PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 10(4): 97–104
https://doi.org/10.14719/pst.2373

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REVIEW ARTICLE

Biogenesis of nanoparticles using microorganisms: A Review

Anjum Singhal, Pooja Baweja, Sandhya Gupta, Haritma Chopra & Pinkey Bajaj Gandhi*

Maitreyi College, University of Delhi, Delhi - 110021, India

*Email: pbajaj@maitreyi.du.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 22 January 2023
Accepted: 11 May 2023
Available online
Version 1.0 : 14 August 2023
Version 2.0 : 01 October 2023

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS,UGC Care etc. See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Singhal A, Baweja P, Gupta S, Chopra H, Gandhi P J. Biogenesis of nanoparticles using microorganisms: A Review. Plant Science Today. 2023; 10(4): 97–104. https://doi.org/10.14719/pst.2373

Abstract

Bionanoparticles are synthesized using novel strategies through environmentally benign approaches. Emphasis is on synthesizing nanoparticles using green chemistry principles to reduce the burden of pollution on the environment. The biological approach for the synthesis of metallic nanoparticles is also described as green synthesis (bioprocess) of nanoparticles, is now being looked at as an alternative to physio-chemical approaches and generally uses biological components like plants and microbes (bacteria, fungi, algae and yeast) and cause minimal harm to the nature. The naturally occurring potential biodegradable agents like enzymes (secreted by microbes) act as reducing agents and play a very distinct role in the synthesis of nanoparticles. Most bioprocesses occur under normal air pressure and temperature, resulting in vast energy savings and reducing the use of expensive chemicals making the green approach less costly. This process of synthesis of nanoparticles using biological systems is referred to as nanobiotechnology. Nanobiotechnology has emerged as an integration between biotechnology and nanotechnology for developing biosynthetic and environmentally friendly technology for nanoparticle synthesis. This review is mainly focused on the microbial synthesis of nanoparticles utilizing the extract of bacteria and algae. In the present review, the bio-reduction capacity of various bacteria and algae is highlighted in detail, which has yet to be discussed earlier. This is a comprehensive work underlining the synthesis of nanoparticles, their bio-reduction ability, and application of nanoparticles.

Keywords

bionanoparticles, bacteria, algae, biosynthesis, microbes

Introduction

The ever-increasing pollution in today's world has necessitated using environment-friendly technologies for nanoparticle production and to reduce the various environmental hazards in the process (1). Nanotechnology involves the synthesis of particles at the molecular level and characterization along with their application in various fields (2). The use of green technology to synthesize nanoparticles is needed in today's world. Here, bionanoparticles are synthesized using biological/green products, proving the process to be environment-friendly and cost-effective, reducing the usage of toxic and costly chemicals. Nanoparticles are particles with at least one measurement less than 100 nm (3). The nanoparticles synthesized biologically are defined as bionanoparticles, and they are known to occur naturally, either intracellularly or extracellularly, depending on the place of their formation in plants and microbes (4).

Nanoparticles demonstrate unique chemical, physical, magnetic, optical, and biological properties (improved antimicrobial and anti-inflammatory activity) as they have increased surface area to volume ratio (3,5). These properties exhibit tremendous utilised in chemical industries, metallurgical sector, energetic, and agriculture (3). In addition, metallic nanoparticles also exhibit surface plasmon resonance (SPR) in the visible region of UV-visible spectrophotometer (6). Surface plasmon resonance is defined as the collective oscillation of electrons in the metal surface when hit by certain incident light with a certain angle of incidence, giving rise to the SPR band appearing in the visible region (7).

Nanoparticles are majorly grouped into two classes: organic and inorganic. The organic ones include nanoparticles of carbon such as nanotubes, mainly cylindrical shapes, and spherical buckyballs, known as fullerenes (8). Magnetic, noble metal (gold, silver, copper, palladium, and platinum) and semiconductor nanoparticles like Zinc sulphite, cadmium sulphite, and Zinc oxide (ZnS, CdS, and ZnO) are examples of inorganic nanoparticles (9). Among them largest market share is occupied by nanotube of carbon, fullerenes, and metallic nanoparticles with a wholesale price range of 4 to 18 €g^{-1} (3). Magnetic nanoparticles can be manipulated by means of a magnetic field and contains magnetic elements such as nickel, cobalt, iron, and their chemical compounds. The noteworthy properties of metallic nanoparticles give rise to promising applications in various fields such as medical field, cosmetics, optical industries, chemical industries, wastewater treatment, etc. (2). Metallic nanoparticles are known to show size and shape-dependent properties such as catalyst, antibacterial activity, sensors, etc. (10). For instance, gold and silver nanoparticles have promising applications in biomedical field for example gold nanoparticles are used for protein detection, immunoassay, protein assay, detecting cancer cells and capillary electrophoresis (11). The silver nanoparticles have high antimicrobial activity and are used in health, medicine, cosmetics, packaging, animal husbandry, etc. It is evident that smaller the size of silver nanoparticles, the higher the antibacterial properties (10). Similarly, the catalytic activity of other metallic nanoparticles increases as the size decreases. They have a high antimicrobial effect against various microbes such as *Escherichia coli*, *Bacillus subtilis, Staphylococcus aureus*, *S. epidermidis,* and *Klebsiella pneumoniae* (11,12). Despite huge applications in the medical field, silver nanoparticles are also extensively used in integrated circuits, sensors, bio-labeling, filters, antimicrobial deodorant fibers, cell electrodes, etc. (13). Nanoparticles also find their application in environmental remediation, where they are used as a catalyst in degradation of toxic textile dyes (14). Nanoparticles of noble metals have huge biomedical applications. Semiconductor nanoparticles are utilized in biological labelling, barcodes, and fluorescent materials for display screens (8). Nanoparticles of gold, silver, selenium, platinum, palladium, silica, titania, zirconia, and uraninite are mainly synthesized biologically.

