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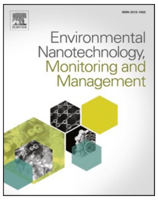

A comparative analysis of chemical vs green synthesis of nanoparticles and their various applications

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ABSTRACT

The synthesis of high-quality nanomaterials by different of methods have been developed through physical, chemical, biological, microbial, green synthesis, coprecipitation, hydrothermal treatment, flame pyrolysis, and biogenic reduction processes. The nanomaterials produced have offered substantial benefits to society through their successful implementation in numerous fields, such as food safety, transportation, energy, catalysis, medicine, antimicrobial, anticancer, antioxidant nanodrugs, vaccines, capacitors, fuel cells, and batteries. Many hazardous effects have been reported due to chemical synthesis, so the potential utility of nanomaterials is also recognized in environmental management,as there is growing demand to control diverse pollutants. At present, there is a green synthetic route for the development of nontoxic and eco-friendly materials in a sustainable manner. The main objective of this review is to provide a perspective overview by comparing green versus chemical synthesis methods concerning the types, advantages, disadvantages, and persistent solutions for extermination caused by toxic nanoparticle production methods.

1. Introduction

Nanoparticles (NPs)are the smaller particles having size in the range of 1–100 nm (Kaushik et al., 2010). They have unique and intriguing features because of their small size, substantial surface area with free dangling bonds, and higher reactivity than their bulk counterparts (Zharov et al., 2005). A significant number of dangerous and undesirable compounds are being emitted, and rapid industrialization, urbanization, and population growth are contributing to the destruction of the Earth's atmosphere. Understanding natural products and the environment is imperative and will help us enhance nanoparticle synthesis techniques. Thus, developing synthesis methods that do not include hazardous substances is becoming increasingly essential. The use of harmful byproducts, the production of poisonous solvents, and the imperfection of the surface structure are only a few of the issues with these expensive processes. Becauseof the complexity and unpredictability of their composition, chemical procedures typically include use of the multiple chemical species or molecules, which could enhance their toxicity and particle reactivity and affect both living and nonliving organisms (Li et al., 2011). The development of practical green synthesis methods instead of harmful, costly and energy-intensive chemical methods has prompted researchers to turn to biological methods (Dhillon et al., 2012). Thus, available alternative to physico-chemical approaches for the creation of nanoparticles is green/biological

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Abbreviations: NPs, Nanoparticles; NMs, Nanomaterials; IC_{50}, Inhibitory concentration; FT-IR, Fourier Transform Infrared; Huh-7, Human hepatoma derived cells; ppm, Parts per million; UV–Vis, Ultra violet Visisble; CNTs, Carbon nanotubes; CNFs, carbon nano fibers; CVD, Chemical vapour deposition; HIV, Human Immunodeficiency virus; Atm, Atmospheric; UTEX, University of Texas; Zn-NFs, Zinc Nanoflowers; CS NWs, Chemically synthesized nanowires; BS NFs, Biosynthesized nanofibres; *W. coagulans*, *Withania coagulans*; *S. aureus*, *Staphylococcus aureus*; *P. aeruginosa*, *Pseudomonas aeruginosa*; *E. Coli*, *Escherichia coli*; *A. mellifera*, *Apis mellifera*; *F. cretica*, *Fagonia cretica linn*; *Lactuca sativaL.*, *Lactuca sativa Linn*; *G. mangostana*, *Garcinia mangostana.*

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synthesis over nanomaterials made via physico-chemical processes; NPs created using biological means are preferred due to their unique qualities (Singh et al., 2015). When green synthesis is applied, different particles are created than in physicochemical methods. In a bottom-up method known as "green synthesis," a natural extract from a product, such as fruit or leaves from a tree or crop, is applied in place of an expensive chemical reducing agent to create nanoparticlesof metals and their oxides. The potential for the creation of NPs in biological organisms is enormous. The biological reduction of metal initiators to match NPs is cost-effective (Mittal et al., 2013), environment-friendly (Jayaseelana et al., 2012), sustainable (Gopinath et al., 2014), devoid of chemical contamination (Chandran et al., 2006), and suitable for mass production (Iravani et al., 2011). Additionally, the green production of nanomaterials enables the recycling of expensive metal salts such as Au and Ag in waste streams.

There are reports of NPs being produced in vivo by plants, algae, yeast, fungi, and bacteria (Duran et al., 2011). Plants or their extracts exhibit the finest biological properties because they are widely accessible and appropriate for mass-producing NPs. Their waste products are environmentally acceptable, in contrast to some microbial extracts (Lee et al., 2011). The biogenesis and possible uses of various metallic and semiconductor NPs, including Cu, Fe, Au, Ag, Ru, Pd, PbS, CdS, CuO, CeO_2, Fe_3O_4, TiO_2, and ZnO, have been investigated. The biological components that stabilize NPs, primarily proteins, enzymes, carbohydrates, and sometimes entire cells, enable NPs to interact with other biomolecules and enhance interactions with microbes, increasing antimicrobial activity (Botes et al., 2010). Furthermore, biological entities must stabilize and cap substances needed as growth inhibitors to prevent aggregation (Kharissova et al., 2013). The structure of NPs is influenced by the concentration and kind of biological entities in addition to organic reducing agents (Aromal et al., 2012). Additionally, the growthmediumcharacteristics, including pH, temperature, salt concentration, and exposure period, substantially influence the size and form of NPs (Gericke et al., 2006). For the creation of nanomaterials, metal precursors are bioreduced either in vitro or in vivo. All other substances, however, primarily function as stabilizing and reducing agents, including proteins, carbohydrates, and phytochemicals such as terpenoids, flavonoids, and phenols (Kaushik et al., 2010).

Compared to their nonnanoscale or bulk counterparts, metals at the nanoscale have a larger surface area. Additionally, they possess unusual physicochemical properties not found in nonnanomaterials because of their small size, surface, interface, and quantum effect. Numerous nanoscale metals are extensively used in engineering, biology, and other fields (Zhao et al., 2016). For instance, Au nanoparticles are applied in biological applications such as regulating enzymes, antibacterial activity, and muscular relaxation (Islam et al., 2015). Both gram-positive and gram-negative bacteria are inhibited by Ag NPs growth and activity (Ajitha et al., 2014).

Because of their ramifications in numerous technological fields, the generation of nanomaterials is gaining relevance (Pascariu et al., 2013). In the first scenario, one of the most crucial processes in the manufacture of dyes, pigments, and refractories in the raw chemical sector is the synthesis of inorganic nanosized powders by flame pyrolysis. In the latter, certain classes of nanomaterials are still regarded as niche goods. Batch chemical processes still produce them, frequently necessitating precise and challenging control over the necessary process variables (Reverberi et al., 2016). When a chemical procedure is used to create NPs, a variety of species are frequently used as reagents, complexants, stabilizers, and surfactants as primary chemicals or correctors, aiming to tune the characteristics of the as-produced nanophase.

For instance, a reduction process necessitates the use of inorganic or organic electron donors that are harmful to people or the environment because of toxicity, irritation, mutagenicity, or other adverse effects. This review focuses on affordable, safe, and environmentally friendly reactants that replace harmful compounds. Such reagent substitution necessitates the development of a new trade-off between environmental sustainability, reaction yield, and safety issues related to modifications in process variable settings (Thunugunta et al., 2015). Biochemistry plays a key role in highlighting the elements that need to be changed to achieve a higher level of sustainability and environmental soundness and problems of changes in reagents and process variables for NPs synthesis, according to inherent safety concepts already applied in conventional processes (Fabiano et al., 2012). The promise of nanomaterials in the future is significantly impacted by green chemistry. Creating secure, eco-sustainable NPs in this field of nanoscience should be the ultimate goal of the field, and nanotechnology should broadly accept this goal.

Nanoagricultural, or the use of innovative technologies to increase crop productivity, is the term for the role of nanoparticles in agriculture (Duhan et al., 2017). There are applications for nanoparticles synthesized from many biological sources in agriculture (Kaur et al., 2018). By controlling the germination of old seeds and their vigour, it was reported that TiO_2 nanoparticles can promote spinach germination and plant growth (Zheng et al., 2005). Plants can consume metal nanoparticles in micronutrients, and their high dose causes soil pollution (Rajput et al., 2018). The best solution metal oxide for reducing the dose while maintaining excellent efficacy is to embed these metal nanoparticles in biocompatible polymers. Using chitosan as a polymer, researchers created chitosan-metal nanocomposites with excellent antifungal properties against *Fusarium wilt* and demonstrated favourable effects on chickpea plant development metrics.

Nanotechnology is also used to create nanofertilizers, insecticides, herbicides, and sensors. Since the Earth's genesis, NPs are expected to be present in soil, water, volcanic dust, and minerals. NPs and the nanomaterials they give rise to are widely used in many sectors, notably food, agriculture, cosmetics, pharmaceuticals, and others. Food processing, food preservation, and packaging are the applications of NPs in the food industry (nanocoatings, nanosensors, nanocomposites, edible coating NPs, etc.). Nanotechnology is used in medicine to deliver multiple antibacterial, antifungal, antiplasmodial, anti-inflammatory, anticancer, antiviral, antidiabetic, and antioxidant medicines. Early diagnosis of fatal diseases such as cancer is another nanotechnology application (Dikshit et al., 2021). Because of their antibacterial properties, NPs are occasionally called "nanoantibiotics." In consumer industries, including food, space, chemical, cosmetics, and health, all use nanoparticles, which necessitates a green and environmentally friendly synthesis process (Sharma et al., 2019).

Compared with conventional chemical and physical methods, green methods for the synthesis of nanoparticles are less costly, easy, eco-friendly and biosynthesisfriendly (Adelere et al., 2016). Scenarios have reported immensework in the creation of nanoparticles by green methods, like the synthesis of Ag-doped ZnO/CaO nanoparticles by a green method with the use of *Caccinia macranthera* seed extract, zinc, calcium, and silver salt solutions, have been reported. The structure of the nanoparticles was studied by FT-IR spectroscopy. An X-ray diffraction pattern was observed for the crystallite structure with a 23 nm size and spherical morphology. The cytotoxicity of synthesized nanoparticles was also examined in Huh-7 (human hepatoma-derived) cells, and the inhibitory concentration (IC_{50}) was 250 parts per million (ppm). Furthermore, the antibacterial and photocatalytic properties of nanoparticles were also examined against both gram-positive and gram-negative bacteria, with the range of 0.97–125 ppm being reported as the minimal inhibitory concentration (Sabouri et al., 2022).

Using a plant extract called *Rheum turkestanicum* as a stabilizing agent, a sol–gel technique was utilized to create cerium(IV) oxide nanoparticles in a green manner. Many techniques of spectroscopy have been reported to identify the produced nanoparticles. The X-ray diffractogram of the CeO_2 nanoparticles revealed a cubic fluorite structure. The particles had a spherical radius of 30 nm, and a prominent absorption band was detected in their UV–Vis spectra. The cytotoxic impact and photocatalytic activity of CeO_2-NPs are linked to cancer cells and sewage water contaminants, respectively (Darroudi *et al*., 2022).

Aquatic plants such as *Piaropus crassipes* and *Lemna gibba* were utilized to make low-cost nanoparticles, and their feasibility for the removal of Zn(II) ions was studied. Fourier transform infrared spectroscopy,scanning electron microscopy, and other techniques were used to characterize the produced nanoadsorbents. Zn(II) adsorption by*Piaropus crassipes* and *Lemna gibba*occurred via surface complexation, ion exchange and diffusion. Desorption studies were performed to analyse the recovery potential of Zn (II) ions. This work suggested the economic synthesis of green nanoparticles and their potential utilization in heavy metal remediation (Maheswariet al., 2021).

1.1. Development and classification of nanoparticles

Nanoparticles have a long history; they are a discovery of modern science. Nanotechnology dates back thousands of years. Nevertheless, no one can precisely pinpoint the advantages of nanoparticles in many fields. One of the leading and most important characteristics of nanoparticles is their optical quality. A silver nanoparticle, for example, has a yellowish-grey color. A typical red wine hue can be seen in a gold nanoparticle that is 20 nm in size. Black nanoparticles of Pt and Pd are present. The application of nanoparticles in painting dates back to the fourth century AD because of their optical properties. Until the middle ages, gold was effective for treating dysentery, epilepsy, and heart disease. It was also helpful in the identification of diseases such as syphilis. Due to its many applications in various sectors, including food safety, transportation, renewable energy, environmental science, and catalysis, and medicine, nanotechnology has experienced incredible growth over the past ten years. Being free of severe operating conditions, dangerous chemicals, and the inclusion of outside stabilizing or capping agents makes the production of nanoparticles utilizing green synthesis methods particularly desirable (Dikshit et al., 2021).NPs with small particle size, shape, and crystallinity can be applied in biomedicine, biosensors, catalysts for bacterial biotoxin elimination, and inexpensive electrodes (Antonyraj et al., 2013). Detection is among the most appropriate applications (Xia et al., 2013); emerging and future research will focus on the biosynthesis of NPs rather than chemical synthesis.

