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Review article

Plants, bacteria, fungi, and algae as biological systems for green synthesis of nanocomposites and nanomaterials: A review of current knowledge

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Abstract

Objective: Nanoparticles and nanocomposites have attracted significant attention in engineering and biomedical sciences. Conventional physical and chemical synthesis methods, however, pose environmental and health risks. This review aims to highlight green synthesis as a sustainable alternative, summarize biological systems used for nanocomposite fabrication, evaluate their advantages and limitations, and assess their potential for industrial applications.

Materials and Methods: A systematic literature search was performed in PubMed, Scopus, Google Scholar, and other databases using keywords such as *green synthesis*, *nanocomposites, nanobiotechnology,* and specific plant, bacterial, fungal, and algal species. Articles were screened by title and abstract, followed by full-text review. Relevant data were extracted, organized, and critically synthesized.

Results: Findings indicate that plants provide abundant natural metabolites useful as reducing and capping agents, bacteria contribute bacterial cellulose, and fungi offer chitin and chitosan with ease of cultivation. Green nanocomposites combine the advantages of organic polymers and natural fillers, yielding materials with notable strength, stiffness, biodegradability, and cost-effectiveness. Challenges such as low reproducibility and poor homogeneity can be solved using bioreactor-based approaches and improving standardization methods. Potential mechanisms, active metabolites, and species with green synthesis capability were also identified.

Conclusion: Green synthesis offers a promising alternative method for fabricating eco-friendly nanocomposites with applications in biomedical and environmental fields. Despite limitations, advancements such as bioreactor technology enhance reproducibility, supporting the feasibility of scaling these processes to industrial levels. Continued research into biological systems and mechanisms will accelerate the development of sustainable nanomaterials.

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Introduction

Nanobiotechnology is a field of study with potential applications in nanomaterial design and synthesis, which combines biological and chemical sciences (Rezvani Amin et al. 2016). In recent years, nanomedicine has led the way in developing novel pharmaceutical systems for the diagnosis, prevention, and treatment of diseases (Mazayen et al. 2022). Nanoparticles (NPs), which possess high surface area-to-volume ratios and quantum effects, bridge the gap between bulk materials and atomic/molecular systems. Aside from NPs, nanocomposites (NCs) have been extensively used for a variety of applications. Beyond individual NPs, the development of NCs has introduced additional advantages. An NC material is made up of many phases, each with at least one, two, or three nano-sized dimensions. Taking material dimensions down to the nanoscale level provides phase interfaces, which are particularly significant for enhancing the materials' qualities (Omanović-Mikličanin et al. 2020). Due to their nano-size, NCs have superior characteristics to regular composites by maximizing interfacial adhesion (Winey and Vaia 2007). Incorporating nano-sized particles into a matrix substrate is effective in enhancing the physical stability and conductivity properties of NCs (Ebrahimi et al. 2022). Their unique properties make NPs and NCs highly applicable in medicine, chemistry, biotechnology, materials science, optics, microbiology, and environmental remediation (Mondal et al. 2020; Samadian et al. 2023).

Despite the growing use of NPs, conventional synthesis methods—such as chemical and physical approaches—have raised considerable environmental and health concerns. These methods require toxic solvents, generate hazardous by-products, and consume high amounts of energy (Ijaz et al. 2020; Zeng et al. 2012). Green synthesis approaches, which use biological systems such as plants, bacteria, fungi, and algae, have emerged as an eco-friendly, cost-effective, safe, scalable, and sustainable alternative for the synthesis of NPs and NCs (Nadaroglu et al. 2017; Salarbashi et al. 2018b; Singh and Mijakovic 2024). The main benefits of green composites are that they are environmentally benign, completely degradable, and sustainable materials that can be discarded or composted without affecting the environment (Adeosun et al. 2012). Thus, the fabrication of eco-friendly and green bionanocomposites has piqued researchers' interest as a novel technique for protecting the environment from the negative impacts of conventional methods (Salarbashi et al. 2017).

Green synthesis methods can occur either intracellular or extracellular, with extracellular synthesis being more favorable due to easier nanoparticle recovery (Rezvani Amin et al. 2019; Salarbashi et al. 2018a; Salarbashi et al. 2018c). Bioreduction, biosorption, and interaction of metal ions with cell wall components play a role in their conversion from ionic to nanoform. This process is carried out by enzymes, cofactors, proteins, and various natural compounds, each of which gives a special characteristic to the produced nanomaterial and, in addition to being effective in the reduction, capping, and coating processes, can also alter or improve its biological activities. This change is usually accompanied by a color change in the culture medium, which is confirmed by performing additional analytical tests such as UV-visible spectroscopy, Fourier transform infrared (FTIR), size analysis, and electron microscope images (Mostafazade et al. 2024). Applications of these biosynthesized nanomaterials range from photocatalysis and environmental remediation to biomedical uses such as antioxidant, antibacterial, anticancer, and catalytic activities (Cuong et al. 2022; Kashid et al. 2022; Matussin et al. 2020; Vijayaram et al. 2024).

The purpose of this study is to investigate the green synthesis of NCs and nanomaterials by the green synthesis method using plants, bacteria, fungi, and algae. In addition, the mechanisms, applications, advantages, and disadvantages of each method to fabricate these nanostructures have been discussed. Understanding the role of active molecules in NPs and NCs synthesis can pave the way for scientists to manipulate these chemical features for further nanostructure research.

Materials and Methods

A systematic literature search was conducted in PubMed, Scopus, Google Scholar, and other databases using relevant keywords such as green synthesis, nanocomposites, nanobiotechnology, related plants, bacterial, fungal, and algal species. Titles and abstracts were screened, followed by a full-text review of eligible articles. In the end, 131 relevant articles were included, with an emphasis on more recent studies (approximately 80% of articles between 2015-2025), while other articles were excluded. Additionally, some older articles were also included due to their high significance. Data from the selected studies were extracted, organized, and synthesized for critical analysis.

Results

Plant-mediated green synthesis

Plants include a variety of components and biochemicals that can be used to stabilize and reduce green NPs throughout the synthesis process. The NP synthesis using plant extracts is an affordable procedure and results in higher yield due to the large quantity of phytochemical components, which can also act as reducing and stabilizing agents, transforming metal ions into metal NPs (Pandit et al. 2022). Plants have a wide range of phytochemical substances with oxidation-reduction properties, including phenolics, terpenoids, polysaccharides, and flavonoids (Fazly Bazzaz et al. 1997; Xiao et al. 2019). The fabrication of stabilized NPs requires a precise understanding of the phytochemical components. In general, plants' secondary metabolites (polyphenols) are the most critical substances that play an essential role in the evolution of the green synthesis of NPs and NCs (Vijayaram et al. 2024).

Mechanism of synthesis

Plant-mediated NP formation can be categorized into three levels. During the activation phase, metal ions are converted from monovalent or divalent oxidation states to zerovalent states, and reduced metal atoms are nucleated. The development stage enhances the thermodynamic persistence of NPs, but extended nucleation may result in the buildup of produced metal NPs, altering their morphology. Plant metabolites cover the termination phase, during which NPs achieve their greatest activity and maintain a consistent shape (Chokkareddy and Redhi 2018). Various functional groups, such as methoxide, carbonyl, hydroxyl, and amino of natural compounds such as flavonoids, phenolic acid, alkaloids, saponins, steroids, and tannins, play an important role in reducing and stabilizing metal ions by creating electrostatic bonds. Adjusting the reaction conditions affects the shape, dispersion, and other properties of these particles (El-Seedi et al. 2019). The choice of solvent, reducing agents, and stabilizing agents is very important in the green synthesis by plants (Ghaffari-Moghaddam et al. 2014). Exposure of plants to high doses of metal ions initiates a process called bioaccumulation. In this process, which is considered a type of detoxification, the production of reactive oxygen species (ROS) leads to the disruption of metabolic and physiological functions that induce the production of chelating agents, cysteine-rich oligoproteins, phytochelatins, and metallothioneins. In addition, enzymes of the phenylpropanoid pathway also play a role in this process. This plant defense response also likely plays a role in the biosynthesis of nanomaterials. The complexation of metal ions with hydroxyl and carbonyl groups present in natural compounds is very important, and compounds such as quercetin and catechol, which have multiple active sites for binding, are suitable candidates in the green synthesis. In general, the role of flavonoids in the plant-mediated green synthesis is very critical (Marslin et al. 2018).

Species and natural compounds

Different species of plants are used in the green synthesis of nanostructures and NCs. *Punica granatum* (pomegranate) has been utilized to create several metal NPs and NCs (Adyani and Soleimani 2019; Das and Sharma 2020). The primary chemical components of pomegranate peels include polyphenols such as ellagic tannins, ellagic acid, and gallic acid. These components in pomegranate peel extract function as reducing and protective agents, allowing them to reduce metal ions and stabilize NPs (Adyani and Soleimani 2019). *Mentha longifolia* contains phytochemicals including monoterpenes, monoterpenoids, sesquiterpene (β-caryophyllene), tannins, and flavonoids. The leaf extract contains triterpenoids, steroids, beta-sitosterol, phenolic compounds, and hexacosyl (E)-ferulate. These compounds are effective in the green synthesis of nanostructures (Mohammadi-Aloucheh et al. 2018; Wang et al. 2022). *Euphorbia* plants are known for their vast diversity of medicinal phytochemicals, including phenolic compounds, aromatic esters, steroids, alkaloids, triterpenoids, essential oils, and other bioactive elements found in various parts such as leaves, stems, roots, and flowers (Atarod et al. 2015; Sajjadi et al. 2017). Some of its species have been used in NC synthesis, such as *E. heterophylla*, *E. peplus*, and *E. wallichii* as reported (Atarod et al. 2015; Atarod et al. 2016; Sajjadi et al. 2017; Tajbakhsh et al. 2016). The leaves of *Azadirachta indica*, also known as neem, contain a variety of compounds, including polyphenols and quercetin. These chemicals have been shown to help transform chemical salts into NPs and act as capping agents. Neem has been used to produce useful NCs (Slathia et al. 2021). In one study, selenium NPs biosynthesized by *Citrus reticulata* peel extract, chitosan NPs synthesized by ionotropic gelation, and sodium tripolyphosphate were used as a crosslinking agent in the structure of an NC with antifungal activities. The high concentration of ascorbic acid in citrus peels compared to other parts of the fruit is very important for green synthesis and reduction reactions (Desouky et al. 2025). Using curcumin as a natural compound in the green synthesis of nanomaterials, in addition to being effective in increasing its solubility, can also be effective in improving the antimicrobial effects of the nanomaterial (Mohammadi et al. 2021). Apigenin and gallic acid can also be effective in the green synthesis of anticancer nanomaterials as coating agents (Hormozi-Moghaddam et al. 2024; Neshastehriz et al. 2020). Eugenols, linalool, chlorogenic acid, cyclic peptides, salicin, kaempferol, menthol, epigallocatechin, catechin, and epicatechin gallate are other probable plant active metabolites involved in the green synthesis (Marslin et al. 2018). Table 1 summarizes the plant species used to produce NCs and nanostructures by the green synthesis method.

Applications

Green-synthesized NPs by plant species have shown great promise across a wide range of applications. Zinc oxide nanoparticles (ZnO NPs) fabricated with plant extracts have demonstrated potential in treating fungal and other microbial infections in agricultural animals and plants, providing a preferable alternative to standard antibiotics. The generation of ROS, zeta potential, and size are important factors in determining the antimicrobial activity of these NPs. Additionally, the production of hydrogen peroxide has been shown to damage and destroy pathogens. In addition to antimicrobial applications, the structure and size of nanomaterials also affect their other activities. It was shown that flower-shaped NPs produced by *Carica papaya* had the highest dye degradation compared to other forms (Akintelu and Folorunso 2020). Flower-shaped nanomaterials are of great importance in controlled or sustained release drug delivery systems due to their increased surface area efficiency/reactivity (Sreedharan et al. 2019). Silver nanoparticles (AgNPs) have significant antibacterial characteristics and are widely used in medicinal applications (Ghaffari-Moghaddam et al. 2014; Rajabi et al. 2011). A study discovered that an NC built from silver and zinc oxide manufactured with potato peels could be efficient for wastewater treatment (Alharthi et al. 2020). In another study, it was proven that the silver-graphene NC synthesized using *Melissa officinalis* has anticancer effects (Motafeghi et al. 2023).

