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SUSTAINABLE SYNTHESIS STRATEGIES: BIOFABRICATION'S IMPACT ON METAL AND METAL OXIDE NANOPARTICLES

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ABSTRACT: *Conventional techniques for nanoparticle synthesis pose significant challenges, including the use of hazardous substances, high energy consumption, and prohibitively high costs. Moreover, their reliance on toxic solvents limits their application in critical biomedical fields, contributes to environmental hazards, and impedes scalability and industrial feasibility. In contrast, green synthesis offers a more environmentally friendly approach by utilizing non-toxic solvents, minimizing waste generation, and enhancing biocompatibility. With increasing interest in nanoparticle applications, researchers are intensifying their exploration of metal and metal oxide nanoparticles. This review critically evaluates various green fabrication methods, identifying the most promising strategies for synthesis and characterization. Additionally, it surveys the diverse applications of biofabricated metal and metal oxide nanoparticles, highlighting the immense potential, particularly in medicine. Copper-based and other metallic nanoparticles are examined in depth, predicting their future impact on advancing biomedical technologies.*

KEYWORDS: Biofabrication, Metal Nanoparticles, Metal oxide Nanoparticle, Biological Application, Green Synthesis

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INTRODUCTION

The scientific field that focuses on processes that occur at the molecular level and at nanoscale sizes is known as nanotechnology. It offers the capacity to view, create, work with, and mold matter atom by atom at the molecular level. The creation, modification, synthesis, development, and usage of nanomaterials for biotechnological improvements are the main areas of interest in this rapidly emerging scientific discipline. Over the past few decades, nanoscience and nanotechnology have emerged as significant topics for researchers and engineers. They have been at the forefront of all research and development efforts due to their revolutionary impact on every aspect of life, including energy, medicine, pharmaceuticals, electronics, space, and environmental cleanup, agriculture, and food technology, among others. The fundamental components of nanomaterials and nano-devices are called nanoparticles (NPs). They are highly respected in a variety of fields because of their special physiochemical and optoelectronic properties. These fields range from everyday home products similar to clothes and cosmetics to planetary, communication, electronics, medical, agriculture, and other industries in the form of catalysts, sensors, electronic components, pharmaceuticals, and medical treatments, among others (Ijaz et al., 2022). In comparison to their bulk counterparts, they behave as a cohesive unit and display a variety of peculiar and unique size-dependent properties and uses (Kalpana & Rajeswari, 2018). Thanks to the quantum confinement effect, the broadening of electronic energy levels, and the high surface area to mass ratio of the nanoparticles. NPs exhibit a multitude of unique and extraordinary catalytic, electronic, magnetic, chemical, mechanical, thermal, and electrical, photo electrochemical, and optical capabilities. These include their small size (surface area and size distribution), solubility, form, and aggregation; chemical composition (purity, crystallinity, electrical properties); and exterior structure (surface reactivity, surface groups, inorganic or organic coatings). Similarly, nanomaterials are extra appealing and practical than bulk properties due to a variability of unique phenomena they show, including Surface Plasmon Resonance (SPR), Surface Enhanced Raman Scattering (SERS) in metals, the quantum size effect in semiconductors, and super magnetism in magnetic material (Al-Shammari & Abdulkareem, 2022a).

Natural and synthetic/engineered nanoparticles are the two main categories into which nanoparticles may be separated. Nanoparticles can be found in nature in a variety of forms, such as inorganic ash, soot, sulfur, and mineral particles that can be found in wells or the air, as well as sulfur and selenium nanoparticles made by various bacteria. (Kuppusamy et al., 2016). They can be divided into two more groups: Inorganic nanoparticles, which comprise metal, semiconductor, and magnetic nanoparticles; and organic nanoparticles, which comprise carbon nanoparticles.

When compared to ordinary nanoparticles, green nanoparticles—which are made using justifiable materials and methods—offer a number of advantages. Biocompatibility, enhanced qualities, economy, ecological sustainability, and sustainable growth are some of these advantages. Because they are often made from nontoxic, biodegradable, and renewable elements, green nanoparticles are measured environmentally friendly (Kalpana & Rajeswari, 2018). The synthesis of nanoparticles by synthetic approaches is often associated with a number of difficulties, such as the generation of toxic byproducts, instability problems, exorbitant costs, and significant environmental concerns, because of their special physicochemical characteristics, metal nanoparticles resulting from green synthesis have drawn more attention (Al-Shammari & Abdulkareem, 2022a).

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The traditional approaches to creating nanoparticles have a number of drawbacks, including the use of hazardous chemicals, high energy needs, and expensive expenses. On the other hand, biogenic nanoparticle synthesis is an economical and environmentally sociable substitute that makes use of naturally occurring biological systems, including bacteria, fungus, plants, and animals, to generate nanoparticles (Weng et al., 2017). The green synthesis technique is more environmentally friendly and biocompatible than conventional synthetic methods. Phytochemicals found in plant extracts are critical to the formation of nanoparticles and to increasing their bioactivity (Ying et al., 2022a). Nanoparticles are a fundamentally useful platform that have unique properties that may find wide application. The size resemblance of nanoparticles to biomolecules like proteins and polynucleic acids is one of the elements contributing to their special properties and applications (Tade et al., 2020). According to Carrapiço et al. (2023), the biogenic technique of nanoparticle synthesis produces particles with good stability, diameters, and polydispersity. To create nanoparticles, an increasing variety of microorganisms are used (Chugh et al., 2021). Microorganisms come in a variety of forms, and they all produce nanoparticles through somewhat different reactions with metal precursors.

Each biogenic substance has its own reaction mechanism, but they all essentially work in the same way to produce the desired nanostructures in a "complex broth" (Srivastava et al., 2015). The focus needs to be on extracting and identifying the pertinent biomolecules in order to use them as prototypes for the synthesis of nanomaterials, or more precisely, "biomimetic materials," in addition to characterizing these Nanosystems (Kim et al., 2017). Though they are still in their early stages, some biogenic techniques have evolved into biomimetic approaches, leading to the development of advanced bionano hybrid materials, self-assembled functional materials, and improved biomedical applications (Srivastava et al., 2015). In order to accomplish this, there is increasing interest in using environmentally friendly processes including using biopolymers, plant extracts, and biomolecules (Ahmed et al., 2016). They are the perfect reagents since they work as shape-modulating, capping, and reducing agents, among other functions, and they meet the requirements for biocompatibility and accessibility. The employment of chemicals in specific sectors, such as clean analytical methods, environmentally friendly analytical chemistry, and green analytical chemistry, to assist prevent pollution is known as "green chemistry." Green synthesis is an appropriate technique for producing nanoparticles since it is biocompatible, nontoxic, and environmentally benign (Chugh et al., 2021).