Numerous classifications of nanoparticles are produced biologically and are used for their synthesis. The morphology, size, and form of nanoparticles are used to categorize them into various categories. In this review, a few significant classes of nanoparticles are mentioned. The organic nanoparticles include ferritin, micelles, dendrimers, and liposomes. These hollow spheres, such as micelles and liposomes, are nontoxic and biodegradable. It is also recognized by the names of nanocapsules that are sensitive to heat and light (Tiwari et al., 2008). These properties make organic nanoparticles an excellent option for medication delivery. The term “polymeric nanoparticles” is generally used to describe organic nanoparticles. Inorganic nanoparticles do not include carbon. Nontoxic inorganic nanoparticles are biocompatible, hydrophilic, and more stable than organic nanoparticles.

Metal and metal oxide nanoparticles are made from inorganic metalized nanoparticles by using destructive or constructive techniques. The generation of pure metal nanoparticles begins with metal precursors. The distinct optoelectrical capabilities of metal nanoparticles are caused by their plasmaon resonance properties (Dreaden et al., 2012). Au, Al, Fe, Pb, Ag, Co, Zn, Cd, and Cu are metal nanoparticles. NPs have unique surface characteristics, such as volume ratio to surface area, charge, pore size, density, structural forms, colour, and environmental variables. Iron nanoparticleson oxidationconvertinto iron oxide nanoparticles. Compared with iron nanoparticles, iron oxide nanoparticles are highly reactive. These oxides are manufactured because of an improvement in their reactivity and effectiveness. Oxides of zinc, silicon, titanium, iron, cerium, aluminium and magnetite are metal oxide nanoparticles. Some other nanoparticles are ceramic nanoparticles called “nonmetallic solids,” which can also be polycrystalline, amorphous, porous, dense, or hollow (Sigmund et al., 2006) and used for photocatalysis, catalysis, and imaging applications (Thomas et al., 2015).

A bionanoparticle is formed by the assemblage of atoms or molecules created in a biological system within the range of 1–100 nm, referred to as biological nanoparticles, which are all produced naturally. Ferritin, lipoproteins, exosomes, and magnetosomes are bionanoparticles. Carbon-based nanoparticles include carbon nanotubes, carbon black, fullerenes, graphene, and nanofibers. The dimensions of nanomaterials can be categorized as one-dimensional, two-dimensional, or three-dimensional. These nanomaterials are highly significant for research and are utilized in the production of electronics, storage systems, nanoscale LEDs (Arroyo et al., 2016), optoelectronics, chemicals, biosensing (Alvisatos *et al.*, 2004), magneto-optics (Kong *et al.*, 2001), fibre optic device photocatalysts, and nanoreactors.

2. Synthesis of nanoparticles

This review focuses on comparing green methods against chemical methods of synthesis; thus, we review methods for synthesizing nanoparticles with brief explanations of chemical and green approaches, as shown in Fig. 1.

2.1. Chemical methods for the synthesis of nanoparticles

Top-down synthesis is the destructive strategy employed in this synthesis. The larger molecules broke down into smaller molecules, and these tiny molecules changed into nanoparticles. Synthesis includes methods such as milling or grinding and physical vapour deposition (Irvani et al., 2011). Thermal decomposition, mechanical, lithographic, laser ablation, and sputtering are methods through which nanoparticles can bemanufatured (Singh *et al.*, 2010). The bottom-up method is a constructive method that is the opposite of the top-down method and includes chemical vapour deposition, hydrothermal methods, ultrasound, pyrolysis, flame spray pyrolysis, the sol–gel method, and spinning.

Chemical strategies such as the use of metallic precursors and stabilizing and reducing inorganic and organic agents are the major elements in this process. The useful reducing agents are sodium citrate, sodium borohydride, elemental hydrogen, ascorbate, the polyol process, Tollens reagent, N,N-dimethylformamide, and poly(ethylene glycol)-block copolymers (Zhang et al., 2016). The following is a discussion of a few chemical synthesis techniques.

2.1.1. Top-Down synthesis

A destructive strategy is employed in this synthesis. The larger molecule breaks and changes into smaller molecules, and these tiny molecules change into nanoparticles. Synthesis includes destructive

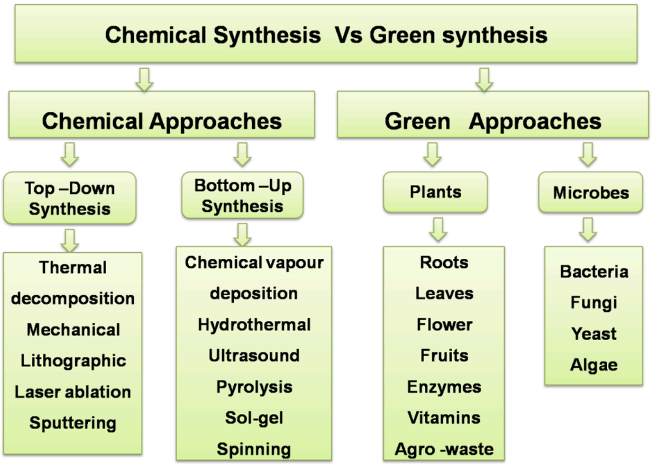


Fig. 1. Representation of chemical Vs green synthesis of nanoparticles.

methods such as thermal decomposition, ball milling or grinding, physical vapour deposition, laser ablation, and lithography (Iravani et al., 2011; Ijazet al., 2020).

2.1.1.1. Thermal decomposition. Chemical breakdown is caused by heat in this endothermic reaction. This heat breaks the chemical link in the molecule (Salavati et al., 2008). The temperature at which an element begins to break down chemically may be called the decomposition temperature metal breakdown at specific temperatures results in nanoparticles. Gadolinium oxide nanoparticles were created by (Ahab et al., 2016) utilizing a thermal breakdown process and functionalized with paramagnetic polyethene glycol.

2.1.1.2. Mechanical method/ball-milling. Developing nanoparticles in bulk is a cheap process. The most basic mechanical mechanism is ball milling (Patil, et al., 2016). Nanoparticles are created in a ball mill through attrition by which kinetic energy is transmitted from the grinding media to the substance being reduced. Consolidation and compaction, industrial-scale process whereprocesses in which nanoparticles are "put back together," are used to create materials with improved characteristics along with numerous metal alloys.

2.1.1.3. Lithographic. The preponderance of micron-sized features can be created using top-down lithographic techniques (Yang et al., 2017), although they are energy and equipment-intensive. For over a decade, lithography has been employed to create printed circuit boards and computers. Various lithography methods exist, including photolithography, electron beam, soft, focused ion, nanoimprint, and dip pin lithography. Photolithography features projection printing as well as contact and proximity printing.

2.1.1.4. Laser ablation. Creating nanoparticles from various solvents using a laser ablation approach is straightforward. Different metals immersed in solutions are exposed to laser radiation, which condenses plasma to create nanoparticles (Amendola *et al.*, 2009). No chemical or stabilizing ingredient is needed to create stable nanoparticles, which are created utilizing laser ablation procedures. This process is performed in a gaseous or liquid medium to controlstructure of the nanomaterial. A nanomaterial collects on a surface in the form of a thin film in a gaseous medium, whereas a colloidal structure is formed in a liquid medium (Rao and Geckeler, 2011). By controlling the intensity, pulse length and wavelength of the laser shape of nanomaterial can be altered.

2.1.1.5. Sputtering. Sputtering is a phenomenon that causes particles to be ejected from something, causing nanoparticles to be deposited (Shah and Gavrin, 2006). The deposition of tiny nanoparticle layers benefits greatly from annealing. Variables such as temperature, layer thickness, annealing time, and substrate affect nanoparticle shape and size (Lugscheider et al., 1998).

2.1.2. Bottom-Up method

The bottom-up approach is a constructive method that reverses the top-down method. This process includes chemical vapour deposition, sol–gel separation, spinning and pyrolysis, as shown in Fig. 1.

2.1.2.1. Chemical vapour deposition. In this technique, a thin coating of a gaseous reactant is deposited on the substrate in a reaction chamber. When gas comes in contact with a heated substrate, it mixes, and a chemical reaction occurs (Bhaviripudi et al., 2007). Due to this reaction, a thin coating of the product was created on the surface of the substrate. This process produces incredibly pure, homogeneous, challenging, and robust nanoparticles. In addition to other uses, graphene glass can be found in windows, touch screens, transparent electrodes, and other materials (Bo et al., 2013; Sun et al., 2016). Other CVD-produced nanomaterials include semiconductors, nanosensors, conductive electrodes, and optics (Zhang et al., 2013).

2.1.2.2. Hydrothermal synthesis. The term hydrothermal synthesis refers to various processes that use the solubility of materials to create crystal structures under high pressure and in boiling water. Manufacturing parts for Na-ion and K-ion batteries is one of the more intriguing uses of hydrothermal synthesis. In particular, the hydrothermal approach is used to create several nanostructures for the electrodes of batteries, including nanorods, nanowires, and nanosheets (Kubota et al., 2018, Lin et al., 2019). Low temperatures in the autoclave make hydrothermal synthesis significantly cleaner and more energy-efficient than other nanomaterial synthesis techniques (Mehraz et al., 2019).

2.1.2.3. Ultrasound synthesis. Sonochemistry, often known as ultrasound, is a typical laboratory method for making nanomaterials. This method manipulates sonic waves to trigger cavitation, which triggers chemical reactions that lead to the development of nanoscale materials. In the cavitation process microbubbles, the ultrasonic energy of microbubbles is stored in a liquid and rapidly expands and collapses, after which the ultrasonic energy is released into the environment. This causes an interaction with an environmental precursor, and a chemical reaction results in the final nanomaterial. These magnets have applications, such as medicine delivery, which is also possible with nanoparticles produced through sonochemistry. Local magnets placed at the location where the drug is needed help transport the drug-adjoining magnetic nanoparticle across the body (Han et al., 2008).

2.1.2.4. Pyrolysis and flame spray pyrolysis. Pyrolysis is used most frequently in the industry to create nanoparticles. This process involves using a flame to burn the precursor. The precursor could be a vapour or a liquid. To obtain nanoparticles, the precursor is put under high pressure in a furnace (Kammler et al., 2001). To create high temperatures that facilitate easy evaporation, lasers or plasmas may occasionally be used in place of flames (D'Amato et al., 2013). More enthalpy precursors, oxygen, and hydrocarbons are mixed in a flame during the flame spray pyrolysis process to create nanomaterials (Nunes et al., 2019). The resulting nanoparticles pass through a filter and gather on a homogeneous substrate (Teoh et al., 2010). Additionally, this procedure is applied on an industrial scale (Wegner et al., 2011).

2.1.2.5. Sol-gel. The term combines the words "sol" and "gel" where sol is a colloid of solid particles suspended in a liquid stream. A solid macromolecule that is dissolved in a solvent is called a gel. In this technique, an appropriate chemical solution serves as a precursor. Metal oxide and chloride are precursors in the sol–gel process (Ramesh, 2013). This uncomplicated procedure is used to create nanomaterials, including TiO_2, SnO_2, WO_3, Fe_2O_3,ZnO, silica and platinum (Parashar et al., 2020). Widely used nanomaterials made with Sol-Gel include materials for medicine delivery, wastewater treatment, building materials, and several sensors (Doufene et al., 2019).

2.1.2.6. Spinning. The creation of nanoparticles involves spinning. The spinning disc reactor consists of rotating discs where physical parameters such as temperature may be adjusted and used to create the nanoparticles. In the reactor, nitrogen or inert gases are used to prevent chemical reactions and remove oxygen. The liquid, such as water or a precursor, is injected into the reactor or chamber. Magnetic nanoparticles were created using spinning disc processing and the particle size ranged from 3 to 12 nm (Ijazet al., 2020).

Two main approaches to synthesizing metal nanoparticles are top-down and bottom-up, which have their advantages and disadvantages. The imperfections observed on the surfaces and damage to the crystals of nanostructures are the greatest challenges in the top-down approach of synthesizing nanoparticles, and their environmental impacts are given in Table 1.

Table 1
Chemical approaches and their diverse effects and environmental impacts.