Nanoparticles are synthesized by various physical and chemical procedures. Electrochemical, chemical reduction, photochemical, and physical vapor condensation are mostly used processes (3). Various disadvantages of physio-chemical processes are excess cost, high energy consumption, complicated reactions, and toxic chemicals. Further, these processes achieve high purity of 99.995% with perfect shapes but high production costs, almost 90% of the selling price, hampers their development commercially (3). Thus, finding a suitable alternative to synthesize nanoparticles using biological methods is necessary. This involves synthesizing biological material/biomass at ambient pressure and temperature conditions without harmful chemicals. Synthesis of nanoparticles using microbes is new, but the interrelationship between microbes and metal ions has been known for several decades for their ability to accumulate metals in bioleaching and bioaccumulation (2). Various plant products and microbes are used as sources of biological material for biosynthesizing nanoparticles.

Microbes are tiny creatures with huge potential to synthesize nanoparticles in an eco-friendly manner and with a high success rate. Many researchers have mentioned the use of bacteria, fungi, algae, and yeast for the biosynthesis of nanoparticles. Several extracellular enzymes (nitrate reductase), naphthoquinones, and anthraquinones present in microbes behave as a reducing agent for reduction of metal salt to nanoparticles. The use of microbes in bionanoparticles synthesis is a rapidly growing field due to the ease of formation of nanoparticles and cost-effectiveness. Therefore, microbial synthesis of nanoparticles can be an effective and economical alternative to synthesize nanoparticles at a large scale.

Following above, our review is hypothesized to synthesize nanoparticles using green technologies considering the current scenario of increasing environmental pollution. The applications of bionanoparticles synthesized in a sustainably and economically way using bacterial and algal species have been highlighted.

Microbial synthesis of nanoparticles:

Biological synthesis of nanoparticles is receiving tremendous attention now a day. During synthesis, biological reducing agents reduce metal salt to nanoparticles. The non-hazardous and eco-friendly plants and the microbial (bacteria, actinomycetes, viruses, fungi, algae, yeast) extracts are the main sources for the synthesis of bionanoparticles (15). Besides using green biomass, the other benefit of biosynthesis is that reaction is carried out in aqueous media, which is environment-friendly at ambient temperature and pressure. Microbes are considered to be nano-factories with noteworthy capabilities for synthesizing nanoparticles under controlled conditions (4). An intrinsic mechanism in microbial systems synthesizes nanoparticles from metallic salts (16). Microbial cells play an important role in reducing heavy metals to metallic nanoparticles. Microbial cells possess an advantage over others in that they can produce environmentally benign and sustainable nanoparticles at large scale with rapid growth and simple mechanism (17, 18). The bacterial species can survive at higher concentrations of metallic ions and metal salts (17). During the microbial synthesis of nanoparticles, first, metal ions are confined at the cell's surface, and finally, the reducing agent (enzymes) reduces the metal ions to nanoparticles (19). The intracellular process is more complicated as it requires one more step of expulsion of formed nanoparticles from the cell.

Synthesis of nanoparticles generally involves three main components during microbial synthesis: (1) Salt of a metal particle (usually a solvent medium). (2) Reducing agent: Micro-organisms culture extract It is majorly the microbial enzymes/metabolites (e.g., - nitrate reductase from a fungus (*Fusarium oxysporum*), also several naphthoquinones and anthraquinones (20) with reducing properties that act on the respective compounds and give the desired nanoparticles. (3) Stabilizer (capping agent): Chemical methods involve the use of organic solvents as stabilizing agents (which are very harmful). However, in the biosynthesis method, the biooraganism acts as both, a reducing agent and a capping agent (stabilizing agent), thus making the product safer (21).

