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*Review*

# Fungal Nanotechnology: Applications, Challenges, and Future Directions

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**Abstract**

Fungal nanobiotechnology is an emerging discipline that combines the study of fungal biology with nanotechnology to tackle urgent challenges in several areas. This article examines the wide-ranging uses of nanomaterials generated from fungi, focusing on how they might improve antimicrobial treatments, cosmetics, diagnostics, and therapeutic interventions. We explore the creation of advanced liposomal formulations that improve the transportation of drugs and increase their effectiveness in treatment. The text discusses the efficacy of fungal nanotechnologies in agriculture, emphasizing their potential to enhance crop protection and increase production. Furthermore, their industrial applications are analyzed, highlighting their contribution to sustainable manufacturing processes. Although there have been encouraging improvements, the industry is confronted with substantial hurdles like scalability, safety, and environmental effects. An analysis of current challenges is conducted, along with proposed solutions targeted at overcoming these obstacles in order to fully use the potential of fungal nanotechnologies. The conclusion restates the significant influence of fungal nanobiotechnology and its crucial contribution to the progress of future scientific and industrial applications.

## 1. Introduction

Since the last ten years, there has been an increase in public awareness of nanotechnology, which essentially deals with the production of matter at the nanoscale (1-100 nm). Due to the very tiny size and high surface-to-volume ratio of nanoparticles (NPs), which together provide them special capabilities, this technique may be used in multi-sectional areas[1, 2] **.**

Fungal nanotechnology is one of the subfields of nanotechnology. Rai et al.[3] proposed the term "myconanotechnology" to describe fungi-mediated nanofabrication[4]. Physical[5, 6]and chemical approaches may also be used to fabricate nanoscale structures. The importance of these technologies has diminished over time, as nanobiosynthesis, which is demonstrated in bacteria, fungi, actinomycetes, plants, and plant parts[7, 8], has proven superior in many ways.Fungi, however, might be beneficial amongst all biogenic sources for nanoparticle (NPs) production since they are simple to maintain[9], easy to scale up [10], abundant with extracellular enzymes, and most importantly, they can produce nanoparticles without the need of solvents [11].In terms of cellular level regulation and metabolic fluxes of nanofabrication, fungi also have a significant advantage. The investigation of myconanotechnology for diverse applications and the increase in publications were motivated by these factors[12]. The biogenic approach is generally economical. Green biogenic production techniques made it possible to use fungus to create a variety of nanomaterials, including titanium dioxide, zinc oxide, gold, and platinum. This review article aims to provide a comprehensive overview of the applications of fungal nanobiotechnology across various fields. By examining current trends, innovations, and challenges, we seek to highlight the transformative potential of fungal nanobiotechnology and propose solutions to overcome existing barriers.

## 2.Applications for fungal nanotechnology

Fungus nanotechnology refers to the synthesis of metal, oxide, and chalcogenide nanoparticles by negotiation. The use of nanotechnology for the advantage of human health and well-being is what nanoparticles entail[13]. Fungi have the capability to create metal nanoparticles with sizes between (1 – 100 nm) by the use of intracellular or extracellular reducing enzymes, as well as through a process called biomimetic mineralization (see Fig. 1).Table 1 displays a selection of current studies that have investigated the creation of nanoparticles utilizing fungus ,and employed for diagnostics, treatments, and as research tools in the biomedical area, changing the way that medical science is practiced. In order to bind a variety of ligands that turn into biological tools, such as biosensors, targeted molecular delivery vehicles, and imaging agents, nanoparticles with chemically flexible surfaces have been developed. These particles can easily differentiate between diseased and healthy tissue[14]. The use of tools and methodology may provide treatment at the molecular level, curing the illness and aiding in the research of the etiology. More sensitive diagnostic techniques help in early illness diagnosis and provide improved prognoses. Drugs with higher levels of cell specificity are more effective and have fewer side effects, according to studies by [3, 15].Furthermore, since biological processes also take place at the nanoscale and because nanoparticles are amenable to biological functionalization, they have discovered significant uses in the area of medicine (see Fig. 2).