Chemical Approaches	Environmental Impacts
Top-down synthesis	
Thermal decomposition	In the thermal decomposition method gaseous copollutants releases such as CO, CO_2, methane CH_4, C_2H_6, C_3H_8, and other complex hydrocarbons and organic polymers which impact the environment (Pokhrel et al., 2016; Lu et al., 2007).
Mechanical method/ball-milling	Ball milling process, milling temperature is one of the most critical variables to control (Patil and Bhanage, 2016) especially when material is temperature sensitive such as nanocrystalline powders, rubber, metals, and polymers. Other limitations include energy wastage, destruction, disordering crystal structure, noise and contamination.
Lithographic	Lithographic methods are used to make micron-size features but are energy-intensive and require expensive equipment.
Laser ablation	One of the most energy-intensive processes for synthesizing nanomaterials is laser ablation, which has a secondary impact on the environment since coal and gas are frequently used to create the electricity needed to run the laser (Kushnir and Sanden, 2008).The organic solvents utilized in this procedure are hazardous and detrimental to the environment (Joshi and Adhikari, 2019; Akinyemi, et al., 2019).
Sputtering	Certain disadvantages of the method is low purity, energy change into heat that should be removed and sputtering rates are minimal concerning thermal evaporation (Stephenson et al., 2004)
Bottom-up Synthesis	
Chemical Vapour Deposition	Large amounts of energy are required to heat the vacuums to their final temperature (Healy et al., 2008). Disadvantages of the chemical vapour deposition method like poisonous, flammable or explosive precursors, expensive precursors, raised fabrication costs, poisonous gaseous byproducts, and limited substrate use due to high deposition temperature The reaction produces side products created from the substrate or catalyst are frequently toxic to environment and the person performing the synthesis (Cui et al., 2008).
Hydrothermal Synthesis	Hydrothermal methods of synthesis also have limitations such as the instrument is the autoclave which is an expensive process, and while synthesizing the nanoparticles crystal growth cannot be monitored directly (Singh et al., 2012).
Ultrasound Synthesis	For the creation of ultrasonic waves the energy required is less as compared to the energy required for alternatives such as sol–gel synthesis and flame spray pyrolysis (Patil and Bhanage, 2016)
Pyrolysis and Flame Spray Pyrolysis	The fabrication of nanomaterials employing this technology is among the most hazardous and most detrimental to the environment. As an illustration, the fundamental cause of the greenhouse effect is carbon dioxide, which accumulates when hydrocarbon fuel is burned to establish the conditions for the formation of nanomaterials. (Xu and Obbard, 2003). Organic solvents are used as precursors and cause side effects to the environment (Teoh et al., 2010).
Sol-gel	There is some issues related to human health and the environment associated with this technology due to organic solvents are typically utilized to hydrolyse the precursors of nanomaterials (Tobiszewski, et al., 2017). Numerous body systems, including the neurological and reproductive systems, can be impacted by organic solvents. (Ma et al., 2019)
Spinning	Its basic operation and nanomaterial production requires only a high-voltage power source (between approximately 50 and 500 kV/m) and two electrodes connected to opposite potentials. The forces of only a high-voltage electric field create the nanomaterial (Bai et al., 2009).

2.2. *Green synthesis of the nanoparticles*

Methods of creating nanoparticles with biomedical applications use plants and microbes in a green approach to biosynthesis. This method is eco-friendly, economical, biocompatible, secure, and green (Sigmund et al., 2006) because it uses plants, bacteria, fungi, algae, etc. Fig. 2 illustrates that most often, nanoparticles are formed by biosynthesis when microorganisms or plants steal target particles from their state and then convert the metal particles into NPs using cell catalysts. NPs are classified into intracellular and extracellular amalgamations based on where they are framed. More catalytic activity can be seen in NPs made using a biomimetic technique, and the usage of expensive and harmful chemicals is restricted.

2.2.1. *Components of green synthesis*

2.2.1.1. Plants. Plants are increasing significantly as their extract-mediated synthesis of nanoparticles in three different ways inside the plant, using plant extracts and individual phytochemicals. Many plants intracellularly accumulate metals and subsequently transform into NPs. Parts of plants like fruit, root, stem, flower, latex, seed, leaves and seed coats are used for the synthesis by hot, and cold extraction and soxhlet apparatus which are biocompatible, eco-friendly, renewable and nontoxic. Plants contain flavones, ketones, proteins, alkaloids, terpenoids, vitamins,aldehydes, saponins, phenolics, polysaccharides, amino acids and tannins that reduce metals to NPs (Nath and Banerjee, 2013). The process involved mixing plant extracts with metal precursor salt solutions of related metals such as $AgNO_3$, $HAuCl_4$, $PdCl_2$, H_2PtCl_6, $Cu(NO_3)_2{\cdot}3H_2O$, $FeCl_3{\cdot}6H_2O$, Na_2SeO_3, and $(NiNO_3)_2{\cdot}6H_2O$ at the appropriate temperature and pH. Ag, Au, Se, Pt, Cu, Fe and Ni are common nanoparticles (Makarov, et al., 2014; Salih et al., 2020). Plant extracts of *Piper nigrum*, *Ziziphus Spina-christi* and *Eucalyptus globulus* were utilized for the synthesis of Ag nanoparticles (Bali and Harris, 2010). Au nanoparticles accumulate in aqueous solutions of $KAuCl_4$in *Brassica juncea* and *Medicago sativa* plants.

2.2.1.2. Microbes. Metal nanoparticles (NPs) can be synthesized, by different microorganisms, including fungi, bacteria, viruses and actinomycetes. The interaction between microorganisms and metals has been utilized in the past for biological applications, including mineral formation, bioleaching, biological remediation and biocorrosion (Klaus-Joerger et al., 2001). Microorganisms work extracellularly and intracellularly, depending on the type of microbe, because these microbial-based syntheses of NPs are currently an intriguing subject of research (Mohamed et al., 2019).

2.2.1.3. Bacteria. In metal nanoparticle production, prokaryotic bacteria have drawn the most significant attention among the microorganisms becase of their ability to decrease metal exists in bacteria and actinomycetes, such as*Escherichia coli*, *Pseudomonas aeruginosa*, *Plectonema boryanum*, *Pseudomonas stutzeri*, *Salmonella typhus*, *Staphylococcus currens*, and *Vibrio cholerae*, which produce metal nanoparticles in extra and intracellular ways, have drawn the most significant attention among these microorganisms (Konishi et al., 2004).

2.2.1.4. Fungi. A highly effective method with a clearly defined shape is the biological production of metal or metal oxide nanoparticles using fungi which act as biological agents in the formation of nanoparticles because they contain intracellular enzymes (Mohanpuria et al., 2008). In comparison to fungi, bacteria make fewer nanoparticles. *Alternaria alternata* culture filtrate was used to include nanoplatinum and platinum nanoparticles with spherical and triangular particle shapes identified through several spectroscopic analyses (Sarkar and Acharya, 2017). After using a combination of selenium NPs, chitosan, and fungus as a reducing agent, they discovered that the two substances work

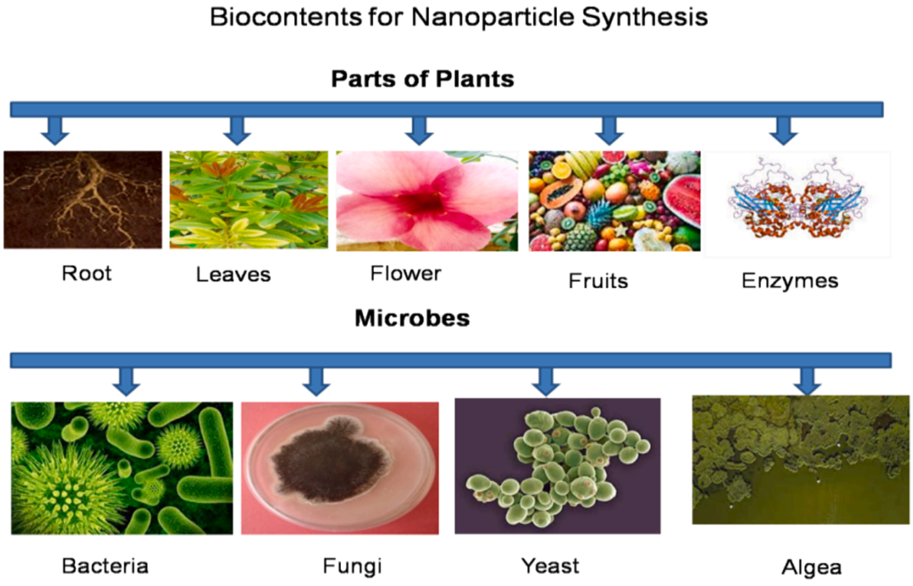


Fig. 2. Environmental approaches for the synthesis of nanoparticles by parts of plants and microbes.

synergistically (Lara et al., 2018). It is straightforward to isolate, downstream processing is considerably simpler than bacterial fermentation, and fungal cultures exude vast amounts of extracellular enzymes (Nayantaraa, 2018).

2.2.1.5. Yeast. Microorganisms called yeasts are monocellular. Numerous scientists have reported the creation of nanoparticles utilizing yeast. The metabolic activity of *Fusarium oxysporum*results in the conversion of silver nitrate into silver oxide, resulting in the formation of well-dispersed NPs. The release of nitrate reductase caused by Ag particles in *Fusarium oxysporum* led to the creation of incredibly stable Ag NPs in solution (Ahmed et al., 2018).

2.2.1.6. Algae. Cyanobacteria and eukaryotic green development genera, such as *Lyngbya majuscule* and*Spirulina subsalsa*, can be exploited as inexpensive materials for the recovery of metal from liquid action courses (Bakir et al., 2018).The most archaic plant, algae, offers several benefits, including being an excellent source of bioethanol and fossil fuel, as well as being a very effective forerunner for the current nanoparticle trend. Because of the biomolecules that make up the metals and reduced to nanometals and stabilized (Hasan *et al*, 2023). The synthesis of nanoparticles can be performed via two methods.The cell metabolites that protrude from the extract in facilitate extracellular processing, which occurs outside of the cell. The readily purification of the nanoparticles and adjustment of physiochemical variables such as pH, temperature, metal concentration, and substrate stimulation to control the size, shape, and aggregation of the NPs, this method of production is more convenient (Zhang et al., 2016). The intracellular production process as being mediated by the movement of certain ions that pass through the cell wall Fig. 3 (Hasan et al., 2015). *Rhizoclonium fontinale*

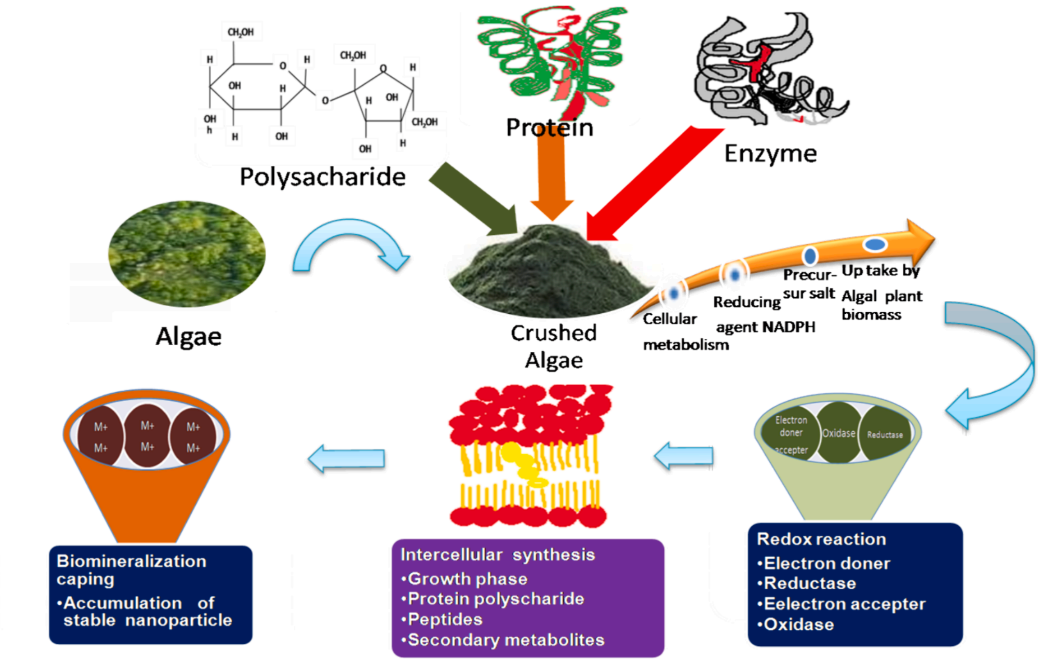


Fig. 3. Synthesis of nanoparticles from algae by intracellular process.

and *Ulva intestinalis* exhibit a visible change in colour from green to purple after being treated with chloroauric acid at 20 °C for 72 h. This shift is indicative of the synthesis of Au-NPs (Chaudhary et al., 2020).

