A REVIEW ON RECENT PROGRESSES IN FUNGI-BASED FABRICATION OF NANOPARTICLES

Abstract

In recent years green fabrication methods of nanoparticles have attracted ample attention. Unlike the conventional methods involving toxic reactants and by-products, these processes are environment-friendly and economic. Nanoparticles produced in these methods have also shown to have more specific surface area and better catalytic reactivity [1]. These biocompatible nanomaterials are suitable for applications in various fields like biomedicines, antimicrobials and biosensors. Earlier reports indicate that nanoparticles of metals like Ag, Au, Se, Pt, Pd, metal oxides of Ti, Zn, Co, Fe, Cu, Sb, Zr and sulphides of Zn and Cd can be synthesized easily through intracellular/ extracellular chemical reactions in uni- or multicellular microorganisms, like yeast and other fungi, algae, actinomycetes as well as in vitro plant mediated synthesis using various parts like stem, root, fruit, seed, callus, peel, leaves and flowers. Yeast-mediated synthesis of Au, Ag, CdS and PbS nanoparticles [2], Fusarium oxysporum mediated synthesis of stable gold, platinum and bimetallic Au–Ag alloy [3], etc., are some of the interesting examples. The present study includes recent progress in fungi-based biogenic fabrication of nanoparticles.

Keywords: Nanoparticles, green synthesis, fungi, metal ions, metal oxides

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I. INTRODUCTION

During the last couple of years, remarkable progress has been recorded in the field of nanoscience and technology. When materials are fabricated in 0.1-100 nm dimensions, their chemical, magnetic, electronic, and optical properties change significantly from those at larger scales. Various types of nanomaterials may be fabricated with specific sizes and shapes, such as quantum dots, nanorods, nanowires, nanospheres, nanotubes, nanosheets, nanoclusters, nanomicelles and so on. Fabrication of desired nanomaterials involves suitable physical, chemical, and engineering techniques, such as co-precipitation, sol-gel processing, solvo-thermal processing, micro-emulsion processing, sono-chemical processing, microwave processing, etc. Nevertheless, these methods offer a generous yield of nanomaterials in relatively short times, however, the majority of them have certain drawbacks. Soft chemical routes often include use of toxic reagents and solvents whereas physical methods involve processes with high temperature and high energy demand. Not only that, the nanoparticles produced in those methods many times show tendency towards aggregation, thus stability in desired nanoscale size is compromised. Owing to these disadvantages, biological materials are gaining attention with time as a replacement of harmful chemicals in the nanoparticle synthesis. Biogenic fabrications of nanoparticles are often greener routes involving non-toxic materials and overall, they are economically viable and eco-friendly processes.

II. FUNGI-BASED BIOGENIC FABRICATION OF NANOPARTICLES: A GREEN APPROACH

Basic principles of 'green synthesis' include prevention/minimization of unwanted or harmful by-products and waste, use of safer reagents and encouraging renewable feedstock. The biogenic fabrication of metal/metal oxide nanoparticles includes a wide range of bioresources- which can be fungi, yeast, algae, bacteria, plant and even biomolecules like fungal enzymes or plant extracts like flavones, amides, terpenoids, carboxylic acids, phenols, etc. In Table 1, few recent examples of such studies have been mentioned.

Table 1: Few recent examples of biogenic fabrication of nanoparticles (silver nanoparticles) using plant parts and various microorganisms

		Bioresource used	Shapes and Sizes of Silver nanoparticles	References
Plant parts	Leaves	Leaf and bark of Indian plant Carissa carandas	Spherical (45 nm to 80 nm)	Manjare et al., 2020 [4]
	Root	Codonopsis pilosula Roots	Spherical (average size 10 ±2.5 nm)	Doan et al., 2020 [5]
	Flower	Musa acuminata colla flower	Spherical (2.6 - 15.7 nm)	Valsalam et al., 2019 [6]
	Fruit	Lemon peel (Citrus limon)	Spherical (9.3 nm to 20.3 nm)	Nasr et al., 2019 [7]
Micro organisms	Bacteria	Serratia marcescens subsp. sakuensis	Well-dispersed spherical nanoparticles (10-20 nm)	Akl et al., 2020 [8]