Eco-friendly nanoparticles with improved stability, therapeutic adaptability, and biocompatibility are produced during the synthesis process. Living things have evolved to be able to endure in settings that contain high amounts of metals. These creatures have the ability to change their chemical makeup and become less harmful. An organism's resistance mechanism to a certain metal leads to the creation of nanoparticles (Dhuldhaj & Pandya, 2021). There are two methods of biogenic metallic nanoparticle production. The first is the biodegradation, dissimilatory metal reduction, a chemical reduction process carried out by biological processes which produces more stable metal ions. The metal ion experiences reduction while the enzyme experiences oxidation. The resulting metallic nanoparticles are carefully removed and put through additional testing. The second is the bio sorption. The organism itself becomes attracted to the metal ions found in an aqueous or soil sample. Certain fungi, bacteria, and plants can produce peptides or cell walls that are bound with metal ions (Mittal & Roy, 2021). The nanoparticles are steadied by these peptides. The choice of biological methods for the synthesis and production of nanoparticles is influenced by a number

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of factors. The form of the metal nanoparticle that is to be shaped is the most important variable. The nanoparticles are stabilized by these peptides. The choice of biological methods for the synthesis and production of nanoparticles is influenced by a number of factors. The form of the metal nanoparticle that is to be produced is the most important variable (Wu et al., 2023).

In a nutshell green synthesis techniques are becoming more and more well-liked because they utilize less waste, cleaner solvents, and produce fewer contaminants than conventional techniques. These techniques, which make use of naturally occurring biological systems like bacteria and plants, provide a more affordable and environmentally responsible way to produce nanoparticles. Green synthesis yields nanoparticles with enhanced properties and advantages, including biocompatibility, economic viability, and environmental sustainability.

Synthesis Method

The production of inorganic metal nanoparticles can be accomplished by a variety of techniques, including chemical, and physical. Laser pyrolysis, laser ablation, ball milling, condensation, evaporation lithography, and other physical synthesis techniques are included in the literature (Ying et al., 2022b). The chemical synthesis method involves using toxic chemicals for capping and harsh chemical agents like hydrazine, sodium hydroxide, potassium hydroxide, and sodium borohydride for reduction (Kim et al., 2017). There is a chance that both approaches could result in negative effects like toxicity or cancer. These characteristics of the artificially created nanoparticles using traditional techniques have kept them out of use in clinical and biological settings. Therefore, the development of a biocompatible, environmentally safe, dependable, and clean approach for the production of nanoparticles—known as biological synthesis—is necessary. An easy and practical substitute for creating metallic nanoparticles is to use the biological system of synthesis (Zhang et al., 2020). These days, the environmental impact of the metal oxide nanoparticle manufacturing process is the key worry. As was previously noted, chemical or physical techniques employ harmful chemicals that have the potential to cause risks, inflict environmental toxicity, or cause cancer (Ying et al., 2022b). The primary source of these effects may be the usage of dangerous materials like stabilizers, reducing agents, or organic solvents. Moreover, the created nanomaterials' use in many biomedical or clinical applications is restricted due to the use of harmful solvents. Therefore, a more dependable, clean, and environmentally friendly method is required (Dhuldhaj & Pandya, 2021). In the world of research, green synthesis pathways have garnered a lot of interest to overcome these constraints. Nowadays, using green synthesis is recommended since it reduces pollution and byproducts, prevents or minimizes waste, and uses cleaner, non-toxic solvents.

Synthesis of Metal/Metal Oxide Nanoparticles Using Biological Extracts

The most studied green synthesis method for metal oxide nanoparticles (NPs) is the use of plant extract and plant-derived components. It has a straightforward production process that can be repeated on a larger scale. Furthermore, the method can be readily scaled up with a moderate reaction medium (pH) and safe, well recognized solvents (such as water) without producing any undesirable byproducts. Plant-mediated green synthesis techniques use different plant parts, such as the seed, fruit, callus, bark, stem, flowers, and leaves, to synthesize metal and metal oxide NPs of different sizes and shapes (Jahangirian et al., 2018b). Some non-metal nanoparticles are promising in developing a cleaner environment. Sulaiman et al. (2023) proposed a novel method for manufacturing silica particles using the extraction-precipitation

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process. Silica particles were extracted from sugarcane bagasse, their identity confirmed by Fourier Transform Infra-Red (FT-IR) analysis, and their size measured using a Scanning Electron Microscope (SEM). The researchers produced smaller silica particles by extracting silica from sugarcane bagasse using sodium hydroxide and then reducing the pH to promote precipitation. To increase particle size, a two-step technique was used: first, sodium hydroxide was reintroduced into the silicate solution prior to pH correction, and then the resulting precipitate was treated at higher temperatures. This approach not only enhanced size expansion but also reduced hydroxyl content.

However, metal and metal oxide nanoparticles seem to have more benefit of using green synthesis for the production of metal oxide nanoparticles is the need for fewer purification steps without requiring harsh treatments such as vacuum conditions, high pressure, or high energy (Kim et al., 2017). During the creation of metallic nanoparticles, a variety of metabolites included in plant extracts function as stabilizing and reducing agents. The complexity of the bioreduction process is widely acknowledged. By giving the metal ions electrons, the biomolecules in the extract operate as a reducing agent, causing the metal ions to be reduced to the elemental metal. After the produced atoms function as a nucleation site, nearby smaller particles unite to form larger NPs during a growth phase. To this end, plant extracts can stabilize NPs during the last phase of synthesis, which in turn regulates their desirable and energetically stable form. Piper nigrum leaf and stem extract was used to create silver nanoparticles. The plant extracts of Salvia officinalis, Punica granatum, and Lippia citriodora were used to create gold nanoparticles, Chrysanthemum indicum was used to create silver nanoparticles, which is an easy, economical, and environmentally beneficial method (Weng et al., 2017). Using seaweed Kappaphycus alvarezii as a source of stabilizing and reducing agents, magnetite nanoparticles (Fe3O4-NPs) were created. The aqueous leaf extract of Eucalyptus Globulus was combined with a microwave-assisted technique to create silver nanoparticles using ethanol and Syzygium aromaticum extract, gold nanoparticles were created, and their anticancer potential was examined using the SUDHL-4 cell line (Mittal & Roy, 2021). Acinetobacter sp. SW 30 was isolated from activated sludge and utilized for the intracellular manufacture of gold nanoparticles under varied physiological conditions. The produced gold nanoparticle has numerous uses in medication delivery, cancer treatment, and nano biosensors. Using Sinapis arvensis, silver nanoparticles were produced from silver nitrate. Gram positive Streptomycetes isolated from rice fields were used to produce extracellular silver nanoparticles. Extracts from the leaves and stems of Piper nigrum plants were used to create silver nanoparticles (Bhatt et al., 2023).