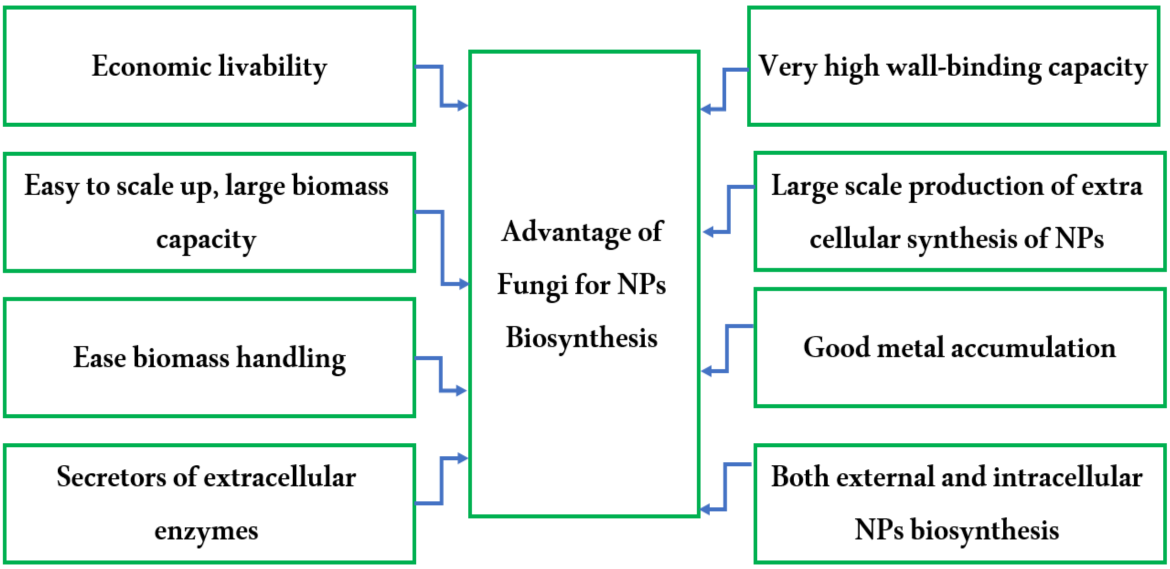


**Fig. 1** Fungi possess several notable benefits when employed as bioreactors for natural product synthesis.

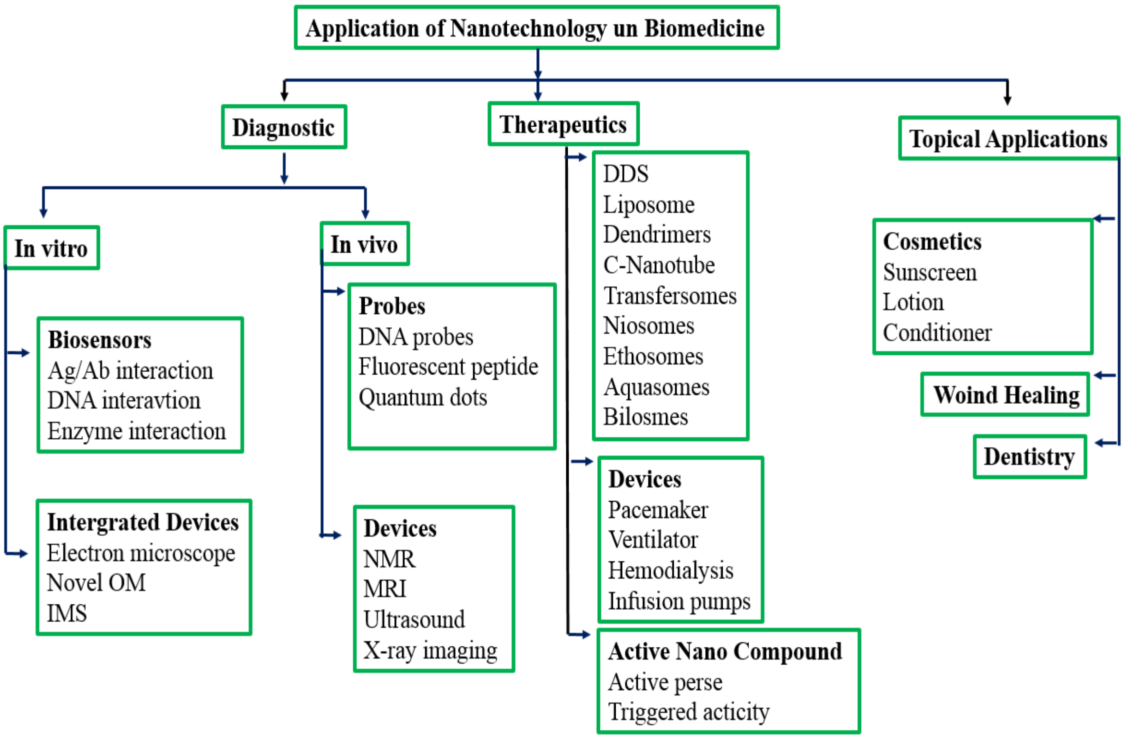


**Fig. 2** Nanotechnology's application in the medical sciences.

**Table 1.** Some recent research on the use of fungi in the manufacture of NPs.

| Nanoparticle | Fungus | Application | Extra/ Intra | Ref. |
|---|---|---|---|---|
| Pt | *Fusarium oxysporum* | Nano medicine | Extra | [16] |
| Se,Au , Ag | Mushrooms | Biomedicals | Both | [17] |
| Au | Cladosporium | Antimicrobial, Antioxidant | Extra | [18] |
| $CO_3O_4$ | *Aspergillus nidulans* | Energy storage | Extra | [19] |
| $Fe_2O_3$ | *Aspergillus niger* | Wastewater treatment | Extra | [20] |
| Cu | *Aspergillus niger* | Antidiabetic and Antibacterial | Extra | [21] |
| Ag | *Aspergillus terreus* | Anticancer, antibacterial | Extra | [22] |
| Ag | *Aspergillus brunneoviolaceus* | Antibacterial, Antioxidant | Extra | [23] |
| Au | *Cladosporium oxysporum* | Catalysis | Extra | [24] |
| Ag | *Penicillium oxalicum* | Antimicrobial, Antioxidant, and Anticancer | Extra | [25] |
| Ag | *Nostoc carneum* | Photocatalytic, anticoagulative and antibacterial activity | Extra | [26] |

### *2.1.Nanotechnology antimicrobial*

Because nanoparticles interact with biological molecules at the nanoscale, they open up new avenues for research and development. Both the internal and extracellular environments may be used to understand how nanoparticles interact with biomolecules[27]. Due to their increased surface area and strong antibacterial activity at the nanoscale, which allows them to interact with microbes more effectively than their huge counterparts, nanoparticles are becoming more and more significant. Different nanoparticles are utilized as effective antibacterial treatments because the nanosize alters the physiochemical characteristics of metals.It is a potent and quick-acting antimicrobial drug that works well against a variety of common bacteria and fungi that are used in a variety of medical science procedures. Silver nanoparticles (Ag NPs) are one of them and have been shown to have potent antimicrobial (antibacterial and antifungal) action[28, 29].It has been discovered to have very powerful antibacterial properties against both Gram-negative and Gram-positive bacteria that interrelate with components of the bacterial membrane and cause cell destruction. Using the agar well diffusion technique, the antibacterial activity of Ag NPs was investigated against *S. aureus*[28, 29].