	Fungi	Penicillium expansum	Spherical (15-40 nm)	Estevez et al., 2019 [9]
	Algae	Red algae Portieria hornemannii	Spherical (35 to 50 nm)	Fatima et al., 2020 [10]

Among these microorganisms, the fungi based biogenic fabrication has certain advantages. Fungi are eukaryotic decomposer organisms with a worldwide variety of more than 5 million fungal species among which nearly 70,000 species only have been identified [11]. The fungi can be divided into two categories. Among them, yeasts are single and small cells, whereas the other one is hyphal, which presents tubular and polarized cells and they grow continuously.

Fungi have many merits over other microorganisms, as they can synthesize significant amounts of nanoparticles (larger amounts compared to bacteria). Many species of fungi are easy to culture and maintain in the laboratory. Not only that, they can secrete a number of bioactive metabolites and antimicrobial compounds that take part in synthesis of nanoparticles from the precursor molecule. Their efficiency in producing extracellular enzymes and appreciable tolerance for bioaccumulation of nanoparticles makes 'Fungi-based Biogenic Fabrication' an excellent candidate among the microorganisms. In addition, the mycelial structure of fungi offers a large surface area for growing the nanoparticles.

III. METHODS AND MECHANISM BEHIND FUNGI BASED BIOGENIC FABRICATION OF NANOPARTICLE

Extra- And Intra-Cellular Methods: Fungi can accumulate metals by physicochemical and biological mechanisms. There are broadly two kinds of approaches for synthesis of metal nanoparticles- extracellular and intracellular. The 'intracellular' fungi mediated synthesis of nanoparticles involves transport and bioaccumulation of ions inside the cells to form nanoparticles in the presence of enzymes. On the other hand, in extracellular formation of the metallic nanoparticles, metals are likely to bind to the cell surface through extracellular metabolites and biopolymers or may bind to certain polypeptides. The biomolecules and enzymes secreted from fungi trigger the reduction of metal ions to elemental metal nanoparticles. Fungi also provides the essential molecules required for the stabilization of the metal nanoparticles. The nanoparticles synthesized inside the fungal cell are comparatively smaller in size. However, the extracellular synthesis has more applications than the intracellular synthesis as the former method is more robust and one can avoid unnecessary adjoining of cellular components on nanoparticles from the cell.

IV. MECHANISTIC PATHWAYS

Although the mechanistic pathways of intra- or extra-cellular synthesis of metal nanoparticles using different fungal species may be different, the main process is almost common:

- Firstly, metal ions fed by precursor solutions are accumulated by binding to the fungal cell wall or different metabolites/ biomolecules/polypeptides in the cell extract medium.

- In the presence of biomolecules like cellular peptides and polysaccharides the metal ions can now undergo processes like enzymatic oxidation-reduction, sorption and chelation. Metal ions also undergo membranous transport and enter inside the fungal cell in triggering the intra-cellular mechanism.
- In the next step towards nanoparticle formation, the metal ion goes through reduction, like Ag(I) to Ag(0) or Au(III) to Au(0), etc., followed by stabilization in presence of capping agents. Proteins, peptides and many other biomolecules can act as capping agents and/or stabilize the nanoparticles.

Most literature on fungi based biogenic fabrication of nanoparticles are on silver nanoparticle synthesis. The biochemical pathways for silver nanoparticle synthesis are pretty simple, rapid and consistent. The nitrate reductase enzyme is considered as the key component of this much successful nanofabrication mechanism. In 2014, Karthik et al. [12] proposed a possible mechanism for the bio-reduction of silver ions by nitrate reductase enzyme of Streptomyces sp. into nano-particles at room temperature. The study not only demonstrated nitrate reduction to nitrite, but also showed reduction of nitrite to nitrogenous gases. The synthesized small size (~5 mn) silver nanoparticles were found to be stable without any particle aggregation for months without using any capping agents. In another report NADPH-dependent nitrate reductase enzyme secreted from F. oxysporum was found to transfer electrons to the silver cations with the help of NADP as cofactor [13]. In the case of Yeast, oxidoreductase mechanism was reported to be responsible for CdS nanoparticle synthesis [14]