Advantages and disadvantages

Green synthesis through plants offers the general benefits of green synthesis, such as biocompatibility, no use of toxic materials, reduced waste, and reduced pollution. These environmentally friendly materials, since they are produced through clean processes, have high potential for use in removing environmental pollutants with minimal harm to the environment and human health (Ahmed et al. 2022). Green synthesis by plants has a prominent advantage over other biological systems, which is that, unlike others, it does not require the complex processes of maintaining cell cultures (Ghaffari-Moghaddam et al. 2014). In general, plant preparations are less challenging to scale up to an industrial scale compared to microbes. Extraction in plants is generally carried out with higher efficiency than in microbes; the speed of reduction reactions in green synthesis processes is faster in them, and we are faced with a large number of natural compounds, each of which gives unique properties to the final product (Singh et al. 2023). Despite all these advantages, problems such as selecting appropriate materials, maintaining synthesis conditions, reproducibility, and product quality control are limiting factors. These limitations are especially evident in the scale-up and industrial production of these materials (Ying et al. 2022). Standardizing these processes is crucial for reducing heterogeneity and batch-to-batch variations, thereby achieving a stable, high-quality, and storable product. Additionally, identifying and removing contaminants and impurities is critical to maintaining quality. Obtaining a high-quality final product requires the use of high-performance purification, identification, and characterization techniques to produce a product with appropriate functionality and applicability, such as use in clinical studies or industrial scale (Singh et al. 2023).

Bacteria-mediated green synthesis

Bacteria are very important as another group producing nanomaterials by the green synthesis method. Various compounds and enzymes carry out intracellular or extracellular production of these materials (Alsaiari et al. 2023; Rezvani Amin et al. 2019). The investigation of bacterial cellulose (BC)-based NCs has gained great attention in recent years due to their excellent characteristics. Several bacteria, including *Acetobacter*, *Rhizobium*, *Agrobacterium*, *Sarcina*, *Pseudomonas*, *Achromobacter*, *Alcaligenes*, *Aerobacter*, and *Azotobacter*, have the ability to produce cellulose. Among them, the rod-shaped aerobic Gram-negative bacteria of the *Acetobacter* genus (e.g., *Acetobacter xylinum*) are frequently explored and used for BC production due to their great yield potential (Qiu and Netravali 2014). The production of BC using *Komagataeibacter xylinus* (formerly *A. xylinum*) is indeed well-known, but the high cost associated with BC production has been a challenge due to the low productivity of bacterial strains.

The usual production of BC from bacterial strains is approximately 5 g/L, which limits its commercial viability. To solve this constraint, researchers have concentrated on searching for BC-producing strains in order to uncover more efficient producers. It is possible to boost BC productivity by increasing the diversity of bacterial strains capable of making it. Additionally, improving the culture medium, culture regimes, and establishing cell-free culture systems are tactics for increasing BC production efficiency. Furthermore, researchers investigated the utilization of waste products in BC manufacturing. Stillage, whey, and molasses have been examined as alternate sources for BC production, with the potential to boost yields and reduce costs in BC manufacturing methods. Using these waste materials as substrates, researchers want to improve the manufacturing of BC and make it a more economically feasible material for numerous purposes (Revin et al. 2022).

Fermentation mechanisms and processes

BC fermentation can occur under static, agitated, or stirring conditions, resulting in the creation of several types of cellulose. Static circumstances create a three-dimensional linked reticular pellicle, whereas agitated and stirred conditions yield irregularly shaped sphere-like cellulose particles (SCP). The yield of cellulose under static conditions is determined by the concentration of the carbon source and the amount of air supplied. Because of its poor output, agitated fermentation is widely used in commercial applications. Agitated conditions create SCP in a variety of forms, including fiber suspensions, spheres, pellets, and irregular masses**.** The biorefinery idea emphasizes the use of economically renewable materials as feedstock for chemicals, materials, and fuels. Studies have looked into employing agricultural waste and industrial by-products as suitable culture media for BC production. Waste beer yeast, dry oil mill residue, thin stillage, and grape skin have all demonstrated potential as carbon sources. Glucose as a carbon source can result in the development of gluconic acid, a by-product that can reduce BC synthesis by lowering the pH of the culture medium. However, the presence of antioxidants and polyphenolic substances can prevent gluconic acid production (Esa et al. 2014).

Static growth of BC pellicles is a simple process that requires placing the culture media in trays and allowing the bacteria to develop and produce cellulose for 5-20 days. While this technology is widely used and reasonably easy to implement, it has limitations that may prevent its industrial application. The primary disadvantages of static cultivation are low productivity and the lengthy cultivation time required to obtain a considerable yield of cellulose. The low productivity of static cultivation means that the amount of BC generated per unit of time and resources invested is insufficient for industrial-scale production. Furthermore, the increased culture time required to achieve the appropriate level of cellulose synthesis might raise production costs and reduce process efficiency. To address these constraints, researchers and industry professionals are investigating alternate cultivation methods, such as agitated or stirred fermentation, which can result in higher yields of BC in a shorter time. By adjusting fermentation conditions such as carbon sources, oxygen supply, and agitation levels, BC production can be increased in productivity and made more economically viable for industrial uses (Lin et al. 2013).

The use of an agitated culture has been proposed as a possible solution to the high cost and poor production rates associated with static culture methods for BC synthesis. The distribution of oxygen is critical for BC production; however, the static culture method frequently fails to give enough oxygen to allow adequate growth. Increasing oxygen supply can also reduce BC production; therefore, access to an optimal amount of oxygen is important.

The idea behind agitated cultures is to increase oxygen delivery to the bacteria during cultivation. Agitating the culture improves oxygen distribution throughout the media, perhaps leading to greater BC production. However, studies have yielded inconsistent findings when comparing the usefulness of this approach to static cultures. Some studies have shown that, despite increased oxygen delivery, both agitation/shaking and static cultures can produce comparable amounts of BC during the same time span. Furthermore, certain research found that agitated/shaking cultures produced less BC than static cultures. It is vital to note that the efficiency of the agitated/shaking culture procedure varies according to the bacterial strain used. Overall, while agitated cultures have been presented as a method of increasing BC synthesis by improved oxygen delivery, the outcomes vary across research and bacterial strains (Wang et al. 2019).

To reach commercial-scale production, static culturing was modified to include a new culture vessel with an oxygen-permeable silicone membrane surface at the bottom. This resulted in a doubling of cellulose production because BC pellicles grew on both the liquid-air surface and the silicone membrane. Surface roughness influenced the rate of cellulose generation on the silicone membrane, with a glossy membrane producing five times more cellulose than an embossed surface. The use of an airlift bioreactor for BC production has several advantages, including decreased power usage when compared to agitated bioreactors. In this method, air or oxygen-enriched air is fed from the bottom to stimulate the circulation of the culture medium. To increase BC output, various airlift bioreactor configurations have been used. This process offers a more energy-efficient and possibly scalable way to produce BC on a commercial basis. Another example is biofilm reactors, which are a form of immobilized-cell reactor that can improve BC production efficiency by enabling high biomass density systems. They have several advantages over suspended cell reactors, including higher output yields, easier operation, and maintenance (Lin et al. 2013). Overall, biofilm reactors can improve BC manufacturing processes while potentially lowering capital costs in the long run.

Species and materials

Various Gram-negative bacteria, including species from the genera *Komagataeibacter*, *Agrobacterium*, *Achromobacter*, *Enterobacter*, *Rhizobium*, *Pseudomonas*, *Salmonella*, *Azotobacter*, and *Alcaligenes*, have the ability to synthesize BC. In addition, some Gram-positive bacteria, such as *Sarcina ventriculi* and *Rhodococcus* are also capable of producing BC (Revin et al. 2022). The matrix material, which can be polymer, metal, ceramic, or composite, keeps the reinforcement material in place while also acting as a medium for load transfer and shielding the reinforcements from environmental conditions. Organic components in BC composites are derived from living organisms and include polymers such as carbon fibers or natural fibers. NPs, metals, metal oxides, clays, and solid particles are all examples of inorganic materials. These materials are utilized as reinforcements in BC composites to improve qualities including mechanical strength, flexibility, thermal, and electrical conductivity. Composites can attain a balance of qualities that neither material alone can provide. The subclassifications of BC composites based on reinforcement materials assist in dividing them into more precise categories depending on the nature of the reinforcing material used (Shah et al. 2013).

Applications

Biocomposites synthesized using bacterial strains are environmentally friendly materials utilized in a variety of industries, including paper manufacture, food packaging, medicine delivery, tissue engineering, automobile components, and construction materials. They provide biodegradability, biocompatibility, and lightweight qualities, promoting ecologically friendly practices and product development (Ullah et al. 2016). The combination of polyvinyl alcohol (PVA) and BC fibers in NCs provides a distinct set of characteristics suitable for biological applications. PVA's hydrophilic characteristic ensures good biocompatibility, whereas BC fibers give strength and mechanical reinforcement. Physical crosslinking of PVA via freeze-thaw cycles produces a solid hydrogel with increased mechanical properties, making it appropriate for applications requiring strength and durability. The addition of BC fibers significantly increases the mechanical properties of the NC, permitting the production of materials with qualities similar to those of cardiovascular tissues like the aorta and heart valve leaflets. Overall, the combination of PVA and BC fibers in NCs is a promising path for developing biomedical materials with customized mechanical properties, biocompatibility, and prospective uses in tissue engineering, drug delivery, and medical devices (Millon and Wan 2006). The chemical deposition of CuNPs on BC membranes synthesized by *Gluconacetobacter hansenii* bacteria, ATCC 23769 strain, was successfully controlled via hydrothermal synthesis. The analysis of BC-Cu NCs confirmed the presence of copper NPs and their effect on overall characteristics. Furthermore, the antibacterial activity of the BC-Cu NCs was evaluated (Araújo et al. 2018). Green tea was employed as both a substrate for *A. xylinum* bacteria fermentation and a reducing agent for silver NP synthesis in a unique technique to produce BC/silver NCs. The study demonstrated significant antibacterial capabilities, with 100% bacterial reduction against *Staphylococcus aureus* and *Escherichia coli* (Fadakar Sarkandi et al. 2021). BC generated by *Achromobacter* sp. M15 was used to make titanium dioxide nanoparticles (TiO_2 NPs) in a green procedure. The resulting BC/TiO_2NPs NC demonstrated unusual traits such as self-cleaning capabilities and excellent antibacterial properties (Farag et al. 2021). Another study reported the formation of an NC by depositing silver nanoparticles (AgNPs) over nanofibrillated BC for antibacterial applications. The BC-AgNPs composite displayed effective antimicrobial properties specifically against *E. coli* (Audtarat et al. 2022). An environmentally friendly method was utilized to create AgNPs within a BC membrane using the *Komagataeibacter intermedius* (MBS-88) strain. The BC/AgNP composites were effectively synthesized using BC as a template and hydrothermal synthesis, with BC acting as a reducing and stabilizing agent. The BC/Ag NC demonstrated superior antibacterial activity against *Staphylococcus epidermidis*, *S. aureus*, and *Pseudomonas aeruginosa*. This suggested that the synthesized BC-AgNPs could be utilized in managing wound infections as a sustainable alternative to chemical synthesis methods that may harm the environment (Kumar et al. 2023).

A new spherical Fe_3O_4/BC NC was successfully produced using *Gluconacetobacter xylinus* fermentation. This NC may adsorb heavy metals such as Pb^{2+}, Mn^{2+}, and Cr^{3+} and can be reused several times due to its superparamagnetic characteristics. The NCs are easily separated by a magnetic field, making them a sustainable and efficient alternative for heavy metal removal in many applications (Zhu et al. 2011).