It is commonly accepted that the key component of silver's antibacterial activity is its great proximity to sulfur and phosphorus. According to this study, Ag NPs bind to sulfur-containing proteins on the bacterial cell membrane and can also combine with phosphorus moieties of DNA, disrupting DNA replication and increasing membrane permeability while inhibiting enzyme activity, ultimately leading to cell death[30].It shows that Ag ions generated by the active surfaces of Ag NPs cause bacterial cells to produce intracellular reactive oxygen species (ROS) and decouple respiratory electron transfer from oxidative phosphorylation to protons and phosphates.These nanoparticles' antibacterial properties are dependent on chemisorbed $Ag^{+}$, which is produced on the surface of Ag NPs due to their great sensitivity to oxygen. As a reliable method for delivering antibiotics, coating materials for various devices, and cleaning filters, silver nanoparticles have been examined to understand the mechanism behind their inhibitory action on a range of bacteria.They have likewise been used to treat infections, wounds, and burns[15, 29, 31, 32].

### *2.2.Cosmetics Nanotechnology*

Cosmetics are substances applied to the human body to improve its appealing qualities, cleanliness, look, or odor. Cosmetic pharmaceuticals, also known as cosmeceuticals, are medicines produced under the name cosmetic that are added to cosmetic goods and claim to offer medical or drug-like advantages. It is used topically and affects how the skin functions biologically. Cosmetics are said to have originated with the Egyptians about 4000 BC. Innovative multifunctional products with a focus on treatment and aesthetics and active substances are formulated using the most recent technological advancements[33]. This technology focuses on the applications of delivery systems in cosmetics, which assess the most popular techniques for improving the qualities of skin penetration as well as innovative ways for getting advanced cosmetic goods. The fundamental goal of topical treatment is to reduce systemic involvement by modulating the skin's limiting function and delivering an active component to specific skin layers or compartments[34]. By installing medicine on the charger particles such as nanoparticles, lipid particles, liposomes, microspheres, microbiology, etc., that adjust the properties of the release and absorption of the drug, modern technology provides smart technologies for unique aesthetic delivery systems. The goal of nanotechnology is to create biologically active nanotechnology components and analytical tools for studying cells at the molecular level [33].Nanotechnology is the creation of materials on the nanoscale that may be solid or soft, insoluble or soluble, and have a wide range of shapes, sizes, and properties for different uses. These nanoparticles include metals (Ag, Au), lipophilic nanoparticles, metal oxides ($TiO_2$, ZnO, $Fe_2O_3$, $SiO_2$),carbon nanotubes, quantum dots (QDs), andfullerenes, which are employed in an increasing variety of commercial goods. Solid lipid nanoparticles and liposomes, both of which are lipophilic nanoparticles,have been developed for transcutaneous medication administration.It is believed that nanoemulsions and liposomal nanoparticles have a bright future in cosmetic goods because they do not interfere with the safety of the skin's lipid bilayers and are not washed when cleaning the skin.Since nanoparticles have a huge surface area and reflect/scatter UVA and UVB rays, $TiO_2$ and ZnO are often used in cosmetics, including lotion, sunscreen, and conditioner, to minimize UV radiation that causes skin cancer. The skin barrier must be permeable for nanoparticles to convey their contents and leave the body without causing harm. Anatomical locations, cuticle thickness, and species-specific hair follicle density all have an impact on nanoparticle skin penetration. Accumulation of nanoparticles in hair follicles and stratum corneum penetration through the skin with a compromised barrier are widespread phenomena that affect many species. QDs are often employed by in cosmetic products as hair elimination agents and have been shown to permeate both mouse skin treated by ultraviolet B radiation and ex vivo human skin. According to an authorized in vivo research of nanoparticles given to pigs in sunscreen, the impact of UVB radiation boosts nanoparticle ($TiO_2$ and ZnO) stratum corneum penetration. The stratum corneum barrier must be broken by the nanoparticles in order for them to enter cells via receptor-mediated mechanisms. As a result, several methods have been devised, such as tape stripping, microneedles, gene guns, electroporation, and ultrasound, to agitate the stratum corneum and help in the transport ofnanoparticles [35]. Wound healing and antimicrobials targeted therapies and skin cancer imaging, vaccine distribution, and immunomodulation are the three primary therapeutic uses in the skin. ZnO and $TiO_2$ nanoparticle penetration poses just a little health risk. The stratum corneum of the skin causes the disintegration and penetration of zinc ions, an important mineral that has no serious effects as ZnO is soluble in acidic situations.$TiO_2$ nanoparticles are prone to aggregation and very insoluble, which prevents them from penetrating the skin[35].

### *2.3.Diagnostic Nanotechnology*

The majority of disorders can currently only be diagnosed using current techniques based on the patient's outward symptoms, which decreases the likelihood that the patient will respond to therapy. Therefore, the likelihood of finding a cure increases with earlier illness diagnosis. In today's healthcare, biomedical laboratory diagnostics is essential. The typical possibilities are becoming more diverse thanks to nanotechnology, which will lead to more subtlety, higher effectiveness, and more economy. The field of nanotechnology that contracts with biochemical and biological applications and uses is known as nanobiotechnology. It pushes the boundaries of diagnostics to the nanoscale and creates nanodevices for detecting genetic abnormalities, detecting mutations in cardiovascular, neurodegenerative, and cystic fibrosis diseases, and performing diagnostic imaging during infection and pregnancy. Nanotechnology's diagnostic applications hold a lot of hope for accurately addressing the clinical laboratory's needs for sensitivity, cost-effectiveness, and multiplexing capacities. The identification of disease cells in vivo and in vitro using nanoparticles is possible in both quantitative and qualitative ways. The development of nanodiagnostic instruments and devices is a result of the many uses of nanomaterials in diagnostics. In order to effectively diagnose diseases, specific ligands (amino acids, peptides, and proteins) may be immobilized on the surface of nanoparticles(NPs), revealing their distinctive features at the nanoscale. As a result, they become ideal candidates for sensitive detection and highly effective contrast agents for imaging, and they also help in the development of biomarkers with clearly defined colors. Improved fluorescent markers for screening and diagnosis will be one of the initial uses for nanoparticles. Fluorescent markers that are used traditionally need a rich hue. Fluorescent substances like magnetic nanoparticles, quantum dots, and gold nanoparticles are utilized to spot cancer and other illnesses in their early stages. Research efforts are continuing to determine the state/status of biomarkers for various kinds of malignancies. These NPs are connected with biomarkers, which may differ in their pattern of adherence.The huge surface area provided by the surface of nanoparticles makes the usage of nanosystems to read the status of biomarkers crucial. Some tests based on nanotechnology are being created that seem to be very straightforward, accurate, and quick in detecting viruses, antibodies, DNA proteins, *E. coli*, etc. Diagnostic capacities may be considerably enhanced by nanotechnology. The effectiveness and accuracy of diagnoses made from bodily fluid samples will be improved by nanoparticles. Northbrook, a business located in Illinois (USA), has created a method that enables medical professionals to visually identify the genetic makeup of biological material using individual target probes employing spherical gold nanoparticles. Target molecules marked with quantum dots (QDs) will make it easier to directly examine the intracellular signaling complex using optical methods, such as confocal fluorescence microscopy when they exhibit fluorescence[15, 36].

