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REVIEW ARTICLE

Bio-mediated synthesis of nanoparticles: A new paradigm for environmental sustainability

Bharathi C[1], Rajeswari R*[2], Janaki P[3], Sivamurugan A P[4], Senthil Kumar G[1], Radhamani S[1], Sathya Priya R*[1], Sangeetha M[5], Thenmozhi S[6], Chiranjeevirajan N[2], Sharmila R[7], Ramya B[8] and Balamurugan R[9]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[2]Department of Soil Science & Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[3]Nammazhlvar Organic farming Research Centre, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[4]Centre for water and geospatial studies, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[5]KVK, Papparapatti, Dharmapuri, Tamil Nadu Agricultural University , Tamil Nadu, India
[6]KVK, Nilgiris, Tamil Nadu Agricultural University, Tamil Nadu, India
[7]Department of Nematology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[8]Department of Plant Breeding and Genetics, Mother Teresa College of Agriculture, Illupur, Pudukkottai, Tamil Nadu, India
[9]Department of Agronomy, RVS Padmavathy College of Horticulture, Sempatti, Madurai, Tamil Nadu, India

*Email: rrajeswaritnau@gmail.com, sathyapriyaagri@gmail.com

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Abstract

The synthesis of nanoscale metals and non-metals is an intriguing subject, and the green synthesis of nanoparticles (NPs) is increasingly utilized across various sectors, including environmental science, agriculture, engineering, and food processing. Traditionally, the production of nanoscale materials relies heavily on physical and chemical processes, which can lead to significant challenges such as high energy consumption and environmental contamination. Poor management of agricultural and industrial waste contributes to greenhouse gas emissions, exacerbates climate change and disrupts ecosystems. Conversely, green nanotechnology offers a safer alternative by leveraging biological materials, that inherently provide capping and reducing agents. This approach is not only more cost-effective but also results in lower pollution levels, thereby enhancing environmental safety. Green synthesis involves the reduction of metallic and non-metallic atoms using plant extracts, microorganisms, and agricultural waste instead of conventional harmful substances. The bioactive compounds, including flavonoids, alkaloids, tannins, and saponins, play a critical role in the bio-reduction of metals and the production of nanoparticles. There has been the increasing interest in utilizing these biological sources for green nanoparticle production over the past decade from their potential to serve as economical and environmentally friendly alternatives. Overall, green nanotechnology demonstrates its potential to revolutionize industries and pave the way for a more sustainable and resilient future.

Keywords

green synthesis; mechanisms; agricultural waste; microorganism; plant extract; application

Introduction

Nanoscience offers an extensive array of materials at the nanoscale, playing a vital role in creating sustainable technology for the betterment of humanity and preservation of the environment (1). Nanoparticle synthesis can be achieved using chemical, physical and biological approaches. While chemical and physical synthesis methods produce regulated and uniform NPs, these methods have drawbacks including the generation of harmful and noxious by-products and the excessive bonding of chemicals to the surface of the nanoparticles. These constraints have prompted the emergence of eco-friendly alternatives referred to as green nanotechnology, which emphasizes the use of biological resources or ecologically friendly methods for nanoparticle production. The synthesis of nanoparticle synthesis towards sustainable and eco-friendly approaches is illustrated in Fig. 1. Green synthesis is widely recognized for its ability to swiftly and easily produce stable and biocompatible nanoparticles (2). Several studies have demonstrated the efficacy of green synthesis methods in producing nanoparticles with favourable characteristics. Green synthesis techniques offer a feasible result by employing biological materials such as agricultural residues, microorganisms, and plant parts as sustainable resources for the production of nano particles (3).

Unfortunately, an immense quantity of agricultural waste, estimated at approximately 380 million tons, is generated annually in India (4). The common practice of burning agricultural waste after harvest releases harmful gases such as carbon dioxide, methane, and nitrous oxide along with contaminants such as carbon monoxide, ammonia, sulfur dioxide, volatile organic pollutants, and particulate matter, severely impacting the environment through air and water pollution, and contributing to global warming (5). A novel method for converting agricultural wastes and industrial byproducts into bio-nanosorbents, bio-nanodisinfectants, and bio-nanocatalysts has been made possible by the use of green nanotechnology (6). Microorganisms such as bacteria, fungi, yeast and algae are utilized in the synthesis of nanoparticles because the growth conditions such as nutrient, pH, pressure, and temperature can be adjusted to manage the process. The synergistic interaction among microorganisms leads to several beneficial characteristics, including accelerated rates of multiplication, diverse secondary metabolite production, rapid growth in confined environments and the ability to deactivate pollutants in a synergistic manner. As a result, microorganisms provide an ideal platform for synthesizing nanozerovalent particles, thereby improving reduction processes and the decomposition of pollutants. The abundance and diversity of plant species offer a plentiful supply of bioactive chemicals, including flavonoids, alkaloids, tannins, and saponins, which play a critical role in the bio-reduction of metals and the production of nanoparticles (7), drawing significant attention to plant-mediated synthesis (8,9). The potential of numerous plant parts to reduce metal ions and promote