Microbiological Synthesis

It is known that plant extracts and cell-free supernatants of liquid microbial cultures can be joined with metal salts to create (table 1). That being said, there are not many differences in the various MNPs' biosyntheses. For example, distinct MNPs are produced by different precursors, and metal oxide nanoparticles (Ag2ONPs) or metal chloride nanoparticles (AgClNPs) instead of metal nanoparticles (AgNPs) may be formed depending on changes in the concentration of elements such as molecular oxygen (O_2) or chloride (Cl^-) (Carrapiço et al., 2023). Furthermore, it has been demonstrated that a number of reaction parameters, including temperature, oxygenation, pH, precursor concentration (metal salt), microbial growth phase (following supernatant collection), incubation duration, and irradiation, have a significant impact on the reaction's yield as well as the characteristics of the MNPs (Waktole

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& Chala, 2023). But the understanding of the mechanism underlying these events is still incomplete. Nevertheless, a number of investigations have been carried out employing plant extracts and the cell-free supernatants of microorganisms in an effort to pinpoint the molecules accountable for the stabilization and decrease (capping agents) of these NPs (Singh et al., 2018).

Table 1: Fabrication of Nanoparticles Using Bacteria, Archea, Fungi, and Microalgae

Metal	Microbial genes	NPs size (nm)	Main properties	Ref
Ag	Acinetobacter	11-9	Antimicrobial	(Ahmed et al., 2016)
Ag	Arthrobacter	12-50	Antimicrobial	(Chugh et al., 2021)
Ag	Amycolatopsis	35	Antimicrobial	(Ijaz et al., 2022)
Ag	Bacillus	11-38	Photocatalytic	(Chouke et al., 2022)
Ag	Bacillus	18-39	Antimicrobial	(Rafique et al., 2017)
Ag	Bacillus	10-20	NS	(Du et al., 2017)
Zn	Bacillus	35-90	Antimicrobial	(Bandeira et al., 2020)
Zn	Bacillus	16-25	Antibiofilm	(El-Gebaly et al., 2024, p. 202)
Au	Paracoccus	20.93 (mean value)	Antioxidant	(Herizchi et al., 2016)
Cu	Brevandimonas	20-80	Antimicrobial	(Wu et al., 2023)
Cu	Klebsiella	19-47	NS	(Chouke et al., 2022)
Fe	Bacillus	60-80	Antioxidant	(Waktole & Chala, 2023)
Ti	Pseudomonas	6.83 (mean value)	Antimicrobial	(D. Kim & Kim, 2023)

Bacteria and Fungi Mediated Green Synthesis

The silver nanoparticles' mass synthesis is enhanced by the fungal species. In the presence of *Thiobacillus species*, it reduces ferric ions when grown on elemental sulfur as a source of energy. The bacterial strain (CS 11) was isolated from metal-contaminated soil and utilized to synthesize extracellular silver nanoparticles at room temperature (Ijaz et al., 2022). Silver and gold nanoparticles were created using an aqueous extract of the seaweed *Turbinaria conoides*. Using extracellular agents made from isolated bacterial strains such *Bacillus pumilus, B. persicus,* and *Bacillus licheniformis,* the silver nanoparticles were created. A unique technique was used to create silver nanoparticles utilizing the culture supernatant of broth that had been damaged by phenol. *Myxococcus virescens* cell filtrate was used to create extracellular silver nanoparticles (Chugh et al., 2021). Tricalcium phosphate was utilized to create phosphorus nanoparticles utilizing *Aspergillus tubingensis* TFR-5 (NCBI GenBank Accession No. JQ675306). Nickel oxide nanoparticles were produced and absorbed by *hypocrea lixii.* Silver

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nanoparticles were synthesized using endophytic *Colletotrichum sp.* ALF2-6. The biosynthesis of AgNPs was carried out by *Proteus mirabilis*, and the initial harmful effects were identified. Crude extracellular keratinase from *Bacillus safensis* LAU 13 (GenBank accession No. KJ461434) was used to create silver nanoparticles *Penicillium expansum* HA2N and *Aspergillus terreus* HA1N, two distinct microbial strains, were used to create silver nanoparticle (Srivastava et al., 2015).

Combinations of fundamental cellular biochemistry, metal ion transport (both inside and outside of cells), bacterial resistance mechanisms to toxic metals and activated metal binding sites, accumulation of intracellular metal ions, and metal oxide nucleation are among the pathways by which microbes synthesize nanoparticles (Bhatt et al., 2023). The fact that bacteria can manufacture large quantities of enzymes and amino acids has earned them the status of being efficient organisms. Additionally, bacteria include vitamins and polysaccharides that may have metal ion-reducing properties. Bacteria have the ability to grow in high concentrations of hazardous metals and chemically detoxify themselves, in addition to cells.

Numerous studies conducted in the last few years have shown that bacteria like *Brevibacterium frigoritolerans, Pseudomonas deptenis, Bacillus methylotrophicus, Visella oriza,* and *Bhargavaea indica* may successfully synthesize gold (Au) and silver (Ag) nanoparticles. However, the primary drawback of bacterial production is the challenging procedures involved, including growing, storage, microbial sample, and isolation (Ahmed et al., 2016).

The green production of metal/metal oxide nanoparticles by fungal aided synthesis is another very efficient method for producing monodispersed nanoparticles with distinct morphologies. Because fungi have a variety of internal enzymes, they are good biological agents for the creation of nanoparticles (Bhatt et al., 2023). Compared to bacteria, able fungi are able to yield greater amounts of NPs. Furthermore, because their cell structures cover proteins, enzymes, and reducing agents, fungi have many advantages over other creatures. Reductase, an enzyme established in the fungal cell wall or inside the cell, is the process responsible for the creation of metal nanoparticles (Chouke et al., 2022). Nevertheless, there are a number of drawbacks to this fabrication process, including synthesis conditions, material selection, application, and product quality control. The primary obstacles to moving toward industrial production and large-scale use are the aforementioned factors of green-synthesized nanoscale metallic materials.

For the purpose of this study, we draw some analysis between the bacteria and fungi assisted methods. Nanoparticle fabrication with bacteria and fungi has various advantages and limitations (table 2). Bacteria, known for their ability to produce huge amounts of enzymes and amino acids, are used in nanoparticle creation via pathways including fundamental cellular biochemistry, metal ion transport, resistance mechanisms, and nucleation processes (Bhatt et al., 2023). Despite its effectiveness, bacterial synthesis requires difficult procedures such as growth, storage, microbial sample collection, and isolation (Ahmed et al., 2016). Fungal-assisted synthesis, on the other hand, provides an alternate strategy by utilizing numerous internal enzymes, particularly reductase, which is required for nanoparticle formation (Bhatt et al., 2023; Chouke et al., 2022). Fungi can produce more nanoparticles than bacteria because their cell structures contain proteins, enzymes, and reducing agents.