### *2.4.Therapeutics Nanotechnology*

For the benefit of people, nanobiotechnology has been used in practically every field of medical research, including stem cell-based treatments for serious illnesses, including cancer, heart disease, and infections. Nanotechnology has greatly revolutionized the biotechnology and medical fields. Nanotechnology has proved effective in the initial testing of several medication delivery systems, cancer or tumor therapy, or tumor diagnostics. Nanoparticles are tiny, simple to inject, and intended for a particular area of the body[37]. Gold nanorods, which have great infrared absorption and scattering properties, have been utilized effectively in recent years to identify and eliminate cancer cells without harming healthy cells. It is crucial because, unlike chemotherapy, it would not damage healthy cells. Nanotechnology can effectively provide innovative medicine formulations with fewer adverse effects and convenient drug delivery methods. Due to their small size and large surface area, NPs are used as drug carriers because they are quickly carried into cells and nuclei and can be targeted with the necessary specificity. Numerous tools, including nanospheres, nanocapsules, nanopores, liposomes, micelles, vesicles, and dendrimers, among others, are used to do this.Drugs may be packaged into nanocapsules and delivered to specific bodily regions. By opening the capsule with an external stimulation such as infrared light or a magnetic field or under certain physiological circumstances, the drug may then be released quickly or gradually, depending on the intended effect. The modes of epidermal application, oral administration, nasal administration, and ocular administration are examples of how the nanoparticle medication system works. This approach is being used to develop new drug delivery systems to treat diseases, including cancer, diabetes, fungal infections, gene therapy, bacterial infections, and viral infections. The primary benefits of this approach to treatment are improved safety and drug targeting [31].

### *2.5.Liposomes*

The interaction of brain and blood cells with fungus-causing pathogens and infection sites depends on intricate interactions between cells and surface properties. By changing surface properties at nanoscale resolutions, nanofabrication unravels the intricacy of these interactions, which may result in hybrid biological systems. This hybrid material has potential usage in medical devices, drug screening, sensors, and implants. A polymer coating created by the Irish pharmaceutical firm Elan may alter the surface of medications with low water solubility[38].

As lipid bilayers, liposomes are the first examples of nanoscaled drug delivery systems.They can be used as targeted drug delivery systems and can contain pharmaceutical substances positioned either in the lipid membrane or in the aqueous compartment.Medications that are lipid-soluble are integrated into the liposomal membrane, whereas medications that are water-soluble are loaded into the aqueous compartment. Both passive and active techniques may be used to target a particular cell, tissue, or organ. Immunoliposomes and ligand-directed liposomes, which are combined with an antibody aimed at the tumor antigen, are active targeted medicines. For the treatment of illnesses, these liposomes are being tested in combination with the medications epirubicin, doxorubicin, and hamycin. In comparison to nontargeted liposomal pharmaceuticals, targeted liposomal formulations of medications are proven to be more effective [39].

Nanobiotechnology enables the treatment of illnesses that are impossible to cure with conventional medications. Conventionally, the traditional pharmaceutical sector focuses primarily on 500 universally acknowledged diseases, while this technology ensures that targets are addressed even on solid substrates through cross-linking, controlling chemical reactions in a much faster process that involves fewer materials. This advancement not only ensures a wide range of options among the population of highly particular medications but also significantly lowers the cost of innovative drug research[39].

Diseases that are incurable with traditional medicine may now be treated thanks to nanobiotechnology. The pharmaceutical industry often concentrates on 500 widely recognized ailments, but this method enables target manipulation even on solid substrates by tethering, directing chemical reactions in a much speedier procedure requiring less components. In addition to guaranteeing a wide variety of possibilities among the population of highly specialized treatments, this development also greatly reduces the cost of cutting-edge drug research methods for producing both common and highly customized nanomaterials for scaling up medication delivery and diagnostics[39].

### *2.6.Application of fungal nanobiotechnology in agriculture*

The development of many agricultural sectors and related industries has the greatest potential for fungal nanobiotechnology, which has the capacity to manufacture a wide range of nanostructured materials[40, 41]. Numerous authors have reported on the diverse agricultural uses of myconanofabrications, including their use as nanofungicides, nanopesticides, nanoinsecticides, and nanofertilizers, among other things [42]. A new class of biosensors known as nano biosensors can be created using fungi-based nanobiotechnology.Biological agents such as metabolites, nucleic acids, antibodies, and viruses can be found using nanoscale biosensors.The current demand of the moment is for technical breakthroughs in the agricultural industry to address global concerns such as population expansion, declining soil fertility, pests' resistance to pesticides, climate change, and limited availability of resources[43]. Research on the application of fungal nanotechnology in agricultural science and engineering is progressing and holds promise as a potential solution to several challenges in the agriculture and food industry. Figure 3 illustrates the potential of nanomaterials/technology mediated by fungi in the agri-food industry for various applications[44].