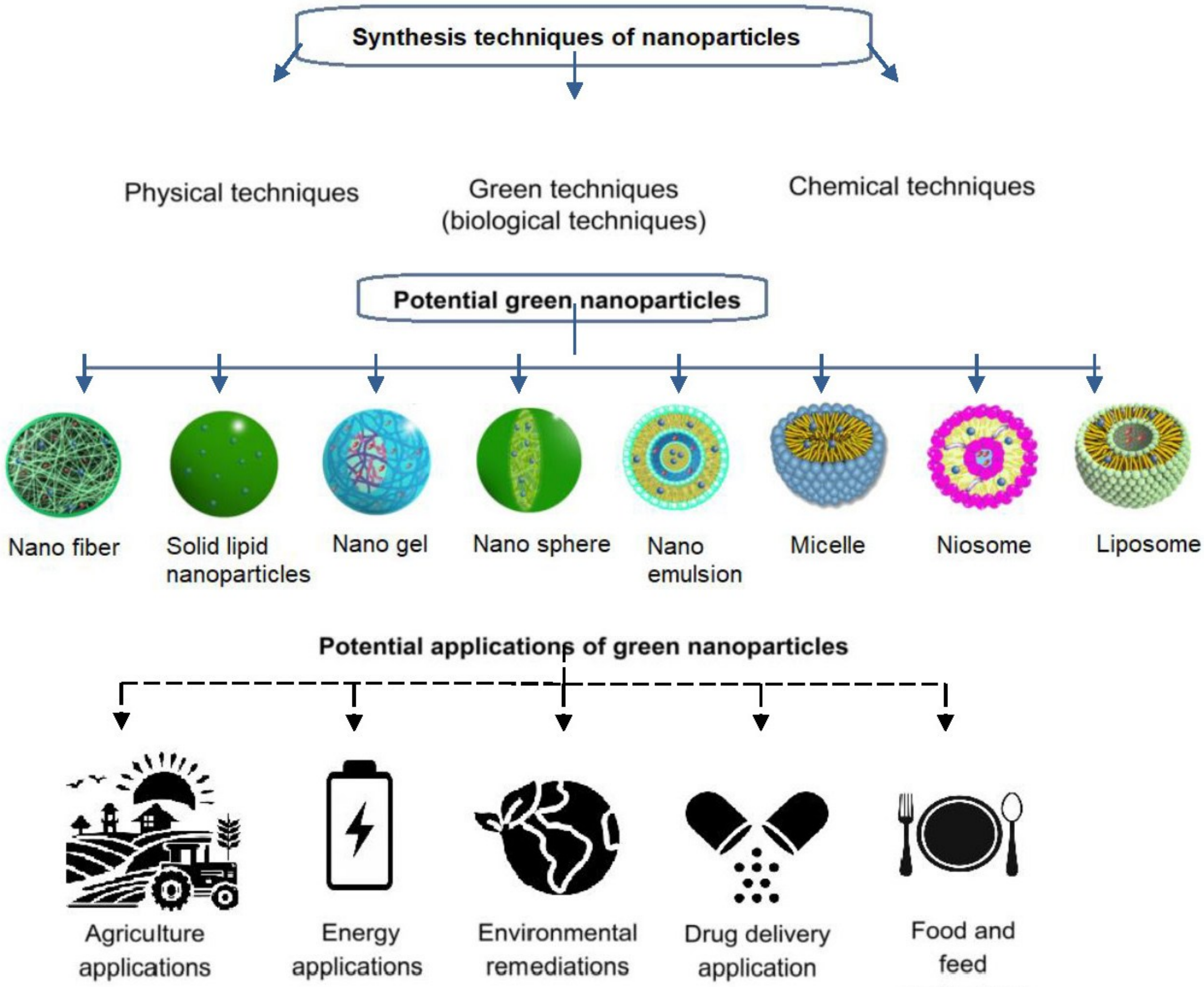

Fig. 1. Approaches for synthesis of nanoparticles and their prospective uses (9).

the synthesis of nanoparticles has been studied and these components include leaves, roots, and seeds.

Biocompatibility and the controlled release of chemicals are two key features of green-synthesized nanoparticles. The effective use of nanoparticles is contingent upon various factors including NPs size, shape, types, and capping layer surrounding them. These characteristics are impacted by the source of synthesis. By reducing the amount of hazardous chemicals present, green nanoparticles use improves safety and provides an environmentally conscious and sustainable agricultural system. This review highlights the synthesis and applications of green nanoparticles in environmental remediation, agriculture, engineering, processing and many other fields, emphasizing their potential to revolutionize industries and bring about a new era of sustainability (10).

Synthesis of nano particles

The two main approaches used for the synthesis of nano materials are, top-down and bottom-up approaches as shown in Fig. 2. Top-down methodologies involve breaking down bulk materials to create nanostructure materials. These techniques encompass mechanical milling, laser ablation, etching, sputtering, and electro-explosion. The bottom-up approach involves building nanoparticles from smaller units, such as atoms, molecules, or ions, which are assembled into nanoscale structures. These techniques encompasses sol-gel method, laser pyrolysis, and spinning., In green synthesis, this approach can be made more sustainable by using natural resources or biological agents instead of toxic chemicals.

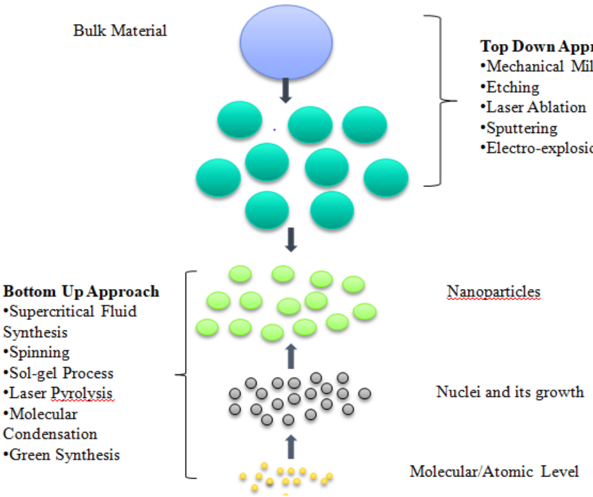

Fig. 2. Synthesis of nano particles.