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Table 2: Comparisons of Bacteria and Fungi Mediated Biofabrication Methods

	Bacteria-Mediated Synthesis	Fungi-Mediated Synthesis
Advantages	**1. Efficiency in Enzyme Production:** Bacteria are effective makers of enzymes and amino acids, which helps to reduce metal ions and synthesize nanoparticles (Ahmed et al., 2016).	**1. Enzymatic Capability:** Fungi contain a wide range of internal enzymes, making them effective biological agents for nanoparticle formation (Bhatt et al., 2023).
	2. **Metal Resistance Mechanisms:** Bacteria have systems for repelling harmful metals, allowing them to proliferate in high metal concentrations and detoxify themselves.	2. **Higher Yield:** Fungi produce more nanoparticles than bacteria, most likely due to their complex cell structures that include proteins, enzymes, and reducing agents (Chouke et al., 2022).
	3. **Diverse Microbial Species:** Several bacterial species, including Brevibacterium frigoritolerans, Pseudomonas deptenis, Bacillus methylotrophicus, Visella oriza, and Bhargavaea indica, have shown the potential to produce gold and silver nanoparticles (Ahmed et al., 2016).	3. **Green Production:** Fungi-mediated synthesis is regarded as environmentally beneficial, providing a green alternative to nanoparticle production (Bhatt et al., 2023).
Challenges	**Complex Procedures:** Bacterial nanoparticle production requires difficult methods such as growth, storage, microbial sample preparation, and isolation, which can limit scaling and industrial application (Ahmed et al., 2016).	**Synthesis Conditions:** The synthesis parameters for fungal-mediated nanoparticle formation need to be carefully controlled, as they affect repeatability and scalability (Bhatt et al., 2023).

Based on the available literature, we realized that fungal-assisted synthesis appears to offer several advantages over bacterial synthesis for nanoparticle fabrication. Fungi have demonstrated the ability to yield larger quantities of nanoparticles, attributed to their cell structures containing proteins, enzymes, and reducing agents (Bhatt et al., 2023; Chouke et al., 2022). Additionally, fungi possess various internal enzymes, particularly reductase, which plays a crucial role in nanoparticle creation. The challenges of bacteria aided strategy are tough, including growth, storage, microbial sample preparation, and isolation, which can hinder scalability and industrial application (Ahmed et al., 2016). While both methods encounter challenges such as synthesis conditions, material selection, and product quality control, fungal-assisted synthesis seems to offer a more efficient and potentially scalable approach for nanoparticle production.

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Algae-Mediated Green Synthesis

Another environmentally safe way to create metal and metal oxide nanoparticles is by algae-based synthesis. As an alternative to synthesis based on bacteria, algae do not need cellular upkeep. An important source of phytochemicals for the fabrication of metal nanoparticles is algae (Zhang et al., 2020). However, as of their hyper-accumulation of heavy metals, significantly higher rate of CO_2 sequestration, lack of harmless byproducts, ability to use biomolecules (enzymes and pigments) as capping and reducing agents, and low energy input, cyanobacteria and microalgae are becoming more and more popular in the field of green synthesis. Algae are great providers of proteins, pigments, phytonutrients, and other nutrients, therefore throughout time, the synthesis process has become more efficient, making algae an important bio-manufacturer for the production of nanoparticles (Weng et al., 2017).

Characterization of Metal and Metal Oxide Nanoparticles

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) has arisen as an effective analytical method for investigating the surface chemistry and functional groups of metal and metal oxide nanoparticles. This technique uses molecular vibration concepts to characterize nanomaterials' chemical composition and bonding environments. In a typical FTIR test, infrared radiation passes through a sample, and the absorption of specific wavelengths by chemical bonds reveals their presence and structure (Al-Shammari & Abdulkareem, 2022b). For metal nanoparticles, FTIR examination reveals the type of stabilizing agents or capping ligands that surround the metallic core. These organic compounds regulate the size, shape, and stability of nanoparticles in solution. Researchers can detect functional groups such as carboxylates, amines, or thiolates that chemically bind with the metal surface by observing distinctive peaks in FTIR spectra. The strength and position of these peaks provide information about metal nanoparticles' coordination chemistry and surface reactivity. Similarly, FTIR study of metal oxide nanoparticles provides useful information on their surface chemistry and phase composition. Metal oxide nanoparticles have unique vibrational modes linked with metal-oxygen bonding, which appear as discrete absorption bands in the FTIR spectrum. The position and intensity of these bands are related to the crystal structure, oxidation state, and surface functionalization of metal oxide nanoparticles. Besides, FTIR spectroscopy may identify surface hydroxyl groups, adsorbed water molecules, and organic pollutants that affect the physicochemical properties of metal oxide nanoparticles. For example, Bhatt et al. (2023) used FTIR to explore the surface functionalization of gold nanoparticles with thiol-based ligands. The researchers discovered characteristic peaks corresponding to sulfur-hydrogen stretching vibrations, which confirmed the progress of gold-thiol bonds on the nanoparticle surface. Furthermore, FTIR analysis revealed the presence of carboxylate groups from citrate stabilizers, which shed light on ligand interchange processes and surface modification strategies for customized nanoparticle manufacturing (El-Gebaly et al., 2024).

Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDS)

Scanning Electron Microscopy (SEM) joint with energy-dispersive X-ray spectroscopy (EDS) is an effective method for determining the shape, size distribution, and elemental content of metal and metal oxide nanoparticles. This integrated approach provides high-resolution imaging and quantitative elemental analysis, making it essential for researching nanomaterials

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in a variety of scientific domains. SEM uses a concentrated electron beam to scan the sample surface, providing detailed information about the surface shape and assembly of nanoparticles (Kim & Kim, 2023). The interaction of the electron beam with the sample produces signals such as secondary electrons (SE) and backscattered electrons (BSE), which are then used to create pictures with nanometer-scale resolution. SEM imaging empowers researchers to see the size, shape, aggregation state, and surface properties of metal and metal oxide nanoparticles. EDS, when used in conjunction with SEM, allows for elemental analysis of nanoparticles by identifying distinctive X-rays generated by the sample when it interacts with an electron beam. Each element generates X-rays with distinct energy signatures, which lets for the identification and measurement of elements in the sample. EDS spectra of metal and metal oxide nanoparticles disclose the elemental composition and relative abundance of constituent elements, allowing for better characterization of nanoparticle composition, purity, and stoichiometry used SEM-EDS analysis to evaluate the size distribution and elemental composition of iron oxide (Fe_3O_4) nanoparticles engendered using a solvothermal technique. SEM imaging demonstrated that the nanoparticles had a homogeneous spherical morphology, whereas EDS spectra established the presence of iron (Fe) and oxygen (O) components, which are consistent with the composition of magnetite. The quantitative analysis of EDS data revealed information regarding the elemental stoichiometry and purity of the produced nanoparticles, demonstrating the efficacy of SEM-EDS for nanoparticle characterization (Jahangirian et al., 2018b).

Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is a study imaging method commonly used to characterize metal and metal oxide nanoparticles at the nanoscale. TEM runs high-resolution imaging capabilities, allowing scholars to see the morphology, size, crystallinity, and atomic structure of nanoparticles in unprecedented detail. Furthermore, selected area electron diffraction (SAED) in TEM can reveal important information on nanomaterials' crystallographic characteristics and phase composition (Okafor et al., 2013). When united with energy-dispersive X-ray spectroscopy (EDS), TEM allows for elemental analysis and mapping of nanoparticles, providing detailed information about their structural and chemical features. (Zhang et al., 2020) used TEM to discover the shape and crystalline structure of platinum (Pt) nanoparticles supported on reduced graphene oxide (rGO) for electrocatalytic applications. TEM imaging verified that Pt nanoparticles were uniformly distributed on the rGO surface, with well-defined crystalline facets and regulated particle size. Also, the SAED analysis validated the crystalline nature of the Pt nanoparticles and revealed their crystallographic orientation. EDS elemental mapping supplemented TEM imaging by revealing the elemental composition and spatial distribution of Pt and carbon (C) within the nanocomposite, shedding light on the structural properties and interaction of Pt nanoparticles with rGO support. (Adeyemi & Fawole, 2023). Used TEM to explore the size, shape, and crystal structure of manganese dioxide (MnO2) nanoparticles generated hydrothermally TEM imaging revealed the creation of MnO2 nanoparticles with various morphologies, such as nanorods, nanowires, and nanosheets, depending on the synthesis circumstances. High-resolution TEM investigation revealed the crystalline lattice fringes of MnO2 nanoparticles, allowing for the resolution of crystal phase and orientation. ED’s elemental analysis provided quantitative information about the nanoparticles' elemental composition, verifying the existence of manganese (Mn) and oxygen (O) elements and allowing for better characterization of MnO_2 nanoparticle structure and composition.

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X-ray diffraction (XRD)

X-ray diffraction (XRD) is a common technique for determining the crystal structure, phase composition, and crystallite size of metal and metal oxide nanoparticles. XRD analysis gives useful information about the arrangement of atoms in nanomaterials, permitting scholars to identify crystal phases, calculate lattice parameters, and quantify crystallinity. By studying the diffraction patterns produced (Chhipa, 2017). When X-rays interact with a crystalline sample, XRD allows for the comprehensive characterization of nanoparticles and the consideration of their structural features (Rinkevicius et al., 2022).

Overall, FTIR spectroscopy offers insights into surface chemistry and phase composition of metal oxide nanoparticles by detecting characteristic absorption bands. It provides information on crystal structure, oxidation state, and surface functionalization. SEM-EDS enables elemental analysis, aiding in nanoparticle characterization by identifying constituent elements. TEM with EDS allows for detailed structural and chemical analysis, providing information on nanoparticle distribution and composition. XRD analysis offers comprehensive characterization of nanoparticles, identifying crystal phases and structural features. Each technique provides valuable information for understanding the properties and behavior of metal and metal oxide nanoparticles, with complementary strengths in different aspects of characterization.

Based on the information provided, a complementary technique for characterizing metal and metal oxide nanoparticles could be X-ray Photoelectron Spectroscopy (XPS).

X-ray Photoelectron Spectroscopy (XPS) is a surface-sensitive technique that provides information about the elemental composition, chemical state, and electronic structure of materials. It can be used to analyze the surface chemistry of metal and metal oxide nanoparticles, including oxidation states, surface functionalization, and chemical bonding (Smith, 2020). By analyzing the photoelectrons emitted from the sample surface when irradiated with X-rays, XPS can provide valuable insights into the surface properties of nanoparticles, complementing techniques such as FTIR, SEM-EDS, TEM-EDS, and XRD.

Integrating XPS with other characterization techniques would offer a more comprehensive understanding of the structural, chemical, and morphological properties of metal and metal oxide nanoparticles, enhancing their characterization for various applications.

Dynamic Light Scattering (DLS) measures the size distribution of particles in a solution by analyzing the fluctuations in light scattering intensity caused by Brownian motion (Berne & Pecora, 2016).

DLS can provide valuable information about the hydrodynamic size, size distribution, and aggregation state of metal and metal oxide nanoparticles in solution. This information is particularly useful for understanding nanoparticle stability, dispersion behavior, and colloidal properties, which are important considerations for various applications such as drug delivery, catalysis, and nanocomposite fabrication (Berne & Pecora, 2016).

We hereby suggest that integrating DLS with other techniques such as TEM or SEM-EDS can offer a more comprehensive characterization of nanoparticles by providing complementary information about their size, morphology, and elemental composition, as well as their behavior

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in solution. This integrated approach can enhance the understanding of nanoparticle properties and aid in the development of tailored nanoparticle-based materials and technologies.

Biological Applications of Metal and Metal Oxide Nanoparticles

In this section, we will look at the numerous and powerful biological applications of metal and metal oxide nanoparticles. These nanoparticles show promise in clinical and diagnosis (like dealing with cancer), agricultural development, and beyond (figure 1), as they tackle microbial dangers with antibacterial characteristics and provide significant antioxidant effects. By investigating these tendencies, we want to reveal nanotechnology's biological broad potential for addressing critical difficulties in a variety of sectors.

Antimicrobial Activity

Furthermore, in the domain of antimicrobial applications, categories such as antiviral, antifungal, and antibacterial activities might be examined (figure 1), demonstrating the varied functions that metal and metal oxide nanoparticles play in treating a wide range of microbial threats.

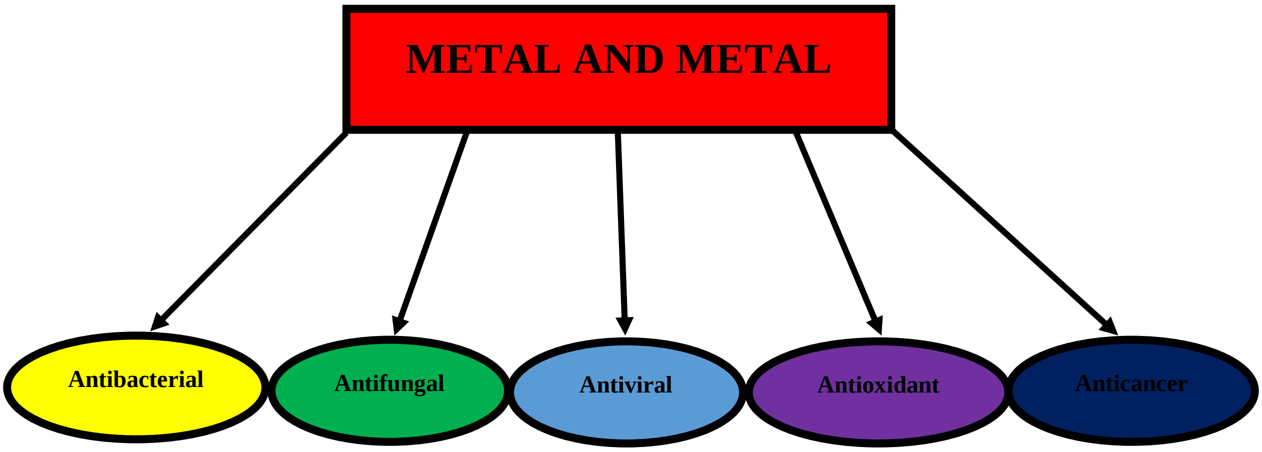

Fig. 1: Metal/Metal Oxide NPs and their Biological Applications.