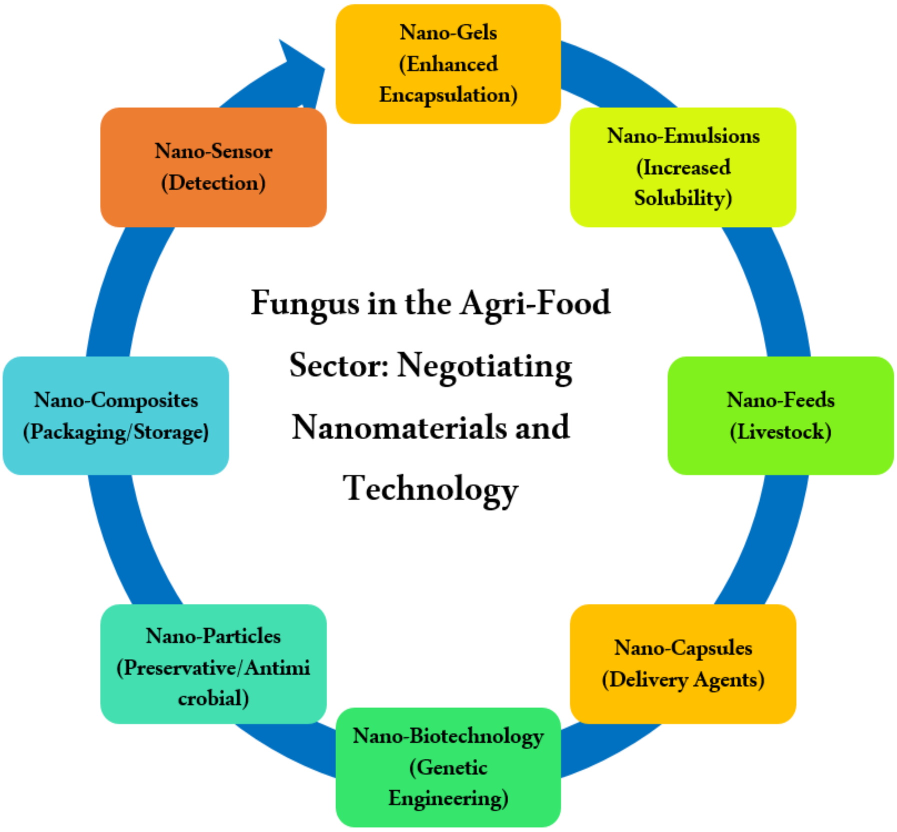


**Fig. 3** Potential application of technology and nanomaterials mediated by fungi in the agri-food industry.

According to Prasad et al. [42], nano biosensors can be used to detect a wide range of fertilizers, soil pH,  pathogens, pesticides, moisture, and herbicides. Farmers can use these methods to determine the ideal time for harvesting and planting. Fungal nanobiotechnology has been used extensively in a number of agricultural industries, as has been previously documented. Elgorban et al. [45]evaluated the impact of the produced silver nanoparticles against *Sclerotinia sclerotiorum* and *Botrytis cinerea* in strawberry plants through the fungus *Aspergillus versicolor*. The resulting data indicated a dose-dependent action versus pests, with *B. cinerea* showing the strongest observed impact. According to Qian et al. [46], the pathogenic fungi C. *albicans*, *Aspergillus fumigatus*, *Sporothrix schenckii*, *Aspergillus flavus*, *Cryptococcus neoformans*, and *Fusarium solani*were all targets of the biologically produced nanoparticles from the fungus *Epicoccum nigrum*. The phytopathogenic fungi *Colletotrichum* *sp.*, *Curvularia lunata*, and *Rhizoctonia solani*may be under the control of nanoparticles made from the fungus Guignardia mangiferae, according to research by Balakumaran et al. [47]. In other research, it may be possible to treat wheat, barley, and corn seeds contaminated with several types of plant pathogenic fungi using nanoparticles manufactured from the plant pathogenic fungus *Fusarium solani* (isolated from wheat)[48].

The interaction of biogenic nanoparticles with conventional biocides has been well-documented by numerous authors. Gajbhi et al. [49]established the potential evaluation of Alternaria alternata-mediated nanoparticle synthesis, in combination with the antifungal drug fluconazole against the fungi Phoma glomerata, Phomaherbarum, and *Fusarium semitectum*, along with the biological control agent Trichoderma sp. the human pathogenic fungus *Candida albicans*. *C. albicans* showed the greatest sensitivity to the combination of fluconazole and nanoparticles after exposure, followed by T*richoderma sp.* and *P. glomeruli*.In tests on larvae and pupae of dengue-carrying mosquitoes *Aedes aegypti*, other scientists have shown the agricultural importance of bioproduction of nanoparticles from *Trichoderma harzianum* with mortality [50].

Agricultural methods have included nanobiotechnology to increase food production in terms of nutritional content, quality, quantity, and security.The best ways to enhance food production are to effectively manage fertilizers, pesticides, herbicides, and plant growth regulators using nanocarriers for controlled release. For example, poly(epsilon-caprolactone) nanocapsules for atrazine have recently been produced[51]. The herbicidal effect of atrazine-loaded poly(epsilon-caprolactone) nanocapsules on mustard (Brassica juncea) plants was significantly increased compared to commercial atrazine, resulting in weight loss and growth restriction of the plants tested, as well as a significant reduction in net photosynthetic rates, and oral delivery. As modified release systems to carry pesticides in a controlled manner, polymeric nanoparticles [52], silica nanoparticles [53], and other nanocarriers have also been created**.**

Over time, these creatures are effectively transported and released via nanoscale transporters. According to Duhan et al. [54], precision agriculture is an agricultural technology that increases crop productivity while reducing water damage and soil. The most intriguing aspect of nanoencapsulation is that it may lower herbicide doses without reducing effectiveness, which is advantageous for the environment. Nanoparticle-mediated gene or DNA transfer in plants, together with nanocarriers, are used to create insect-resistant cultivars [55].