Biosynthesis using Bacteria: Bacteria belong to prokaryotes, the largest group of unicellular living organisms found everywhere (soil and water) and in symbiosis with other organisms. Commonly nanoparticles are synthesized extracellularly using bacteria (2). The genus *Bacillus* and *Pseudomonas* are extensively used for the biosynthesis of nanoparticles in living or dead conditions (2). Gold nanoparticles have been synthesized using *Rhodococcus* sp., *Pseudomonas aeruginosa*, *Shewanella oneidensis* (22-24) (Table 1). Silver nanoparticles are well known for their antimicrobial activity against various Gram-positive and Gram-negative bacteria such as *Escherichia coli*, *Bacillus subtilis*, *Acinetobacter* sp., *Staphylococcus aureus*, *S. epidermidis,* etc. Ganesh Babu & Gunasekaran (25) (Table 1) synthesized spherical silver nanoparticles with a 4-5 nm size range using metallic resistant bacterial strain isolated from the electroplating industry. Gurunathan et al. (26) reported a reduction of silver metal salt to trigonal or hexagonal silver nanoparticles (50 nm) using culture supernatant of *E. coli* (Table 1). Oxide nanoparticles (magnetic and non-magnetic) have also been synthesized using bacteria. *Aquaspirillum magnetotacticum* has been used for the synthesis of octahedral prism shaped Fe_3O_4 nanoparticles with a size range of 40-50 nm (27) (Table 1). Hassan & Mahmood (28) synthesized spherical Fe_2O_3 nanoparticles (27.7 nm) using a culture supernatant of *E.coli* (Table 1). Some examples of nonmagnetic oxide nanoparticles are TiO_2, CuO, ZnO, Sb_2O_3, SiO_2, $BaTiO_3$, and ZrO_2. *Bacillus amyloliquefaciens* has been used for the synthesis of TiO_2 nanoparticles having a spherical shape with a size range of 22.11-97.28 nm (29). CuO nanoparticles have been synthesized using *Trichoderma asperellum* (30), and *Periconium* sp. has been used for ZnO nanoparticles (31) (Table 1). Sweeney et al. (32) synthesized sulphide nanoparticles (with wurtzite crystal phase, size 2-5 nm) through *E. coli* (Table 1). Nanoparticles of ZnS and PbS are successfully synthesized using immobilized *Rhodobacter sphaeroides* with an average particle size of zinc sulphide (8nm) and lead sulphide (10.5 nm) (33-34) (Table 1).

Biosynthesis using Algae: Algae are thalloid plants ranging from microscopic to macroscopic levels and are utilized to synthesize nanoparticles. Algae are easily accessible to collect, as they are found naturally in the lentic ecosystem, such as ponds, lakes, and oceans (35). Microalgae comprise high protein levels and high lipid content, especially omega-3 fatty acids, which can be a reducing agent for synthesizing of bionaoparticles (36). The macroscopic algae have an advantage over the microscopic algae due to their high metal uptake capacity. *Chlorella vulgaris* and *Sargassum wightii* have been

Table 1. Bacterial mediated biosynthesis of nanoparticles.

Name of the bacteria	Average size (TEM/ SEM/ XRD)	Morphology/Shape of AgNPs	Absorption peak in UV-visible spectrophotometer	Name of the nanoparticles	Reference
Aquaspirillum magnetotacticum	40-50 nm	Octahedral prism	-	Fe_3O_4	(27)
Bacillus amyloliquefaciens	22-97 nm	spherical	-	TiO_2	(29)
Bacillus cereus	4-5 nm	spherical	420 nm	Ag	(25)
Escherichia coli	50 nm	Triangular, hexagonal	420	Ag	(26)
Escherichia coli	2-5 nm	Spherical, elliptical	-	CdS	(32)
Escherichia coli	67 nm	spherical	473 nm	Fe_2O_3	(28)
Periconium sp.	16-78 nm	Hexagonal	-	ZnO	(31)
Pseudomonas aeruginosa	15-30 nm	polygonal	-	Au	(23)
Pseudomonas putida	12-30 nm	irregular	-	CdS	(58)
Rhodobacter sphaeroides	8 nm	spherical	-	ZnS	(33)
Rhodobacter sphaeroides	10.5 nm	spherical	-	PbS	(34)
Rhodococcus sp.	13 nm	spherical	540 nm	Au	(22)
Shewanella oneidensis	2-50 nm	spherical	-	Au	(24)
Trichoderma asperellum	10-190 nm	spherical	285-295 nm	CuO	(30)

reported for the biological synthesis of gold nanoparticles (37,38) (Table 2). *Chaetoceros calcitrans*, *Tetraselmis gracilis*, *Isochrysis galbana,* and *Chlorella salina* are used to synthesize silver nanoparticles (39) (Table 2). These silver nanoparticles are found to have good antimicrobial activity against selected strains of *Escherichia coli*, *Proteus* sp., *Pseudomonas* sp., and *Klebsiella* sp. (39) (Table 2). Both magnetic and non-magnetic oxide nanoparticles have also been synthesized using algae. Magnetic nanoparticles (Fe_3O_4) have been synthesized through brown and red seaweed from the Mediterranean Sea, Egypt (40,41). Non-magnetic oxide nanoparticles of CuO (5 -45nm; spherical) have been obtained through extracts of brown algae such as *Bifurcaria bifurcate* (42) (Table 2). *Spirulina (Arthrospira) platensis* is used for the synthesis of spherical CdS nanoparticles with a size range of 8-12 nm (43) (Table 2).