2.2.1.7. Actinomycetes. Actinomycetes are useful for synthesizing metal nanoparticles both within and outside of cells. Actinomycetes (Yu et al., 2015) generate stable, well-polydispersed nanoparticles that have strong biocidal effects on a range of illnesses (Kumar et al., 2016). The Thermoactinomycete *Rhodococcus, Streptomyces Viridogens, Nocardia farcinica, Thermomonospora,* and *Streptomyces hygroscopicus* all efficiently generated Au-NPs. Conversely, Cu, Ag, Mn, and Zn are effectively produced by Streptomyces (Batal et al., 2015).

2.2.1.8. Enzymes. For instance, Ag NPs were merged with an enzyme-induced growth process on solid substrates in the synthesis of NPs. This is because enzymes have a well-defined structure and are readily available in pure form. Direct production of bimetallic Fe/Pd particles in a membrane domain was achieved by including enzymes in polymer multilayer-assembled membranes through electrostatic interactions (Smuleac et al., 2011). For the first time, extracts of green tea were used to generate Fe/Pd bimetallic NPs because they can function as capping and reducing agents (Smuleac et al., 2011). A hybrid electrically dynamic biomaterial can be created by functionalizing Au NPs using a redox enzyme, which acts as an electron transmitter between the electrode and the biocatalyst, and the electrode provides a hybrid electrically dynamic biomaterial that can be utilized in different sensor applications (Virkutyte and Varma, 2011).

2.2.1.9. Vitamins. Vitamin B_2 enabled the green combination of silver and palladium nanospheres, nanowires, and nanorods. The reducing agent for creating the nanowires and nanorods is vitamin B_2. This novel strategy in green nanotechnology proposes the use of natural agents to progress this field, for instance, their effects on various tumor cells (Nadagouda and Varma, 2006). Due to the ability of chitosan to interact with metal ions, ascorbic acid is also utilized as a capping and reducing agent, and chitosan is used as a stabilizing agent.

3. Characterization of nanoparticles by various techniques

The distinct chemical, physical, and mechanical characteristics of NPs, such as their features, surface morphology, area, stability, size, shape, elemental and mineral breakdown, homogeneity, intensity, are essential information that ultimately defines their end-use applications. Characterization of the NPs are performed by spectroscopic techniques such as X-ray, fourier transmission infrared, dynamic light scattering, scanning electron microscopy and transmission electron microscopy. Size and form of nanoparticles in an aqueous suspension and ultraviolet–visible spectra were also determined (Rajesh et al., 2009). Additional techniques used for characterization include atomic force microscopy, condensation particle counters, and photon correlation spectroscopy. Magnetic characteristics include electron paramagnetic resonance, superconducting quantum interference devices and vibrating sample magnetometers (Mourdikoudis et al., 2018; Punia et al., 2021). ZnO NPs were also biosynthesized from extracts of coloured*Sargassum myriocystum*, red *Hypnea valencia*, and green *Caulerpa peltata* seaweeds (Nagarajan and Arumugam Kuppusamy, 2013).

4. Discussion on contrastive and comparative analysis of the green vs chemical synthesis of nanoparticles

A growing body of research is being conducted today using chemical, physical, and eco-friendly methods to create nanoscale metals (Horwat et al., 2011). Green synthesis methods are gradually replacing physical and chemical methods because of their high energy requirements, the emission of poisonous and dangerous substances, the use of complex equipment, and synthesis conditions (Alsammarraie et al., 2018). Physical techniques such as aerosols, ultraviolet radiation (Wojnarowicz et al., 2018), and thermal breakdown require high temperatures and pressure. In contrast, green synthesis (Ahmed et al., 2016) uses organic and environmentally safe components (reducing agents). Accordingly, (Devi et al., 2019), some environmentally friendly materials can simultaneously serve as agents, such as end-capping agents and dispersants, reducing energy use and avoiding hazardous and toxic chemicals. Polyphenols and proteins included in green materials can act as reducing agents to convert metal ions into lower energy forms in place of chemical reagents (Can, 2020). Metal nanoparticles made by green methods sometimes outperform those made using chemical processes in terms of quality. For instance, Gokila et al. (2021) reported that Fe_3O_4 nanoparticles produced via a green synthesis approach have a particle size ranging from 2–80 nm, which is significantly smaller than that of the 87–400 nm particles produced via a wet chemical process. The mechanism of chemical synthesis (Singh et al., 2018) is shown in Fig. 4. A new era of widely applicable, cost-effective, remarkably stable, and repeatable synthesis of zinc oxide (ZnO) nanoflowers (NFs) involving plant-mediated NF synthesis techniques has occurred. The impacts of chemically synthesized nanowires (CS NWs) and biosynthesized nanofibres (BS NFs) on soybeans were investigated using a gel-free/label-free proteomic approach. Zinc oxide (ZnO) at a 10 ppm concentration increased the length and weight of the roots, including the hypocotyl. ZnO was linked to redox metabolism, protein folding, and hormone metabolism, while BS NFs and CS NWs had oppositely altered proteins. While it remained unchanged in CS NWs ZnO, the abundance of heat shock protein 70 (HSP70) increased in BS NFs ZnO (Hasan et al., 2022). Based on these findings, BS NFs ZnO might enhance soybean growth by promoting protein folding.Theaccumulation of HSP70 and redox metabolism occursthrough the detoxification of hydrogen peroxide. On the other hand, CS NWs ZnO-treated soybean plants experienced a decrease in protein folding and increased oxidative stress.

Conventional fertilization contributes to eutrophication as well as increasing soil acidity. This study examined the stimulatory and inhibitory effects of foliar fertilization with Cordia-based silver nanoparticles (AgNPs) on the accumulation of biomass, antioxidant activity, and morphological and anatomical alterations of lettuce (*Lactuca sativa* L.) (Hasan et al., 2022). The agriculture industry has recently seen a rise in the use of foliar spraying of NPs produced by chemical and biological processes as nanofertilizers (Luo et al.,2021; Wasaya, 2020). Compared with those of conventional soil root applications, the efficacy of nanopesticide and nanofertilite emulsions has increased (Shahid et al.,2019). Further investigation is required to identify the primary physiochemical

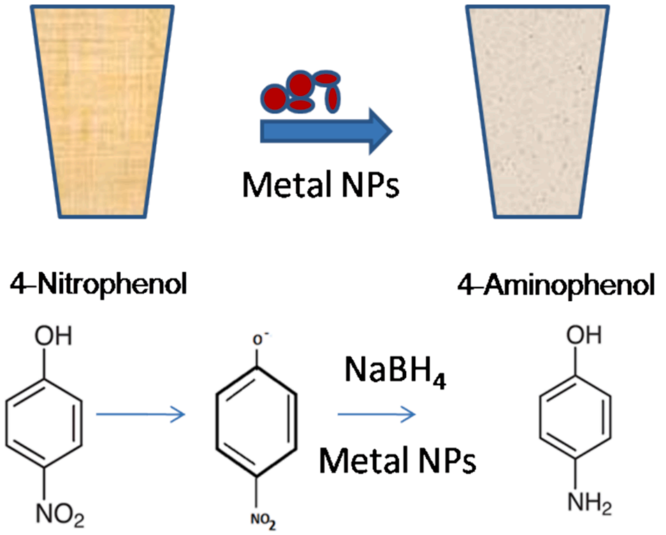


Fig. 4. Synthesis of the nanoparticles by a mechanistic chemical approach.

pathways controlling these morphoanatomical alterations in lettuce when green-synthesized AgNPs are applied topically.

It is imperative to produce antibiotic-free antibacterial materials to decrease the use of antibiotics in combating drug-resistant microorganisms. Most plant materials, including extracts of leaf from *Azadirachta indica, Veronica amygdalina, Pleurotus giganteus, pomegranate peel, Avicennia officinalis*, and *Xylocarpus granatum*, are used in the green synthesis of silver nanoparticles (Mankad et al., 2018; Debnath et al., 2019; Das et al.,2019). Dioscorea cirrhosa is from Dioscoreaceae family, and its tubers contain a significant amount of condensed tannins. This plant contains mostly useful active chemicals that are utilized to treat a variety of illnesses, including antioxidants, hypolipidaemia, hypotension, haemostasis, and antitumour agents (Zhong et al., 2019). Consequently, Dioscorea cirrhosa tuber extract used as a green reducer to reduce Ag NPs via a green synthesis approach which is easy, economical, and ecologically responsible technique to produce green-synthesized silver nanoparticles (Hasan et al., 2022). The antibacterial test revealed that the average widths of the inhibition zones of the green-synthesized Ag NPs against *Escherichia coli* and *Staphylococcus aureus*were 13.01 ± 0.72 mm and 14.17 ± 0.84 mm, respectively. By calculating the minimum bactericidal concentration (MBC) and minimum inhibitory concentration (MIC), the antibacterial properties of the Ag NPs were further assessed. The findings showed that Ag NPs have exceptional antimicrobial activity. Additionally, DCTE-Ag NPs exhibit good bacteriostasis, as they may rupture the membrane of bacterial cells to allow leakage of internal contents and impede the ability of Na^+/K^+-ATPase to prevent the conversion of energy.

ZnO nanocrystals were prepared by a chemical method using Zn-(II) acetate and potassium hydroxide as the starting materials and methanol as the solvent asgiven in Fig. 5. The material was characterized by various spectroscopic techniques, and the patterns indicated that the hexagonal wurtzite phase was crystalline, spherical in nature and had a hydroxyl group, indicating the highly active surface of nano-ZnO (Dhoke, 2023).

Chemical synthesis is the most common, most abundant, and most effective way of creating metallic nanoparticles (Szczyglewska et al., 2023). While in chemical techniques uses of solvents and hazardous chemicals required for stabilizing nanoparticles is not ecologically friendly (Anwar et al., 2018). Furthermore, it is frequently seen that the final nanoparticles are contaminated with chemicals, and a sizable number of hazardous byproducts are created (Huqet al., 2022). The foundation of biological techniques by various biological systems that, because of the diminished capacities of proteins and metabolites found in these systems, may transform metal ions into metal nanoparticles. As potential ecological substitutes for physico-chemical processes, biological approaches for the manufacture of nanoparticles employing microorganisms, natural plant extracts, bacterial extracts, enzymes, have been proposed (Saallah and Lenggoro, 2018).

$$mMen^+ + nRed \rightarrow mMe^0 + nOx$$

$$Ag^+Ag^+Ag^+ + Reducingagent \ \rightarrow Ag^+Ag^0 + Stablizer \ \rightarrow Ag^0Nanoparticle$$

Taking an appropriate reducing agent is particularly crucial since its nature leave impact on the size, shape, and distribution of particles. The metal precursor undergoes reduction by adding a reducing agent. The following reducing agents (De Souza et al., 2019) like formaldehyde, oleyl amine, sodium borohydride, ethylene glycol, carbon oxide(II), hydrazine, ethanol, oxalic acid, hydrogen peroxide, vitamin C, and citric acid are used most frequently. Because of hazardous nature of reducing agents extensive safety precautions must be taken both in laboratory and industrial settings. Therefore, replacing dangerous reducing agents with environmentally friendly alternatives is a major difficulty in the production of nanoparticles. In green approaches, reducing agents such as phytochemicals, flavonoids, minerals, lipids, fatty acids, protein, carbs, vitamins, enzymes, and amino acids are used (Sharma et al., 2022; Sarkar et al., 2021).The nontoxicity of polysaccharides makes them green reducing agents for the production of nanoparticles that have the potential to improve the planet only when they are applied for beneficial reasons (Zafar et al., 2024).The chemical equation for synthesizing CuO NPs is as follows:

$$Cu(NO_3).3H_2O + G.mangostana \xrightarrow{Heating+Stirring} CuO/G.mangostana$$

The extract interacted with the functional groups of the G. mangostana components to create [CuO/G. mangostana] when copper nitrate was dispersed in the G. mangostana aqueous solution matrix (Aminuzzaman et al., 2018).Biosynthesizing of ZnO NPs represented in Scheme 1

Biological techniques are the ideal way to create nanoparticles since they are straightforward, nontoxic, and economical. In the generation of nanoparticles, capping and reducing agents are crucial. The physicochemical methods used for synthesizing nanoparticles involve dangerous and highly poisonous substances, which can cause environmental damage. Nanoparticle syntheses by green and biological methods are preferable (Alsammarraie et al., 2018).For medical and biological applications where the purity of NPs is crucial, the biogenic reduction of metal precursors to produce matching NPs is environmentally benign, less expensive, and free of chemical impurities. Additionally, nanoparticle shape and size are affected by the properties of biological entities at various concentrations in combination with reducing chemical agents. In contrast to chemical and physical processes, green synthesis offers numerous benefits, including being nontoxic, pollution-free, environmentally friendly, economical, and more sustainable. However, the extraction of raw resources, response time, and product quality are problematic. Examples include the limited availability of raw ingredients, the length of the synthesis process, and the very homogenous particle size of the product (Gao et al., 2016). The chemical methods and eco-friendly synthesis of nanomaterials are analysed and discussed in this review, along with an assessment of the pertinent restrictions. This review aims to highlight the critical problems and difficulties of chemically and greenly synthesized metallic nanoparticle creation and to outline future research directions. An in-depth study and discussion of synthesis procedures are provided in the review,which may help to progress nanoparticle research in the future.