V. DESIGN AND SYNTHESIS OF NANOMATERIALS

The way in which fungi-based biomolecule-reduced metal atoms pass nucleation with subsequent growth and results in the formation of nanostructures is a good example of a bottom-up strategy. The advantage of bottom-up strategy is the preferred feasibility of controlling the variable parameters of the synthesis approach in order to obtain desired nanostructures such as nanorods or nanosheets, etc. Bottom-up strategy also ensures fewer defective nanoparticles with good homogeneous chemical composition. In general, either the cell-free extract of the endophytic fungi or its mycelia suspension is challenged with a suitable metal salt under controlled conditions.

For synthesizing biogenic nanoparticles, the reported fungi species have been in general collected from its natural environment (e.g., Helvella leucopus [15]) or from infected plant parts (e.g., Botryosphaeria rhodina fungus was isolated from the medicinal plant, Catharanthus roseus [16]) or the fungal strains are purchased (e.g., fresh fruit bodies of Enoki mushroom or Flammulina velutipes were purchased from the local market [17]).

The fungi with macroscopic fruit bodies are directly treated with distilled water with convenient heating and stirring to obtain the fungal extract [17] with which the precursor solution, e.g., Silver Nitrate ($AgNO_3$) solution for obtaining silver nanoparticles or chloroauric acid ($HAuCl_4.4H_2O$) solution to produce gold nanoparticles. Otherwise, the fungi are generally grown in suitable culture medium. One of such culture mediums is Potato-dextrose broth (PDB) which is extensively used in fungi based biogenic fabrication. The medium contains many biomolecules from small molecules like sugars or amino acids to long polymers like potato-starch. Most of the components in PDB culture medium, like glucose, amino acids and proteins, are capable of reducing metal ions like Au(III) or Ag(I) to their zero-oxidation state or elemental state which is essential for nanoparticle formation. An example of semisynthetic medium reported for fungal culture in nanoparticle production is the modified Czapek-Dox medium [18]. It contains glucose as a reducing agent which is capable of reducing Ag(I) to Ag(0) or Au(III) to Au(0). Thus Czapek-Dox culture medium can be advantageous in minimizing disturbing factors like reduction potential of its components in comparison with PDB medium which is a multi-component system. However, it cannot be guaranteed that all glucose would be consumed during the fermentation process of fungi. Also, biomolecules in PDB medium can stabilize the fungi mediated nanoparticles by acting as a protecting capping agent to them, which is not possible for Czapek-Dox medium. Molner et al., 2018 [18] showed that without presence of stabilizing or capping agent, the nanosized dimension of the particle can be lost resulting in only black coloured microscopic gold precipitate while synthesizing gold nanoparticles using fungal strains, like-Rhizomucor pusillus ATCC® 42782TM, Termomyces lanuginosus ATCC® 46882TM, Termoascus thermophilus ATCC® 26413TM and Sporotrichum thermophile ATCC® 36347TM grown in Czapek-Dox medium.

In the biosynthesis process, the culture is incubated, and fungal biomass is separated from the nutrient broth by centrifuging, followed by a washing procedure. Thereafter the fungal biomass or the extract of the biomass (obtained by further incubation and filtering) is exposed to the precursor solution. In a considerable number of reports, incubation of the fungal extract with precursor solution at 28°C in dark condition for approximately 72 hours of duration has been successful for ‘fungi based biogenic fabrication’- indicating the process as an easy, simple and economic bottom-up technique.

VI. SYNTHESIS OF METAL AND METAL OXIDE/SULPHIDE NANOPARTICLES

During the last decade, noble metals like Au and Ag have been extensively studied for biogenic fabrication of nanoparticles of different sizes and shapes, both intra or extracellularly. In contrast, the number of research works is significantly less for other metals like Se, Cu, Pt, etc. or metal alloy (e.g., Ag-Au) nanoparticles. Green nanoparticles fabrication of oxides and sulphides of zinc, titanium, copper, iron, cadmium, etc., are now gaining importance as they have versatile applications.