Mechanism of nanoparticles synthesis

The formation of nanoparticles by microbes is a significant part of geo-cycles and occurs specifically as a stress response ensuing in defence against metal poisoning (44). Thus, the microorganisms able to synthesize nanoparticles are generally metal resistant. It is reported that contact of negative anionic cell constituents with positive cationic metal ion lead to the formation of nanoparticles via reduction, chelation, or hydrolysis. To cope up with metal toxicity, the microorganism can take into enzymatic reduction, precipitation, dissimilatory oxidation, complexation, or transport via efflux systems to remove the metals from the cell (45). The pathways involving enzymes, exopolysaccharides, and proteins are broad mechanisms for synthesizing nanoparticles (44). Nanoparticle synthesis using microbes is advantageous over other greener routes as it gives control over shape and size. Mainly monodispersed nanoparticles are formed, which can be replicated at the industrial level in bioreactors. The size and shape can be controlled by varying the external parameters such as pH and temperature. Enzymes are the most prominent things responsible for reducing metal to nanoparticles via redox reactions occurring inside (intracellular) and outside (extracellular) microbial cells. The exact mechanism of nanoparticle synthesis by biological extracts is difficult and has yet to be understood thoroughly. Reductases, naphthoquinones, flavonoids and, anthraquinones, and biomolecules such as amino acids, peptides, proteins, enzymes, aromatic and aliphatic compounds are the main reducing agents which reduce metal ions to nanoparticles form in microbes (46). Several polysaccharides, peptides, pigments in algae, and discrete enzymes found in the bacterial cell, like NADH-dependent reductase or nitrate-dependent reductase, play the role of reducing agent. The metal salt of a nanoparticle is reduced by reducing agents or enzymes present in microbes. The metal is present in (M^+) form in metal salt, and enzymes provide electrons, reducing the metal cation to metallic form (M^0) or nanoparticles. The reaction can be summarised as:

$$M^+ + e- \rightarrow M^0$$

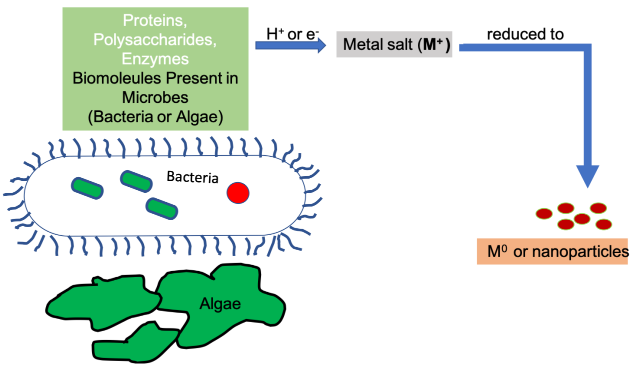
Table 2. Algal mediated biosynthesis of nanoparticles.

Name of the Algae	Average size (TEM/ SEM/ XRD)	Morphology/ Shape of AgNPs	Absorption peak in UV-visible spectrophotometer	Name of the nanoparticles	Reference
Bifurcaria bifurcate	5-45 nm	spherical	260 and 650 nm	CuO	(42)
Chaetoceros calcitrans (green algae)	53-71 nm	-	420 nm	Ag	(39)
Chlorella salina (green algae)	53-71 nm	-	420 nm	Ag	(39)
Chlorella vulgaris	2-10 nm	-	530 nm	Au	(37)
Chlorococcum sp. MM11	20-50 nm	spherical		Fe	(59)
Colpomenia sinuosa (brown seaweed)	11.24-33.71 nm	spherical	402 nm	Fe_3O_4	(40)
Isochrysis galbana (green algae)	53-71 nm	-	420 nm	Ag	(39)
Padina pavonica	10 -19.5 nm	-	402 nm	Fe_3O_4	(41)
Pterocladia capillacea (red seaweed)	16.85-22.47 nm	spherical	415 nm	Fe_3O_4	(40)
Sargassum acinarium	21.6 - 27.4 nm	-	415 nm	Fe_3O_4	(41)
Sargassum bovinum	5-10 nm	octahedral	-	Pd	(60)
Sargassum wightii	8-12 nm	spherical	527 nm	Au	(38)
Shewanella	5 nm	-		Pt	(61)
Spirulina (Arthrospira) platensis	8-12 nm	spherical	420 nm	CdS	(43)
Tetraselmis gracilis (green algae)	53-71 nm	-	420 nm	Ag	(39)

The mechanism of producing nanoparticles varies with different biological species and location of their formation (either extracellularly and intracellularly) (47).

Either extracellular or intracellular mechanisms are involved in the microbial synthesis of nanoparticles, which mostly requires oxidoreductase enzymes (e.g., NADH-dependent nitrate reductase, NADPH-dependent sulphite reductase flavoprotein subunit α, and cysteine desulfhydrase) and cellular transporters (48). In the extracellular process, synthesis occurs at the cell surface, whereas in intracellular synthesis, nanoparticles form inside the cell in the presence of enzymes. For extracellular synthesis, it is mainly the microbial reductase enzyme, proteins, bacterial cell wall components, and organic molecules in the culture medium responsible for reducing metal ions into nanoparticles. The NADH-dependent enzyme acts as an electron carrier and withdraws electrons from NADH (reducing it to NAD^+) and the available electrons, in turn, reduces metal ions to nanoparticles (46). Extracellular enzymes such as nitrate reductase help in the transfer of electrons from various groups (e.g., hydroxyl groups) to metal salt and thus lead to the formation of nanoparticles (Fig. 1). In the intracellular process, the metal ion needs to be transported inside of the microbial cell, where cell wall plays a very important role. The probable mechanism comprises the electrostatic interaction of negatively charged carboxy group cell walls with positively charged metal ions, resulting in metal ions across the cells and reduction by intracellular proteins to produce nanoparticles (17). Further, intracellular enzymes like cytochrome oxidase also help in reduction of metal ions to nanoparticles with the help of electron transference amongst cytoplasm constituents (e.g., NADH/NADPH), vitamins, and organic acids (49).

Figure 1. Probable mechanism to biosynthesize nanoparticles.