Fig. 6 shows the enzymes, sugars, carbohydrates, proteins, etc., involved in the formation of NPs during the microbial manufacturing process (Prabhu and Poulose, 2012). Since each bacterium has a different method for producing NPs, a thorough understanding of microbial nanoparticle synthesis needs to be improved. While nitrate-dependent reductase or carboxylic groups employed for reducing silver in fungi and bacteria to manufacture extracellular and intracellular Ag NPs, nitrate-dependent reductase or sulfur-containing proteins play

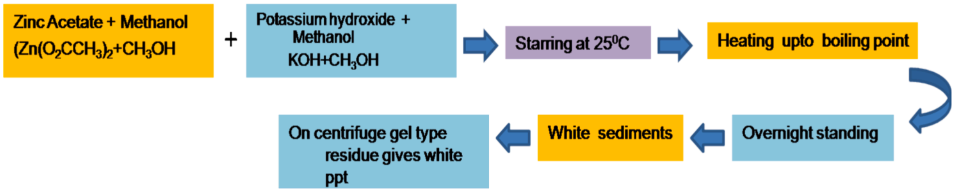
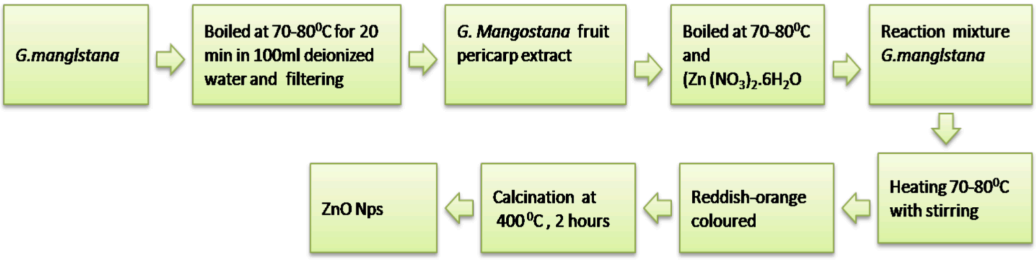


Fig. 5. Schematic representation of chemical synthesis of ZnO nanopaprticles.



Scheme 1. Biosynthesis of ZnO NPs using aqueous extract of *Garcinia mangostana* fruit pericarp.

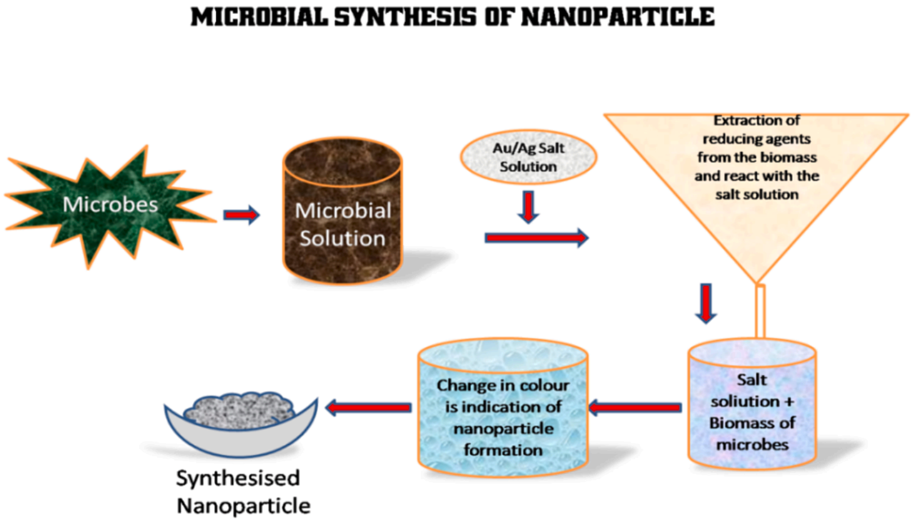


Fig. 6. Synthesis of nanoparticles by oxidation/reduction from microbial cells.

important roles in bacteria. Due to its quick and straightforward purification methods, the extracellular synthesis approach was used. Separation and purification steps are required in the intracellular NP manufacturing approach, which is difficult and expensive. Compared with bacteria or algae, fungi have significant advantages in terms of processing biomass and downstream processes. They also secrete a high quantity of protein, which boosts productivity by multiple orders of magnitude. The generation of inoculums and growth media, strain isolation, culture medium maintenance, and operation conditions make microorganism-mediated synthesis quite complex and challenging.

In contrast, using plant extracts is straightforward and practical, and there is no need for complicated cell culture or maintenance techniques. Typically, it takes 24 to 120 h to reduce NPs when employing microbes; however, it takes only a few hours to 48 h when using plant extracts. The reduction rate of plants is significantly faster than that of microorganisms, reflecting the physical and chemical effects of these methods. Compared to plants requiring less reaction completion, the use of microbes for the creation of more NPs is not feasible. According to past investigations and biological approaches, the plant-based synthesis of Ag NPs has a high rate of manufacturing, size, and morphological properties (Sabri et al., 2016).

Consequently, plant-based synthesis of NPs is effective for other biological approaches and physicochemical methods. With a clean, safe, economical, and eco-friendly method, green synthesis methods can be used to create nanomaterials that use microorganisms such as bacteria, fungi, algal species, yeast, and some plants as substrates. The presence of different active molecules and precursors, such as metal salts, determines the ultimate structure of the nanoparticle. Additionally, green synthesis offers nanomaterial advantages such as natural reducing and stabilizing characteristics, antibacterial qualities (Sivaraj et al., 2020), and other properties. Since the most recent comprehensive review of nanomaterials by, active molecules of the microorganisms used as green synthesis substrates have been discovered (Saratale et al., 2018). When creating nanomaterials, specialized enzymes, amino acid groups, proteins, or chemical structures are frequently used from green sources (Pugazhendhi et al., 2018).

In general, the function of active molecules offers a more in-depth perspective on the capabilities of nanoparticle production from green synthesis methods in future applications. The synthesis of nanomaterials has increased, as have the methods by which they can be produced without endangering the earth and its inhabitants.The green chemistry principles of 12 rules (Anastas *et al.*, 2000) were released in the book “Green Chemistry” at the beginning of the twenty-first century, which laid the foundation for green chemistry, as shown in Fig. 7.

The release of toxic substances into the environment and human exposure to these compounds should be minimized whenever possible by abiding by these 12 guidelines (Gałuszka et al., 2013). Creating nanoparticles from plants is not complicated; using plant extract, a metal salt is created, and the reaction takes only a few minutes to a few hours to complete at room temperature. Silver and gold NPs are safer than other metallic nanoparticles. Using more toxic and hazardous chemicals could increase reactivity and toxicity and have unintended negative consequences on health and the environment (Hussain et al., 2016). Green synthesis techniques are incredibly appealing for decreasing NP toxicity. As a result, the use of amino acids, vitamins and plant extracts is becoming increasingly common (Baruwati et al., 2009).Fig. 8 shows a comparative analysis of chemical and green synthesis and their impacts on the environment.

Numerous stabilizing and reducing agents, including dodecyl benzyl sulfate (Akbarzadeh and Dehghani, 2017), polyvinyl pyrrolidone (Pandey et al., 2018), sodium borohydride ($NaBH_4$) (Banne et al., 2017), potassium bitartrate (Tan et al., 2003), formaldehyde (Norris, et al.,

Fig. 7. Principles of green chemistry for a safer and more sustainable environment.

Fig. 8. Comparative analysis of chemical synthesis and green synthesis.

2010), methoxy polyethylene glycol (Mallick et al., 2004), and hydrazine (Eluri and Paul, 2012), have already been investigated for the synthesis of NPs. In-depth discussions have already been mentioned regarding the uses of NPs in several fields, including medicine, wastewater treatment, agriculture, etc.

4.1. Role ofcapping agent and functional group

The stabilizing effects of capping agents, which prevent nanoparticles from growing too much and from aggregating or coagulating during colloidal synthesis, are crucial. At the interface between the nanoparticles and their preparation medium, the capping ligands provide stability. Nanoparticles with specific structural characteristics are thought to undergo surface capping. These changes in physicochemical and biological properties are caused by the steric effects of capping agents through surfacial deposition on nanoparticles (Javed et al., 2020). To facilitate their use in biologicalsystems, capping agents should possess the following qualities: they should be readily absorbed by the organism, biocompatible, welldispersed, biosoluble, and nontoxic. Because of this, their nonspecific interaction with biological components is lessened, which decreases their toxicity to cells (Rajendran and Sen, 2015). Surface capping imparts improved biological characteristics to nanoparticles. Surface capping improves the biological characteristics of nanoparticles. In combination with biocompatible nanoparticles, capping agent-emerging therapeutic agents have been linked to these materials, demonstrating their clinical importance. The hydrophilicity/hydrophobicity, processability, charge, dispersibility, and colloidal stability of nanomaterials are influenced by their surface chemistry and surface functional groups (Heuer-Jungemann et al., 2019; Huhn et al., 2017). Furthermore, functional groups allow the controlled modification and functionalization of nanomaterials through the covalent binding of functional molecules, such as hydrophilic ligands; biomolecules such as proteins, peptides, or oligonucleotides; sensor dyes; and antifouling agents (Wolfbeis, 2015; Silvi et al., 2016). This leads, for example, tothe creation of targeted nanoprobes and nanosensors. These include amino groups (–NH2), carboxy groups (–COOH), hydroxyl and phenol groups (–OH), and thiol groups (—SH) for biomolecules such as peptides and proteins, including antibodies and enzymes. As such, it is an important and application-relevant parameter for all types of nanomaterials in addition to size, size distribution, and shape morphology (Sapsford et al., 2013). Table 2 summarizes the reducing agents, sizes, and morphologies of the metallic nanoparticles.

4.2. Some metallic and metallic oxide nanoparticles

Fig. 9 shows a comprehensive path forward shortly that follows the benefits of green synthesis energy efficiency, low-cost production, fewer accidents, a safe product, economy, and less waste; therefore, it is also called “environmentally friendly, competitive advantages, protect public health and communities, use in the biomedical and other pharmaceutical applications.

4.2.1. Au

Reduction of gold ions with reducing agents derived from plant extracts or microbes is the standard procedure for sustainably producing Au NPs. Typically, the extracts are made by allowing ground plants to soak in solvents in a suitable atmosphere for an appropriate amount of time. After the extracts are added to a gold ion solution, the solution turns red, indicating the production of Au NPs (Tharishini et al., 2014).

Table 2
Synthesis of metallic nanoparticles by chemical, green, and biological methods.