BC nanofibers are used as a strong biotemplate to make unique gold nanoparticle-bacterial cellulose nanofiber (AuNP-BC) NCs .The BC is produced by the acetic acid bacteria *A. xylinum*. These NCs have good biocompatibility, conductivity, and a nanofiber network structure, which allows biomolecules to be easily entrapped while maintaining their bioactivities. This makes the Au-BC NCs appropriate for use as biosensors.

Furthermore, the Au-BC NCs can be used to encapsulate various enzymes, resulting in enzyme/Au-BC NCs with numerous applications in bioelectroanalysis and bioelectrocatalysis (Zhang et al. 2010). BC, produced by *A. xylinum* is often used in wound dressings due to its high-water retention and robust structure. A novel antimicrobial dressing made of BC/methylglyoxal (MGO) has been created, demonstrating greater antimicrobial capabilities against a variety of bacteria when compared to previous similar wound dressing materials. This BC/MGO NC holds promise as an antibacterial dressing for chronic wounds (Yang et al. 2020). Regenerated bacterial cellulose (RBC) composites with zinc-oxide nanoparticles (ZnO NPs) were synthesized utilizing a unique approach to improve their biological uses. RBC-ZnO NC films outperformed RBC alone in terms of thermal, mechanical, and antibacterial properties. The composites were fabricated in an environmentally benign manner and demonstrated biocompatible and non-toxic behavior toward animal cells, making them promising for use in biomedical applications. These composites stand out for their significant antibacterial capabilities, which emphasize their potential for treating infections in medical settings (Ul-Islam et al. 2014). The BC/ZnO NC was highly UV-blocking and had antibacterial properties against both Gram-positive and Gram-negative bacteria. This emphasizes its potential as a multifunctional material for applications requiring UV protection and antibacterial characteristics (Wahid et al. 2019). New raw bamboo biomass-based magnetic BC/Fe NC materials were successfully created and exploited as an effective adsorbent for the removal of methylene blue dye from synthetic dye-containing effluents (Sen 2023). Figure 1 represents the application of NCs produced by bacteria using the green synthesis method. BC plays an important role in the synthesis of these structures. Table 2 also briefly describes these NCs.

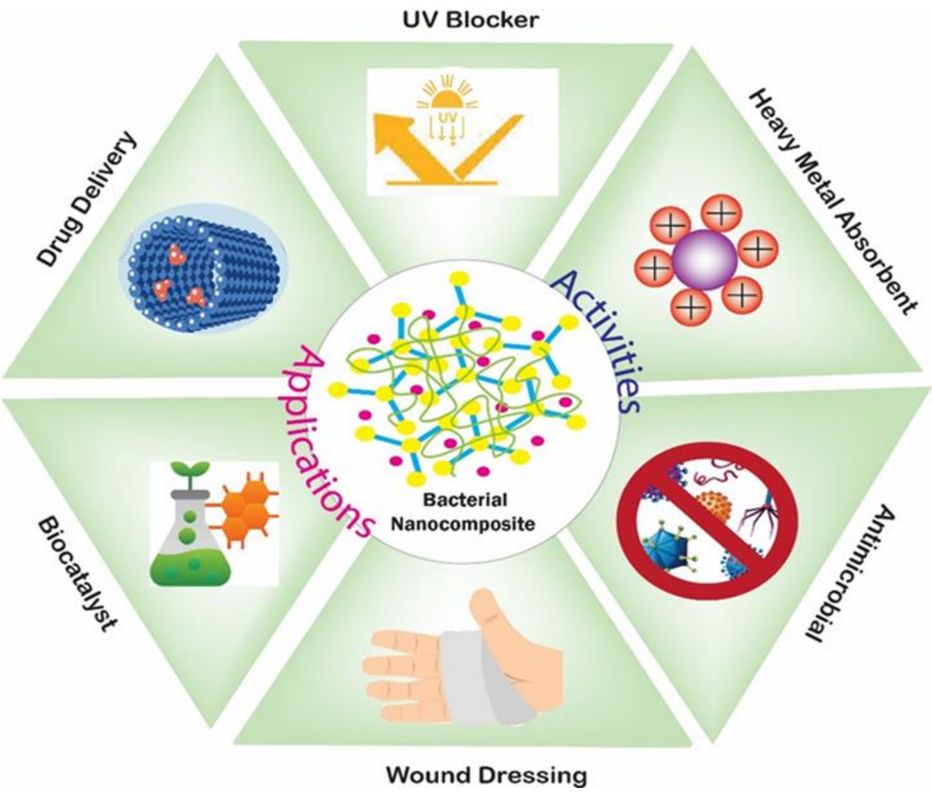

Figure 1. Green synthesis of nanocomposites and nanomaterial using bacteria along with their applications

Table 1. Plants-mediated green synthesis of nanocomposites and nanostructures

No.	Species	Parts of plant	Nanocomposites*	Metal salts	Applications	References
1	*Adhatoda vasica*	Leaf	CuO/C	$CuSO_4$	Antimicrobial activity	(Bhavyasree and Xavier 2020)
2	*Azadirachta indica*	Leaf	Ag/ZnO	$Zn(NO_3)_2$ - $AgNO_3$	Solar cells, gas sensing, biosensors, and antibacterial activity	(Slathia et al. 2021)
3	*Cassytha filiformis*	Leaf	Cu/MgO	N/A	Reduction of toxic dyes	(Nasrollahzadeh et al. 2018a)
4	*Euphorbia heterophylla*	Leaf	Ag/HZSM-5	$AgNO_3$	Reduction of organic dyes	(Tajbakhsh et al. 2016)
5	*Euphorbia heterophylla*	Leaf	Ag/TiO_2	AgNO3	Reduction of variety of dyes in water	(Atarod et al. 2016)
6	*Euphorbia peplus*	Leaf	Ag/Fe_3O_4	$AgNO_3$ - Fe_3O_4	Magnetically recoverable catalyst	(Sajjadi et al. 2017)
7	*Euphorbia wallichii*	Leaf	Cu/rGO/Fe_3O_4	$CuCl_2$ - $FeCl_3$	Reduction of toxic dyes in water	(Atarod et al. 2015)
8	*Hibiscus tiliaceus*	Leaf	Pd/Fe_3O_4	N/A	Purification of wastewaters	(Nasrollahzadeh et al. 2018b)
9	*Melissa officinalis*	Leaf	ZnO/CuO	N/A	Reduction of toxic dyes	(Bordbar et al. 2018)
10	*Mentha longifolia*	Flower	Ag/Fe_3O_4	N/A	Antioxidant and anti-lung cancer	(Wang et al. 2022)
11	*Mentha longifolia*	Leaf	ZnO/CuO	$Zn(NO_3)_2$ - $Cu(CH_3COO)_2$	Minimization of bacterial infections	(Mohammadi-Aloucheh et al. 2018)
12	*Moringa oleifera*	Leaf	$ZnFe_2O_4$	$Fe(NO_3)_3$ - $Zn(NO_3)_2$	Anode materials of the lithium batteries, photo-catalyst and gas sensor	(Matinise et al. 2018)
13	*Punica granatum*	Fruit juice	Ni/Ag/rGO	$AgNO_3$ - $Ni(NO_3)_2$	N/A	(Das and Sharma 2020)
14	*Punica granatum*	Fruit peel	Ag/Fe_3O_4/rGO	$AgNO_3$ - $Fe_2(SO_4)_3$ - $FeSO_4$	Catalytic activity for reduction of organic pollutants	(Adyani and Soleimani 2019)
15	*Punica granatum*	Fruit peel	PPP-TiO2	$Ti(OCH(CH_3)_2)_4$	Antimicrobial activity for water disinfection	(Abu-Dalo et al. 2019)
16	*Solanum tuberosum*	Tuber	Ag–ZnO	$Zn(NO_3)_2$ - $AgNO_3$	Reduction of toxic dyes	(Alharthi et al. 2020)
17	*Theobroma cacao*	Seed bark	ZnO/CuO	$Zn(NO_3)_2$ -$Cu(NO_3)_2$	N/A	(Yulizar et al. 2018)

* rGO: reduced graphene oxide, PPP: pristine pomegranate peel

Table 2. Bacteria-mediated green synthesis of nanocomposites and nanostructures

No.	Species	Parts of bacteria	Nanocomposites*	Applications	References
1	*Acetobacter xylinum*	Wall cellulose	Ag-BC nanocomposite	Antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*	(Fadakar Sarkandi et al. 2021)
2	*Acetobacter xylinum*	Wall cellulose	BC/MGO nanocomposite	Effective antimicrobial dressing for treating chronic wounds	(Yang et al. 2020)
3	*Achrmobacter* sp. M15	Wall cellulose	BC/TiO_2NPs nanocomposite	Nanocomposite with self-cleaning abilities and strong antimicrobial properties	(Farag et al. 2021)
4	*Gluconacetobacter hansenii* ATCC 23769	Wall cellulose	BC-Cu nanocomposite	Antimicrobial activity	(Araújo et al. 2018)
5	*Gluconacetobacter xylinum* ATCC 10245	Wall cellulose	BC/NBG nanocomposite	Biomedical industries like bone regeneration and wound healing	(Abdelraof et al. 2019)
6	*Gluconacetobacter xylinum*	Wall cellulose	Fe_3O_4/BC nanocomposite	Adsorbs heavy metals such as Pb^{2+}, Mn^{2+}, and Cr^{3+}, sustainable and efficient solution for heavy metal removal	(Zhu et al. 2011)
7	*Komagataeibacter intermedius* MBS-88	Wall cellulose	BC/AgNP nanocomposites	Enhanced antibacterial properties against *Staphylococcus epidermidis* ATCC 2228 and *Staphylococcus aureus*	(Kumar et al. 2023)
8	N/A	Wall cellulose	RBC-ZnO nanocomposite	Biomedical	(Ul-Islam et al. 2014)
9	N/A	Wall cellulose	BC/ZnO nanocomposite	UV-blocking capabilities and displayed antibacterial effects against both Gram-positive and Gram-negative bacteria	(Wahid et al. 2019)
10	N/A	Wall cellulose and bamboo	BC/Fe nanocomposite	An efficient adsorbent for the removal of methylene blue dye from synthetic dye-containing effluents	(Sen 2023)
11	N/A	Polyvinyl alcohol and bacterial cellulose	PVA and BC nanocomposite	Tissue engineering and medical devices	(Millon and Wan 2006)

*BC: bacterial cellulose, MGO: methylglyoxal, NP: nanoparticle, NBG: nanobioactive glass, RBC: regenerated bacterial cellulose, PVA: polyvinyl alcohol

Advantages and disadvantages

BC has advantages over regular cellulose, but as mentioned, its poor yield and restricted bioactivity have prevented its industrial usage. A study aimed to increase BC yield by incorporating nanobioactive glass (NBG) into the production process using the BC-producing strain *G. xylinum* ATCC 10245. The composites were prepared through in situ fermentation, and the effects of NBG addition on cellulose production, biocompatibility, bioactivity, and antimicrobial properties were investigated. The BC/NBG combination offers promise for applications in biomedical industries like bone regeneration and wound healing because of its non-harmful nature to humans (Abdelraof et al. 2019). The presence of a negative charge on the surface of the bacterial cell wall plays a role in the absorption and transport of metal ions and their rapid conversion. In addition, the rapid replication of bacteria and the simple culture medium required for growth and metabolite production are other advantages. In general, the use of bacteria in the green synthesis faces several challenges. Bacteria-mediated green-synthesized NPs mainly have low diversity in size and shape compared to conventional methods, which limits their commercial viability. Also, producing these structures intracellularly has problems such as complex purification processes, which are less common in extracellular synthesis (Alsaiari et al. 2023). Achieving a suitable design for the bioreactor, providing oxygen and necessary nutrients such as carbon, is also another challenge in working with bacteria, especially on an industrial scale (Lin et al. 2013).