Metal oxide nanomaterials, includingCuO, $TiO_2$, and ZnO, are reality studied for their inherent toxicity to protect plants from pathogenic diseases. Nanoparticles also act as insecticides with improved toxicity and allergenicity. For instance, ZnO nanoparticles have been shown to successfully limit the development of a variety of bacteria, including *Fusarium graminearum*[56], *Aspergillus niger*, *Aspergillus flavus*, *Aspergillus fumigatus*, *F. oxysporium*, and *F. culmorum* [57]***.***

Conventional mineral fertilizers suffer from low nutrient uptake rates and significant losses, but the creation of nano fertilizers has provided an innovative solution to this financial loss. By lowering nutrient depletion and enhancing nutrient absorption, nanofertilizers may aid soil microbes and crops in consuming more nutrients [58]. Commercial nano fertilizers are mostly micronutrients such as N, Mn, Fe, Cu, Zn, Mo, and B at the nano level. Other nanomaterials can be used instead of traditional crop fertilizers to improve crop quality and growth, such as carbon nano-onions [59] and chitosan nanoparticles [60]. Over the next 10 years, new nanofertilizers are expected to transform and inspire existing fertilizer processing industries.

Due to various beneficial properties of nanomaterials, nanosensors, especially wireless nanosensors, have been created to monitor crop diseases and development, nutrient production, and environmental conditions in the field. Proper application of nano-fertilizers, nano-pesticides, and nano-herbicides, coupled with on-site and real-time monitoring devices, will help reduce potential crop losses and enhance crop productivity. For example, engineered nanosensors can detect pathogens and chemicals, such as pesticides and herbicides, in food and agricultural environments at a trace level. A recent study found that copper-doped montmorillonite can be used to test propene fungicides online in fresh and saltwater aquatic ecosystems, with a detection limit of about 1 meter[61].

The use of fungal nanobiotechnology in food production and storage has enhanced food safety.Food-grade $TiO_2$ nanoparticles, for instance, have been shown to exist at the nanometer scale up to 40%[62]. Many conventional compounds used as food additives or packaging materials have also been found to occur partly at the nanoscale. By using nanoencapsulation and nanoemulsion, nanomaterials, like the components of animal feed, are effectively created as preservatives, carriers for dietary supplements, and additions for color or flavor. Due to its thermal, mechanical, and insulating properties, as well as its low cost, nanoclay is one of the most widely used and researched new nanomaterials for food packaging. The specific properties of engineered nanomaterials, such as food additives or supplements, have great benefits for food production.

The capacity of edible nanomaterial-encoded coatings to preserve and store food has also been shown, with coated fresh produce, including fruits and vegetables, remaining edible throughout storage and transit. Active respiration processes can lead to significant post-harvest losses and poor aesthetic and nutritional quality in items with high transportation and storage times; however, managing this weight and nutrition loss is essential to increase the shelf life of fresh food products. The effects of temperature and relative humidity on the respiration of fresh food and microbiological activity in commodities are quite significant. In order to improve mechanical characteristics and sensory perception, prevent microbiological deterioration, and extend the shelf life of fresh foods, a thin coating of hybrid nano-edible filmstypically less than 100 nm thickcan be utilized as a gas and moisture barrier [63].

Due to the highly sensitive properties of nanomaterials listed in Table 2, other applications in food packaging currently being researched and developed include the detection of pesticides [64], pathogens [65], and toxins [66]. In addition, ZnO quantum dots (ZnO QD) can photocatalyze pesticides during the reaction. Other nanomaterials, including carbon nanotubes, gold nanoparticles, copper nanoparticles, and silver nanoparticles, have also been developed as devices for Nanoscale sensors for real-time food safety monitoring.

**Table 2.**Possible fungal isolates that might be employed in the manufacture of metal/metal oxide nanoparticles.

| Species of fungi | NPs | Localization | Shape | Size (nm) | Application | Ref. |
|---|---|---|---|---|---|---|
| *Aspergillus fumigatus* | ZnO | Extracellular | Hexagonal and spherical | 1.2-6.8 | Agricultural and industrial | [67] |
| *Aspergillus fumigatus* | ZnO | Extracellular | | | - | [68] |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Botrytis cinerea* | Au | Extracellular | Spherical, hexagonal ,decahedral, triangular, pyramidal | 1-100 | - | [69] |
| *Hormoconis resinae* | Ag | Extracellular | Cubic | 20-80 | - | [70] |
| *Aspergillus oryzae* | $FeCl_3$ | - | Spherical | 10-24.6 | Engineering and agricultural | [67] |
| *Rhizopus stolonifer* | Ag | - | Quasi-spherical | 25-30 | - | [71] |
| *Aspergillus tubingensis* | $Ca_3P_2O_8$ | Extracellular | Spherical | 28.2 | Engineering and agricultural | [72] |
| *Fungi isolated from the soil* | Mg , Zn and Ti | extracellular | - | Various | - | [73] |
| *Fusarium spp.* | Zn | Intracellular | Irregular, some spherical | 100-200 | - | [74] |
| *Aspergillus flavus TFR7* | $TiO_2$ | Extracellular | - | 12-15 | Plant nutrient | [75] |
| *Aspergillus tubingensis* | $TiO_2$ | Extracellular | Fuzzy surface | 1.5-30 | - | [76] |
| *Trichoderma Koningii* | Au | - | Spheres | 10-40 | - | [77] |
| *Trichoderma viride* | Ag | | Spherical | 5-40 | Preserving fruits and vegetables | [78] |
| *P. nagiovense AJ12* | Ag | Extracellular | Spherical | 25 | - | [79] |
| *Penicillium citrinum* | Ag | Extracellular | Cubic | 18 | Agricultural | [80] |
| *Penicillium cyclopium* | Ag | Extracellular | - | 16 | - | [81] |
| *Aspergillus fumigatus JCF* | ZnO | Extracellular | spherical | 60-80 | - | [68] |
| *Pleurotus sajor-caju* | Ag -Au | Extracellular | spherical | 20-40 | - | [82] |