Nanoparticlessynthesized by chemicalmethod					
Chemical Synthesis	Metal NPs	Metal salt	Reducing agent	Size(nm)	References
	Ag	$AgBF_4$	H_2,85 °C,4atm^1 BIm	0.8–2.8 and 1.3–4.4	(Hulkoti and Taranath, 2014)
	Ag	$AgNO_3$	Tween 85	3–10	(Geet al., 2007)
	Au	$HAuCl_4$	Ascorbic acid	20–50	(Obliosca et al., 2010)
	Au	$HAuCl_4$	$NaBH_4$	0.5–4	(Lazarus et al., 2010)
	Au	$HAuCl_4$-$3H_2O$	Glycerol	5–7	(Khare et al., 2010)
	Cu	$Cu(OAc)_2$-H_2O	H_2NNH_2-H_2O	80–130	(Raut *et al.*, 2009)
MetallicNanoparticles synthesized fromvariousplantextracts					
Green Synthesis	Metal NPs	Plant Origin	Morphology	Size (nm)	References
	Au/Ag	*Aloebarbadensis*Miller (Aloe vera)	Spherical, Triangular	10–30	(Chandran et al., 2006)
	InO	*Aloebarbadensis*Miller (Aloevera)	Spherical	5–50	(Maensiri et al., 2008)
	Ag	*Acalyphaindica*	Spherical	20–30	(Krishnaraj et al, 2010)
	Ag/Au	Apiinextractedfrom hennaleaves	Spherical, Triangular, and quasispherical	39	(Kasthuri et al., 2009)
	Au	*Avenasativa*(oat)	Rod-shaped	5–20	(Armendariz et al., 2004)
	Au/Ag	*Azadirachtaindica*(neem)	Spherical,triangular, Hexagonal	5–35and50–100	(Shankar et al.,2004)
	Au/Ag	*Camelliasinensis*(black tea leaf extracts)	Spherical,prism	20	(Mondal *et al.*, 2011)
MetallicNanoparticles synthesizedfromvariousbiologicalspecies					
Biological Synthesis	Metal NPs	Species	Morphology	Size(nm)	References
	Ag	*Bacilluscereus*	Spherical	20–40	(Sunkar and Nachiyar, 2012)
	Ag	*Pseudomonasproteolytica, Bacilluscecembensis*	Spherical	6–13	(Shivaji et al., 2011)
	Au	*PlectonemaboryanumUTEX* ^{2} *485*	Cubic,octahedral	<10–25	(Lengke et al.,2006)
	Au	*Bacillussubtilis168*	Hexagonal, Octahedral	5–50	(Southam and Beveridge, 1994)
	Ag	*Rhizopusnigricans*	Round	35–50	(Ravindra and Rajasab, 2014)
	Ag	*Verticillium*	Spherical	21–25	(Mukherjee et al., 2001)
	Ag	*Aspergillusfumigates*	Spherical	5–25	(Bhainsa and D'Souza, 2006)
	Si	*Fusarium oxysporum*	Spherical	5–15	(Bansal et al.,2005)
	Ti	*Fusarium oxysporum*	Spherical	6–13	(Bansal et al.,2005)
	Pd	*Saccharomyces cerevisiae*	Hexagonal	32	(Sriramulu and Sumathi, 2018)

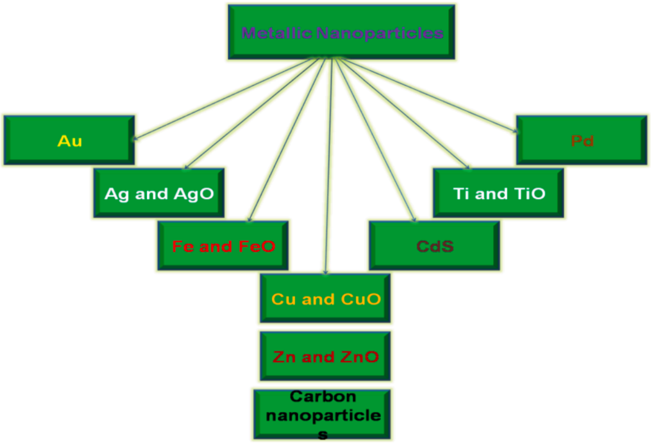


Fig. 9. Metallic, metallic oxide and carbon-based synthesis of nanoparticles by green methods.

This method converted chloroauric acid into Au nanoparticles using extracts from the leaves of *Cassia auriculate* and *Cinnamomum zeylanicum* (Smitha et al., 2009). In the medical sector, Au NPs are also commonly utilized (Lee and Park, 2020). For example, Au NPs are used as carriers of bioactive molecules such as anticancer agents, which greatly aid in the treatment of diseases, particularly cancer (Kumari and Meena, 2020).

4.2.2. Ag

Silver nitrate solution is mixed with reducing agents obtained from plants as part of the typical green synthesis process for Ag NPs. Following the standard technique outlined above, extracts were made from plants and placed in Au NPs before being combined with silver nitrate solution. The solution colour changes to a brownish colour, which indicates the formation of Ag NPs (Khatamiet al., 2018; Yu et al., 2019). Ag NPs can be made from waste, but they can also be utilized to lessen air pollution caused by burning agricultural wastes, which benefits the environment. The antibacterial capabilities of Ag NPs have been investigated (Ruttkay-Nedeck et al., 2019). The shapes and sizes of the green-synthesized Ag NPs vary, but the most prevalent shapes are spherical, triangular, and hexagonal (Ping et al., 2018; Kumar et al., 2017; Arokiyaraj et al., 2017).

4.2.3. Pd

Palladium is an expensive high-density metal. It frequently functions as a biosensor and catalyst in medical diagnostics. It increases yield while successfully catalyzing many types of chemical reactions. The creation of Pd NPs has been widely studied because of their unique ligand-free catalytic ability (Siddiqi and Husen, 2016). In the Suzuki-Miyaura coupling reaction, Pd NPs created using black tea leaf extract worked well as catalysts (Li et al., 2017). Gram-positive and Gram-negative bacteria respond favourably to Pd NPs produced by *Filicium decipiens* (Veisi et al., 2016).

4.2.4. Fe

Iron and iron oxide nanomaterials synthesized by green methods have been widely studied. Extracts from mango leaves (Wenget al., 2016), eucalyptus leaves and grape seeds (Pattanayak and Nayak, 2013), pear tree leaves (Martinez et al., 2016), vine leaves (Machado et al., 2013), and *Terminalia* chebula fruits (Kumar et al., 2013) were taken for the green synthesis of Fe NPs that exhibited antioxidant solid capacity.

4.2.5. CdS

Biomass of *F. oxysporum* was used to synthesize cadmium sulphide quantum dots with sizes ranging from 2–6 nm (Cardenas et al., 2017). This type of microorganism is used for the formation of nanoparticles by absorbing toxic metals for detoxification of the environment (Elsalam et al., 2018). The fungus, which is exposed to toxic Cd without an external source of sulphur, transforms toxic Cd to nontoxic CdS nanoparticles and thus has great potential for use in the remediation of toxic metals from soils using low-cost, green and reproducible *Saccharomyces cerevisiae* (Sanghi and Verma, 2009).

4.2.6. Cu

The extraction process of the above materials is relatively complex. However, the process of obtaining citron juice is simpler than that of other plant extracts. The prewashed fruits were squeezed and filtered through muslin cloth to obtain the citron juice. The Cu NPs synthesized using citron juice exhibited antibacterial and antifungal effects on plant pathogenic fungi. Among the bacteria tested, Cu NPs were effective in inhibiting the growth of*Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa, Propionibacterium acnes*, and *Salmonella typhi* in decreasing order. Among the plant pathogenic fungi, *Fusarium graminearum* was the most sensitive, followed by *Fusarium oxysporum and Fusarium ulmorum*. The synthesis of Cu NPs from citron juice is very convenient and cost-effective and is valuable (Shende et al., 2015).

4.2.7. CuO

In another report, the sol–gel method using coffee powder was employed to synthesize monoclinic CuO NPs at different calcination temperatures (Fardood and RamazaniA. , 2016). *Azardirachta Indica*leaf extract (Rajendran and Sen, 2015) and *Callistemon viminalis* flower extracts were also used in the synthesis of CuO NPs. Aloe leaf extract and copper sulfate (Cu_2SO_4) solution under vigorous stirring at 130 °C for 7 h resulted in the synthesis of monodisperse CuO NPs(Gunalan et al., 2012). The NPs were found to have antibacterial effects on pathogenic bacteria such as *Staphylococcus aureus* and *Klebsiella aeroegenes*.

4.2.8. ZnO

Due to the unique phytochemicals of plants, plant components roots, fruits, leaves, stems, and seeds have been used to synthesize ZnO NPs. ZnO NPs exhibit exceptional semiconducting capabilities, including vigorous catalytic activity and optic and UV filtering properties, anti-inflammatory properties, and wound healing (Mirzaei, *et al.*, 2017; Stan et al., 2015). It is widely utilized in cosmetics, such as sunscreen creams, due to its UV-filtering properties (Wodka et al., 2010). It has numerous medicinal uses, including the transport of medications and its anticancer, antidiabetic, antibacterial, antifungal, and agricultural effects (Sangani et al., 2015; Hameed et al., 2016). Different morphologies of ZnO NPs, including nanoflakes, nanoflowers, nanobelts, nanorods, and nanowires, have been observed (Paulkumar et al., 2014).

4.2.9. TiO_2

TiO_2 NPs (36–38 nm, spherical) were synthesized from a titanium hydroxide solution using a leaf extract of *Eclipta prostrata* at room temperature (Rajakumar et al., 2012). This decrease was attributed to the stretching of the carboxyl(–COOH) and amine (–NH_2) groups present in theextract. *Azadirachta Indica* leaf possibly contains amide, carboxyl andnitro groups, and its extracts were used for the synthesis of TiO_2 NPs 124 nm in size witha spherical shape. They also investigated the role of NPsas effective photocatalysts for the remediation ofpollution (Sankar et al., 2014).

4.2.10. FeO

Iron oxide NPs were synthesized by using *Eucalyptus globulus* leaf extract in the $FeCl_3$ aqueous solution (Madheswaran et al., 2014).The plant-based synthesis of Fe and Ag NPs was performed using sorghum extracts as both reducing and capping agents in aqueous media (Njagi et al., 2011). The produced NPs effectively catalyzed H_2O_2 degradation, which has applications in the environmental remediation and treatment of hazardous waste.

4.2.11. SnO_2

Nitric acid was dissolved in a raw material that was obtained by leaching printed circuit boards to make SnO_2. First, tin oxide is extracted from nitric acid solution using three distinct methods: conventional heating, microwave heating, and ultrasonic treatment (Cerchieret al.,2017).

4.2.12. Carbon nanofibers

Because of their remarkable mechanical and electrical qualities, carbon nanofibers are classified as exceptional nanostructured materials. Carbon nano fibres have been produced in the past by a range of processes, including CVD, plasma-enhanced CVD, electrospinning, dry autoclaving, arc discharge, sonochemical/hydrothermal procedures, and laser ablation (Alfarisa et al., 2015).

4.2.13. Carbon nanotubes

Carbon-based materials with a particular size and particle structure are called nanocarbon materials. Carbon nanotubes (CNTs) have been synthesized using a variety of carbon precursors, including acetylene, benzene, and methane (Widiatmoko et al., 2020). Carbon nanotubes have been broadly used in a variety of applications, such as polymers, sensors, electronics, catalysts, separation, sensors, electronics, and energy storage electrodes in supercapacitors (Yan et al., 2015). As environmental concerns and the market for carbon nanotubes (CNTs) have increased, several researchers have attempted to boost CNT manufacturing while creating green technologies (Fathy et al., 2020).

4.2.14. Carbon quantum dots

As a surface passivation agent for inorganic materials, carbon quantum dots, or NPs, are smaller than 10 nm. Their excellent stability, superior solubility, and ease of control over size and functional groups are other advantages. Agri-based wastes, including frying oil waste (Muthoni et al., 2014), egg whites and yolks (Wang et al., 2012), and eggshells (Ke et al., 2014), have been proven to be useful in the synthesis of carbon quantum dots by earlier research.

4.2.15. Graphene

Graphene is made entirely of carbon atoms organized in a sheet to resemble a honeycomb. This layer of carbon is just one atom thick and should be emphasized, even if some writers classify up to ten layers of carbon as graphene (Robaiah et al., 2017). Graphene has many applications and exceptional electrical, optical, magnetic, thermal, and mechanical characteristics, making it one of the most appealing carbon nanomaterials. Several techniques, including chemical synthesis, mechanical exfoliation, chemical exfoliation, and pyrolysis, are employed in the synthesis of graphene (Bhuyan et al., 2016).

5. Applications

Nanotechnology is widely used in many different industries, including health and medicine, electronics, energy, and the environment, as shown in Fig. 10. Nanotechnology presents a viable solution for the efficient removal of contaminants and microorganisms in water purification by desorption (Ali*et al.*, 2017). An explanation of how drugs, proteins, and cancer peptides are delivered via nanotubes has

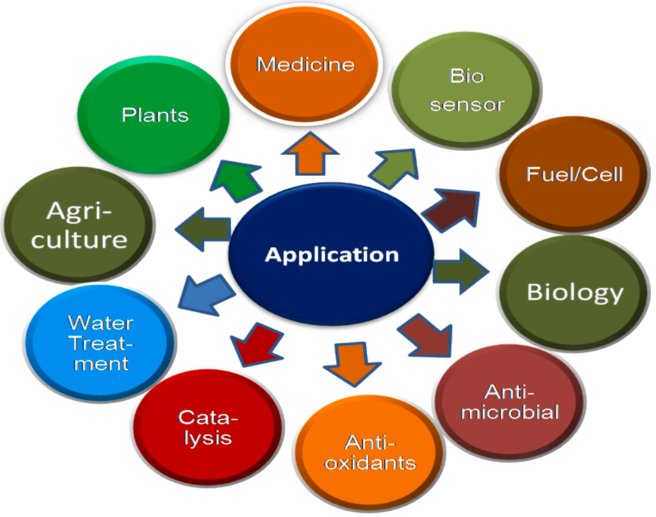


Fig. 10. Important applications of nanoparticles in various fields.

been provided. Various kinds of nanoparticles, including wire nanoshells and carbon dioxide nanoparticles, are available for the treatment of cancer. (Pavlovicet al.,2013). "Green nanotechnology" refers to the production of green nanoproducts and their use, which is favoured over chemical technology to support sustainable development.