Yeast-mediated synthesis of ‘quantum semiconductor crystals’ of CdS nanoparticles [19] is one of the early reports on fungi-based biosynthesis of particles in nanoscale. In another earlier example of synthesis of Ag nanoparticles, use of the silver-resistant bacterial strain of Pseudomonas stutzeri was reported. Intracellular formation of equilateral triangle and hexagon shaped silver nanoparticles were observed through this method [20]. Nanoparticles produced in these green methods have also shown to have more specific surface area and better catalytic reactivity [21]. Proteins and other biomolecules secreted by microorganisms can act as both capping and stabilizing agents yielding biocompatible and less toxic nanoparticles. These biocompatible nanomaterials are suitable for applications in various fields like biomedicines, antimicrobials and biosensors. Earlier reports indicate that nanoparticles of metals like Ag, Au, Se, Pt, Pd, metal oxides of Ti, Zn, Co, Fe, Cu, Sb, Zr and sulphides of Zn and Cd can be synthesized through intracellular/ extracellular chemical reactions in uni- or multicellular microorganisms, like yeast and other fungi, algae and actinomycetes.

A brief overview is hereby given accounting the recent progresses in the field of biogenic nanofabrication of some of the metal and metal oxide/sulphide nanoparticles.

1. **Silver Nanoparticles-** Silver (Ag) and Ag-based compounds are promising for controlling bacterial growth in a variety of applications. However, their antimicrobial activities are compromised when Ag-based compounds gradually aggregate and precipitate in emulsions. A perfect solution to this problem is the use of Ag nanoparticles. Among the research articles on fungi mediated synthesis of all nanoparticles, production of silver nanoparticles is the most extensively studied. During the last decade, plenty of fungal species, like Alternaria sp., F. oxysporum, Trichoderma asperellum, Trichoderma viridae, Aspergillus clavatus, Phaenerochaete chrysosporium, Penicillium brevicompactum, Penicillium fellutanum, Penicillium citrinum, Fusarium oxysporum, Rhizoctonia sp., etc., have been investigated in biofabrication of Ag nanoparticles [22]. Majority of the methods resulted in formation of spherical Ag nanoparticles with varied sizes from 1-100 nm depending on the fungal strains used and experimental conditions employed. Formation of polydispersed spherical/hexagonal Ag nanoparticles [23] and cubic Ag-nanoclusters [24] has also been reported among them. Most used precursor for Ag nanoparticles is silver nitrate, which, upon interaction with fungal strain, gets reduced by fungal enzymes like nitrate reductase, or hydrogenase enzyme. Fungi also supply the stabilizing agents aiding in nanosized bioaccumulation of the metal. According to assays performed, the cell wall contains negatively charged carboxylate groups which interact with the positively charged silver metal and takes part in fabrication of Ag nanoparticles [24]. Few recent reports on silver nanoparticles have been depicted in Table 2.

Table 2: Few recent reports on biogenic fabrication of silver nanoparticles

Fungal species used	**Shapes and Sizes of Silver nanoparticles**	**Remarks on the nanoparticle**	**References**
Helvella leucopus collected from different localities of Northern Kashmir, India	spherical (80-100 nm)	Nanoparticles showed significant inhibition against rot causing fungal pathogens like P. chrysogenum, A. niger and A. alternata. This property can be useful for the apple growers and food industry to improve long time storage and preservation strategies	Talie et al, 2020 [15]
Fusarium scirpi was isolated from mining tails located at Zacatecas, Mexico	quasi-spherical (2 - 20 nm)	Strong antimicrobial activity was reported against Uropthogenic Escherichia coli (UPEC), the main pathogen associated with Urinary Tract Infections	Rodríguez-Serrano et al., 2020 [25]