Application of nanoparticles

Bionanoparticles, with their unique properties, find their applicability in medicine, food preservation, catalysis, and environmental remediation or wastewater treatment. Numerous metallic nanoparticles, such as silver, copper, zinc, gold, and titanium, are recognised for their antimicrobial properties. Also, nanoparticles of silver are well-known for possessing high anti-fungal, anti-viral, and anti-inflammatory properties, increasing their applicability in the medical field (16). According to a recent report by Bartoš et al. (50) and Vochozka et al. (51), the pricing of metals plays a key role in the production of nanoparticles on a commercial scale. It is reported that the price of metals such as copper and aluminum is intended to increase in the coming years (as per the detailed study from 2011 to 2022). The production of aluminium was showing an increasing trend whereas production of copper is known to stagnant due to high price and a limited quantity of copper metal. The growing trend of metal pricing might impede the products made from them, such as nanoparticles. Another report by Rowland et al. (52) described that the price of silver from 2011 to 2022, which is highly prone to the economic cycle of the world economy. The data shows that the price reached 37 USD per ounce in the initial months of 2012 and 35 USD in 2022. The price of zinc was also evaluated, which is expected to increase slightly by 2030 to 410 USD per ton (53).

Magnetic bionanoparticles have distinct features like super paramagnetic and high coercive force with applications in biological separation and biomedical fields due to micro-configurational arrangement. The most common magnetic nanoparticles are Fe_3O_4 (magnetite) and Fe_2O_3 (maghemite). They are biocompatible and actively studied for the treatment of cancer (magnetic hyperthermia), drug delivery, stem cell sorting and manipulation, gene therapy, and magnetic resonance imaging (MRI). Sulphide nanoparticles are semiconductor nanocrystals, gaining widespread attention due to their unique electronic and optical properties in elementary research as quantum-dot fluorescent biomarkers, cell labelling agents, and nanoelectronics. The extracellular nanoparticles have wide applications in optoelectronics, electronics, bio-imaging, and sensor technology as in other intracellular synthesized nanoparticles (15).

Bionanoparticles are used in the food industry as a disinfectant and sterilization. For example, the addition of nanoparticles in coating of food packaging act as an antibacterial agent which helps in disinfecting the food and preventing it from putrefaction (16). Urbanization and industrialization have led to increased pollution in the environment. There are many sources of water pollution, the major being the industries that discharge their untreated effluent into the water bodies. Recently, nanotechnology has been considered a good candidate for treating polluted water by disinfection, purification, and desalination (4).

The high surface area to volume ratio of bionanoparticles also imparts them high catalytic activity. Thus they are applied as nanocatalysts in treatment and degradation of organic pollutants, such as dyes, nitrophenols, etc. Bionanoparticles of silver, Iron, and nano-nickel zinc ferrite catalysts are used for degradation of various toxic and hazardous dyes such as methyl orange, methyl red, methylene blue, malachite green, reactive black, brilliant blue (14,54). Organic compounds such as 4-nitrophenol and its derivatives are used in manufacturing of many herbicides, and insecticides and can considerably damage the ecosystem/nature. This can be reduced by using nanocatalysts such as gold, silver, copper oxide, and palladium in the presence of reducing agents (55).

Nanoparticles are also utilised for the fabrication of biohydrogen, such as nanoparticles of Ag, Au, Cu, Fe, activated carbon, Ni, Pd, SiO2, Ti, and carbon nano-tubes have been reported. The higher surface area to volume ratio of nanoparticles provide them greater potential to adsorb charged particles, thus stimulating biohydrogen fabrication (56). Recently, nanoparticles of aluminum synthesized from a waste mixture of polyethylene and aluminum (PE-Al) or 'tetra pack' (used for liquid packaging) are utilised to increase the effectiveness of biodiesel (57).

Considering the low production cost compared to conventional methods and remarkable applications of nanoparticles in enormous fields, further research can be attempted to discover the potential of bacterial and algal species for mass production of nanoparticles on a larger scale and the perspective of other microorganisms in the biosynthesis of nanoparticles can also be looked upon.

Conclusion

Microbes are biological entities present in abundance in nature, and synthesizing nanoparticles using them is an eco-friendly process. The bionanoparticles can be synthesized using green chemistry principles and are being looked at as alternative to conventional approaches. The microbial organisms are readily available, and the technique for synthesis is cost-effective. It is a valuable substitute for the extensive production of metal nanoparticles. Further, bionanoparticles have wider applications in various fields like medicine, water remediation, as a catalyst for various biosynthetic reactions, etc., and using them will lower the complete application cost. Also, to fulfill the demand, these bionanoparticles can be synthesized at a large scale with emphasizing low-cost, high-yield production.

Acknowledgements

Authors wish to acknowledge Maitreyi College for providing resources in completion of this review paper.