5.1. Effect on plants

Because of their small dimensions and significant surface area, nanogrowth stimulants are favourable for seed germination (Aslani et al., 2014), as they may ultimately grasp the seed pores and activate the phytohormones essential for seed development and germination (Kasote et al., 2019). For instance, applying nano-SiO_2 and nano-TiO_2 to soybean plants increased the activity of nitrate reductase, which in turn increased seed germination. However, it was more beneficial to combine the two nanomaterials (Lu et al., 2002). Biologically produced Au, Ag, Ti, Ca, N, and Fe nanoparticles have been used more frequently as nanofertilizers (Hasan et al., 2020; Irshad et al., 2021; Ramiezet *et al.*, 2020).An extract from the Aegle marmelos plant was utilized to create iron oxide nanoparticles, and their potential to reduce Cr stress in *Triticum aestivum* was assessed. Additionally, a morphophysiological examination of wheat plants in response to 450 ppm green iron oxide nanoparticles was conducted. Because the phytochemicals in the plant Aegle marmelos function as reducing or capping agents during the synthesis process, Fe_2O_3-NPs were synthesized utilizing ferric chloride hexahydrate and ferrous chloride solution as an iron precursor with the aqueous extract of the plant. To minimize the detrimental effects of Cr metal stress on wheat and to promote environmentally friendly farming and global food resilience, new methods for addressing plant stress responses have been developed (Hasan *et al.*, 2024) as shown in Fig. 11.

According to Hasan et al. (2020), an examination of EDX data revealed that 34.91 % of iron oxide creation occurred during biological synthesis, whereas 25.8 % occurred during chemical synthesis. The green synthesis of iron oxide nanorods was achieved by the use of the *Withania coagulans* plant and reduction precipitation. As evidenced by the progressive decrease in peak intensity at 553 nm and 550 nm under solar radiation, the degradation of safranin dye in the presence of *W. coagulans*-based nanorods was 30 % greater than that in the presence of chemically synthesized nanorods. Compared to NRs made via a chemical technique, *W. coagulans*-based NRs showed good antibacterial activity against *S. aureus* and *P.* aeruginosa. The unique bioreducing source *W. coagulans* is used to explore new bionanomaterial frontiers.

5.2. Medicines

Medicines, therapeutic applications, and in vitro diagnostic applications benefit significantly from green synthetic nanoparticles (NPs). Nanomedicines bind biomolecules and decrease tissue inflammation and oxidative stress. They have an anti-proliferative impact and act as effective anticancer drugs. Ag NPs can be coated to lessen their toxicity and extend their biological half-life, enabling targeted killing of cancer cells (Elangovan et al., 2015). NPs with gold nanoparticles are anticancers and cause oxidative stress. They take in and transform incident photons into heat, killing malignant cells. The HIV-1 virus readily binds to NPs on glycoprotein knobs. This NP-NP interaction prevents the virus from attaching to host cells, assisting in the prevention and management of HIV infection (Elechiguerra et al., 2005). They are highly advantageous in increasing medication bioavailability, solubility, toxicity protection, pharmacological activities, distribution, and avoidance of physico-chemical deterioration and the stability of pharmaceuticals inside the body (Zoroddu et al., 2014).

5.3. Antimicrobial activity

NPs produced using green approaches exhibit excellent antibacterial (Awwad et al., 2015), antifungal (Sanghi and Verma, 2009), and antiparasitic activities. The degree of effectiveness, potency, and differential activity against microbes is demonstrated by metallic nanoparticles such as Ag with Cu, Au, Pt, Ti, and Zn. In addition to the synthetic antimicrobial agents benzoic, propionic, and sorbic acids, other antimicrobial nanoparticles include natural biopolymers such as chitosan and enzymes such as peroxidase and lysozyme (Kalita and Baruah, 2019). The incorporation of Ag NPs into gelatin-based nanocomposite films promisingly enhanced their antimicrobial activity against both gram-negative

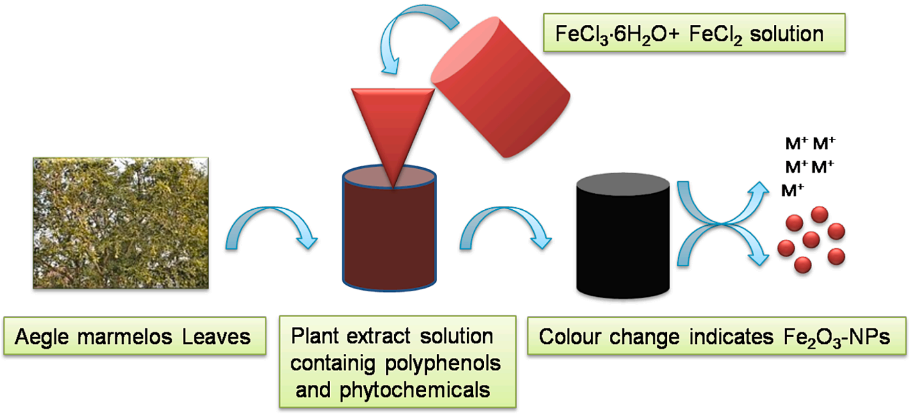


Fig. 11. Synthesis of nanoparticles with aqueous extract of the plant leaves.

and gram-positive food-borne pathogens (Kanmani and Rhim, 2014). ZnO NPs may be incorporated into a variety of polymers, including polypropylene, and their antibacterial properties increase as the particle size decreases (Shankar et al., 2015). TiO_2, ZnO, WO_3, MgO, Ag_2O, ZnO, CuO, CaO, and MgO nanoparticles have potential antibacterial effects on a variety of microbes. According to in vitro research, numerous bacterial species, including *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, and others, may be inhibited by metal nanoparticles (Masoumbaigi et al., 2015). Bimetallic nanocomposites Ag with nickel and cobalt were synthesized by using the extract of *W. coagulans.*Ag@Co had strong antibacterial effects on the gram-positive bacteria*Staphylococcus aureus*,with 48.9 % and 32.1 % inhibition,and Ag@Ni had strong antibacterial effects on the gram-negative bacteria *E. coli,*with 33.1 % and 25.7 % inhibition zones. *W. coagulans* extract was used to create bimetallic nanocomposites Ag with nickel and cobalt. Ag@Co exhibited robust antibacterial activity against gram-positive bacteria, such as *Staphylococcus aureus*, exhibiting 48.9 % and 32.1 % inhibition, whereas Ag@Ni inhibited gram-negative bacteria, such as *E. coli*, by 33.1 % and 25.7 %, respectively (Huang et al., 2023). Clusters of zinc oxide nanoflowers that were 30 nm in size utilizing the chemical reduction-precipitation process and had an average size of 25 nm using *W. coagulans* fruit extract. By inhibiting *S. aureus* and *P. aeruginosa*by 78 % and 88 % and 85 % and 94 %, respectively, the bioactivity of the biologically synthesized ZnO NFs increased. When ZnO NFs were used chemically, their antifungal activities against *Candida albicans* and *Aspergillus niger*were 78 % and 80 %, respectively (Saif et al., 2021).

W. coagulans fruit extract was used as a capping and reducing agent in the synthesis of silver and zinc oxide nanoparticles (NPs). For novel use against bacterial and fungal pathogens that affect honey bees (*Apis mellifera*), green synthetic nanoparticles with unique characteristics were created. Pathogens affecting honey bees, both bacterial and fungal, were isolated, recognized, and given the names *Paenibacillus larval, Melissococcus plutonius*, and *Ascosphaera apis*. Silver nanoparticles and ZnO exhibit noteworthy percentages of 76 % and 74 %, respectively (Hussain et al., 2023) ZnO NPs were produced via Fagonia cretica natural plant extract. Phytochemical screening of the presence of biologically active chemicals in the *F. cretica* water extract revealed that the ZnO NPs had potent antibacterial effects on two types of bacteria, *Staphylococcus aureus* and *Escherichia coli*. Fig. 12 shows antimicrobial application of nanoparticles (Hasan *et al.*, 2023). Using a naturally occurring plant extract of *Withania coagulans* that was optimized by the concentration of the extract and precursor, highly pure nanosponge Co_3O_4 were created using a green technique. The mature, extremely porous, surface-modified nanosponge was obtained at the lowest precursor concentration and with the concentrated extract. The biocompatible surface area of fully developed cobalt nanosponges (Co_3O_4 NS) is reinforced by many interaction sites etched with pores and holes. In the end, Co_3O_4 NS promotes bacterial entrapment through particular interactions and cause cell death via apoptosis (Zafaret al., 2021).

5.4. Antioxidant activity

An antioxidant protects cells from oxidation. In biological oxidation, free radicals are produced and cause a chain reaction because the radicals are reactive, consequently, a cell may be damaged or may die during the reaction (Rao, 2016). Antioxidants bind free radicals, prevent harmful chain reactions and change them to harmless species. Antioxidants control oxidative stress and are used to treat neurodegenerative disorders, aging processes, heart disease, and cancer caused by free radicals. *W. coagulans* fruit extract and a chemical reduction-precipitation technique was able to effectively create clusters of zinc oxide nanoflowers that were 30 nm in size on average. The antioxidant potential of the chemical and biological ZnO NFs was 56.5 % and 67.8 %, respectively, at 50 mg/ml. ZnO NFs, which are less hazardous than chemically made materials, also have significant antioxidant activity (Saif et al., 2021).

5.5. Water treatment

Organic compound (dyes, pesticides, surfactants), inorganic (fluoride, arsenic, copper, mercury), microbial (algae, bacteria, viruses), and radiological (caesium, plutonium, uranium) contaminants render water derived from natural resources unfit for human consumption (Anjum et al., 2019). The aquatic ecosystem has become degraded due to increased wastewater discharge into the environment due to industrialization and the excess use of chemicals. The severance of viruses from drinking water (Gusseme et al., 2010) reported by employing biogenic silver created by *Lactobacillus fermentum*. Organisms, their products, or nanoparticles clean harmful materials in these greener approaches and treat pollutants (Singh and Naraa, 2013). Green nanomaterials are used to treat surface water, groundwater, and wastewater contaminated by hazardous metal ions, organic and inorganic solutes, and microorganisms. Self-cleaning nanoscale surface coatings could replace several cleaning agents required in routine maintenance procedures. Due to their quickly evolving uses for soil remediation of heavy metals and water disinfection (Mahdavi et al., 2013).

5.6. Fuel/cell

Due to their large surface area, photocatalytic applications, catalytic nature, optical behaviour, and widespread use in energy production from the splitting of electrochemical water and photoelectrochemical processes, scientists have discovered that NPs are the best materials for these applications (Ning et al., 2016). In addition to reduction, water splitting, the electrochemical CO_2 process, and fuels, solar cells and piezoelectric generators are reasonably advanced possibilities for producing energy. The finest option is the utilization of nanoparticles in microwiring for producing a printed wiring board in the electrical industry, metal nanoparticle paste (Karim, 2014). Carbon nanotubes, organic nanoparticles, and ceramic nanoparticles may also be present in

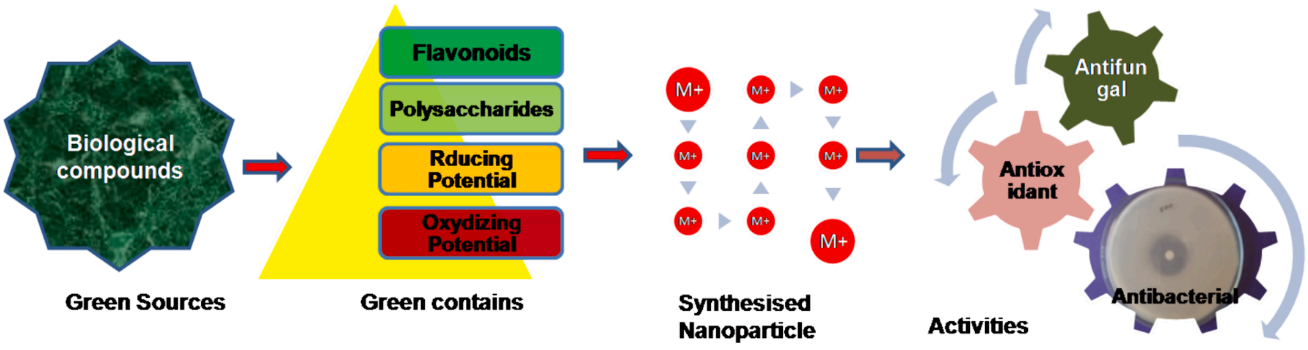


Fig. 12. Potent antimicrobial effects of nanoparticles synthesized by green sources.

these inks (Kosmala et al., 2011). Nickel, lead, silver, and platinum have all been employed as specific metal catalysts for chemical reactions. Gold is a catalyst in hydrogenation and oxidation reactions because gold nanoparticles do not react in these processes.

