and optimization parameters like pH, temperature, biomass concentration and culture medium composition. Different edible mushroom species have been reported to demonstrate unique biofabrication patterns; *Pleurotus giganteus* and *Agaricus bisporus* have been reported to show optimal silver nanoparticle bio-fabrication at 40°C [15, 17, 19]. The precursor (metal) concentration mainly determines the particle quantity and size, with most studies employing 1 or 0.5 mM $AgNO_3$ and $AuCl_3$ [5, 14, 19,]. Optimization parameters significantly influence the bio-fabrication efficiency and particle characteristics in species-specific patterns. Temperature effects vary among species; edible mushrooms-mediated synthesis has been reported to stabilize within 20 minutes to an hour below 40°C [14, 18, 19]. Furthermore, pH optimization typically favors neutral to slightly alkaline conditions, with *Pleurotus ostreatus* and *Ganoderma lucidum*-mediated zinc oxide nanoparticles demonstrating maximum production at pH 7-11 [11]. Biomass concentration and culture medium composition are very important in the bio-fabrication of nanoparticle. biomass of *Ganoderma lucidum* and *Pleurotus sajor-caju* grown in potato

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Table 2. Types of nanoparticles synthesized using edible mushroom extracts.

Metallic nanoparticles	Mushroom	Properties	Ref.
Silver Nanoparticles (AgNPs)	*Agaricus bisporus*, *Pleurotus ostreatus*, and *Ganoderma lucidum.*	*Agaricus bisporus*, *Pleurotus ostreatus*, and *Ganoderma lucidum* extracts have demonstrated significant antimicrobial activity against a broad spectrum of pathogens, including multi-drug-resistant bacteria	[4, 11, 15, 17]
Gold Nanoparticles (AuNPs)	*Pleurotus florida* *Lentinula edodes*	Gold nanoparticles synthesized using extracts of *Pleurotus florida* and *Lentinula edodes* showed potential for use in catalytic applications and biosensors.	[5, 18]
Copper and Copper Oxide Nanoparticles (CuNPs/CuONPs)	*Agaricus bisporus* *Pleurotus sajor-caju*	These nanoparticles demonstrated both catalytic activity and antimicrobial properties, despite challenges in stabilization due to copper's susceptibility to oxidation	[11, 14]
Zinc Oxide Nanoparticles (ZnONPs)	*Pleurotus ostreatus* *Ganoderma lucidum*	These nanoparticles exhibited photocatalytic activity and significant antibacterial properties, making them suitable for environmental and biomedical applications.	[11]
Metal-Metal Oxide Composites: Ag-ZnO and Au-Fe3O4 nanocomposites	*Ganoderma lucidum*	Silver nanoparticles synthesized using *Ganoderma lucidum* extract exhibited enhanced catalytic and antimicrobial properties compared to their single-component counterparts	[15]
Selenium Nanoparticles (SeNPs)	*Pleurotus* species	*Pleurotus* species have been utilized to synthesize silver and gold nanoparticles with enhanced bioavailability compared to other selenium forms. These nanoparticles showed significant antioxidant and anticancer activities.	[3, 18, 19]

dextrose medium has been reported to facilitate the bio-fabrication of nanoparticles with great physicochemical properties at lower biomass concentrations of 1 to 2 g per 100 mL [11, 15].

Experimental procedures have shown that edible mushroom-mediated nanoparticles produce higher yields and performance compared to other biogenic methods employed in the bio-fabrication of metallic nanoparticles, Mushrooms have been known to have high tolerance to metals, secrete large quantities of extracellular proteins that contribute to nanoparticle capping, and produce adequate biomass without requiring additional extraction procedures, unlike bacterial systems [8, 10]. The high enzymatic diversity of mushrooms is evidenced by their production of more than 6000 bioactive compounds, with quinones and NADH-dependent nitrate reductase enzymes responsible for nanoparticle bio-fabrication, demonstrating good bio-reduction capacity compared to other microorganisms [3, 7]. Edible mushroom-mediated nanoparticles exhibit unique properties, including biological activity, enhanced biocompatibility, increased stability, and low toxicity of residues [8].