Authors' contributions

AS wrote the manuscript with support from PB and PBG, SG and HC supervised the project.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1. Varma RS. Greener approach to nanomaterials and their sustainable applications. Curr Opin Chem Eng. 2012;1(2):123-28. http://dx.doi.org/10.1016/j.coche.2011.12.002
2. Vijayaraghavan K, Ashokkumar T. Plant-mediated biosynthesis of metallic nanoparticles: A review of literature, factors affecting synthesis, characterization techniques and applications. J Environ Chem Eng. 2017;5(5):4866-83. http://dx.doi.org/10.1016/j.jece.2017.09.026
3. Maroušek J, Maroušková A, Periakaruppan R, Gokul GM, Anbukumaran A, Bohatá A et al. Silica nanoparticles from coir pith synthesized by acidic sol-gel method improve germination economics. Polymers. 2022;14(2). https://doi.org/10.3390/polym14020266
4. Ijaz I, Gilani E, Nazir A, Bukhari A. Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. Green Chem Lett Rev. 2020;13(3):59-81. https://doi.org/10.1080/17518253.2020.1802517
5. Gericke M, Pinches A. Biological synthesis of metal nanoparticles. Hydrometallurgy. 2006;83(1-4):132-40. https://doi.org/10.1016/j.hydromet.2006.03.019
6. Talabani RF, Hamad SM, Barzinjy AA, Demir U. Biosynthesis of silver nanoparticles and their applications in harvesting sunlight for solar thermal generation. Nanomaterials. 2021;11(9). https://doi.org/10.3390/nano11092421
7. Firdhouse MJ, Lalitha P. Biosynthesis of silver nanoparticles and its applications. J Nanotechnol. 2015;2015(September 2014):1-18. http://www.hindawi.com/journals/jnt/2015/829526/ https://doi.org/10.1155/2015/829526
8. Manivasagan P, Venkatesan J, Sivakumar K, Kim SK. Actinobacteria mediated synthesis of nanoparticles and their biological properties: A review. Crit Rev Microbiol. 2016;42(2):209-21. https://doi.org/10.3109/1040841X.2014.917069
9. Asmathunisha N, Kathiresan K. A review on biosynthesis of nanoparticles by marine organisms. Colloids Surf B Biointerfaces. 2013;103:283-87. http://dx.doi.org/10.1016/j.colsurfb.2012.10.030
10. Abou El-Nour KMM, Eftaiha A, Al-Warthan A, Ammar RAA. Synthesis and applications of silver nanoparticles. Arab J Chem. 2010;3:135-40. https://doi.org/10.1016/j.arabjc.2010.04.008
11. Iravani S. Green synthesis of metal nanoparticles using plants. Green Chem. 2011;13(10):2638-50. https://doi.org/10.1039/c1gc15386b
12. Singhal A, Singhal N, Bhattacharya A, Gupta A. Synthesis of silver nanoparticles (AgNPs) using *Ficus retusa* leaf extract for potential application as antibacterial and dye decolourising agents. Inorg Nano-Met Chem. 2017;47(11). https://doi.org/10.1080/24701556.2017.1357604
13. Prusty A, Parida P. Development and evaluation of gel incorporated with biogenically synthesised silver nanoparticles. J Appl Biopharm. 2015;3(1):1-6. https://doi.org/10.14205/2309-4435.2015.03.01.1
14. Singhal A, Gupta A. Efficient utilization of Sal deoiled seed cake (DOC) as reducing agent in synthesis of silver nanoparticles: Application in treatment of dye containing wastewater and harnessing reusability potential for cost-effectiveness. J Mol Liq. 2018;268:691-99. https://linkinghub.elsevier.com/retrieve/pii/S0167732218318014 https://doi.org/10.1016/j.molliq.2018.07.092
15. Narayanan KB, Sakthivel N. Biological synthesis of metal nanoparticles by microbes. Adv Colloid Interf Sci. 2010;156(1-2):1-13. http://dx.doi.org/10.1016/j.cis.2010.02.001
16. Li X, Xu H, Chen ZS, Chen G. Biosynthesis of nanoparticles by microorganisms and their applications. J Nanomat. 2011;2011. https://doi.org/10.1155/2011/270974
17. Lahiri D, Nag M, Sheikh HI, Sarkar T, Edinur HA, Pati S et al. Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade. Front Microbiol. 2021;12. https://doi.org/10.3389/fmicb.2021.636588

18. Ghosh S, Ahmad R, Zeyaullah M, Khare SK. Microbial nano-factories: Synthesis and biomedical applications. Front Chem. 2021;9. https://doi.org/10.3389/fchem.2021.626834

19. Saravanan A, Kumar PS, Karishma S, Vo DVN, Jeevanantham S, Yaashikaa PR et al. A review on biosynthesis of metal nanoparticles and its environmental applications. Chemosphere . 2021;264:128580. https://doi.org/10.1016/j.chemosphere.2020.128580

20. Kumar V, Yadav SK. Plant-mediated synthesis of silver and gold nanoparticles and their applications. J Chem Technol Biotech. 2009;84(2):151-57. https://doi.org/10.1002/jctb.2023

21. Mittal AK, Chisti Y, Banerjee UC. Synthesis of metallic nanoparticles using plant extracts. Biotech Adv . 2013;31(2):346-56. http://dx.doi.org/10.1016/j.biotechadv.2013.01.003

22. Markus J, Mathiyalagan R, Kim YJ, Abbai R, Singh P, Ahn S et al. Intracellular synthesis of gold nanoparticles with antioxidant activity by probiotic *Lactobacillus kimchicus* DCY51T isolated from Korean kimchi. Enz Microb Technol. 2016;95:85-93. http://dx.doi.org/10.1016/j.enzmictec.2016.08.018

23. Husseiny MI, El-Aziz MA, Badr Y, Mahmoud MA. Biosynthesis of gold nanoparticles using *Pseudomonas aeruginosa*. Spectrochimica Acta - Part A: Mol Biomol Spect. 2007;67(3-4):1003-06. https://doi.org/10.1016/j.saa.2006.09.028