Mechanism of green nanoparticle synthesis

The involvement of living organisms like bacteria, fungi, plants, and so on to assist in the reduction of metals into nanoparticles is termed "green biosynthesis." This process is usually mediated by the intrinsic characteristics of biomolecules present in these types of species such as flavonoids, terpenoids, phenols, carbohydrates, saponins, steroids, etc. As shown in Fig. 3, a multitude of studies have demonstrated that the attachment of enzymes or their substrates to nanoparticle surfaces can improve catalyzation (11). Because of their complex three-dimensional folding, enzymes have specific catalytic capabilities owing to the spatial arrangement of important functional groups present in their active section.

The biological constituents, *viz*., enzymes, proteins, and secondary metabolites in microorganisms and plants are accountable for reducing metals and creating a protective layer around individual nanoparticles known as the "capping layer" or "biological corona" (12). The biological corona enveloping the nanoparticles contains biological elements discharged from the plant or microorganism in an extract or culture medium employed during synthesis. This covering provides enduring stability to the nanoparticles in aqueous solutions, shielding them from clumping, and notably contributing to the interaction of green nanoparticles with cells. This facilitates the easy penetration of nanoparticles into bacterial, fungal, or plant cells and their organelles. Hence, the biological corona plays a crucial role in nanoparticle production and its diverse applications across various fields.

Factors influencing green synthesis

Numerous factors influence the structure of metallic nanoparticles during green production, including the synthesis source, reaction time, salt concentration, pH, and temperature. These particles dictate the formation and activity of metallic nanoparticles. The reaction time is critical in nanoparticle synthesis, and determines their stability, shape and size. Likewise, temperature plays a critical part in nanoparticle morphology. Higher temperatures facilitate rapid reduction and can lead to agglomeration if prolonged. The synthesis of monodisperse AgNPs from rowan fruits at 90℃ was demonstrated. Moreover, it was found that at lower temperatures, the spherical gold nanoparticles tended to synthesis, whereas rod and plate shaped nanoparticles formed at higher temperatures (14). Green synthesis occurs rapidly at temperatures ranging from 70 to 90°C, however, prolonged reaction times and higher temperatures may result in the agglomeration with

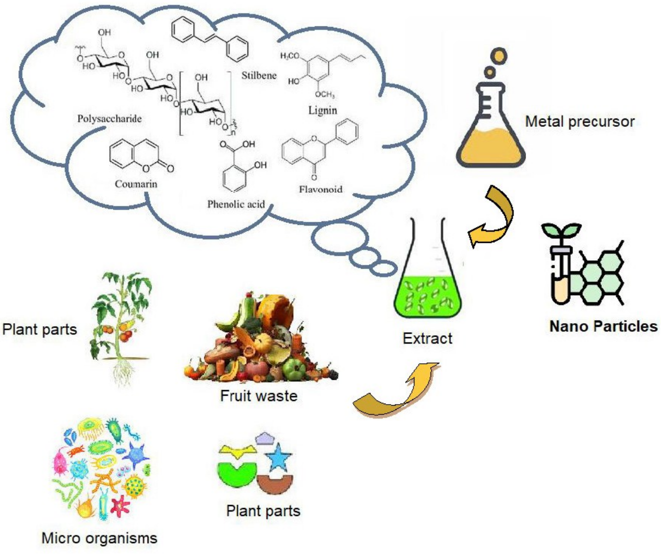

Fig. 3. Mechanism for green synthesis of nanoparticles (95).

various plant extracts (13). pH significantly influences nanoparticle size and shape, the acidic pH favours the formation of larger nanoparticles with fewer structural groups attached to the corona layer (15). Furthermore, the chemical composition of the reaction constituents affects the synthesis of nanoparticles, especially the biomolecules that are accessible for reduction.

Green nanoparticle synthesis

Green nanoparticles are produced using biological systems, including plants, microorganisms (bacteria, fungi, and algae), and other biological entities. This eco-friendly and cost-effective approach has gained attention due to its potential for large-scale synthesis without the use of harmful chemicals. The main types include metallic nanoparticles like silver (Ag) and iron (Fe) are effective in water purification and pollutant removal, with iron oxide (Fe_3O_4) nanoparticles being particularly useful for magnetic separation of contaminants. Metal oxide nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO_2) act as photocatalysts for degrading organic pollutants and improving water and air quality. Other types include carbon-based nanoparticles like graphene oxide and polymeric nanoparticles derived from natural polymers such as chitosan, contribute to wastewater treatment and soil restoration. Quantum dots, bimetallic nanoparticles (e.g., Au-Ag), and specialty nanoparticles such as selenium, tellurium, and silica also play roles in areas like imaging, and catalysis. These nanoparticles are valued for their biocompatibility, scalability, and sustainable production methods. The types of nanoparticles synthesized biologically are listed in Table 1.

Utilizing plant extract for green nanoparticle synthesis

Plants are recognized as natural chemical factories. The use of plant extracts in nanoparticle production has advantage over theo other organic techniques such as microbial synthesis because it avoids the difficulties associated with managing microbial colonies. A workflow for the green production of NPs using plant extracts was shown in Fig. 4. Flavonoids, phenolic acids, and tannins are among the several polyphenolic substances found in mango leaves and inflorescence. These compounds function well as reductants in reaction involving the production of nanoparticles (16). These polyphenols assist to generate silver nanoparticles (AgNPs) from silver nitrate and have antioxidant propertes. Many phytochemicals found in ivy gourd stems including phenolic compounds, flavonoids, and terpenoids are essential for the production and stability of gold nanoparticles (AuNPs) (17). These substances facilitate the reduction of gold ions (Au^{3+}) from hydrochloroauric acid ($HAuCl_4$) to produce AuNPs, which are used to enhance for the absorption rate of drug molecules in curing the cataracts (18). Flavonoids and phenolic acids, which are abundant in okra blossoms, function as reductant in the manufacturing of silver nanoparticles (AgNPs). Similarly, phytochemicals such as flavonoids, phenolic compounds, and terpenoids found in the leaves and roots of castor oil plants aided the formation of AgNPs by reducing the ionic metals. To enhance the bioavailability of drugs, these AgNPs are used in bioadhesive films for ocular distribution (19). Gallic acid from fig is an efficient reducing agent that helps in the production of dysprosium stannate nanoparticles. These nanoparticles are gas sensitive and can be used in gas sensor devices to detect volatile organic compounds and pollutants (20). Arecanut seed contains cellulose of 25–35%, hemicellulose of 20–30%, lignin of 10-15%, ash of 5–8%, silica of 1–2% and lauric-acid which have excellent antibacterial, antioxidant, and antiviral properties. AgNPs have been synthesized by reducing aqueous $AgNO_3$ using the extract of arecanut by exposing it to microwave radiations at a rate of 2.45 GHz. The synthesized AgNPs are used as potential antimicrobial agents.