Dry baker's yeast obtained from AB/MAURI Co., Ltd.	uniform spherical shape, av. size 13.8 nm.	The nanoparticles are promising against antibiotic-resistant bacterial cells. In combination treatment with ampicillin, they were successful to reverse the resistance in ampicillin-resistant E. coli cells while showing negligible cytotoxicity toward Cos-7 cells.	Shu et al., 2020 [26]
Penicillium oxalicum strain obtained from Quaid-i-Azam University	nearly spherical shape 60 to 80 nm	Nanoparticles showed excellent antibacterial activity of biosynthesized silver nanoparticles against Staphylococcus aureus, S. dysenteriae, and Salmonella typhi.	Feroze et al., 2019 [27]
Botryosphaeria rhodina isolated from the medicinal plant, Catharanthus roseus (Linn.)	spherical and well dispersed uniform shape (2 to 50 nm)	The nanoparticles, even in low concentration, were found effective in scavenging free radicals and triggering apoptosis in lung cancer cell lines (A-549) under in vitro conditions.	Akther et al., [16]

2. **Gold Nanoparticle:** Though gold as a metal is expensive, the gold nanoparticles are stable, most biocompatible and eco-friendly. Gold nanoparticles are now widely used in biosensors, needle-free drug delivery, cancer diagnostics and antimicrobials [28]. In the case of bio-mediated synthesis of gold nanoparticles, fungi are known to be more efficient than various microorganisms, like bacteria, in producing the smaller size nanoparticles. Biogenic synthesis of gold nanoparticles in the size range of 10 to 200 nm were reported involving diverse species of fungi, e.g., Helminthosporum solani, Hormoconis resinae,Cylindrocladium floridanum, Sclerotium rolfsii, Epicoccum nigrum, Fusarium solani, Aspergillus terreus IFo, Phanerochaete chrysosporium, Aspergillus niger Coriolos versicolor, etc. [22] . The reported gold nanoparticles show a variety of shapes like sphere [29], Triangles, hexagonals, decahedrals, androds, isotrophic spherical [30], etc.

3. **Selenium Nanoparticles:** Selenium nanoparticles possess interesting photoelectric and semiconducting properties [31]. They are also being explored for their antimicrobial, antioxidant, anticancer and anti-inflammatory nature [32]. Joshi et al. reported Trichoderma atroviride fungal culture aided synthesis of spherical selenium nanoparticles with sizes ranging from 60.48 nm to 123.16 nm showing broad spectrum antifungal activity against different phytopathogens [33]. In another study, fermented extract from fungal species Aspergillus orayzae was used to reduce selenium ion from selenium

dioxide precursor into nanoparticles with average size of 55 nm in the presence of gamma rays and was tested towards multidrug-resistant (MDR) bacteria [34].

4. **Copper/Copper Oxide Nanoparticles:** Recently, copper oxide nanoparticles (CuO) have gained significant importance due to their wide range of applications in catalysis, sensor and solar energy harvesting. Some remarkable antibacterial properties of copper at nanoscale are also coming into picture [35]. Probably, fungi mediated approach to synthesize copper nanoparticles was opted for the first time in 2012, by Honary et al. [36], in which they used three species- Penicillium vaksmanii, Penicillium aurantiogriseum and which were segregated from soil, for the synthesis of copper nanoparticles from Penicillium citrinumcopper sulphate precursor. Cuevas et al. [37] reported white-rot fungus Stereum hirsutum mediated synthesis of copper/copper oxide nanoparticles from three different precursor salts $CuCl_2$, $CuSO_4$, and $Cu(NO_3)_2$. The resulting nanoparticles were spherical and particle size was around 5 to 20 nm. Saravanakumar et al. [38] reported formation of spherical shaped CuO nanoparticles of size ranging from 10 to 190 nm (average of 110 nm) by using cell-free extract of Trichoderma asperellum.

5. **Zinc Oxide/Sulphate Nanoparticles:** Apart from being a promising candidate for use in various devices, such as batteries and solar cells, nanoparticles of zinc oxide (ZnO), has emerged as a potential antimicrobial agent and biosensor too. On other hand, zinc sulphide (ZnS) nanoparticles are excellent optical sensors. In a recent report [39]. large ZnO nanorods of 11.6-43.97 nm diameter, and 355.91 nm length was biogenically fabricated from precursor zinc sulphate using Aspergillus sp. In another study involving Alternaria tenuissima, spherical ZnO nanoparticles of 46.58 nm average particle were obtained from the same precursor [40]. In a recent report (2018) rare earth metal (Gd)-doped ZnS nanoparticles were synthesized from zinc sulphate and gadolinium nitrate precursors using the endophytic fungi Aspergillus flavus isolated from leaf segments of Nothapodytes foetida. The resulting nanoparticles were polycrystalline in nature, with a mean size of 10–18 nm [41].