Applications for metal and metal oxide nanoparticles (NPs) produced by biogenic methods include antibacterial properties. Individually and in combination, biogenic CuO, ZnO, and WO_3 nanoparticles have shown strong antibacterial activity against drug-resistant infections (Tade et al., 2020). Natural sources of biogenic nanoparticles have demonstrated advantageous properties in medicine, such as medication transport and biosensing (Waktole & Chala, 2023).

The use of fungus as the reducing agent in the synthesis of metal nanoparticles (Mt NPs) has advantages over chemical synthesis in terms of yield and eco-toxicity, as well as economic and

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environmental benefits (Mittal & Roy, 2021). The quick-growing fungus can be grown in controlled environments to generate proteins, enzymes, and bioactive secondary compounds that aid in the manufacture of Mt NPs. These bioactive compounds, which offer significant biocompatibility and superior antibacterial characteristics, are coated on Mt NPs. Ag, Cu, Zn, Au, MgO, Fe, TiO2, and PbSe on Mt NPs have antibacterial qualities that are useful for biological and agricultural applications and also reported the biosynthesis of Cu NPs utilizing A. eriophyllum leaf extracts for the bioreduction of CuSO4 solutions, resulting in spherical-shaped NPs with a size of 31.34 nm. High antifungal, antibacterial, antibiotic, antiviral, and antiparasitic activities against all tested species of bacteria and fungus were also revealed by the environmentally-benign approach employed (Waktole & Chala, 2023).

Green and biogenic methods for biofabricating metal and metal oxide nanoparticles have demonstrated potential for antiviral applications (Okafor et al., 2013). Excellent antibacterial capabilities of nanoparticles have been synthesized by the use of fungus and natural bioresources as reducing agents. As an illustration, antibacterial activity of silver, copper oxide, and zinc oxide nanoparticles has been shown against a range of bacteria and fungi (Sathiyaseelan et al., 2023). Furthermore, Lawsonia inermis L. seeds were used to create zinc oxide nanoparticles, which have demonstrated potential in biosensor and medicinal applications. Moreover, zinc oxide nanoparticles with a modest average size that are appropriate for a variety of applications have been biofabricated using *Penicillium italicum* fungi (Issa et al., 2022). The potential for antiviral applications of copper and copper oxide nanoparticles, which are manufactured using plant extracts, has been highlighted by their antibacterial efficacy against fungus and bacteria. In general, green and biogenic approaches for the biofabrication of metal and metal oxide nanoparticles hold promise for the development of antiviral medicines.

Green synthesis of copper nanoparticles (Cu NPs) using plant extracts has drawn attention due to its economical, environment benign, and non-toxic method. Various species of plant such as *Pimpinella anisum*, *Diaplazium esulentum*, and others have been used in the biosynthesis of Cu NPs (Yilmaz & Hamdullah, 2023; Luque-Jacobo et al., 2023). The synthesized Cu NPs have shown outstanding pharmacological applications, including antioxidant, antibacterial, antifungal, and anticancer properties (Tanur et al., 2022; Baju et al., 2022; Dadure et al., 2022). The Cu NPs have strong antioxidant activity, even better than the plant extracts themselves. They also showed antibacterial activity against both gram-positive and gram-negative bacteria, with a selective effect against drug-resistant bacteria. Moreover, the Cu NPs showed excellent antifungal activity against different fungal strains. It also exhibited significant anticancer activity against human cancer cell lines. These findings suggested that Cu NPs synthesized through plant-mediated biosynthesis have the potential to be used as alternative agents in pharmaceutical applications due to their pharmacological capabilities.

Based on the existing research, in this context, we realized that biofabricated copper and copper oxide nanoparticles is the leading (but not only) species commonly used for several antimicrobial applications leading to biomedical advantages. For this reason, for proper analysis, we bisect the biofabricated metal nanoparticles into: Metal and metal oxide nanoparticles from biogenic methods. Copper nanoparticles Cu NPs synthesized via plant extracts. This was each based on pharmacological (table 3) and diagnostic application (table 4).

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Table 3: Pharmacological View of Metal/Metal Oxide and Copper Nanoparticles

Mode of View	Metal and Metal Oxide Nanoparticles (NPs) from Biogenic Methods	Copper Nanoparticles (Cu NPs) Synthesized via Plant Extracts
Specific Application	They have high antibacterial activities against drug-resistant infections, which is critical for fighting microbial disorders (Tade et al., 2020).	Cu NPs have a wide range of pharmacological applications, including antioxidant, antibacterial, antifungal, and anticancer activities, indicating their potential for a variety of therapeutic treatments (Tanur et al., 2022; Baju et al., 2022; Dadure et al., 2022).
Challenges	Obtaining reliable synthesis and scalability of biogenic NPs for mass production can be difficult. Furthermore, preserving stability and minimizing potential toxicity issues in vivo are critical considerations.	Controlling the size and form of Cu NPs generated using plant-mediated biosynthesis can be challenging. Furthermore, it is critical to understand their long-term effects on biological systems, as well as possible toxicity.
Future Perspective	With additional research, these biogenic NPs could become essential components in pharmaceutical formulations for treating bacterial infections, providing a viable alternative to traditional antibiotics.	Cu NPs generated using plant-mediated techniques have promise for pharmaceutical applications because of their varied pharmacological characteristics, presenting prospective options for many medicinal therapies.

Table 4: Diagnostic View of Metal/Metal Oxide and Copper Nanoparticles

Mode of View	Metal and Metal Oxide Nanoparticles (NPs) from Biogenic Methods	Copper Nanoparticles (Cu NPs) Synthesized via Plant Extracts
Specific Application	These nanoparticles show promise in biosensing applications, implying their utility in diagnostic technologies for identifying biological markers and disorders (Waktole & Chala, 2023).	Cu NPs generated from plant extracts have the potential to be used in diagnostic applications due to their unique characteristics and interactions with biological systems.
Challenges	To achieve consistent and dependable performance in biosensing applications, synthesis procedures and surface functionalization techniques may need to be further optimized.	Further improvement of Cu NPs for diagnostic applications may necessitate more surface modification and

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		functionalization to improve their specificity and sensitivity.
Future Perspective	Biogenic nanoparticles could play an important role in the development of new diagnostic tools, providing sensitive and specific detection capabilities for a variety of diseases and pathogens.	More research is recommended to unveil the promising diagnostic capability of Cu NPs generated via plant-mediated techniques, which could provide fresh solutions for disease detection and monitoring.

Antioxidant Application

Potential antioxidant benefits of metal and metal oxide nanoparticles have been extensively researched. Through a variety of processes, these nanoparticles, which include manganese dioxide (MnO2), cerium oxide (CeO3), titanium dioxide (TiO2), and silver (Ag), and zinc oxide (ZnO), display antioxidant effects. They have the ability to mimic the actions of antioxidant enzymes, scavenge reactive oxygen species (ROS) and reactive nitrogen species (RNS), and reduce metal concentrations. These nanoparticles' antioxidant activity has been assessed utilizing tests like DPPH, ABTS, and FRAP. To guarantee their safe usage, the possible toxicity of these nanoparticles has also been investigated. Applications for metal and metal oxide nanoparticles in medicine, cosmetics, functional food additives, and the treatment of age-related conditions like cancer, diabetes, heart disease, neurological illnesses, and osteoarthritis have all shown promise (Rakhman et al., 2022).