24. Suresh AK, Pelletier DA, Wang W, Broich ML, Moon JW, Gu B et al. Biofabrication of discrete spherical gold nanoparticles using the metal-reducing bacterium *Shewanella oneidensis*. Acta Biomater. 2011;7(5):2148-52. http://dx.doi.org/10.1016/j.actbio.2011.01.023

25. Ganesh Babu MM, Gunasekaran P. Production and structural characterization of crystalline silver nanoparticles from *Bacillus cereus* isolate. Colloids Surf B Biointerfaces. 2009;74(1):191-95. https://doi.org/10.1016/j.colsurfb.2009.07.016

26. Gurunathan S, Kalishwaralal K, Vaidyanathan R, Venkataraman D, Pandian SRK, Muniyandi J et al. Biosynthesis, purification and characterization of silver nanoparticles using *Escherichia coli*. Colloids Surf B Biointerfaces. 2009;74(1):328-35. https://doi.org/10.1016/j.colsurfb.2009.07.048

27. Mann S, Frankel RB, Blakemore RP. Structure, morphology and crystal growth of bacterial magnetite. Nature. 1984;310(5976):405-07. https://doi.org/10.1038/310405a0

28. Hassan DF, Mahmood MB. Biosynthesis of iron oxide nanoparticles using *Escherichia coli.* Iraqi J Sci. 2019;60(3):453-59.

29. Khan R, Fulekar MH. Biosynthesis of titanium dioxide nanoparticles using *Bacillus amyloliquefaciens* culture and enhancement of its photocatalytic activity for the degradation of a sulfonated textile dye Reactive Red 31. J Colloid Interf Sci. 2016;475:184-91. http://dx.doi.org/10.1016/j.jcis.2016.05.001

30. Saravanakumar K, Shanmugam S, Varukattu NB, MubarakAli D, Kathiresan K, Wang MH. Biosynthesis and characterization of copper oxide nanoparticles from indigenous fungi and its effect of photothermolysis on human lung carcinoma. J Photochem Photobiol B Biol. 2019;190:103-09. https://doi.org/10.1016/j.jphotobiol.2018.11.017

31. Ganesan V, Hariram M, Vivekanandhan S, Muthuramkumar S. Periconium sp. (endophytic fungi) extract mediated sol-gel synthesis of ZnO nanoparticles for antimicrobial and antioxidant applications. Mater Sci Semicond Process. 2020;105:104739. https://doi.org/10.1016/j.mssp.2019.104739

32. Rozamond Y Sweeney , Chuanbin Mao, Xiaoxia Gao, Justin L Burt, Angela M Belcher, George Georgiou BLI. Bacterial biosynthesis of cadmium sulfide nanocrystals. Chem & Biol. 2004;11:15553-59. 10.1016/j.chembiol.2004.08.022 https://doi.org/10.1016/j.chembiol.2004.08.022

33. Bai HJ, Zhang ZM, Gong J. Biological synthesis of semiconductor zinc sulfide nanoparticles by immobilized *Rhodobacter sphaeroides*. Biotechnol Lett. 2006;28(14):1135-39. https://doi.org/10.1007/s10529-006-9063-1

34. Bai HJ, Zhang ZM. Microbial synthesis of semiconductor lead sulfide nanoparticles using immobilized *Rhodobacter sphaeroides*. Mater Lett. 2009;63(9-10):764-66. http://dx.doi.org/10.1016/j.matlet.2008.12.050

35. Maroušek J, Gavurová B, Strunecký O, Maroušková A, Sekar M, Marek V. Techno-economic identification of production factors threatening the competitiveness of algae biodiesel. Fuel. 2023;344. https://doi.org/10.1016/j.fuel.2023.128056

36. Maroušek J, Maroušková A, Gavurová B, Tuček D, Strunecký O. Competitive algae biodiesel depends on advances in mass algae cultivation. Bioresour Technol. 2023;374. https://doi.org/10.1016/j.biortech.2023.128802

37. Annamalai J, Nallamuthu T. Characterization of biosynthesized gold nanoparticles from aqueous extract of *Chlorella vulgaris* and their anti-pathogenic properties. Appl Nanosci (Switzerland). 2015;5(5):603-07. https://doi.org/10.1007/s13204-014-0353-y

38. Singaravelu G, Arockiamary JS, Kumar VG, Govindaraju K. A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. Colloids Surf B Biointerfaces. 2007;57(1):97-101. https://doi.org/10.1016/j.colsurfb.2007.01.010

39. Merin DD, Prakash S, Bhimba BV. Antibacterial screening of silver nanoparticles synthesized by marine micro algae. Asian Pac J Trop Med. 2010;3(10):797-99. http://dx.doi.org/10.1016/S1995-7645(10)60191-5

40. Salem DMSA, Ismail MM, Aly-Eldeen MA. Biogenic synthesis and antimicrobial potency of iron oxide (Fe3O4) nanoparticles using algae harvested from the Mediterranean Sea, Egypt. Egypt J Aquat Res. 2019;45(3):197-204. https://doi.org/10.1016/j.ejar.2019.07.002