6. **Titanium Dioxide Nanoparticles**: Among the commercially manufactured nanoparticles, titanium dioxide TiO2 nanoparticles resides in the top for its extensive use in sunscreen products, paints, printing ink, biomedical and self-cleaning sanitary ceramic, etc. However, in contrast biogenic fabrication of these nanoparticles have barely been attempted. In biosynthesis of TiO_2 nanoparticles, using Aspergillus flavus as a reducing and capping agent [42], spherical and oval shaped nanoparticles having the size of 62–74 nm were reported. The nanoparticles showed excellent antimicrobial properties against pathogenic bacteria Escherichia coli.

7. **Iron Oxide Nanoparticles :** Iron oxide nanoparticles have an important and unique ability to remove heavy metals from contaminated water due to their nanoscale size, higher surface area, biocompatibility and superparamagnetic properties which allow easy separation of adsorbents from the system. Biogenic fabrication of iron oxide is gaining attention recently. In a report in 2020, Chatterjee et al. used manglicolous filamentous fungus Aspergillus niger BSC-1 (isolated from mangrove biosphere, Sundarban, India) for the synthesizing iron oxide nanoparticles from two precursors ferric chloride and ferric sulphate [43]. In a similar study, biosynthesis of iron oxide nanoparticles was

attempted from ferric chloride precursor using three manglicolous fungi, STSP10 (Trichoderma asperellum), STSP 19 (Phialemoniopsis ocularis) and STSP 27 (Fusarium incarnatum) isolated from Indian Sundarban estuarine mangrove sediment, West Bengal. The nanoparticles obtained were spherical with little difference in particle size from different fungal strains. The nanoparticles obtained showed average particle size ranging between 25 ± 3.94 nm for T. asperellum, 13.13 ± 4.32 nm for P. ocularis and for F. incarnatum the reported size of the nanoparticles is in the range 30.56 ± 8.68 nm [44].

Few recent reports on various metal/metal oxides nanoparticles (except silver nanoparticles) and excellent properties shown by these bio-fabricated nanoparticles (antimicrobial, anticancer and antioxidant) have been depicted in Table 3. Advantages of Fungi-mediated nano-fabrication have been depicted in Figure 1.

Table 3: Few recent reports on biogenic fabrication of other metal/metal oxide nanoparticles

Fungal species used	Nanoparticles Produced	Shapes and Sizes of nanoparticles	Remarks on the nanoparticle	References
Flammulina velutipes or Enoki mushroom purchased from the local market on Penang Island, Malaysia	Gold nano particles	mixture of triangular, spherical, and irregular shapes, av size 74.32 nm.	The nanoparticles can greatly enhance rates of decolorization of organic dye (e.g., methylene blue) with high catalytic efficacy	Rabeea et al., 2020 [17]
Fusarium oxysporum (PTCC) purchased from the Pasteur Institute of Iran	Gold nano particles	spherical, hexagonal, and octagonal (20–50 nm)	Study conducted on nanotoxicity of the biologically produced nanoparticles on human fibroblast cell line CIRC-HLF	Pourali et al., 2017,
Fungal strain of A. niger (MTCC 2587) obtained from Institute of Microbial Technology, Chandigarh, India	Gold nano particles	Crystalline (fcc lattice) with sizes in the range 10-30 nm	Synthesized nanoparticles can offer a rapid and environment-friendly approach for mosquito vector control strategy as they trigger mortality in larval stages of A. stephensi, C. quinquefasciatus, and A. aegypti.	Soni et al., 2012 [46]