Fig. 4. Integrating plant extracts for the green synthesis of nanoparticles (96).

Zinc oxide nanoparticles (ZnONPs) were synthesized from zinc nitrate hexahydrate using *Parthenium hysterophorus* whole plant aqueous extract in which, the presence of phytochemicals such as flavonoids, saponins, phenols, terpenoids and tannins are essential for capping, stabilizing, and reducing metal ions from high oxidation

Table 1. Types of biologically synthesized nanoparticles

Type of Nanoparticle	Materials Involved	Biological Source
Metal Nanoparticles	Gold, silver, copper, zinc, platinum	Plants, bacteria, fungi, algae
Oxide Nanoparticles	TiO_2, ZnO, Fe_2O_3, CuO	Plants, bacteria, fungi, algae
Carbon Nanoparticles	CNTs, graphene, fullerenes	Fungi, algae
Polymeric Nanoparticles	Chitosan, alginate	Algae, fungi
Quantum Dots	CdS, Se, semiconductor materials	Plants, bacteria, fungi
Composite Nanoparticles	Metal-polymer composites	Plants, microorganisms

state to zero-valent species (21). The synthesized ZnONPs are employed to breakdown methylene blue dye from aquatic environments (22). Secondary metabolites including alkaloids, phenols, carbohydrates, saponins, and proteins found in the extract of *Cyperus rotundus* roots serve as stabilizing agents during the synthesis of metal nanoparticles. Gold nanoparticles (AuNPs) were generated by treating different ratios of *Cyperus rotundus* aqueous extract with a fixed volume of gold chloride (1:1, 1:2, 1:3, 1:4, 1:5) using hot air heating method and the formation of gold nanoparticles was confirmed by observing the colour change from light yellow to greyish pink. The resultant AuNPs has antibacterial properties against *Salmonella paratyphi* and *Staphylococcus aureus.* With an increase in the concentration of AuNPs, the inhibitory potential of AuNPs towards both gram-positive and gram-negative bacteria increases (23). *Cynodon dactylon* is particularly valued for its high content of phytochemicals such as flavonoids and phenolic acids which possess strong reducing and stabilizing properties. These compounds are capable of efficiently reduce the titanium precursor compound titanium isopropoxide, to form TiO_2 nanoparticles (24). The resultant TiONPs were used in the removal of organic pollutants from water bodies. Owing to their high surface area, photocatalytic activity and stability, these nanoparticles can effectively degrade organic pollutants under ultraviolet (UV) or visible light irradiation (25). The significance of plant extract-derived green nanoparticles is shown in Table 2.

Agricultural waste for the synthesis of green nanoparticles

Green treatment methods utilizing agricultural and agro-industrial biowaste for bio-fabrication of nanomaterials due to the presence of biomolecules, which are capable of acting as capping or stabilizing agents, making them ideal for nanomaterial fabrication (26). It offers minimal toxicity, low cost, and resource-conserving advantages over traditional methods. The synthesis of nanoparticles from different sources of agricultural wastes such as fruit waste, vegetable waste etc., was shown in Fig. 5. Jackfruit peel is one of the underutilized wastes that have high amounts of pectin (0.12%), cellulose (27.75%), protein (0.03%), and starch (4%). Higher concentration of antioxidants in peel makes it a promising source of important biomolecules (1). When the solution of $FeCl_2$ was added to peel extract, the solution instantly changed colour from yellow to vivid black, represent the development of FeNPs-JF as shown in Fig. 6 (27). FeNPs can be synthesized with excellent catalytic activity because of their large surface area, which affords active sites to produce hydroxyl radicals. The active species involved in the oxidative degradation of fuchsin basic dye by fenton-like oxidation. This is because of their high temperature at 80^0C for AgNPs synthesis. Excellent antibacterial activity was demonstrated by non-woven textiles loaded with the bioinspired silver nanoparticles (4). Sapota pomace is considered as waste after extraction of juice from *Manilkara zapota.* The pomace contains high dietary fiber and is a significant source of phenolics (1–5%) and terpenoids (0.1–1%) and polysaccharides (10–40%) and flavonoids (0.5–2%). These compounds have been utilized as reducing agents for the production of AgNPs (reactivity, strong adsorption capacity, and low cost), they have gathered a lot of interest as possible catalysts for environmental remediation (28). Mango peel contain polymers such as polysaccharides of 20–40%, lignin of 1–5%, flavonoids of 0.5–2%, hemicelluloses of 5–15%, and pectins of 5–15%, are used to produce Ag nanoparticles. Mango peel extract has been used to reduce aqueous $AgNO_3$, and then incubated (29). These AgNPs are moderately stable and show antibacterial activity against both gram positive and negative microorganisms (30). Papaya peel contains various phyto-constituents such as alkaloids (0.1%), terpenoids (0.1–1%) and flavonoids (0.5–2%) (31). These phyto-constituents act as stabilizing as well as reducing agents during the green synthesis of CuONPs from copper (II) nitrate trihydrate salt (32). The synthesized CuONPs are pure and crystalline with a band gap energy of 3.3 eV, possessing excellent electrical, catalytic, optical, magnetic and biological properties (33). The CuONPs have significant photocatalytic performance in degrading Palm Oil Mill Effluent (POME) with reduced phytotoxicity. The hydrolyzed lemon peel extract contains hesperidin flavanol, which functions as a reducing agent by releasing aglycone. For the first time, TiO_2NPs were synthesised from lemon peel extract by reducing the bulk powder of titanium (34). The resulting nanoparticles absorption