## *2.7.Application of fungal nanobiotechnology in industry*

Numerous industrial processes have been found to be useful for a variety of fungi-mediated nanoparticles. In addition to the significance of fungus-mediated nanoparticles for industry, fungi release large quantities of these nanoparticles extracellularly[83]. In addition to being suitable and appealing for industrial uses, fungus can survive in severe settings because they have unique enzymes that can carry out difficult chemical reactions, according to Viswanath et al.[84]. The laccase is the most popular fungi-mediated nanoparticle used in numerous industrial operations. Although laccase can be found in bacteria, insects, and plants, fungi continue to be the primary source of laccase. Some biological functions for laccases in fungi have been proposed, including spore tolerance, pigmentation, and fluorescence of plant cell walls[85-87].

Surprisingly, over 60 fungal strains from the Basidiomycetes, Deuteromycetes, and Ascomycetes families possess laccase activity, making them the bulk of biotechnologically useful laccases (those with high redox potentials). According to Shraddha et al. [86], ectomycorrhizal and litter-decomposing fungi also produce laccases, and laccase offers a range of oxidations, including non-phenolic substrates, in the attendance of tiny redox mediators. Laccase production is highest in lignin-degrading white-rot fungi. Because they use little resources to create bioelectrocatalysis and simply provide water as a byproduct, fungal laccases are thus regarded as suitable green catalysts with considerable biotechnological impacts [88].Contrarily, a laccase-mediator device (LMS) may increase the biotechnological usefulness of laccase.Laccase and LMS have potential uses in delignification [89], biobleaching of pulp [90], enzymatic dye-bleaching and fiber modification in the textile and dye industries [88], phenolic compound elimination in beverages wine and beer stabilization, fruit juice processing [91], and enzymatic cross linking of lign Because of its catalytic properties and potential biotechnological uses, laccase has received a lot of research [85].

This is why laccase is so useful in a number of biotechnological processes: it can oxidize a wide range of organic and inorganic compounds, including mono-, di-, polyphenols, methoxyphenols, aminophenols,and metal complexes. Due to their potential use in phenolic compound bioremediation and pollution detoxification, laccases have recently attracted significant attention [92]. Fungal enzymes may convert materials such asplastic, paint and wood into nutrients and are often used in processing paper,pulp and creating fine chemicals.

Extracellular xylanases produced by microorganisms are enormously important in industry, with cellulase, pectinase, and xylanase accounting for nearly 20% of the global enzyme market. Xylanase is another fungal enzyme of substantial biotechnological significance. According to Kalim et al. [93], the demand for industrial enzymes has increased significantly in recent years, rising from an estimated $1 million in 1970 to a reported 4.5 billion dollars in 2012 and then anticipated to reach roughly 7.1 billion dollars in 2018. The processing of food as well as the pulp and paper industries both rely on microbial enzymes like xylanases [94]. It is crucial to many biotechnological processes, such as those that increase the digestibility of chicken feed, the purity of fruit juice, the bleaching of beer and wine, and the pulp, paper, leather, and baking industries [95]. Extracellular polymeric substances (EPS), starch, green feed, coffee, silage,and plant oils are among the foods that they are employed to collect [96]. Additionally, xylanase has been shown to be efficient in the lignocellulose-based biofuel manufacturing process [95]. Different species of bacteria and fungi are known to synthesize xylanase under different production processes, but filamentous fungi are the most successful producers of xylanase, as mentioned previously[97]. The most recent interest in green nanoparticle synthesis for significant biomedical applications; According to Shahi et al. [98], Aspergillus and *Trichoderma spp.* are the primary commercial producers of xylanases**.***Trichoderma spp.*, which are the main agents responsible for the decomposition and decomposition of agricultural wastes, have an extensive range of enzymes and are therefore considered to be producers of lignocellulolytic enzymes. In contrast, Aspergillus species have the ability to synthesize a wide diversity of enzymes responsible for weakening plant cell walls. It was recently discovered that the xylanase activities of isolates of *Aspergillus niger*, *Aspergillus flavus*, *Trichoderma longibrachiatum*, *Aspergillus fumigatus*, *F. solani*, and *Botryodiplodia sp.* were employed in the rising of dough and the confirmation of juice [93]. Table 3 lists more commercial applications for fungi-mediated nanoparticles.

**Table 3.** Fungi and the characteristics of fungi-mediated nanoparticles used in agriculture, industry, and other applications.

| Types of fungus | NPs | Localization | Size (nm) | Shape | Application | Ref. |
|---|---|---|---|---|---|---|
| *Separated fungi from the soil* | Ti, Zn and Mg | extracellular | Various | - | - | [67] |
| *Aspergillus versicolor mycelia* | Hg | Surface of mycelia | 20.5±1.82 | Alteration | - | [99] |
| *Fusarium sp.* | Zn | Intracellular | 100-200 | Some irregular and spherical | - | [74] |
| *F.sp. lycopersici ,Fusarium oxysporum* | Pt | Extra-and intracellular | 10-100 | Pentagonal, hexagonal, circular, rectangles, squares | - | [100] |
| *Aspergillus flavus TFR7* | $TiO_2$ | - | 12-15 | Extracellular | Plant nutrient | [75] |
| *Verticillium sp.* | $Fe_3O_4$ | Extracellular | 20–50,100–400 | Quasi-spherical ,Cubo-octahedral | - | [101] |
| *Fusarium oxysporum* | $Fe_3O_4$ | Extracellular | 20-50 | Quasi-spherical, irregular | - | [101] |
| *Fusarium oxyporum* | Au–Ag | Extracellular | 8-14 | Quasi-spherical | | [102] |
| *Botrytis cinerea* | Au | Extracellular | 1–100 | Pyramidal, spherical, hexagonal, triangular, decahedral | | [69] |
| *Aspergillus fumigatus* | ZnO | Extracellular | 1.2–6.8 | Hexagonal and spherical | Agriculture and industrial sectors | [103] |
| *Aspergillus oryzae* | $FeCl_3$ | - | 10–24.6 | Spherical | Areas of agriculture and engineering | [103] |
| *Aspergillus tubingensis* | $Ca_3P_2O_8$ | Extracellular | 28.2 | Spherical | Engineering and agricultural sectors | [72] |
| *Rhizopus oryzae* | Au | Cell surface | 10 | Nanocrystalline | Pesticides | [99] |
| *Fusarium semitectum* | Au | - | 25 | Spherical | Optoelectronics | [104] |
| *Trichoderma viride* | Ag | - | 2–4 | Mostly spherical | Biosensor and bio imaging | [105] |