Physical Application

Nanoparticles of metal and metal oxide have a variety of physical uses. They are employed in a variety of industries, including diagnostics, clinics, food processing, material research, and agriculture (Mittal & Roy, 2021). Metal oxide nanoparticles are employed as nanopesticides, herbicides, and fertilizers in agriculture. In biomedical research, they are also employed in gene delivery, theranostics, and catalysis. Metal and metal oxide nanohybrids have demonstrated promise in the reduction of environmental pollutants (Luo et al., 2021). Furthermore, applications such as electrostatic potential analysis, self-organization of nanoparticle systems, and physisorption of gasses have been carried out using metal oxide nanoparticles in the physics and chemistry of nanoparticles. Metal and metal oxide nanoparticles are produced by physical processes such as abrasion, condensation, evaporation, and melting.

Agricultural Application

Overuse of mineral fertilizers and dangerous pesticides has led to pollution and serious health issues. Nanoscience could be used to generate better-performing nanomaterials to solve those issues. Enhanced release and targeted delivery efficiency can be found in nanofertilizers such as N, P, K, Fe, Mn, Zn, Cu, Mo, and carbon nanotube fertilizers. Nanopesticides including Ag, Cu, SiO2, ZnO, and nano formulations show better broad-spectrum pest prevention efficiency than conventional pesticides (Gutiérrez et al., 2023).

The food business uses metal and metal oxide nanoparticles for a variety of purposes. They can be added to food packaging to increase food safety, prolong shelf life, and stop microbiological deterioration (Wu et al., 2023). Strong antimicrobial materials can be produced by synthesizing

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these nanoparticles from metals like iron, zinc, and silver and incorporating them into films and coatings. Metal nanoparticles have the potential to prolong the shelf life of both raw materials and ready-to-eat meals by lowering the rate of microbiological deterioration and blocking lipid oxidation. However, there is a risk to the food product's safety due to the migration of metal ions from the coating (Kim & Kim, 2023).

The antibacterial qualities of zinc oxide nanoparticles, in particular, have drawn attention from the food and agriculture sectors since they can enhance both human health and food quality. The possible toxicity of metal oxide nanoparticles to human health must be taken into account when employing them in food packaging.

Biomedical and Clinical Application

Clinical applications for metal and metal oxide nanoparticles have been demonstrated. They can be used in place of antibiotics because of their broad-spectrum antibacterial action (He et al., 2023). These nanoparticles have been used in drug delivery systems, cancer therapy, and antibacterial medicinal therapies (Etemadi et al., 2023). Their large payload, ability to modify the surface, and reactivity to magnetic fields are among their intriguing features. Specifically, metal oxide nanoparticles have been investigated for the diagnosis and treatment of breast cancer, particularly metastatic and multidrug-resistant forms. Although the exact processes behind the antibacterial activity of metal and metal oxide nanoparticles are still being investigated, bacterial strain, biofilm development, and the physico-chemical characteristics of the nanoparticles have all been linked to their effectiveness. To further understand antibacterial mechanisms, increase biosafety, and investigate novel applications for these nanoparticles, more research is necessary (Periakaruppan et al., 2023).

The use of metal and metal oxide nanoparticles in diagnostic applications has demonstrated significant promise. They are suited for biosensing because of their special physicochemical qualities, which include a high surface-to-volume ratio, outstanding selectivity, and high catalytic efficiency. In particular, metal oxide nanoparticles have shown great promise as instruments for cancer treatment and diagnosis. They can be applied to drug administration, diagnostics, and imaging of the breast, as well as to metastatic and multidrug-resistant breast malignancies (Alhalili, 2023). Applications of metal and metal oxide nanohybrids in nanoscience and biomedical research have also been thoroughly investigated. They can be applied to theranostics, catalysis, gene delivery, tumor detection, and the visualization of particular disease locations particularly, gold nanoparticles have been thoroughly investigated for their potential uses in biodetection and diagnostics, including photo-imaging and molecular sensing. Biosensing, immunotherapeutics, drug delivery, regenerative medicine, and bioimaging are just a few of the biomedical applications that have made use of metal oxide nanomaterials, including transition metal oxides (Periakaruppan et al., 2023).

Metal and metal oxide nanoparticle-based photothermal therapy has demonstrated potential in the treatment of cancer. When functionalized with biomolecules, metallic nanoparticles like palladium, gold, silver, and platinum show increased anticancer effects. In order to promote wound healing and eradicate biofilms, copper-gold nano-assemblies have been designed as dual-responsive agents for photothermal therapy (Ge et al., 2022). Gold nanoparticle photothermal therapy has been shown to be effective in simulation experiments, and the ideal treatment conditions have been proposed (He et al., 2023) . Gold nanoparticles coated with doxorubicin have been used to investigate combination therapy incorporating photothermal therapy and chemotherapy, leading to increased therapeutic efficiency. The application of photothermal treatment to gold nanostars has also been studied, with an emphasis on surface overheating

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problems (Yadav & Maurya, 2021). The potential of metal and metal oxide nanoparticles in photothermal therapy is demonstrated by these investigations.

DISCUSSION AND FUTURE PERSPECTIVE

Green synthesis is recommended these days since it uses cleaner, non-toxic solvents, eliminates or reduces waste, and lowers contaminants and byproducts. The standard techniques of generating nanoparticles have significant drawbacks, including the use of hazardous chemicals, large energy requirements, and expensive costs (Ying et al., 2022a). The use of hazardous solvents limits the use of nanomaterials in many biomedical or clinical applications. However, biogenic nanoparticle synthesis produces nanoparticles in a cheap and environmentally beneficial manner by utilizing naturally occurring biological systems such as bacteria, fungi, plants, and animals (Weng et al., 2017). Compared to ordinary synthetic procedures, green synthesis technology is more biocompatible and environmentally friendly. Green nanoparticles, which are manufactured using approved materials and procedures, have various advantages over ordinary nanoparticles. Biocompatibility, better features, economic viability, ecological sustainability, and sustainable growth are some of the benefits. Green nanoparticles are considered environmentally friendly since they are typically made from nontoxic, biodegradable, and renewable elements (Kalpana & Devi Rajeswari, 2018).