Table 2. Role of green nanoparticles synthesized from plant extract

Sl. No	Plants	Parts	NPs	NPs size (nm)	References
1.	*Coccinia grandis*	Stem	Au	20	(69)
2.	*Mangifera indica*	Inflorescence	Ag	30–70	(70)
3.	*Morinda citrifolia*	Leaf, fruit, seed	Ag	3–11	(71)
4.	*Toxicodendron vernicifuum*	Rind	Ag	2–40	(72)
5.	*Capparis cantoniensis*	Leaf	Ag	23	(73)
6.	*Nerium oleander L*	Rind	Au	20–40	(74)
7.	*Stevia rebaudiana*	Leaf	NiO	20–50	(75)
8.	*Abelmoschus esculentus*	Flower	Ag	5.5–32	(76)
9.	Castor-oil plant	Leaf, root	Ag	38 , 29	(77)
10.	*Garcinia mangostana*	Peel	ZnO	25–70	(78)

Fig. 5. Generally used agricultural waste for the synthesis of nanoparticles i. Jackfruit peel waste; ii. Cauliflower leaf waste; iii.Mango peel waste; iv. Sapota pomace waste; v. Papaya peel waste; vi. Lemon peel waste; vii.Arecanut waste; viii.Rice husk waste; ix.Garlic peel waste; x. Saw dust; xi.Walnut shell; xii.Corn cobs; xiii.Cotton waste; xiv.Coconut shell waste; xv.Banana peel waste; xvi.Parthenium weed waste.

spectra confirm that TiO_2NPs with a band gap of 3.08 eV and utilized in self-surface cleaning, electronics, batteries and water treatment (35). Banana peels contains polymers such as hemicellulose, pectins, and lignin, which can be utilized to make palladium and silver nanoparticles. In the synthesis of palladium nanoparticles (PdNPs) the source of palladium was palladium chloride ($PdCl_2$) which is reduced by banana peel extract to form palladium nanoparticles (PdNPs). These bio-inspired nanoparticles find applications as catalysts, sensors and making active membranes (36). Mangosteen peel is well known for having a high concentration of polyphenolic chemicals, including xanthones which have potent antioxidant effects and act as reducing agents in reaction involving the production of ZnO nanoparticles, having UV-blocking and antimicrobial properties when xanthones effectively reduce zinc ions from zinc nitrate hexahydrate solution (37, 10).

Cauliflower leaves are abundant in polyphenols, which serves as a reductant to produce nanoparticles. Leaf waste extract reduces Ag^{1+} in $AgNO_3$ solution to Ag^0 to produce silver nanoparticles (38). This process was verified by spectrophotometry which showed a colour shift from yellow to black. Biosynthesized AgNPs showed promising photocatalytic activity for degrading harmful synthetic methylene blue dye and efficient colorimetric sensing ability for detecting Hg^{2+} ions in industrial wastewater (39). Garlic peel stands out as a unique material that can serve as a lignocellulosic precursor for producing porous carbons. They have an extensive surface area and

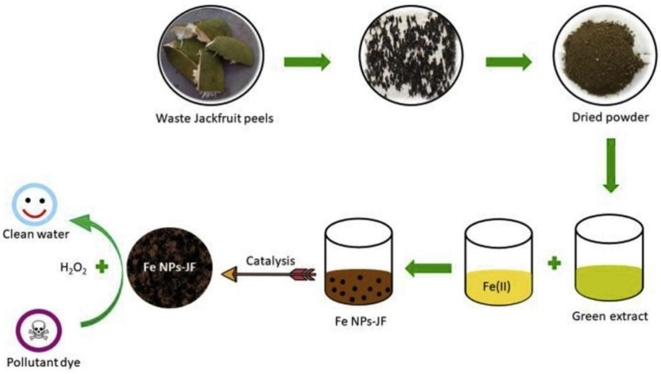

Fig. 6. FeNPs synthesized sustainably with jackfruit peel extract (1).

multilayered porosity, a tailor-made need for effective energy storage devices (40).

Cellulose nanocrystals were produced from arecanut husk fibers by sulfuric acid hydrolysis following the ultra sound method (7). Cellulose nanocrystals exhibited effective antibacterial and antifungal activities against pathogens. Increased coconut crop production has led to a massive increase in coconut waste production. Coconut shell is composed mainly of lignin (36.51%) and cellulose (33.61%) and it absorbs less moisture content than other agricultural waste. The silver nanoparticles (AgNPs) were prepared by reducing the $AgNO_3$ using coconut shell extract (CSE). CSE-AgNPs exhibited a wider range of inhibition than CSE against specific pathogens. The greater surface area of CSE-AgNPs may account for their higher inhibitory effect (41). Cotton residue stands out among agricultural residues due to its large production and high cellulose content, which enables r recycling and stimulates interest in cost-effectiveness, and environmental responsive. Owing to their abundance, bio-compatibility, bio-degradability, and renewability, nanocelluloses (NCs) are a highly appealing way to recycling lignocellulosic residues (42). Cotton waste is hydrolyzed in an acidic solution to produce nanocelluloses. The resulting NCs are made up of long, pure fibres with a diameter of 30 nm. NCs are effective biomaterials that find usage in a variety of industries such as food, electronics, and green nano-composites (43).