Fungi-mediated green synthesis

Since 2001, numerous studies have examined the synthesis of NPs utilizing fungi, with an emphasis on the production of silver NPs both extracellularly and intracellularly (Crisan et al. 2021; Estevez et al. 2020; Mukherjee et al. 2001; Tsivileva et al. 2021). Fungi can create different NPs on their mycelia surfaces, resulting in noticeable color changes in the fungal biomass or culture medium. For example, the change from pink to red can signal the deposition of elemental selenium (Poluboyarinov et al. 2009). In addition to the many secreted or structural compounds of fungi, such as enzymes, proteins, etc., which play a role in the processes of reducing and capping of NPs and nanostructures, today, numerous products in the field of nanomaterials are produced from the extraction of two fungal compounds called chitin and chitosan (Mostafazade et al. 2024). The chitin-glucan complex in the cell wall of fungi makes them a good candidate for preparing structures such as nanopapers. In a study, different parts of *Agaricus bisporus*, such as stalk, cap, and fruiting body, were used for the extraction of chitin-glucan using a mild procedure. Nanopapers were prepared by vacuum filtration and pressing methods, and the generated nanopapers were consolidated in an oven and cooled. This method is a simple method with few steps that gives us homogeneous nanostructures without the need to apply additional modifications. These nanostructures can be used in packaging films and composites with decreased water wettability but increased mechanical strength (Nawawi et al. 2020).

Mechanism of extraction

Extraction of chitin and chitosan is a key element in the production of NCs by fungi. To extract chitin, after washing and cleaning the mushrooms using distilled water, the fungal juice is combined, diluted, heated, and agitated to extract the soluble components. After centrifugation, the gel extract is immersed in sodium hydroxide alkaline solution and agitated at high temperatures to remove proteins, lipids, and alkali-soluble glucan. Then the extract is neutralized and centrifuged again. The neutral gel is suspended in water, blended, and stored at refrigerator temperature. For chitosan, first, the freeze-dried mycelia powder is soaked in sodium hydroxide. Following autoclaving and centrifugation, the resultant pellet is rinsed with water and ethanol, diluted in acetic acid, precipitated with sodium hydroxide, and freeze-dried to generate fungal chitosan (John Kasongo et al. 2020; Nafary et al. 2023). Also, today there are many other methods for extracting chitin and chitosan from biological systems, such as chemical (demineralization, deproteination, and solvation in ionic liquids) and biological (enzymatic and fermentation) methods (Kozma et al. 2022).

In green synthesis processes, minor changes in the reaction conditions, such as changes in salt concentration, temperature, pH, and the presence of external factors such as gamma radiation, lead to widespread changes in the final product (Mostafazade et al. 2024). This change is justified by the fact that metabolite production in fungi is largely dependent on conditions, and slight alterations in the culture medium are effective in upregulation and downregulation of natural product synthesis. New metabolites may even be produced that were not produced in previous cultures (Takahashi et al. 2024).

Species and materials

Similar to previous methods, proteins, enzymes, polysaccharides, flavonoids, alkaloids, phenolic, and organic acids also play a role in the green synthesis of nanomaterials by fungi. Studies show that materials such as cofactor NADH and nitrate reductase enzymes are involved in this matter. This process can also occur extracellularly, intracellularly, or through interaction with fungal cell wall components (Rai et al. 2021). Other studies suggest that compounds with low molecular weight, such as hydroquinone and proteins containing L-cysteine residues, are involved in the processes of reduction or stabilization of metal ions; for example, this is observed in the green synthesis of silver NPs by *Stereum hirsutum* reusable chitosan fungal beads (Hermosilla et al. 2023). Multiple fungal species such as *Agaricus bisporus*, *Pleurotus eryngii*, *Lentinula edodes*, *Grifola frondosa*, *Hypsizygus marmoreus*, *Cunninghamella elegans*, *Saccharomyces cerevisiae, Alternaria alternate*, *Penicillium* sp., *Aspergillus terreus*, *Candida albicans*, *Fusarium avenaceum*, *Metarhizium anisopliae*, *Geotrichum candidum*, and *Fusarium oxysporum* are used in mycofabrication of NCs (Table 3).

Among fungi, endophytes are also very important. Endophytes are primarily symbiotic plants that not only benefit the plant but also offer tremendous potential in the field of metal NP production. Endophytes are capable of producing gold, copper, iron, and other NPs. Endophytic fungi include *Alternaria colitotricum*, *Fusarium*, *Gibberella*, *Glomerella*, *Guignardia Leptosphaerolina*, *Nigrospora*, *Phoma*, *Phomopsis,* and *Xylaria,* which can also be useful in the preparation of NCs (Mostafazade et al. 2024). There are other species of fungi with the ability to produce nanostructures. In one study, various strains of xylotrophic basidiomycetes were tested for growth on liquid media enriched with organic selenium. The effects of 1,5-diphenyl-3-selenopentanedione-1,5 at various concentrations on mycelial growth were studied. Fungal cultures demonstrated promising properties for reducing and stabilizing organic selenide and elemental selenium. As a result, Se-containing bionanocomposites were effectively generated using mycosynthesis (Tsivileva 2019). Table 3 shows the NCs synthesized using the green synthesis method by fungi.

Applications

These NCs are known for their antitumor, anticancer, immunomodulation, antimicrobial, and catalytic activities with infrared thermotherapy, wound dressing, magnetic fluids, pharmaceutical industries, surgical, and bioremediation applications (Mostafazade et al. 2024). For example, in one study, the extracellular cell-free filtrate of *Fusarium oxysporum f. sp. cucumerinum* (FOC) was used to synthesize ZnO/ZnS NC. This NC has antimicrobial and anticancer properties and can also act as a catalytic agent in the degradation of methylene blue dye (Salaheldin et al. 2024). In another study, silver NPs produced by the green synthesis using *Bijerkandra* sp.R1 extracellular culture filtrate were used in the structure of a wound dressing containing carboxymethyl cellulose, which had significant antibacterial effects (Osorio Echavarría et al. 2022). Chitosan itself has superior properties as a non-toxic, recyclable, durable, and economical biopolymer (Azmana et al. 2021). Chitosan-based nanocomposites are important in two ways. Chitosan exhibits some antimicrobial, anticancer, and antioxidant properties. In addition, it has high biodegradability and bioavailability properties, and also has a suitable loading capacity for drug delivery (Abdel-Bary et al. 2020; Mostafa et al. 2023). The combination of all these characteristics alongside the green synthesis shows how potentially useful biological systems are. A researcher can prepare a nanostructure in which the polymer and drug loaded in it are all of natural origin, which may even have synergistic effects when combined (Paul and Deepa 2025). In a study, the green synthesis of a nanocomposite consisting of chitosan, silver, and kaempferol was accompanied by a change in the color of the reaction medium to brown. This material has dose-dependent antibacterial effects and can induce apoptosis in the triple-negative breast cancer cell line (MDA-MB-231) (Bharathi et al. 2023). Figure 2 depicts many applications for fungi-produced NCs.

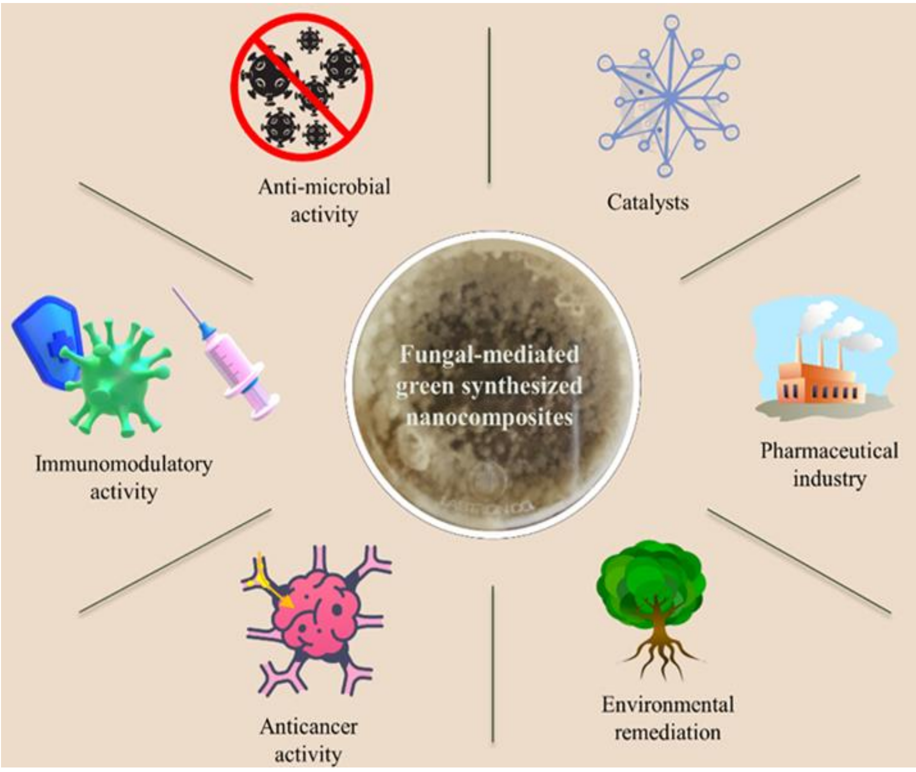

Figure 2. Applications of fungi-derived nanocomposites

Table 2. Fungi-mediated green synthesis of nanocomposites and nanostructures

No.	Species	Parts of fungi	Nanocomposites	Applications	References
1	*Agaricus bisporus*	Whole fungi	Chitin-glucan nanopapers	N/A	(Nawawi et al. 2020)
2	*Agaricus bisporus*	Whole fungi	Chitin nanofibers	Potential antitumor and immuno-modulating activity	(Ifuku et al. 2011)
3	*Alternaria alternata*	Whole fungi	HPMC-γ -Fe_2O_3 nanocomposite film	Potentially applicable in different fields such as magnetic data storage, catalytic activity, magnetic fluids, cancer therapy, etc.	(Sarkar et al. 2017)
4	*Aspergillus terreus*	Whole fungi	Organic–inorganic hybrid nanoflower	Increased antibacterial action, medical applications, cancer therapy, and to overcome drug resistance	(Uras et al. 2023)
5	*Candida albicans*	Mycelium	Chitosan bio-nanocomposites	Cytotoxicity against different tumor cell lines and antimicrobial activities	(El-Sheshtawy et al. 2021)
6	*Chaetomium globosium*	Whole fungi	Chitosan/acrylamide/gold nanocomposite hydrogel	Antibacterial activities against Gram-positive (*Staphylococcus epidermidis* and *Staphylococcus aureus*) and gram-negative (*Pseudomonas aeruginosa*) bacteria	(Oladipo et al. 2024)
7	*Cunninghamella elegans*	Mycelium	Fungal chitosan/*Aloe vera* extract/*Cuscuta reflexa* mediated biosynthesized silver nanoparticles	Wound dressing	(Sathiyaseelan et al. 2017)
8	*Fusarium avenaceum*	Mycelium	Chitosan bio-nanocomposites	Cytotoxicity against different tumor cell lines and antimicrobial activities	(El-Sheshtawy et al. 2021)
9	*Fusarium oxysporum*	Fungal-free extract	[*Fusarium oxysporum*/$Fe_2H_{11}O_{14}$ PS] bio-nanocomposite	Antibacterial against Gram-positive and Gram-negative bacteria and yeast	(Shalaby et al. 2022b)
10	*Geotrichum candidum*	Fungal-free extract	[*Geotrichum candidum*/ Cu_8O_7+P_2O_5] nanocomposite	Antibacterial and anti-fungal	(Shalaby et al. 2022a)
11	*Grifola frondosa*	Whole fungi	Chitin nanofibers	Potential antitumor and immuno-modulating activity	(Ifuku et al. 2011)
12	*Hypsizygus marmoreus*	Whole fungi	Chitin nanofibers	Potential antitumor and immuno-modulating activity	(Ifuku et al. 2011)
13	*Lentinula edodes*	Whole fungi	Chitin nanofibers	Potential antitumor and immuno-modulating activity	(Ifuku et al. 2011)
14	*Metarhizium anisopliae*	Mycelium	Magnetic nanobiocomposite	Environmental remediation and pest control in agriculture	(Chaves et al. 2022)
15	*Penicillium* sp.	Whole fungi	TiNi-TiO_2	Surgical applications	(Reyes et al. 2013)
16	*Pleurotus eryngii*	Whole fungi	Chitin nanofibers	Potential antitumor and immuno-modulating activity	(Ifuku et al. 2011)
17	*Saccharomyces cerevisiae*	Whole fungi	Selenium nanocomposite	Antimicrobial activity	(Hariharan et al. 2012)