Neurospora crassa (FGSC: 2489 obtained from Fungal Genetics Stock Centre (FGSC), Kansas, USA	Copper carbonate nano particles	spherical shape formed irregularly (100–200 nm)	The role of eleven different amino acids that are secreted from Neurospora crassa fungi was studied in nanoparticle formation mechanisms.	Liu et al., 2019 [47]
Trichoderma asperellum (SKCGW003) isolated from the sediment collected from coastal wetland, Gangwan do, the Republic of Korea	Copper oxide nano particles	spherical (10 to 190 nm and an average of 110 nm)	The nanoparticle showed excellent photothermal induced anticancerous activity in human lung carcinoma, A-549 cell line (KCLB-10185).	Saravanakumar et al., 2019 [38]
Alternaria tenuissima AUMC10624 from Culture Collection of Assiut University Mycological Center, Egypt	Zinc oxide nano particles	spherical shape with mean particle size 46.58 nm.	The nanoparticles showed promising in vitro antimicrobial (against P. aeruginosa, K. pneumoniae, E. coli S. aureus and pathogenic fungi A. solani, A. niger, and F. oxysporum), anticancer (in hepatocelluar HepG-2 and human breast carcinoma MCF-7 cell lines) and antioxidant activities as well as the photocatalytic activities against methylene blue dye	Abdelhakim et al., 2020 [48]
Aspergillus flavus isolated from leaf of Nothapodytes foetida from the Agumbe forest, India	ZnS:Gd nano particles	polycrystalline, mean size 10–18 nm.	The nanoparticles were proved to be sensitive and effective fluorescence based nanosensor to detect Pb (II), Cd	Uddandarao et al., 2019 [41]

			(II), Hg (II), Cu (II) and Ni (II).	
Aspergillus flavus, Aspergillus terreus, Aspergillus tubingensis, Aspergillus niger, Rhizoctonia bataticola, Aspergillus fumigatus and Aspergillus oryzae collected from agricultural soil of Central Arid Zone Research Institute (CAZRI), Jodhpur, India.	zinc, magnesium and titanium nano particles	various sizes in the range ~10-98 nm depending on the fungal strains and different precursor solutions used	The biofabricated zinc and titanium nanoparticles can be stored up to 90 days whereas magnesium nanoparticles up to 105 days in their nanoform.	Ralia and Tarafdar, 2014 [49]
Aspergillus flavus (MTCC no. 7369) culture obtained from Microbial Type Culture Collection and Gene Bank, Chandigarh, India.	titanium dioxide nano particles	spherical, oval in shape (62–74 nm)	The titanium oxide nanoparticles showed excellent antimicrobial properties against for Escherichia coli	Rajakumar et al., 2014 [42]
Aspergillus niger BSC-1 isolated from sediments sample of Bali Island, Sundarban Mangrove Biosphere, India	iron oxide nano particles	magnetic nanocrystals of 20-40 nm size	The nanoparticle showed efficient and selective removal of toxic Cr(VI) by adsorption on nanoparticle	Chatterjee al., 2019 [43]

Figure 1: Advantage of Fungi-mediated nano-fabrication

VII. CONCLUSION

Some recent scientific reports on fungi- mediated biogenic fabrication of nanoparticles of metals like Ag, Au, Se, Cu and metal oxides like titanium dioxide, iron oxide, copper oxide and zinc oxide/sulphate have been discussed in little scope of this review. Fungi are known to be able to secrete a high amount of proteins and enzymes that intrigues the nanoparticle formation. In addition, the mycelial structure of fungi offers a large surface area for growing the nanoparticles. Fungi, as a living mechanism, is easy to grow on a large scale economically. In a nutshell, it can be stated that this field of research is yet to be investigated extensively on how to control/tailor the shape, and size distribution in nanoparticles formation. Dealing with the polydispersity during fungi based biogenic nanoparticle synthesis, is another serious challenge to be addressed through scientific research in future. Since fungus is a eukaryotic organism, elaborate research work is much needed to properly identify the reaction mechanisms of formation of nanoparticles in both intra and extracellular synthesis and role of fungal enzymes and other biomolecules in those mechanistic pathways. Apart from this scenario, the green biogenic fabrication routes are simple, inexpensive, and do not involve unnecessary use of expensive and toxic chemicals.

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