Rice husks contains of cellulose (30–45%), lignin (15–25%), hemicelluloses (20–35%), and silica (15–20%). SiNPs were produced using rice husk ash as the silica source and cetyltrimethyl ammonium bromide (CTAB) as the surfactant using the sol-gel approaches. It offers several uses like treatment of wastewater and the fabrication of nanocomposite materials (44). Corn cobs accounted for 20% of the total corn yield. Biochar, synthesized from corn cob waste by pyrolysis process was impregnated with macro and micronutrients to formulate as nanocomposite. Owing to the studies on salt index, water absorbance and retention, slow release column, and retention, biochar nanocomposite (BNC) has a lot of promise for application as a nanofertilizers (45). Various green NPs synthesis from agricultural waste and its application are given in the Table 3.

Green hybrid nanoparticle synthesis

Green hybrid nanoparticles are eco-friendly materials synthesized using biological sources such as plant extracts or microbes, combined with other nanomaterials such as metals or polymers. This hybrid approach enhances the properties of the nanoparticles, such as stability, functionality, or biocompatibility, while minimizing environmental toxicity and promoting sustainability in various applications. The utilization of amrita (*Tinospora cordifolia*) extract, aids in reducing copper (II) chloride, thus facilitating the production of copper nanoparticles (CuNPs). Subsequently, a solution containing manganese dioxide (MnO_2) is introduced into the mixture of CuNPs. Where in sodium borohydride operates as reductants, facilitating the bonding of manganese dioxide atoms to the surface of the existing CuNPs. As a result, this process yields copper-manganese dioxide nanoparticles (Cu.MnONPs), effectively amalgamating copper with manganese dioxide particles (46). The synthesized Cu.MnONPs possess excellent adsorption properties; enabling the efficient capture and elimination of various pollutants from water, including heavy metals, organic

Table 3. Synthesis of green NPs from agricultural waste and their application

Sl. No	Vegetable/ fruit	Plant part	NPs synthesis	Size (nm)	Applications	References
1.	Onion	Outer peels	Ag	20–40	Acetylation reaction	(79)
2.	Sapota	Pomace	Ag	30–60	Antibacterial activities	(80)
3.	Lemon	Outer Peels	TiO_2	5–20	Optical and photocatalytic properties	(81)
4.	Grapes	Pomace	Ag	20–50	Used as Antidiabetic, Antioxidant Potential, and Antibacterial Activity Against Human Pathogens	(82)
5.	Pineapple	Leaf	Ag	20–40	Used in enhancing optical properties and antibacterial activities.	(83)
		Peel	ZnO	10–30	Food packaging and Antibacterial activity	(84)
6.	Caulifower	Waste extract	Ag	20–50	Used in biosensing of Hg^{2+} and c degradation of methylene blue (MB) dye.	(85)
7.	Jackfruit	Peel	Fe	20–40	Act as catalyst for the degradation of Fuchsin Basic dye	(1)
8.	Banana	Peel	Pd	20–40	Used in making active membranes and as catalysis in devising sensors	(86)
9.	Mango	Peel	Ag	20–50	Antibacterial activity used in preserving fruits and vegetable	(87)
10.	Papaya	Peel	CuO	10–30	Degrading palm oil mill effluent (POME) by acting as a photocatalyst.	(88)

compounds, and pathogens. Indian mallow *(Abutilon indicum)* extract was used to reduce zinc nitrate hexahydrate, for the synthesis of zinc oxide nanoparticles (ZnONPs). Subsequently, a solution containing copper nitrate is added to the mixture of ZnONPs. Sodium borohydride acts as the reducing agent in this process, aiding in the bonding of copper atoms to the surface of existing ZnONPs. Consequently, copper-zinc oxide nanoparticles (Cu.ZnONPs) were generated and formulated into smart nanofertilizers for precision agriculture (47). These nanoparticles were engineered to gradually copper and zinc ions in response to specific environmental cues such as soil moisture, pH levels, or nutrient deficiencies. By incorporating nanofertilizers with controlled-release mechanisms, farmers can optimize nutrient uptake by plants, minimize nutrient leaching into groundwater, and reduce environmental pollution.

Utilization of microbes for green nanoparticles synthesis

Green nanoparticle production relies considerably on microorganisms, either directly or indirectly. The ability of microorganisms to generate nanomaterial has been investigated in several studies. Microorganisms can produce nanoparticles by reducing or adsorbing metal ions (48). The initial stage of the nanoparticles formation in microorganisms is the internal or external accumulation of metal particles, which is then reduced by an enzyme to produce nanosized particles. Extracellular synthesis is comparatively more common than intracellular synthesis, primarily because of their ease of purification and recycling of nanoparticles generated extracellularly. On the other hand, purification may be more difficult for intracellularly generated nanoparticles as they may damage the cells during gathering. Despite the specific mechanism of microbial intracellular nanoparticle synthesis is unknown, it is thought that positive ions are captured by enzymes which are negatively charged or surfaces of the cell walls and these ions are then reduced to produce nanoparticles.

The marine bacterium *Paracoccus haeundaensis* utilizes its cell-free supernatant inorder to reduce the gold ions in chloroauric acid, resulting in spherical gold nanoparticles that measure 20.93 ± 3.46 nm on average (49). *Proteus vulgaris* ATCC-29905 has been used for producing iron oxide nanoparticles (FeONPs) by the extracellular technique (50). *Proteus vulgaris* functions as a possible agent in the ferric chloride reduction process, which leads to FeONPs (51), and has great antibacterial activities (52). *Lactobacillus acidophilus* converts sodium selenite into selenium nanoparticles with the help of reductants like enzymes and metabolites (53). The resultant nanoparticles exhibit stability and biocompatibility and hold promise for applications as antibacterial agents and dramatically breaking down the prefabricated bacterial biofilms (54). The silver (Ag^+) ions in silver nitrate are effectively reduced to silver (Ag) by *Cupriavidus sp.* reducing agents, which include enzymes and metabolites, promote the creation of silver nanoparticles (55). Thus formed AgNPs demonstrated antibacterial characteristics against clinical human pathogens that are gram-negative and their biofilms (56). Various biological organisms involved in the silver nanoparticle synthesis are shown in Fig. 7.