Advantages and disadvantages

NP synthesis with eukaryotic microorganisms has emerged as a better alternative to prokaryotes because of their high intracellular uptake capability, ability to synthesize NPs with different chemical compositions, ability to produce a large number of metabolites per unit biomass, and easy biomass handling at the laboratory scale (Hulkoti and Taranath 2014; Priyadarshini et al. 2021; Tsivileva et al. 2021). The use of pathogenic bacteria for nanomaterial synthesis is not encouraged due to potential health concerns to humans, animals, and the environment. Fungi are preferred for large-scale NP synthesis because they grow faster than bacteria and continue to develop even after the NPs are produced. Fungi's mycelium development provides a broad surface area for interactions and aggregation of biopolymers, offering numerous reaction sites for NP production and protection within a shell structure (Pantidos and Horsfall 2014; Su et al. 2021; Taherzadeh et al. 2003; Tsivileva et al. 2021). Fungi and their separated cell fractions are similarly efficient in producing NPs with similar characteristics. They may withstand harmful NP elements, such as heavy metals, at levels much exceeding the allowed limits in contaminated environments (Bhavya et al. 2021; Priyadarshini et al. 2021; Tsivileva et al. 2021). Using them to synthesize NPs is favorable because of their nontoxicity, simplicity of culture, and convenience in handling (Agnihotri et al. 2009; Manzoor-ul-Haq et al. 2015). As a result of their enormous secretion of enzymes and proteins, fungi are particularly cost-effective in the green synthesis (Mostafazade et al. 2024). Green synthesis by fungi is a single-step method. For example, the ZnO-cellulose composite synthesized by *Phanerochaete chrysosporium* is superior in terms of time and cost in the synthesis, coating, etc. steps compared to conventional methods (Sharma et al. 2021). In spite of extensive studies, the precise mechanisms of green synthesis by fungi are still ambiguous, which is essential in understanding and controlling the process. Optimizing reaction conditions for the green synthesis by fungi in terms of factors such as pH, temperature, metal ion concentration, and reaction time is important for uniformizing the synthesized nanomaterials. The heterogeneity problems become even bolder in the transformation from laboratory to industrial scale, where the use of genetically engineered strains in conjunction with bioreactors could potentially help overcome these limitations (Sidhu et al. 2025). The presence of allergenic proteins in fungal species is routine, and human health studies in this area are essential. In addition, it is essential to achieve chitin with high purity, good quality, and desired strength and flexibility compared to conventional synthetic polymers (Nawawi et al. 2019).

Algae-mediated green synthesis

Algae's propensity to absorb metals and decrease metal ions makes them a strong contender for NP biosynthesis, and they are referred to as bio-nano factories since both live and dead dried biomass are used to synthesize metallic NPs. Algae are aquatic filamentous photosynthetic organisms in the plant kingdom that can be classified into two types: microalgae and macroalgae. Microalgae, as primitive microscopic plants, provide substantial advantages as cell factories for NP synthesis compared to larger plants. Microalgae, which account for a major amount of the planet's biodiversity, are primarily single-celled, colony-forming, or filamentous photosynthetic microorganisms with multiple legal divisions, including chlorophyll. Unlike most biomass, both algae can be harvested multiple times in the same year. Algae can also develop without the use of any additional chemicals or fertilizers. Algae are advantageous due to their ease of usage, low toxicity, and minimal environmental impact. Furthermore, the synthesis process can be performed at room temperature and pressure with simple aqueous solutions of neutral pH. Microalgae grow extraordinarily quickly, doubling their bulk ten times faster than larger plants. It is well known that different types of microalgae decrease metal ions (Mukherjee et al. 2021; Shalaby 2011).

Mechanisms

There are three main methods for synthesizing NPs using algae, including direct use of live algae cells for NP synthesis, lysis of algal cells followed by extraction using various downstream process techniques such as centrifugation and filtration, and harvesting of NPs from algal broth supernatants (Dahoumane et al. 2017). NP synthesis can be done using either an extracellular or an intracellular technique, depending on the features of the algae. Polysaccharides, reducing carbohydrates, proteins, peptides, fatty acids, antioxidants, carotenoids, or other reducing and stabilizing substances present in the algal extracts may be responsible for extracellular metallic NP synthesis (Fawcett et al. 2017; Khan et al. 2022; Mukherjee et al. 2021). However, there is no unifying procedure for the green synthesis of metal NPs. As a result, there is current interest in the study of algae-mediated metal NP synthesis, with a focus on determining the effect of reaction variables such as temperature, pH, exposure time, and stirring rate on the final NPs in terms of size, morphology, stability, and so on (Alprol et al. 2023; Chugh et al. 2021).

Species

In the green synthesis process, various types of algae such as *Chlorophyceae*, *Phaeophyceae*, *Cyanophyceae*, and *Rhodophyceae* are used (Chugh et al. 2021). It is interesting to investigate the green synthesis of NPs reduced and stabilized by algae polysaccharides, specifically from the genus *Sargassum*, to determine the economic feasibility of this process, as industrial scalability will be of interest in the near future (Vasquez et al. 2016). In one study, dried edible algae, such as *Spirulina platensis*, were used to synthesize gold, silver, and gold/silver NPs using extracellular pathways. Additionally, studies show extracellular fabrication of metal NPs by *Sargassum wightii* and *Kappaphycus alvarezii*. Also, bioreduction of gold has been accomplished using the biomass of the brown alga, *Fucus vesiculosus*, whereas biosynthesis of gold NPs has been proven utilizing the biomass of red alga, *Chondrus crispus*, and green alga, *Spirogyra insignis* (Mukherjee et al. 2021).

Applications

Algae-mediated biosynthesized NPs have antibacterial, anticancer, and antifungal activities, which are applicable in medicine, optics, cosmetics, and other industries. A study reported that marine red algae, *Gelidium amansii*, could be used in green synthesis processes of silver NPs with antibacterial activity against both Gram-negative and positive bacteria (Pugazhendhi et al. 2018). This antibacterial activity has been reported from other metal NPs synthesized using algal species, such as green synthesized silver NPs by seaweed *Gracilaria birdiae* (de Aragao et al. 2019). In one study, silver NPs were fabricated by an algal extract called *Codium capitatum*, and chitosan NPs were derived from *Aspergillus niger*. This NC had better efficacy in antibacterial studies than either of them separately against drug-resistant *Salmonella* and *Staphylococcus* species. This study shows that combining multiple biological systems (here, fungi and algae) can be useful in the green synthesis of NCs, and the advantages of each system can be utilized in the final product (Alsaggaf et al. 2020).

Discussion

This study emphasizes the increasing importance of green synthesis techniques in the fabrication of NPs and NCs from a variety of biological sources, including plants, bacteria, fungi, and algae. These environmentally friendly procedures reduce the use of toxic chemicals and by-products, and as a result, they overcome the limitations associated with traditional chemical and physical synthesis methods. The antibacterial, anticancer, wound healing, and catalytic activities, alongside advantages such as biocompatibility and safety of green-synthesized nanomaterials, make them interesting candidates for a variety of applications, ranging from environmental remediation to medicine. Each biological system used in the green synthesis has advantages and disadvantages compared to each others in terms of cost, growth conditions, natural compounds, and so on. Plants are rich in diverse compounds with high extractability, which limits their use due to issues such as quality control, standardization of methods, and the presence of impurities. In bacteria, bacterial cellulose is considered a suitable candidate for producing nanocomposites. They replicate rapidly and have a simple culture medium, but they are accompanied by challenges such as the purification of the produced material, safety of use, and maintenance of reaction conditions, such as proper oxygen supply. On the other hand, fungi proliferate easily and cost-effectively, have the ability to secrete compounds, and have a large surface area. Chitin and chitosan are two widely used compounds in this field, but they still have problems such as low reproducibility, allergenic proteins, and minor changes in reaction conditions, such as temperature, pH, etc., have a significant impact on the final product. The use of bioreactors and genetic engineering, especially in relation to bacteria and fungi, can largely solve these problems. In general, fewer studies have been conducted on algae, and their potential for application in the field of green synthesis is less well-known. Finding the most effective methods for producing sustainable nanomaterials can be facilitated by comparing these biological systems and green synthesis pathways. Notwithstanding the encouraging advancements, issues with scalability for industrial production, toxicity and impurity control, and standardization still exist. It is anticipated that future studies will concentrate on improving synthesis conditions to maximize functionality and reduce limitations. In the end, interdisciplinary efforts will be necessary to ensure environmental compliance, safety, and reproducibility when integrating green nanotechnology into industrial practice.

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Conflicts of interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

RM: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. AH: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. MMT: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. MV: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. NM: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. BSFB: Writing–review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Data availability

No data was used for the research described in the article.

Artificial Intelligence (AI)

We have not used any AI tools or technologies to prepare this manuscript except to improve the language and readability in the abstract section (ChatGPT).

References

Abdel-Bary AS, Tolan DA, Nassar MY, Taketsugu T, El-Nahas AM (2020) Chitosan, magnetite, silicon dioxide, and graphene oxide nanocomposites: Synthesis, characterization, efficiency as cisplatin drug delivery, and DFT calculations. Int J Biol Macromol 154:621-633 doi:https://doi.org/10.1016/j.ijbiomac.2020.03.106

Abdelraof M, Hasanin MS, Farag MM, Ahmed HY (2019) Green synthesis of bacterial cellulose/bioactive glass nanocomposites: Effect of glass nanoparticles on cellulose yield, biocompatibility and antimicrobial activity. Int J Biol Macromol 138:975-985 doi:https://doi.org/10.1016/j.ijbiomac.2019.07.144

Abu-Dalo M, Jaradat A, Albiss BA, Al-Rawashdeh NA (2019) Green synthesis of TiO_2 NPs/Pristine pomegranate peel extract nanocomposite and its antimicrobial activity for water disinfection. J Environ Chem Eng 7(5):103-370 doi:https://doi.org/10.1016/j.jece.2019.103370

Adeosun SO, Lawal G, Balogun SA, Akpan EI (2012) Review of green polymer nanocomposites. J Miner and Mater Charact Eng 11(04):3-85 doi:http://dx.doi.org/10.4236/jmmce.2012.114028

Adyani SH, Soleimani E (2019) Green synthesis of Ag/Fe_3O_4/RGO nanocomposites by *Punica Granatum* peel extract: Catalytic activity for reduction of organic pollutants. Int J Hydrogen Energy 44(5):2711-2730 doi:https://doi.org/10.1016/j.ijhydene.2018.12.012

Agnihotri M, Joshi S, Kumar AR, Zinjarde S, Kulkarni S (2009) Biosynthesis of gold nanoparticles by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. Mater Lett 63(15):1231-1234 doi:https://doi.org/10.1016/j.matlet.2009.02.042

Ahmed SF, Mofijur M, Rafa N, et al. (2022) Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. Environ Res 204(Pt A):111967 doi:https://doi.org/10.1016/j.envres.2021.111967

Akintelu SA, Folorunso AS (2020) A review on green synthesis of zinc oxide nanoparticles using plant extracts and its biomedical applications. Bionanoscience 10(4):848-

863 doi:https://doi.org/10.1007/s12668-020-00774-6

Alharthi FA, Alghamdi AA, Al-Zaqri N, et al. (2020) Facile one-pot green synthesis of Ag–ZnO nanocomposites using potato peel and their Ag concentration dependent photocatalytic properties. Sci Rep 10(1):202-229 doi:https://doi.org/10.1038/s41598-020-77426-y

Alprol AE, Mansour AT, Abdelwahab AM, Ashour M (2023) Advances in green synthesis of metal oxide nanoparticles by marine algae for wastewater treatment by adsorption and photocatalysis techniques. Catalysts 13(5):888 doi:https://doi.org/10.3390/catal13050888