Mushroom-mediated nanoparticle bio-fabrication is more advantageous than the bacterial bio-fabrication approach, because, recovery processes and scalability for industrial applications are much easier. In extracellular bio-fabrication, precursors (metallic salts) are added to an extract of mushrooms containing biomolecules, resulting in free nanoparticles in dispersion without requiring procedures to release particles from cells, in contrast to bacterial synthesis limitations in purification and geometry control [8, 11, 15]. Furthermore, comparative studies have shown that biogenic nanoparticles (2-10 nm) are smaller than chemically fabricated ones (5-20 nm), with higher cytotoxicity against cancer cells and lower toxicity toward normal cells [14, 18]. Mushrooms can be cultivated on a large-scale with controllable nanoparticle morphology through manipulation of the substrate, culture conditions and biomass quantity [3, 5, 6, 19].

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3.2. Biomedical activities of nanoparticles from edible mushroom

Mushroom-synthesized nanoparticles, particularly silver and copper oxide nanoparticles, have been reported to exhibit remarkable antimicrobial properties against a wide range of pathogens [3, 15]. Silver nanoparticles (AgNPs) synthesized using *Pleurotus ostreatus* extracts have demonstrated significant inhibitory effects against both Gram-positive bacteria (e.g., *Bacillus subtilis, Staphylococcus aureus*) and Gram-negative bacteria (e.g., *Pseudomonas aeruginosa, Escherichia coli,*), with low minimum inhibitory concentrations (MICs) of 6.25 μg/mL [4]. These nanoparticles denature proteins, disrupt bacterial membranes, and generate free radicals e.g., reactive oxygen species (ROS). Furthermore, silver nanoparticles (AgNPs) synthesized using *Agaricus bisporus* extracts have shown selective cytotoxicity against human lung cancer (A549), breast cancer (MCF-7), and colorectal cancer (HCT116) cell lines while exhibiting minimal toxicity toward normal cells [9, 14]. The IC_{50} values typically range from 10-50 μg/mL, depending on the cancer cell type [9, 14, 20].

Metallic nanoparticles synthesized using *Ganoderma lucidum* extracts have shown synergistic effects when combined with conventional chemotherapeutic agents, potentially reducing the required drug dosages and associated side effects [15]. Silver nanoparticles (AgNPs) synthesized using *Lentinula edodes* extracts have been used to develop pH-responsive drug delivery systems that release therapeutic payloads under specific physiological conditions [5]. Table 3 presents the biomedical activities of nanoparticles from some edible mushrooms.

3.3. Environmental remediation potentials of nanoparticles from edible mushroom

Environmental pollution is a global challenge facing countries all over the world, especially developing countries with weak legislation against indiscriminate disposal of waste [26]. These pollutants affect human health, resulting in oxidative stress and cancer, among other effects over short or long term of exposure. Therefore, there is an urgent need to bio-remediate or remove these pollutants through one of the effective approache such as nanotechnology. Fungi have been reported to possess bioremediation potential. Mushroom-synthesized nanoparticles also offer sustainable solutions for wastewater treatment through various mechanisms. Iron oxide nanoparticles synthesized using *Pleurotus ostreatus* extracts have demonstrated 60-80% adsorption capacities for heavy metals such as lead, cadmium, and arsenic from contaminated water [3]. These nanoparticles can be magnetically separated after treatment, facilitating their recovery and reuse reusability. Silver nanoparticles synthesized using *Agaricus bisporus* extracts have been incorporated into filtration membranes to impart antimicrobial properties, effectively reducing bacterial contamination in water [17]. Sabuda et al. [27] also reported the bioremediation of selenium contaminated wastewater using *Alternaria alternata* strain.