## 3.Challenges and future directions for microbial nanobiotechnology

The utilization of fungus and its metabolites to provide products and services to humanity has various hurdles, much like every other area of nanobiotechnology. Below are some of these difficulties and suggestions for enhancing technology.

The main issue with fungal nanobiotechnology is being investigated by fungus. Only a few number of fungi have been thoroughly studied in terms of biology and their ability to produce nanoparticles. This has in some way prevented the whole kingdom from being explored. Because the incubation conditions and medium requirements are either poorly known or simply cannot be satisfied, certain fungi are not even culturable in the lab. Additionally, in this branch of microbial nanobiotechnology, optimizing fungal growth and nanoparticle production has remained a significant difficulty**.**

In general, the hurdles facing nanobiotechnology include insufficient clinical studies on long-term exposure to nanoparticles, little or no regulation governing nanoparticle deployment in most countries, and public acceptability. These issues are sometimes resolved by microbial nanobiotechnology, but tragically, they persist to some extent even with fungal nanobiotechnology. No other nanomaterials are used in human food besides iron oxide and titanium dioxide, which are used as colorants and food pigments, correspondingly[106]. This is primarily because there are insufficient constitutions or laws governing nanotechnology and nanofood as a whole because nanotechnology is complex and lacks in-depth legislation [107]. absence of knowledge about the toxicity and hazard that innovative nanomaterials may provide is a more compelling explanation for the absence of regulation [108]. Numerous studies on the toxicity of nanomaterials have been conducted in vitro, but there is little information available on their effects on living organisms or over time [109]. There are at least a few gaps that need to be addressed, including those concerning the long-term impacts of nanomaterial exposure on human health, the migration of nanomaterials into food, the destiny of depleted nanomaterials in the environment, and the bioaccumulation and ecological effects of nanomaterials. In this broad topic, further research and proper financing will undoubtedly be required[110]**.**

Public acceptance is a crucial component that is often disregarded by scientists, manufacturers, and government organizations [110]. No matter who accepts these revolutionary nanomaterials, the waste will ultimately be disposed of into the atmosphere, having distinct consequences on plants, animals, and ecosystems. It determines if nanotechnology can be adopted and/or authorized by consumers in the long run. A dearth of in vivo toxicity data for nanoparticles, particularly the potential chronic influence on human organs, is made worse by the fact that neither researchers, nano industries, nor governmental organizations have fully explored the right disposal procedure**.**

It is critical to do more clinical studies on the security of fungal nanoparticles if fungal nanobiotechnology is to be generally accepted by people. Research on fungal nanobiotechnology has to evolve to the point where it can assess the safety of nanoparticles in vivo, maybe on a volunteer human population. Additionally, it is crucial to educate people about the advantages and safety of nanoparticles. In general, nanobiotechnology should be welcomed since it may open up opportunities in fields of human effort that previously seemed to be at a dead end. More importantly, each nation should establish strict legal frameworks to direct and encourage the use of nanoparticles in its economy[110].

## 4.Conclusion

The process of biologically synthesizing nanoparticles is both safe and somewhat cost-effective. The utilization of microorganisms for synthesizing metallic nanoparticles has demonstrated significant potential for anextensive range of applications. The use of fungus to produce nanoparticles has been extensively studied due to its benefits, such as their ease of handling and processing in subsequent steps. Several researchers have recently become fascinated with the production of nanoparticles using my nanotechnology. The fabrication of nanoparticles using myconanotechnology is a well-regarded and effective approach for synthesizing different types of nanoparticles. This method has great potential and can be applied in various fields, including agriculture, food, textile, medicine, cosmetics, optics, and electronics. Currently, numerous fungal species play a significant role in nanobiotechnology because they create nanoparticles that are safe, environmentally friendly, adaptable, and valuable. In addition, the nanoparticles are produced abundantly outside the cells, which makes fungal nanobiotechnology more advantageous than other forms of microbial nanobiotechnology. This is because it reduces the expenses associated with downstream processing. Multiple studies in the field have contributed to the advancement of innovative ideas and the wider application of nanobiotechnology in numerous aspects of human life**.**

Fungal nanobiotechnology has been utilized in agriculture, health, and numerous industrial operations. Currently, fungal nanobiotechnology plays a crucial role in the management and control of fungal diseases inplants, animals, and humans. In addition, fungal nanobiotechnology has been lengthily utilized in the areas of food product composition, packaging, and shelf-life enhancement. From a medical standpoint, fungal nanoparticles play a crucial role in drug delivery systems, as well as in the treatment and diagnosis of drug-resistant infections and cancer. Metal nanoparticles generated by fungi show great potential for application as sensors and electronic devices in the field of biomedical imaging. The application of xylanase and laccase enzymes derived from fungi in various industries highlights their significance in enhancing the quality of goods and services, demonstrating the potential of this technology.

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