Alsaggaf MS, Tayel AA, Alghuthaymi MA, Moussa SH (2020) Synergistic antimicrobial action of phyco-synthesized silver nanoparticles and nano-fungal chitosan composites against drug resistant bacterial pathogens. Biotechnol Biotechnol Equip 34(1):631-639 doi:https://doi.org/10.1080/13102818.2020.1796787

Alsaiari NS, Alzahrani FM, Amari A, et al. (2023) Plant and microbial approaches as green methods for the synthesis of nanomaterials: Synthesis, applications, and future perspectives. Molecules 28(1) doi:https://doi.org/10.3390/molecules28010463

Araújo IMS, Silva RR, Pacheco G, et al. (2018) Hydrothermal synthesis of bacterial cellulose-copper oxide nanocomposites and evaluation of their antimicrobial activity. Carbohydr Polym 179:341-349 doi:https://doi.org/10.1016/j.carbpol.2017.09.081

Atarod M, Nasrollahzadeh M, Sajadi SM (2015) Green synthesis of a Cu/reduced graphene oxide/Fe_3O_4 nanocomposite using *Euphorbia wallichii* leaf extract and its application as a recyclable and heterogeneous catalyst for the reduction of 4-nitrophenol and rhodamine B. RSC Adv 5(111):91532-91543 doi:https://doi.org/10.1039/C5RA17269A

Atarod M, Nasrollahzadeh M, Sajadi SM (2016) *Euphorbia heterophylla* leaf extract mediated green synthesis of Ag/TiO_2 nanocomposite and investigation of its excellent catalytic activity for reduction of variety of dyes in water. J Colloid Interface Sci 462:272-279 doi:https://doi.org/10.1016/j.jcis.2015.09.073

Audtarat S, Hongsachart P, Dasri T, et al. (2022) Green synthesis of silver nanoparticles loaded into bacterial cellulose for antimicrobial application. Nanocomposites 8(1):34-46 doi:https://doi.org/10.1080/20550324.2022.2055375

Azmana M, Mahmood S, Hilles AR, Rahman A, Arifin MAB, Ahmed S (2021) A review on chitosan and chitosan-based bionanocomposites: Promising material for combatting global issues and its applications. Int J Biol Macromol 185:832-848 doi:https://doi.org/10.1016/j.ijbiomac.2021.07.023

Bharathi D, Ranjithkumar R, Nandagopal JGT, Djearamane S, Lee J, Wong LS (2023) Green synthesis of chitosan/silver nanocomposite using kaempferol for triple negative breast cancer therapy and antibacterial activity. Environ Res 238(Pt 1):117109 doi:https://doi.org/10.1016/j.envres.2023.117109

Bhavya G, Belorkar SA, Mythili R, et al. (2021) Remediation of emerging environmental pollutants: A review based on advances in the uses of eco-friendly biofabricated nanomaterials. Chemosphere 275:129975 doi:https://doi.org/10.1016/j.chemosphere.2021.129975

Bhavyasree P, Xavier T (2020) Green gynthesis of copper oxide/carbon nanocomposites using the leaf extract of *Adhatoda vasica* nees, Their characterization and antimicrobial activity. Heliyon 6(2) doi:https://doi.org/10.1016/j.heliyon.2020.e03323

Bordbar M, Negahdar N, Nasrollahzadeh M (2018) *Melissa Officinalis* L. Leaf extract assisted green synthesis of CuO/ZnO nanocomposite for the reduction of 4-nitrophenol and Rhodamine B. Sep Purif Technol 191:295-300 doi:https://doi.org/10.1016/j.seppur.2017.09.044

Chaves TdO, Bini RD, Oliveira Junior VAd, et al. (2022) Fungus-based magnetic nanobiocomposites for environmental remediation. Magnetochemistry 8(11):139 doi:https://doi.org/10.3390/magnetochemi stry8110139

Chokkareddy R, Redhi GG (2018) Green synthesis of metal nanoparticles and its reaction mechanisms. In: Ahmed SKaS (ed) Green Metal Nanoparticles: Synthesis, Characterization and Their Applications. p 113-139

Chugh D, Viswamalya V, Das B (2021) Green synthesis of silver nanoparticles with algae and the importance of capping agents in the process. J Genet Eng Biotechnol 19(1):126 doi:https://doi.org/10.1186/s43141-021-00228-w

Crisan CM, Mocan T, Manolea M, Lasca LI, Tăbăran F-A, Mocan L (2021) Review on silver nanoparticles as a novel class of antibacterial solutions. Appl Sci 11(3):1120 doi:https://doi.org/10.3390/app11031120

Cuong HN, Pansambal S, Ghotekar S, et al. (2022) New frontiers in the plant extract mediated biosynthesis of copper oxide (CuO) nanoparticles and their potential applications: A review. Environ Res 203:111-858 doi:https://doi.org/10.1016/j.envres.2021.111858

Dahoumane SA, Mechouet M, Wijesekera K, et al. (2017) Algae-mediated biosynthesis of inorganic nanomaterials as a promising route in nanobiotechnology–a review. Green Chem 19(3):552-587 doi:https://doi.org/10.1039/C6GC02346K

Das TR, Sharma PK (2020) Hydrothermal-assisted green synthesis of Ni/Ag@rGO nanocomposite using *Punica granatum* juice and electrochemical detection of ascorbic acid. Microchem J 156:104-850 doi:https://doi.org/10.1016/j.microc.2020.104850

de Aragao AP, de Oliveira TM, Quelemes PV, et al. (2019) Green synthesis of silver nanoparticles using the seaweed *Gracilaria birdiae* and their antibacterial activity. Arab J Chem 12(8):4182-4188 doi:https://doi.org/10.1016/j.arabjc.2016.04.014

Desouky MM, Abou-Saleh RH, Moussa TAA, Fahmy HM (2025) Nano-chitosan-coated, green-synthesized selenium nanoparticles as a novel antifungal agent against *Sclerotinia sclerotiorum*: in vitro study. Sci Rep 15(1):1004 doi:https://doi.org/10.1038/s41598-024-79574-x

Ebrahimi F, Nouraei M, Seyfi A (2022) Wave dispersion characteristics of thermally excited graphene oxide powder-reinforced nanocomposite plates. Waves Random Complex Media 32(1):204-232 doi:https://doi.org/10.1080/17455030.2020.1767829

El-Seedi HR, El-Shabasy RM, Khalifa SA, et al. (2019) Metal nanoparticles fabricated by green chemistry using natural extracts: Biosynthesis, mechanisms, and applications. RSC Adv 9(42):24539-24559 doi:https://doi.org/10.1039/C9RA02225B

El-Sheshtawy H, Hefni H, Aboutaleb WA, Elaasser M, Mady M, El-Shiekh H (2021) Green synthesis of chitosan bio-nanocomposites and investigation of their antimicrobial and antitumor effects. Iran J Sci Technol Trans A Sci 45:1247-1261 doi:https://doi.org/10.1007/s40995-021-01147-8

Esa F, Tasirin SM, Abd Rahman N (2014) Overview of bacterial cellulose production and application. Agric Agric Sci Procedia 2:113-119 doi:https://doi.org/10.1016/j.aaspro.2014.11.017

Estevez MB, Raffaelli S, Mitchell SG, Faccio R, Alborés S (2020) Biofilm eradication using biogenic silver nanoparticles. Molecules 25(9):2023 doi:https://doi.org/10.3390/molecules25092023

Fadakar Sarkandi A, Montazer M, Harifi T, Mahmoudi Rad M (2021) Innovative preparation of bacterial cellulose/silver nanocomposite hydrogels: In situ green synthesis, characterization, and antibacterial properties. J Appl Polym Sci 138(6):49-824 doi:https://doi.org/10.1002/app.49824

Farag S, Amr A, El-Shafei A, Asker MS, Ibrahim HM (2021) Green synthesis of titanium dioxide nanoparticles via bacterial cellulose (BC) produced from agricultural wastes. Cellulose 28(12):7619-7632 doi:https://doi.org/10.1007/s10570-021-04011-5

Fawcett D, Verduin JJ, Shah M, Sharma SB, Poinern GEJ (2017) A review of current research into the biogenic synthesis of metal and metal oxide nanoparticles via marine algae and seagrasses. J Nanosci 2017(1):8013850 doi:https://doi.org/10.1155/2017/8013850

Fazly Bazzaz BS, Haririzadeh G, Imami SA, Rashed MH (1997) Survey of Iranian plants for alkaloids, flavonoids, saponins, and tannins [Khorasan Province]. Int J Pharmacogn 35(1):17-30 doi:https://doi.org/10.1076/phbi.35.1.17.13275

Ghaffari-Moghaddam M, Hadi-Dabanlou R, Khajeh M, Rakhshanipour M, Shameli K (2014) Green synthesis of silver nanoparticles using plant extracts. Korean J Chem Eng 31:548-557 doi:https://doi.org/10.1007/s11814-014-0014-6

Hariharan H, Al-Harbi N, Karuppiah P, Rajaram S (2012) Microbial synthesis of selenium nanocomposite using *Saccharomyces cerevisiae* and its antimicrobial activity against pathogens causing nosocomial infection. Chalcogenide Lett 9(12):509-515 doi:[cited 2025 Feb 25]. https://www.chalcogen.ro/509_Hariharan.pdf

Hermosilla E, Díaz M, Vera J, et al. (2023) Synthesis of antimicrobial chitosan-silver nanoparticles mediated by reusable chitosan fungal beads. Int J Mol Sci 24(3):2318 doi:https://doi.org/10.3390/ijms24032318

Hormozi-Moghaddam Z, Neshasteh-Riz A, Amini SM, et al. (2024) Investigating the effect of low-intensity ultrasound radiation in the presence of Apigenin-coated gold nanoparticles on the expression of mRNAs affecting the apoptosis of MCF7 breast cancer cells. Food Biosci 57:103486 doi:https://doi.org/10.1016/j.fbio.2023.103486

Hulkoti NI, Taranath T (2014) Biosynthesis of nanoparticles using microbes—a review. Colloids Surf B Biointerfaces 121:474-483 doi:https://doi.org/10.1016/j.colsurfb.2014.05.027

Ifuku S, Nomura R, Morimoto M, Saimoto H (2011) Preparation of chitin nanofibers from mushrooms. Materials 4(8):1417-1425 doi:https://doi.org/10.3390/ma4081417

Ijaz I, Gilani E, Nazir A, Bukhari A (2020) Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. Green Chem Lett Rev 13(3):223-245 doi:https://doi.org/10.1080/17518253.2020.1802517

John Kasongo K, Tubadi DJ, Bampole LD, Kaniki TA, Kanda NJM, Lukumu ME (2020) Extraction and characterization of chitin and chitosan from *termitomyces titanicus*. SN Appl Sci 2(3):406 doi:https://doi.org/10.1007/s42452-020-2186-5

Kashid Y, Ghotekar S, Bilal M, et al. (2022) Bio-inspired sustainable synthesis of silver chloride nanoparticles and their prominent applications. J Indian Chem Soc 99(5):100-335 doi:https://doi.org/10.1016/j.jics.2021.100335

Khan F, Shahid A, Zhu H, et al. (2022) Prospects of algae-based green synthesis of nanoparticles for environmental applications. Chemosphere 293:133571 doi:https://doi.org/10.1016/j.chemosphere.2022.133571

Kozma M, Acharya B, Bissessur R (2022) Chitin, chitosan, and nanochitin: extraction, synthesis, and applications. Polymers 14(19):3989 doi:https://doi.org/10.3390/polym14193989

Kumar M, Dhiman SK, Bhat R, Saran S (2023) In situ green synthesis of AgNPs in bacterial cellulose membranes and antibacterial properties of the composites against pathogenic bacteria. Polym Bull:1-22 doi:https://doi.org/10.1007/s00289-023-05046-3