Plastic contaminants have been reported to be biodegrade by *Pleurotus ostreatus* [28]. There have also been reports of cadmium, copper, lead, iron, and nickel bioremediation from soil and wastewater by *Calocybe indica, Pleurotus platypus,* and *Agaricus bisporus* [29, 30]. Environmental bioremediation applications of edible mushroom-mediated nanoparticles in areas of soil pollutant bioremediation to the adsorption of dyes and heavy metals from wastewater are gaining ground as an innovative approach in bioremediation [26, 31-33]. El-Batal et al. [34] reported the biodegradation of trypan blue, ramazol brilliant blue, ramazol brilliant red, ramazol brilliant yellow and methyl orange with over 80% reduction using gold nanoparticles synthesized from *Pleurotus ostreatus* laccase. Wang et al. [35] also reported 99.44% removal of Cr (VI) at 200 mg L^{-1} from aqueous media by *Lentinula edodes* mediated ferroferric oxide coated nanoparticles. Mondal et al. [36] also reported the production of an indicator for detecting Thorium (Th^{4+}) in aqueous medium using CuO Composite Nanoparticles from *Tricholoma crassum*. Wang et al. [31] reported 73.88% removal of Cr (VI) at 200 mg L^{-1} within 240 minutes from aqueous media by *Agrocybe cylindracea* mediated ferroferric oxide coated nanoparticles. El-Ramady [26] reported the soil nano-remediation using *Agrocybe cylindracea, Lentinula edodes,* and *Tricholoma crassum* in the synthesis of copper, iron oxides and Biochar nano Fe_3O_4 nanoparticles.

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Table 3. Biomedical activities of nanoparticles from edible mushroom.

Nanoparticles	Mushroom	Biomedical Applications		Ref.
Silver Nanoparticles	*Agaricus bisporus*	Antimicrobial activities	The nanoparticles exhibited significant antimicrobial activity against *P. aeruginosa, S. sonnei, S. typhii, E. coli, E. faecalis, B. cereus* and *S. aureus* and *L. quasipneumoniae.*	[11]
	Agaricus bisporus		The nanoparticles exhibited significant antibacterial activities against *S. epidermidis, B. subtilis, S. typhii, P. aeruginosa, E. coli,* and *S. aureus.*	[10]
	Ganoderma sessiliforme		The nanoparticles showed antimicrobial potential against *Bacillus subtilis, Micrococcus luteus Escherichia coli, Streptococcus faecalis,* and *Listeria innocua.*	[21]
	Pleurotus citrinopileatus		The nanoparticles demonstrated antimicrobial properties against *S. aureus* and *E. coli.*	[22]
	Pleurotus cornucopiae		The nanoparticles demonstrated antifungal property against *Candida* sp	[23]
	Pleurotus giganteus		The nanoparticles demonstrated antibacterial properties against *S. aureus, B. subtilis, E. coli,* and *P. aeruginosa,*	[19]
	Lentinula edodes		The nanoparticles demonstrated antibacterial properties against *S. aureus, B. subtilis, E. coli,* and *K. pneumoniae.*	[5]
	Ganoderma lucidum		The nanoparticles demonstrated antibacterial properties against *S. aureus,* and *S. mutans*. Also, the nanoparticles demonstrated antifungal properties against *C. albicans.*	[15]
Copper Oxide Nanoparticles	*Pleurotus citrinopileatus*		The nanoparticles demonstrated antimicrobial properties against *P. aeruginosa, E. coli, K. pneumoniae, B. cereus, S. aureus,* and *S. pneumoniae*	[24]
	Agaricus bisporus		The nanoparticles demonstrated antibacterial properties against *Enterobacter aerogenes.*	[9]
Gold nanoparticles	*Cantharellus sp.*		The nanoparticles demonstrated antibacterial properties against *S. aureus, B. subtilis, B. cereus, Salmonella enterica, Aeromonas hydrophila, Klebsiella pneumoniae, Pseudomonas aeruginosa, Micrococcus luteus* and *Listeria monocytogenes*	[25]
Copper nanoparticles	*Agaricus bisporus*	Antioxidant	The nanoparticles demonstrated anti-oxidant properties against DPPH (72%), ABTS (82%) and nitric oxide radicals (76%).	[9]
Silver-gold nanoparticles	*Pleurotus sajor-caju*	Anticancer	The nanoparticles displayed positive activity against colon cancer cell lines (HCT-116). More specifically, the morphological changes, production of radicals (ROS), cell viability and fragmentation of DNA confirmed the anti-cancer activities of the nanoparticles.	[14]