ZnONPs and CuONPs have been produced from zinc acetate dihydrate and copper acetate monohydrate, respectively, using the *Penicillium chrysogenum* MF318506 strain that showed inhibitory actions towards an array of pathogens, encompassing gram-positive and gram-negative bacteria in addition to certain phytopathogenic fungi (48,57). Titanium dioxide nanoparticles can be produced from titanium tetrachloride ($TiCl_4$) by the filamentous fungus *Aspergillus flavus* where in the fungal biomass acts as a stabilizer and reductant. The resultant nanoparticles are photocatalytically active and promising agents for air and water detoxification and purification (58). Zinc oxide nanoparticles (ZnONPs) were produced sustainably from zinc nitrate using the ubiquitous fungus *Fusarium oxysporum* as stabilizers and reductants (59). These are appropriate for an array of biologic and ecological purposes since they display antibacterial capabilities against both positive and negative gram bacteria (60). Silver nanoparticles (AgNPs) are produced from silver nitrate by filamentous fungus *Trichoderma sp*., which is frequently found in the soil and plant roots. These particles have applications for use in farming, and ecology

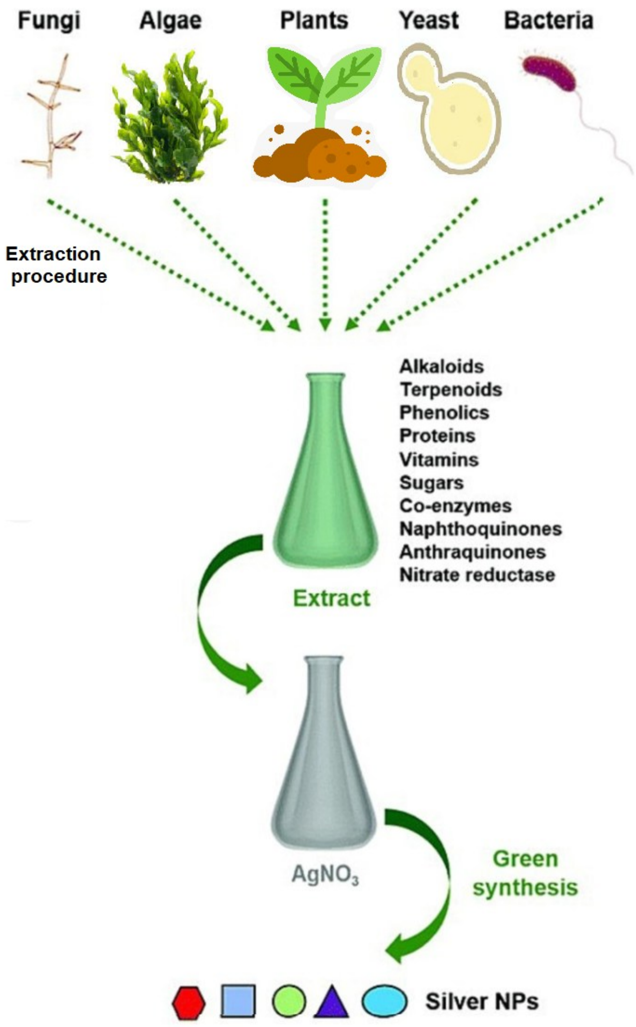

Fig. 7. Biological synthesis of AgNPs (97).

as they exhibit significant antimicrobial action against an array of harmful microbes (61).

Microalgae are primitive microscopic plants. They have significant benefits over higher plants as cell factories for nanoparticle production. Since *Chlorella vulgaris* is a well-known commercial algae with a rapid growth rate, it was chosen as the source of the gold nanoparticles (62). When exposed to gold chloride, the live cells produce large amounts of gold nanoparticles (AuNPs) in their cytoplasm (63). AuNPs are used in catalysis, sensors, biosensors and antibacterial applications. The production of MnO/C microspheres uses *Nannochloropsis oculata*, a spherical microalga with a diameter of 2 µm because of its easy availability and rapid growth rate. *N. oculata* primary cell wall is made of polysaccharides, which enable it to adsorb and absorb metal ions through electrostatic interactions. *N. oculata* culture mixture is introduced to the $KMnO_4$/ Na_2SO_4 solution during the synthesis, causes metal ions to biosorb and spontaneously redox and deposit on the *N. oculata* surface (64). MnO/C microspheres with hollow pores show potential as electrode materials for enhanced batteries powered by lithium-ions (65). The production of green nanoparticles from different microbes is shown in Table 4.

Challenges and future perspective

Green nanotechnology iswidely used, but a several issues must be resolved. These challenges include the ecologically benign synthesis of nanoparticles by plant-mediated methods. To meet this task, it is imperative to standardize green synthesis techniques and optimize reaction conditions (66). Characterizing green synthesized nanoparticles to ensure their quality, stability, and safety for a variety of applications is another critical step. However, the reproducibility and scalability of green synthesis techniques are significant hurdles. Large-scale consistency in nanoparticle synthesis can be challenging to attain due to the inherent variability in plant extracts, environmental factors, biological processes and their limitation was shown in Fig. 8. Evaluating the physicochemical characteristics and biological interactions of these nanoparticles requires the development of robust analytical methods and quality control procedures. In addition, it is essential to take regulatory compliance and risk assessment into account when addressing the negative impacts of green nanotechnology on human well-being and the environment (67). To overcome these obstacles and fully use green nanotechnology for the production of sustainable nanomaterials, cooperation among researchers, industrial stakeholders, and regulatory agencies is vital.