Lin S-P, Loira Calvar I, Catchmark JM, Liu J-R, Demirci A, Cheng K-C (2013) Biosynthesis, production and applications of bacterial cellulose. Cellulose 20(5):2191-2219 doi:https://doi.org/10.1007/s10570-013-9994-3

Manzoor-ul-Haq VR, Singh D, Singh AK, Ninganagouda S, Hiremath J (2015) Dried mushroom agaricus bisporus mediated synthesis of silver nanoparticles from Bandipora district (Jammu and Kashmir) and their efficacy against methicillin resistant *Staphylococcus aureus* (MRSA) strains. Nanosci Nanotechnol Int J 5:1-8 doi:[cited 2025 Feb 25]. https://www.researchgate.net/profile/Ashish-Kumar-Chatrapati/publication/276284396_Dried_Mushroom_Agaricus_bisporus_mediated_ synthesis_of_silver_nanoparticles_from_Bandipora_District_Jammu_and_Kashmir_and_their_efficacy_against_Methicillin_Resistant_Staphylococcus_aureus_MRSA_strain/links/5555cf5908ae6fd2d821fdce/Dried-Mushroom-Agaricus-bisporus-mediated-synthesis-of-silver-nanoparticles-from-Bandipora-District-Jammu-and-Kashmir-and-their-efficacy-against-Methicillin-Resistant-Staphylococcus-aureus-MRSA-strain.pdf

Marslin G, Siram K, Maqbool Q, et al. (2018) Secondary metabolites in the green synthesis of metallic nanoparticles. Materials (Basel) 11(6) doi:https://doi.org/10.3390/ma11060940

Matinise N, Kaviyarasu K, Mongwaketsi N, et al. (2018) Green synthesis of novel zinc iron oxide ($ZnFe_2O_4$) nanocomposite via *Moringa oleifera* natural extract for electrochemical applications. Appli Surf Sci 446:66-73 doi:https://doi.org/10.1016/j.apsusc.2018.02.187

Matussin S, Harunsani MH, Tan AL, Khan MM (2020) Plant-extract-mediated SnO_2 nanoparticles: Synthesis and applications. ACS Sustainable Chem Eng 8(8):3040-3054 doi:https://doi.org/10.1021/acssuschemeng.9b06398

Mazayen ZM, Ghoneim AM, Elbatanony RS, Basalious EB, Bendas ER (2022) Pharmaceutical nanotechnology: from the bench to the market. Pharm Nanotechnol 8(1):12 doi:https://doi.org/10.1186/s43094-022-00400-0

Millon LE, Wan WK (2006) The polyvinyl alcohol-bacterial cellulose system as a new nanocomposite for biomedical applications. J Biomed Mater Res B Appl Biomater 79(2):245-253 doi:https://doi.org/10.1002/jbm.b.30535

Mohammadi-Aloucheh R, Habibi-Yangjeh A, Bayrami A, Latifi-Navid S, Asadi A (2018) Green synthesis of ZnO and ZnO/CuO nanocomposites in *Mentha longifolia* leaf extract: Characterization and their application as anti-bacterial agents. J Mater Sci Mater Electron 29:13596-13605 doi:https://doi.org/10.1007/s10854-018-9487-0

Mohammadi E, Amini SM, Mostafavi SH, Amini SM (2021) An overview of antimicrobial efficacy of curcumin-silver nanoparticles. Nanomed Res J 6(2):105-111 doi:https://doi.org/10.22034/nmrj.2021.02.002

Mondal P, Anweshan A, Purkait MK (2020) Green synthesis and environmental application of iron-based nanomaterials and nanocomposite: A review. Chemosphere 259 doi:https://doi.org/10.1016/j.chemosphere.2020.127509

Mostafa MA, Ismail MM, Morsy JM, Hassanin HM, Abdelrazek MM (2023) Synthesis, characterization, anticancer, and antioxidant activities of chitosan Schiff bases bearing quinolinone or pyranoquinolinone and their silver nanoparticles derivatives. Polym Bull 80(4):4035-4059 doi:https://doi.org/10.1007/s00289-022-04238-7

Mostafazade R, Arabi L, Tazik Z, Akaberi M, Fazly Bazzaz BS (2024) Fungal endophytes: Treasure trove for green synthesis of metallic nanoparticles and their biological applications. Biocatal Agric Biotechnol 60:103307 doi:https://doi.org/10.1016/j.bcab.2024.103307

Motafeghi F, Gerami M, Mortazavi P, Khayambashi B, Ghasemi-Barghi N, Shokrzadeh M (2023) Green synthesis of silver nanoparticles, graphene, and silver-graphene nanocomposite using *Melissa officinalis* ethanolic extract: anticancer effect on MCF-7 cell line. Iran J Basic Med Sci 26(1):57-68 doi:https://doi.org/10.22038/IJBMS.2022.65503.14410

Mukherjee A, Sarkar D, Sasmal S (2021) A review of green synthesis of metal nanoparticles using algae. Front Microbiol 12 doi:https://doi.org/10.3389/fmicb.2021.693899

Mukherjee P, Ahmad A, Mandal D, et al. (2001) Fungus-mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: A novel biological approach to nanoparticle synthesis. Nano Lett 1(10):515-519 doi:https://doi.org/10.1021/nl0155274

Nadaroglu H, Güngör AA, Ince S (2017) Synthesis of nanoparticles by green synthesis method. Int J Innov Res Rev 1(1):6-9 doi:[cited 2025 Feb 25]. https://www.injirr.com/article/view/4

Nafary A, Mousavi Nezhad SA, Jalili S (2023) Extraction and characterization of chitin and chitosan from *Tenebrio molitor* beetles and investigation of its antibacterial effect against *Pseudomonas aeruginosa*. Adv Biomed Res 12:96 doi:https://doi.org/10.4103/abr.abr_205_22

Nasrollahzadeh M, Issaabadi Z, Sajadi SM (2018a) Green synthesis of a Cu/MgO sanocomposite by *Cassytha filiformis* L. extract and investigation of its catalytic activity in the reduction of methylene blue, congo red and nitro compounds in aqueous media. RSC Adv 8(7):3723-3735 doi:https://doi.org/10.1039/C7RA13491F

Nasrollahzadeh M, Issaabadi Z, Sajadi SM (2018b) Green synthesis of Pd/Fe_3O_4 nanocomposite using *Hibiscus tiliaceus* L. extract and its application for reductive catalysis of Cr (VI) and nitro compounds. Sep Purif Technol 197:253-260 doi:https://doi.org/10.1016/j.seppur.2018.01.010

Nawawi WM, Jones M, Murphy RJ, Lee K-Y, Kontturi E, Bismarck A (2019) Nanomaterials derived from fungal sources—is it the new hype? Biomacromol 21(1):30-55 doi:https://doi.org/10.1021/acs.biomac.9b01141

Nawawi WMFW, Lee K-Y, Kontturi E, Bismarck A, Mautner A (2020) Surface properties of chitin-glucan nanopapers from *Agaricus bisporus*. Int J Biol Macromol 148:677-687 doi:https://doi.org/10.1016/j.ijbiomac.2020.01.141

Neshastehriz A, Amini SM, Mohammadi A, Mahdavi SR, Mahabadi VP, Akbari A (2020) In-vitro investigation of green synthesized gold nanoparticle's role in combined photodynamic and radiation therapy of cancerous cells. Adv Nat Sci Nanosci Nanotechnol 11(4):045006 doi:https://doi.org/10.1088/2043-6254/abb8c7

Oladipo A, Kpomah B, Ejeromedoghene O, et al. (2024) Facile fabrication and antibacterial properties of chitosan/acrylamide/gold nanocomposite hydrogel incorporated with *Chaetomium globosium* extracts from *Gingko biloba* leaves. Int J Biol Macromol 255:128-194 doi:https://doi.org/10.1016/j.ijbiomac.2023.128194

Omanović-Mikličanin E, Badnjević A, Kazlagić A, Hajlovac M (2020) Nanocomposites: A brief review. Health Technol 10(1):51-59 doi:https://doi.org/10.1007/s12553-019-00380-x

Osorio Echavarría J, Gómez Vanegas NA, Orozco CPO (2022) Chitosan/carboxymethyl cellulose wound dressings supplemented with biologically synthesized silver nanoparticles from the ligninolytic fungus Anamorphous *Bjerkandera* sp. R1. Heliyon 8(9):e10258 doi:https://doi.org/10.1016/j.heliyon.2022.e10258

Pandit C, Roy A, Ghotekar S, et al. (2022) Biological agents for synthesis of nanoparticles and their applications. J King Saud Univ Sci 34(3):101869 doi:https://doi.org/10.1016/j.jksus.2022.101869

Pantidos N, Horsfall LE (2014) Biological synthesis of metallic nanoparticles by bacteria, fungi and plants. J Nanomed Nanotechnol 5(5):1 doi:http://dx.doi.org/10.4172/2157-7439.1000233

Paul S, Deepa MK (2025) Investigation of the synergistic antibacterial properties of a gel formulated from green-synthesized chitosan-coated copper oxide nanocomposite. J Pharm Innov 20(2):60 doi:https://doi.org/10.1007/s12247-025-09933-2

Poluboyarinov P, Vikhreva V, Leshchenko P, Aripovskii A, Likhachev A (2009) Elemental selenium formation upon destruction of the organoselenium compound DAFS-25 molecule by growing fungal mycelium. Moscow Univ Biol Sci Bull 64:164-168 doi:https://doi.org/10.3103/S0096392509040075

Priyadarshini E, Priyadarshini SS, Cousins BG, Pradhan N (2021) Metal-fungus interaction: Review on cellular processes underlying heavy metal detoxification and synthesis of metal nanoparticles. Chemosphere 274:129976 doi:https://doi.org/10.1016/j.chemosphere.2021.129976

Pugazhendhi A, Prabakar D, Jacob JM, Karuppusamy I, Saratale RG (2018) Synthesis and characterization of silver nanoparticles using *Gelidium amansii* and its antimicrobial property against various pathogenic bacteria. Microb Pathog 114:41-45 doi:https://doi.org/10.1016/j.micpath.2017.11.013

Qiu K, Netravali AN (2014) A review of fabrication and applications of bacterial cellulose based nanocomposites. Polym Rev 54(4):598-626 doi:https://doi.org/10.1080/15583724.2014.896018

Rai M, Bonde S, Golinska P, et al. (2021) Fusarium as a novel fungus for the synthesis of nanoparticles: mechanism and applications. J Fungi 7(2):139 doi:https://doi.org/10.3390/jof7020139

Rajabi O, Fazly Bazzaz BS, Vaseghi AR, Salari R (2011) Standardizing the bactericidal activities of silver nanoparticles made by electrochemical reduction and comparing it with deconex 53 instrument. Iran J Pharm Res 10(3):481-7 doi:https://doi.org/10.22037/ijpr.2011.1006

Revin VV, Liyaskina EV, Parchaykina MV, et al. (2022) Bacterial cellulose-based polymer nanocomposites: A review. Polymers 14(21):4670 doi:https://doi.org/10.3390/polym14214670

Reyes L, Cavazos J, Garza T, Gómez I Biological synthesis of TiNi-TiO_2 nanocomposite and their characterization. In: Proceedings of the World Congress on Engineering, 2013. vol 3. p 2043-2046

Rezvani Amin Z, Khashyarmanesh Z, Fazly Bazzaz BS (2016) Different behavior of *Staphylococcus Epidermidis* in intracellular biosynthesis of silver and cadmium sulfide nanoparticles: More stability and lower toxicity of extracted nanoparticles. World J Microbiol Biotechnol 32:1-11 doi:https://doi.org/10.1007/s11274-016-2110-8

Rezvani Amin Z, Khashyarmanesh Z, Fazly Bazzaz BS, Sabeti Noghabi Z (2019) Does biosynthetic silver nanoparticles are more stable with lower toxicity than their synthetic counterparts? Iran J Pharm Res 18(1):2-10 doi:[cited 2025 Feb 25]. https://pmc.ncbi.nlm.nih.gov/articles/PMC6487435/#:~:text=The%20results%20confirmed%20lower%20toxicity,for%20being%20employed%20as%20biosensors.