Many studies undertaken in recent years have demonstrated that bacteria such as Brevibacterium frigoritolerans, Pseudomonas deptenis, Bacillus methylotrophicus, Visella oriza, and Bhargavaea indica may successfully produce gold (Au) and silver (Ag) nanoparticles. The main disadvantage of bacterial production is the difficult procedures needed, such as growing, storage, microbial sample collection, and isolation (Ahmed et al., 2016). Fungal-aided synthesis is one highly effective way for creating monodispersed nanoparticles with different morphologies. Because fungi include a variety of internal enzymes, they are effective biological agents for nanoparticle production (Bhatt et al., 2023). Compared to bacteria, fungi can produce more NPs. Furthermore, because their cell structures include proteins, enzymes, and reducing agents, fungi have numerous advantages over other animals. Reductase, an enzyme found in the fungal cell wall or within the cell, is responsible for the production of metal nanoparticles (Chouke et al., 2022). However, there are several disadvantages to this manufacturing process, including synthesis conditions, material selection, application, and product quality control. The aforementioned aspects of green-synthesized nanoscale metallic materials pose the principal barriers to industrial manufacturing and large-scale application.

Considering the objective of this study, we conducted various comparisons between bacteria and fungi-assisted approaches. Nanoparticle production using bacteria and fungus offers both advantages and disadvantages (table 2). Bacteria, recognized for their ability to create large amounts of enzymes and amino acids, are used in nanoparticle production through routes such as fundamental cellular biochemistry, metal ion transport, resistance mechanisms, and nucleation processes (Bhatt et al., 2023). Despite its effectiveness, bacterial synthesis necessitates complex methods such as growth, storage, microbial sample collection, and isolation (Ahmed et al., 2016). Fungal-assisted synthesis, on the other hand, offers an alternative approach by leveraging a variety of internal enzymes, notably reductase, which is

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essential for nanoparticle creation (Bhatt et al., 2023). Fungi are capable of producing more nanoparticles (Chouke et al., 2022)

After reviewing the available literature, we concluded that fungal-assisted synthesis appears to have significant benefits over bacterial synthesis for nanoparticle production. Fungi have been shown to produce more nanoparticles due to their cell structures containing proteins, enzymes, and reducing agents (Bhatt et al., 2023; Chouke et al., 2022). Fungi also have a variety of internal enzymes, notably reductase, which is important in the production of nanoparticles. While both approaches face obstacles such as synthesis conditions, material selection, and product quality control, fungal-assisted synthesis appears to be a more efficient and possibly scalable alternative to nanoparticle production.

In view of characterization, overall, FTIR spectroscopy, SEM-EDS, TEM with EDS, and XRD analysis each offer unique insights into metal and metal oxide nanoparticle surface chemistry, elemental composition, structural features, and crystal phases (Smith, 2020). The addition of X-ray Photoelectron Spectroscopy (XPS) as a complementary technique provides further understanding of surface properties, chemical bonding, and electronic structure (Smith, 2020). We think that integrating XPS with other techniques will enhance the comprehensive characterization of these nanoparticles for diverse applications. Additionally, Dynamic Light Scattering (DLS) emerges as a valuable tool for analyzing nanoparticle size distribution and colloidal properties in solution, essential for applications like drug delivery and catalysis (Berne & Pecora, 2016). We also proposed combining DLS with microscopy techniques such as TEM or SEM-EDS will offer a holistic characterization approach, providing insights into nanoparticle behavior in solution and aiding in material development.

In accordance with previous research in this field, we discovered that biofabricated copper and copper oxide nanoparticles are the most often employed species for a variety of antibacterial applications, providing significant biomedical benefits. To ensure accurate analysis, we divide the biofabricated metal nanoparticles into two categories: Metal and Metal Oxide Nanoparticles from Biogenic Methods and Copper nanoparticles (Cu NPs) synthesized using plant extracts. This was based on both pharmacological (table 3) and diagnostic applications (table 4).

Utilizing green and biogenic approaches, these nanoparticles demonstrate strong antibacterial, antifungal, and antiviral properties, making them promising candidates for pharmaceutical applications. Biogenic CuO, ZnO, and WO3 nanoparticles exhibit potent antibacterial activity against drug-resistant infections and offer advantages in medication transport and biosensing, showcasing their potential in medicine. Metal oxide nanoparticles, in particular, hold promise in cancer diagnosis and treatment, offering opportunities for drug administration, diagnostics, and imaging of breast cancer, including metastatic and multidrug-resistant forms. Additionally, Cu NPs synthesized through plant-mediated biosynthesis show diverse pharmacological applications, including antioxidant, antibacterial, antifungal, and anticancer properties. They hold potential as alternative agents in pharmaceutical applications due to their strong pharmacological capabilities. While not explicitly mentioned, Cu NPs synthesized via plant extracts could potentially be utilized in diagnostic applications, offering unique properties and interactions with biological systems. Overall, biofabricated copper and copper oxide nanoparticles emerge as prominent species for antimicrobial applications in biomedical contexts, offering a pathway for innovative biomedical interventions.

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Metal and metal oxide nanoparticles, including manganese dioxide, cerium oxide, titanium dioxide, silver, and zinc oxide, exhibit potential antioxidant benefits by mimicking enzyme actions, scavenging reactive oxygen and nitrogen species, and reducing metal concentrations. Their potential applications in medicine, cosmetics, functional food additives, and treating age-related conditions have shown promise. Overuse of mineral fertilizers and pesticides has led to pollution and health issues. Nanoscience can generate better-performing nanomaterials to address these issues. Nanofertilizers and nanopesticides show better broad-spectrum pest prevention efficiency than conventional pesticides. Metal and metal oxide nanoparticles can increase food safety, prolong shelf life, and prevent microbiological deterioration in food packaging. However, metal ion migration from coatings poses a safety risk. Zinc oxide nanoparticles have antibacterial properties, but potential toxicity must be considered.

Metal and metal oxide nanoparticles have shown potential in clinical applications, including antibacterial treatment, drug delivery systems, cancer therapy, and antibacterial medicinal therapies. They have been used in breast cancer diagnosis and treatment, particularly in metastatic and multidrug-resistant forms. Metal oxide nanoparticles have a high surface-to-volume ratio, excellent selectivity, and high catalytic efficiency, making them ideal for biosensing. They have also been used in biodetection and diagnostics, including photo-imaging and molecular sensing. Metal oxide nanohybrids have been explored for applications in nanoscience and biomedical research, including theranostics, catalysis, gene delivery, tumor detection, and visualization. Metal oxide nanoparticle-based photothermal therapy has shown increased anticancer effects when functionalized with biomolecules. Gold nanoparticles coated with doxorubicin have been used in combination therapy incorporating photothermal therapy and chemotherapy, increasing therapeutic efficiency. Further research is recommended to understand their mechanisms and explore novel applications.

AUTHOR'S CONTRIBUTIONS

Corresponding **Author**: Led manuscript construction, ensured thorough analysis, and monitored editing for clarity.

Co-Author 1: Conducted detailed analysis and comparisons, enriching the article's content.

Co-Author 2: Provided crucial supervision and expertise, enhancing the article's quality.

Co-Author 3: Polished writing style and structure for readability and interest.

Co-Author 4: Played a significant role in editing and revising content.

Co-Author 5: Assisted in editing tasks, focusing on summarizing content.

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COMPETING INTEREST

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the review of this paper.

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