41. El-Kassas HY, Aly-Eldeen MA, Gharib SM. Green synthesis of iron oxide (Fe3O4) nanoparticles using two selected brown seaweeds: Characterization and application for lead bioremediation. Acta Oceanolog Sin. 2016;35(8):89-98. https://doi.org/10.1007/s13131-016-0880-3

42. Abboud Y, Saffaj T, Chagraoui A, El Bouari A, Brouzi K, Tanane O et al. Biosynthesis, characterization and antimicrobial activity of copper oxide nanoparticles (CONPs) produced using brown alga extract (Bifurcaria bifurcata). Appl Nanosci (Switzerland). 2014;4(5):571-76. https://doi.org/10.1007/s13204-013-0233-x

43. Mandal RP, Sekh S, Sarkar N Sen, Chattopadhyay D, De S. Algae mediated synthesis of cadmium sulphide nanoparticles and their application in bioremediation. Mater Res Express. 2016;3(5):1-11. http://dx.doi.org/10.1088/2053-1591/3/5/055007

44. Ghosh S, Ahmad R, Banerjee K, AlAjmi MF, Rahman S. Mechanistic aspects of microbe-mediated nanoparticle synthesis. Front Microbiol. 2021;12:1-12. https://doi.org/10.3389/fmicb.2021.638068

45. Ayesha A. Bacterial synthesis and applications of nanoparticles. Nano Sci Nano Technol. 2017;11(2):119.

46. Rana A, Yadav K, Jagadevan S. A comprehensive review on green synthesis of nature-inspired metal nanoparticles: Mechanism, application and toxicity. J Clean Prod. 2020;272:122880. https://doi.org/10.1016/j.jclepro.2020.122880

47. Hulkoti NI, Taranath TC. Biosynthesis of nanoparticles using microbes-A review. Colloids Surf B Biointerfaces. 2014;121:474-83. http://dx.doi.org/10.1016/j.colsurfb.2014.05.027

48. Grasso G, Zane D, Dragone R. Microbial nanotechnology: Challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. Nanomaterials. 2020;10(1). https://doi.org/10.3390/nano10010011

49. Siddiqi KS, Husen A, Rao RAK. A review on biosynthesis of silver nanoparticles and their biocidal properties. J Nanobiotechnol. 2018;16(1). https://doi.org/10.1186/s12951-018-0334-5

50. Bartoš V, Vochozka M, Šanderová V. Copper and aluminium as economically imperfect substitutes, production and price development. Acta Montan Slovaca. 2022;27(2):462-78. https://doi.org/10.46544/AMS.v27i2.14

51. Vochozka M, Kalinová E, Gao P, Smolíková L. Development of copper price from july 1959 and predicted development till the end of year 2022. Acta Montan Slovaca. 2021;26(2):262-80. https://doi.org/10.46544/AMS.v26i2.07

52. Rowland Z, Bláhová A, Gao P. Silver as a value keeper and wealth distributor during an economic recession. Acta Montan Slovaca. 2021;26(4):796-809. https://doi.org/10.46544/AMS.v26i4.16

53. Nováková L, Novotná L, Procházková M. Predicted future development of imperfect complementary goods – Copper and zinc until 2030. Acta Montan Slovaca. 2022;27(1):135-51. https://doi.org/10.46544/AMS.v27i1.10

54. Pathakoti K, Manubolu M, Hwang HM. Nanotechnology applications for environmental industry . Handb. Nanomater Indust Appl. 2018;894-907. http://dx.doi.org/10.1016/B978-0-12-813351-4.00050-X

55. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P. “Green” synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. J Nanobiotechnol. 2018;16(1):1-24. https://doi.org/10.1186/s12951-018-0408-4

56. Maroušek J. Review: Nanoparticles can change (bio) hydrogen competitiveness. Fuel. 2022;328.

57. Maroušek J. Aluminum nanoparticles from liquid packaging board improve the competitiveness of (bio)diesel. Clean Technol Environ Pol. 2022;1059-67. https://doi.org/10.1016/j.fuel.2022.125318

58. Oliva-Arancibia B, Órdenes-Aenishanslins N, Bruna N, Ibarra PS, Zacconi FC, Pérez-Donoso JM et al. Co-synthesis of medium-chain-length polyhydroxyalkanoates and CdS quantum dots nanoparticles in *Pseudomonas putida* KT2440. J Biotechnol. 2017;264:29-37. http://dx.doi.org/10.1016/j.jbiotec.2017.10.013

59. Subramaniyam V, Subashchandrabose SR, Thavamani P, Megharaj M, Chen Z, Naidu R. *Chlorococcum* sp. MM11—a novel phyco-nanofactory for the synthesis of iron nanoparticles. J Appl Phycol. 2015;27(5):1861-69. https://doi.org/10.1007/s10811-014-0492-2

60. Momeni S, Nabipour I. A simple green synthesis of palladium nanoparticles with Sargassum alga and their electrocatalytic activities towards hydrogen peroxide. Appl Biochem Biotechnol. 2015;176(7):1937-49. https://doi.org/10.1007/s12010-015-1690-3

61. Konishi Y, Ohno K, Saitoh N, Nomura T, Nagamine S, Hishida H et al. Bioreductive deposition of platinum nanoparticles on the bacterium Shewanella algae. J Biotechnol. 2007;128 (3):648-53. https://doi.org/10.1016/j.jbiotec.2006.11.014