Sajjadi M, Nasrollahzadeh M, Sajadi SM (2017) Green synthesis of Ag/Fe_3O_4 nanocomposite using *Euphorbia peplus Linn* leaf extract and evaluation of its catalytic activity. J Colloid Interface Sci 497:1-13 doi:https://doi.org/10.1016/j.jcis.2017.02.037

Salaheldin H, Aboelnga A, Elsayed A (2024) Mycosynthesis of zinc sulfide/zinc oxide nanocomposite using *Fusarium oxysporum* for catalytic degradation of methylene blue dye, antimicrobial, and anticancer activities. Sci Rep 14(1):32165 doi:https://doi.org/10.1038/s41598-024-81855-4

Salarbashi D, Noghabi MS, Bazzaz BSF, Shahabi-Ghahfarrokhi I, Jafari B, Ahmadi R (2017) Eco-friendly soluble soybean polysaccharide/nanoclay Na^+ bionanocomposite: Properties and characterization. Carbohydr Polym 169:524-532 doi:https://doi.org/10.1016/j.carbpol.2017.04.011

Salarbashi D, Tafaghodi M, Bazzaz BSF (2018a) Soluble soybean polysaccharide/TiO_2 bionanocomposite film for food application. Carbohydr Polym 186:384-393 doi:https://doi.org/10.1016/j.carbpol.2017.12.081

Salarbashi D, Tafaghodi M, Bazzaz BSF, Bazeli J (2018b) Characterization of a green nanocomposite prepared from soluble soy bean polysaccharide/cloisite 30B and evaluation of its toxicity. Int J Biol Macromol 120:109-118 doi:https://doi.org/10.1016/j.ijbiomac.2018.07.183

Salarbashi D, Tafaghodi M, Bazzaz BSF, Jafari B (2018c) Characterization of soluble soybean (SSPS) polysaccharide and development of eco-friendly SSPS/TiO_2 nanoparticle bionanocomposites. Int J Biol Macromol 112:852-861 doi:https://doi.org/10.1016/j.ijbiomac.2018.01.182

Samadian H, Vahidi R, Salehi M, et al. (2023) Hydrogel nanocomposite based on alginate/zeolite for burn wound healing: In vitro and in vivo study. Iran J Basic Med Sci 26(6):708 doi:https://doi.org/10.22038/IJBMS.2023.68897.15016

Sarkar J, Mollick MMR, Chattopadhyay D, Acharya K (2017) An eco-friendly route of γ-Fe_2O_3 nanoparticles formation and investigation of the mechanical properties of the HPMC-γ-Fe_2O_3 nanocomposites. Bioprocess Biosyst Eng 40:351-359 doi:https://doi.org/10.1007/s00449-016-1702-x

Sathiyaseelan A, Shajahan A, Kalaichelvan P, Kaviyarasan V (2017) Fungal chitosan based nanocomposites sponges—an alternative medicine for wound dressing. Int J Biol Macromol 104:1905-1915 doi:https://doi.org/10.1016/j.ijbiomac.2017.03.188

Sen TK (2023) Application of synthesized biomass bamboo charcoal–iron oxide “BC/Fe” nanocomposite adsorbents in the removal of cationic methylene blue dye contaminants from wastewater by adsorption. Sustainability 15(11):8841 doi:https://doi.org/10.3390/su15118841

Shah N, Ul-Islam M, Khattak WA, Park JK (2013) Overview of bacterial cellulose composites: A multipurpose advanced material. Carbohydr Polym 98(2):1585-98 doi:https://doi.org/10.1016/j.carbpol.2013.08.018

Shalaby EA (2011) Algae as promising organisms for environment and health. Plant Signal Behav 6(9):1338-50 doi:https://doi.org/10.4161/psb.6.9.16779

Shalaby MG, Al-Hossainy AF, Abo-Zeid AM, Mobark H, Darwesh OM, Mahmoud YA-G (2022a) *Geotrichum candidum* mediated [Cu_8O_7+ P_2O_5] nanocomposite bio fabrication, characterization, physicochemical properties, and its in-vitro biocompatibility evaluation. J Inorg Organomet Polym Mater 32(7):18-1 doi:http://dx.doi.org/10.1007/s10904-022-02252-w

Shalaby MG, Al-Hossainy AF, Abo-Zeid AM, Mobark H, Mahmoud YA (2022b) Synthesis, characterization, physicochemical properties, and in-vitro anti-bacterial evaluation for doped *Fe-Fusarium oxysporum* bio-nanocomposite. J Mol Struct 1259:132643 doi:https://doi.org/10.1016/j.molstruc.2022.132643

Sharma JL, Dhayal V, Sharma RK (2021) White-rot fungus mediated green synthesis of zinc oxide nanoparticles and their impregnation on cellulose to develop environmental friendly antimicrobial fibers. 3 Biotech 11(6):269 doi:https://doi.org/10.1007/s13205-021-02840-6

Sidhu AK, Agrawal SB, Verma N, Kaushal P, Sharma M (2025) Fungal-mediated synthesis of multimetallic nanoparticles: mechanisms, unique properties, and potential applications. Front Nanotechnol 7:1549713 doi:https://doi.org/10.3389/fnano.2025.1549713

Singh H, Desimone MF, Pandya S, et al. (2023) Revisiting the green synthesis of nanoparticles: Uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications. Int J Nanomed 18:4727-4750 doi:https://doi.org/10.2147/ijn.S419369

Singh P, Mijakovic I (2024) Harnessing barley grains for green synthesis of gold and silver nanoparticles with antibacterial potential. Discov Nano 19(1):101 doi:https://doi.org/10.1186/s11671-024-04042-4

Slathia S, Gupta T, Chauhan R (2021) Green synthesis of Ag–ZnO nanocomposite using *Azadirachta indica* leaf extract exhibiting excellent optical and electrical properties. Physica B Condens Matt 621:413287 doi:https://doi.org/10.1016/j.physb.2021.413287

Sreedharan SM, Singh SP, Singh R (2019) Flower shaped gold nanoparticles: Biogenic synthesis strategies and characterization. Indian J Microbiol 59(3):321-327 doi:https://doi.org/10.1007/s12088-019-00804-2

Su Y, Chen L, Yang F, Cheung PC (2021) Beta-d-glucan-based drug delivery system and its potential application in targeting tumor associated macrophages. Carbohydr Polym 253:117258 doi:https://doi.org/10.1016/j.carbpol.2020.117258

Taherzadeh MJ, Fox M, Hjorth H, Edebo L (2003) Production of mycelium biomass and ethanol from paper pulp sulfite liquor by *Rhizopus oryzae*. Bioresour Technol

88(3):167-177 doi:https://doi.org/10.1016/S0960-8524(03)00010-5

Tajbakhsh M, Alinezhad H, Nasrollahzadeh M, Kamali TA (2016) Green synthesis of the Ag/HZSM-5 nanocomposite by using *Euphorbia heterophylla* leaf extract: A recoverable catalyst for reduction of organic dyes. J Alloys Compd 685:258-265 doi:https://doi.org/10.1016/j.jallcom.2016.05.278

Takahashi JA, de Queiroz LL, Vidal DM (2024) A close view of the production of bioactive fungal metabolites mediated by chromatin modifiers. Molecules 29(15) doi:https://doi.org/10.3390/molecules29153536

Tsivileva O (2019) Eco-friendly-made selenium products of mushroom origin for use in agriculture. Teor Prikl Ekol(4):6-14 doi:https://doi.org/10.25750/1995-4301-2019-4-006-014

Tsivileva O, Pozdnyakov A, Ivanova A (2021) Polymer nanocomposites of selenium biofabricated using fungi. Molecules 26(12):3657 doi:https://doi.org/10.3390/molecules26123657

Ul-Islam M, Khattak WA, Ullah MW, Khan S, Park JK (2014) Synthesis of regenerated bacterial cellulose-zinc oxide nanocomposite films for biomedical applications. Cellulose 21(1):433-447 doi:https://doi.org/10.1007/s10570-013-0109-y

Ullah H, Wahid F, Santos HA, Khan T (2016) Advances in biomedical and pharmaceutical applications of functional bacterial cellulose-based nanocomposites. Carbohydr Polym 150:330-352 doi:https://doi.org/10.1016/j.carbpol.2016.05.029

Uras IS, Karsli B, Konuklugil B, Ocsoy I, Demirbas A (2023) Organic–inorganic nanocomposites of *Aspergillus terreus* extract and its compounds with antimicrobial properties. Sustainability 15(5):4638 doi:https://doi.org/10.3390/su15054638

Vasquez RD, Apostol JG, de Leon JD, et al. (2016) Polysaccharide-mediated green synthesis of silver nanoparticles from *Sargassum siliquosum* J.G. Agardh: Assessment of toxicity and hepatoprotective activity. OpenNano 1:16-24 doi:https://doi.org/10.1016/j.onano.2016.03.001

Vijayaram S, Razafindralambo H, Sun Y-Z, et al. (2024) Applications of green synthesized metal nanoparticles—a review. Biol Trace Elem Res 202(1):360-386 doi:https://doi.org/10.1007/s12011-023-03645-9

Wahid F, Duan Y-X, Hu X-H, et al. (2019) A facile construction of bacterial cellulose/ZnO nanocomposite films and their photocatalytic and antibacterial properties. Int J Biol Macromol 132:692-700 doi:https://doi.org/10.1016/j.ijbiomac.2019.03.240

Wang J, Tavakoli J, Tang Y (2019) Bacterial cellulose production, properties and applications with different culture methods–a review. Carbohydr Polym 219:63-76 doi:https://doi.org/10.1016/j.carbpol.2019.05.008

Wang L, Karmakar B, Al-Saeed FA, Bani-Fwaz MZ, El-kott AF (2022) Green synthesis of Ag/Fe_3O_4 nanoparticles using *Mentha longifolia* flower extract: Evaluation of its antioxidant and anti-lung cancer effects. Heliyon 8(12) doi:https://doi.org/10.1016/j.heliyon.2022.e12326

Winey KI, Vaia RA (2007) Polymer nanocomposites. MRS Bull 32(4):314-322 doi:https://doi.org/10.1557/mrs2007.229

Xiao J, Wang W, Huang Q, Li Y (2019) Edible delivery systems based on favorable interactions for encapsulation of phytochemicals. In: Melton L, Shahidi F, Varelis P (eds) Encyclopedia of Food Chemistry. Academic Press, Oxford, p 727-732

Yang M, Ward J, Choy KL (2020) Nature-inspired bacterial cellulose/methylglyoxal (BC/MGO) nanocomposite for broad-spectrum antimicrobial wound dressing. Macromol Biosci 20(8):2000070 doi:https://doi.org/10.1002/mabi.202000070

Ying S, Guan Z, Ofoegbu PC, et al. (2022) Green synthesis of nanoparticles: Current developments and limitations. Environ Technol Innov 26:102336 doi:https://doi.org/10.1016/j.eti.2022.102336

Yulizar Y, Bakri R, Apriandanu DOB, Hidayat T (2018) ZnO/CuO nanocomposite prepared in one-pot green synthesis using seed bark extract of *Theobroma cacao*. Nano-Struct Nano-Objects 16:300-305 doi:https://doi.org/10.1016/j.nanoso.2018.09.003

Zeng H, Du XW, Singh SC, et al. (2012) Nanomaterials via laser ablation/irradiation in liquid: A review. Adv Funct Mater 22(7):1333-1353 doi:https://doi.org/10.3390/ma15175925

Zhang T, Wang W, Zhang D, et al. (2010) Biotemplated synthesis of gold nanoparticle–bacteria cellulose nanofiber nanocomposites and their application in biosensing. Adv Funct Mater 20(7):1152-1160 doi:https://doi.org/10.1002/adfm.200902104

Zhu H, Jia S, Wan T, et al. (2011) Biosynthesis of spherical Fe_3O_4/bacterial cellulose nanocomposites as adsorbents for heavy metal ions. Carbohydr Polym 86(4):1558-1564 doi:https://doi.org/10.1016/j.carbpol.2011.06.061