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Table 3. *(continued)*

Nanoparticles	Mushroom		Biomedical Applications	Ref.
Gold nanoparticles	*Pleurotus florida*		The nanoparticles displayed effective anti-cancer properties against four different cancer cell lines A-549 (human lung carcinoma), HeLa (human cervix), MDA-MB (human adenocarcinoma mammary gland) and K-562 (human chronic myelogenous leukemia bone marrow. No lethal effect was observed in the kidney cell lines of African green monkey.	[18]
Silver nanoparticles	*Pleurotus ostreatus*		The nanoparticles demonstrated a significant decrease in the cell viability of a breast carcinoma MCF-7 cell line.	[4]
Copper nanoparticles	*Agaricus bisporus*		The nanoparticles displayed 60% cytotoxic activity against human colon cancer cell lines (SW620).	[9]
Silver nanoparticles	*Pleurotus giganteus*	α-Amylase Inhibitory Activity	The nanoparticles displayed α-amylase inhibition, which decreased as the nanoparticle concentration increased	[19]

Edible mushroom-mediated nanoparticle bio-fabrication processes have been reported to be an eco-friendly alternative to conventional physico-chemical fabrication processes [37]. Reports have proven that mushroom-mediated nanoparticle bio-fabrication does not require toxic chemical precursors, unlike physico-chemical fabrication processes.

Recent comparative reports show that mushroom-mediated nanoparticle procedures are show promising as eco-friendly and cost-effective alternatives to chemical fabrication [38], although specific biodegradability data comparing mushroom-mediated nanoparticle bio-fabrication procedures with chemically fabricated nanoparticles remain limited in the literature. Research has proven that mushroom-mediated nanomaterials have the potential for efficient bioremediation of environmental contaminants [39], suggesting that they aid environmental bioremediation rather than contribute to pollution [38, 39].

Despite the promising potential of mushroom-synthesized nanoparticles, several challenges need to be addressed, such as the composition of mushroom extracts, which can vary based on extraction methods, species, growth conditions, and storage, leading to variability in nanoparticle characteristics [3]. Standardized protocols and quality control measures are required to ensure reproducible synthesis. Most studies on mushroom-mediated nanoparticle synthesis have been conducted at the laboratory scale. Scaling up production while maintaining nanoparticle quality and economic viability remains challenging [19]. Efficiently separating synthesized nanoparticles from residual mushroom biomolecules without affecting their properties requires the optimization of purification techniques. The long-term stability of mushroom-synthesized nanoparticles under various storage conditions and in biological or environmental matrices needs improvement for practical applications. The detailed molecular mechanisms underlying the reduction, nucleation, and stabilization processes in mushroom-mediated synthesis require further elucidation [3, 19].

4. Conclusions

The use of edible mushroom extracts for the green synthesis of nanoparticles represents a promising frontier in sustainable nanotechnology. This approach harnesses the rich biochemical diversity of mushrooms, to create nanomaterials with unique properties and reduced environmental impact compared to conventional chemical methods. The bioactive compounds in mushrooms including polysaccharides, proteins, phenolics, and terpenoids, effectively facilitate the reduction of metal ions and stabilization of the resulting nanoparticles. Mushroom-synthesized nanoparticles have

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demonstrated significant potential in biomedical applications, including antimicrobial therapy, cancer treatment, drug delivery, and diagnostics. Similarly, their utility in environmental applications, such as wastewater treatment, catalysis, biosensing, and soil remediation, offers sustainable solutions to pressing environmental challenges. The dual applicability in both biomedical and environmental domains underscores the versatility and value of these nanomaterials. Despite the current limitations in terms of reproducibility, scalability, and mechanistic understanding, ongoing research continues to advance this field. Future developments in genetic engineering, continuous flow synthesis, advanced characterization, and targeted functionalization promise to overcome existing challenges and expand their application landscape. The commercial potential of this technology spans multiple industries, suggesting significant economic opportunities alongside environmental benefits. As research in this field progresses, mushroom-mediated synthesis of nanoparticles stands as a testament to the potential synergy between natural resources and cutting-edge nanotechnology, offering a pathway toward more sustainable and environmentally responsible technological advancements.

Authors' contributions

Conceptualization, O.I.C.; writing – original draft preparation, O.S.B., A.A.G., O.A.O.; writing – review and editing, O.I.C., A.A.G.

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Availability of data and materials

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Conflicts of interest

The authors declare no conflict of interest.

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