Research efforts are anticipated to focus on quickening extraction processes from a variety of plants, microorganisms, agricultural leftovers such as crop residues, food processing byproducts, and biomass wastes in order to ensure the efficient use of the available resources (68). Customizing the properties of nanoparticles for specific applications such as agricultural and environmental cleanup, will be a significant field of research. By addressing these future directions, green nanotechnology which uses plants, microorganisms, and agricultural wastes for green nanoparticles can improve resource efficiency and sustainable development.

Conclusion

Growing interest has been shown in the green synthesis of nanoparticles as a non-toxic, eco-friendly, and economical approach. By using fewer chemical reagents and maximizing the benefits of various metals and non-metals, this innovative method produces composite nanoparticles that highlight the ability of plants, microbes, and agricultural wastes to promote synthesis. These naturally occurring substances that function as reductants and stabilizers have revealed uses in anything from environmental cleanup to agriculture having a revolutionary effect. It is critical to improve the use and sustainable growth of green synthetic nanoparticles. A comprehensive evaluation encompassing f agriculture to

Table 4. Synthesis of green nanoparticles from microbes

Sl. No	Organism	Species	NPs type	NPs shape	Size (nm)	References
1.	Bacterium	*Lactobacillus acidophilus*	Se	Non-applicable	2–15	(54)
		Paracoccus haeundaensis	Au	Spheroidal	17.5–24.4	(49)
		Proteus vulgaris	Fe_2O_3	Spheroidal	19.2–30.5	(89)
		Cuprividus sp.	Ag	Spheroidal	10–50	(55)
2.	Fungus	*Cladosporium cladosporioides*	Ag	Spheroidal	30–60	(90)
		Penicillium chrysogenum	ZnO, CuO	Hexagon, spheroidal	9–35, 10.5–59.7	(48)
		Aspergillus sydowii	Ag	Spheroidal	1–24	(91)
3.	Algae	*Chlorella vulgaris*	Au	Spheroidal	10–200	(92)
		Nannochloropsis oculata	MnO_2	Cube	Not applicable	(93)
		Scenedesmus sp.	Ag	Spheroidal polyhedron, rod-shaped	15–20	(94)

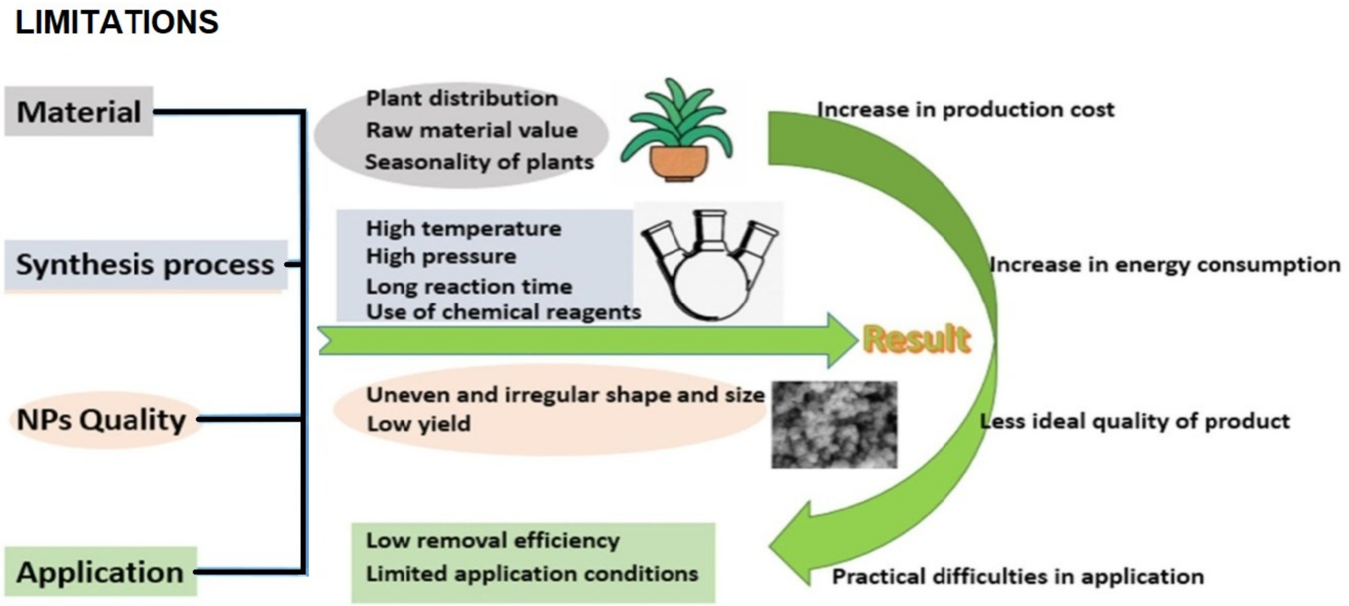

Fig. 8. Limitations and challenges with green synthesis technologies (98).

environmental remediation, food quality enhancement and engineering applications indicates the transformative influence of these particles in various sectors, as we serve towards sustainable growth and wider use of green synthetic particles. This review highlights the critical function of green-synthesized nanoparticles and illuminated a route towards a more robust and sustainable future. Thus, one of the more promising green biotechnologies that could balance the agro-ecosystem and inflict less environmental impact is the green biosynthesis of nanoparticles from agricultural waste, microorganisms, and extracts from plants.

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Author contribution

CB, RR, PJ and RS were responsible for conceptualization and writing of review article. APS, GS and NC were collected scientific materials and contributed for writing the manuscript. SR, MS and ST provided guidance and corrected the manuscript, RS,BR and RB reviewed and edited the manuscript.

All authors read and approved the final manuscript.

Compliance with Ethical Standards

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

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