5.7. *Agriculture*

Nanofertilizers and nanopesticides are currently used to eradicate pests/pathogens/weeds in agricultural practices. Mo, Cu, Fe, Ni, Mn, and Zn nanoparticles serve as micronutrients for nano fertilizers (Rameshaiah et al., 2015). The effects of nanomaterials on plant nanogrowth stimulants are beneficial for seed germination and later development stages. Nanoparticles can infiltrate seed pores and activate the phytohormones needed for seed growth and germination. In recent years, nanopesticides have been used to eliminate pests, pathogens, or weeds impeding crop plant development. For fifty years, nanofertilizers have significantly increased agricultural yields, especially grain yields, and have contributed significantly to meeting the world's food needs, eventually protecting against environmental damage (Mittal et al., 2020). The study examined the effects of chemically and biologically synthesized iron oxide nanorods (NRs) on summer maize (*Zea mays*). Using *Moringa olefera* in conjunction with bulk $FeCl_3$, researchers have found that both chemically synthesized NRs and $FeCl_3$ salt cause growth retardation and impair plant physiological and antioxidative activities at concentrations higher than 25 mg/L due to toxicity caused by overaccumulation. Because of their low toxicity, iron released from biologically synthesized NRs has demonstrated significantly positive results even at 50 mg/L. Specifically, there was an increase in the leaf area (13 %), number of leaves per plant (26 %), total chlorophyll content (80 %), and nitrate content (6 %), all of which were affected by biologically synthesized NRs. Additionally, due to their capacity to generate biologically synthesized NRs, the antioxidative activity of plants is also enhanced upon treatment, and these plants form complexes with metal ions (Hasan et al., 2020). *Lactuca sativaL.* For 25 days, hydroponically grown lettuce plants were subjected to varying quantities of silver ions and nanoparticles to assess their effects on plant development. The interaction of Ag NPs with cells slightly inhibited physiological and biochemical properties, as well as the antioxidant activity of the lettuce plant, as demonstrated by the phytotoxic effects of Ag NPs and ions ($AgNO_3$) on seedling growth parameters and biochemical properties. Compared to those in the control and $AgNO_3$treatments, the concentrations of Ag NPs at 25 and 50 ppm significantly influenced the synthesis of protein, soluble sugar, and chlorophyll. At 100 ppm Ag NPs, the total reducing potential was also observed. Plants may benefit from modest stress to protect them against pathogen attacks and disease control (Hasan et al., 2021).

5.8. *Biology*

NPs have been applied in fluorescent biological labelling, gene transport, biological pathogen detection, protein identification, and DNA structure analysis, among other medical applications. In recent years, interest in medications based on nanotechnology has significantly increased (Elsaesser and Howard, 2012). Lignin nanoparticles and alginate gel beads were prepared, characterized, and used to remove methylene blue (Luo et al., 2022). Chemical processes create most nanoscale metals, which can have unforeseen environmental consequences, energy usage, and even health risks. Green synthesis has been designed to solve these problems since it reduces metal ions without using harmful industrial chemicals. Because it is less expensive, produces less pollution, and enhances environmental and human health safety, green synthesis is preferable to conventional chemical synthesis. However, green synthesis offers an alternate development path and future applications in light of the environmental issues and pollution caused by chemical synthesis.

5.9. *Biomedical*

Iron and its oxide nanoparticles are paramagnetic and have wide biomedical uses in drug delivery, tissue repair cell labelling and magnetic resonance imaging (Catherine and Adam, 2003). Au NPs of different sizes (Khanet al., 2013) exhibit optical properties that are useful for biosensors and cancer nanotechnology (Visaria et al., 2006). ZnO NPs were produced via *Fagonia cretica* natural plant extract. Phytochemical screening of the presence of biologically active chemicals in the *F. cretica* water extract revealed that the ZnO NPs had potent antibacterial effects on two types of bacteria: *Staphylococcus aureus* and *Escherichia coli*(Hussain et al., 2023). Using a naturally occurring plant extract of *Withania coagulans* that was optimized by the concentration of the extract and precursor, highly pure nanosponge Co_3O_4 NS were created using a green technique. The mature, extremely porous, surface-modified nanosponge was obtained at the lowest precursor concentration and with the concentrated extract. The biocompatible surface area of fully developed cobalt nanosponges (Co_3O_4 NS) is reinforced by many interaction sites etched with pores and holes. In the end, Co_3O_4 NS promote bacterial entrapment through particular interactions and cause cell death via apoptosis (Zafar et al., 2021).

5.10. *Biosensing*

Biologically synthesized Au nanoparticles provide an essential technique for detecting hormones in urine samples from pregnant women (Kuppusamy et al., 2014). Medical detection of adrenaline is required because adrenaline functions as a medication in the treatment of allergies, heart attacks, asthma, and cardiac surgery. Pt nanoparticles have been demonstrated to be an innovative biosensor with great sensitivity for adrenaline detection (Brondaniet al., 2009).

5.11. *Food industry*

In the manufacturing, preservation, packing, and delivery of food items, nanoparticles are crucial. In food packaging, it is used as a nanosensor, nanoadditive, nanocarrier, anticaking agent, and antibacterial agent (Ezhilarasi et al., 2013). To increase nutritional absorption and delivery without changing the flavour, colour, or texture of food items, nanoceuticals and nutrients generated by nanotech are offered as nano-supplements, powders, and nanocochleates. Vitamin spray-induced nanodroplets are also utilized to improve micronutrient absorption.Using *W. coagulans* as a reducing agent, ZnONPs and AgNPs were created and then applied to Rohu (Labeo rohita), one of the main carp fish in India and a popular food in South Asia. L. rohita was used in the in vivo experiment, and after 4 and 15 days of exposure, an appropriate quantity and optimized concentration of L. rohita were applied to examine the hematological, enzymatic, and protein characteristics of the organism. ZnONPs were shown to be more active than AgNPs, enhancing the survival potential and improving the cellular modulations in L. rohita. On average, they were 58, 69, and 29 % on day 4 and 34, 51, and 70 % on day 15, respectively. The in vitro and in vivo mechanisms were emphasized by the notable quantities of nanoparticles (Hasan et al., 2022).

5.12. *Electrical*

Ag and graphene oxide nanoparticles exhibit electrical, optical, and physical properties. According to electron and atomic force microscopy data, nanoparticles with a size of 60 to 100 nm were used. Compared to those of pure graphene oxide (Neustroev et al., 2018), the permeability and electrical resistance of these materials indicate higher optical transparency and electrical conductivity.

5.13. Catalysis

Metal oxide nanoparticles are used as catalysts in reactions such as oxidation–reduction, depolation, biosynthesis, green chemistry, and photocatalysis. Iron oxide nanoparticles are important catalysts in refining and petrochemical processes and are used to improve environmental quality (Vedrine, 2017). Degradation of azo dyes by Pd NPs is achieved by soya leaf extracts (Petla et al., 2012). Crystal violet dye was used as a model pollutant that adsorbed on Fe_3O_4 NPs coated with soluble biobased products (Magnacca et al., 2014).Heterogeneous photocatalysis occurs on catalysts, and the preadsorption of pollutants is essential for their degradation. Many nanomaterials, such as TiO_2, activated carbon, stainless steel, silica, zeolites or clay materials, have been used to prepare hybrid photocatalysts (Szczepanik, 2017). ZnO NFs produced chemically and biologically used as a prototype reactant to illustrate the photocatalytic activity. The ZnO NFs-dependent dye removal effectiveness was assessed forof the industrial dye methylene blue, which is toxic and often utilized when exposed to sunshine. The removal of the dark blue dye confirmed that all of the toxic organic components that make up MB had degraded. The deterioration of methylene blue was investigated using UV–visible spectroscopy by continuously measuring the absorbance intensity. Additionally, up to 90 % of methylene blue may be degraded by ZnO NFs when utilizing photoreflexive ZnO NFs, and up to 78 % may be degraded when using chemically generated ZnO NFs (Saif et al., 2021). Using W extract, bimetallic nanocomposites of Ag with nickel and cobalt were used to create coagulants. Next, using photocatalysis, the composites showed significant 90.2 % and 82 % degradation for Ag@Co and Ag@Ni, respectively, against methyl orange (MO). Additionally, the Ag@Ni and Ag@Co nanocomposites demonstrated a 90 % adsorptive removal rate for lead ions from water with notable antioxidant potential and an effective adsorption capacity for heavy metals (lead) at pH 7 for 45 min. The elimination of hazardous contaminants through effective adsorptive and catalytic potentials is a suitable and promising application for nanocomposites (Hasan et al., 2023).

5.14. Energy storage

Graphene and carbon tube nanoparticles offer a variety of advanced applications in energy storage, biological applications, and electrolytes because of their mechanical, electrical, and thermal properties (Saba et al., 2018). Electrochemical double-layer and pseudo supercapacitors are supercapacitors with more power and excessive energy density; they produce more energy than conventional batteries and Li-ion batteries (Emmett et al., 2014; Xu et al., 2018). The electrical energy is stored through the electrostatic accumulation of charge and in pseudocapacitors through reversible reactions.

6. Toxicity of metal nanoparticles

However, the extensive discharge of NPs into the air, water, and soil by a variety of sectors produces nanowaste, which is hazardous to living organisms and jeopardizes the equilibrium of ecosystems. NPs are more susceptible to many ailments, including bronchial asthma, allergies, diabetes, cancer and inflammation (Pandey et al., 2018). The toxicity of different NPs, including Au and TiO_2, affects the animal reproductive system (Semmler-Behnke et al., 2014; Gao et al., 2012). The enzymatic activity of other microbes has also been decreased by several NPs, including Ag, Cu, ZnO, and Ni. Furthermore, an overabundance of NPs has an impact on the ecosystem's food chain (Dash and Kundu, 2020). Plant toxicity mostly results from lipid peroxidation, which also damages DNA and reduces photosynthetic pigments, biomass, soluble protein content, and other factors (Zhu et al., 2019). The genotoxic and phytotoxic effects of nanoparticles in plants, such as DNA damage in plant cells, can be detected, while changes in the morphology and physiology of plants can be used to evaluate the phytotoxic effects of NPs. NPs are also able to penetrate the blood–brain membrane and enter the brain (Oberdorster et al., 2009). Due to their special properties, nanomaterials may easily breach cellular layers, tissues, and compartments to cause harm to cells. The potential toxicity, surface reactivity, and adsorption properties are further improved by increasing the surface area of the same chemical (Bakand and Hayes, 2016). However, the majority of any negative consequences (such as oxidative stress) are borne by target organs, including the central nervous system (Oberdorster et al., 2009; Thunugunta et al., 2015).

7. Future challenges and perspectives

Since NPs have several applications, we believe that there are strong opportunities for industrial-scale manufacturing. Overall,the fascinating field of nanotechnology has the potential to influence future developments in nanoscience (Usman et al., 2020), such as the utilization of waste materials and algae for the green synthesis of nanomaterials. These nanomaterials are made primarily using organic solvents, which pose a significant risk to reproductive and neurobehavioral health throughout the synthesis process (Joshi, *et al.*, 2019; Akinyemi et al., 2019). High pressure and heat conditions can also contribute to hazardous working conditions (Teoh et al., 2010). The most serious side effects of these processes are volatile vapour and excessive carbon dioxide generation, which significantly add to greenhouse impacts (Caramazana et al., 2018; Pourzahedi and Eckelman, 2015). Bioavailability, adverse responses, cellular interactions, biodegradation and other aspects must be taken into consideration. It takes a long time and much effort to successfully translate nanomedicines into the clinic since there are toxicity hazards to consider. Finding novel, affordable, safe, and environmentally friendly reactants to utilize in place of the previously described hazardous compounds is presently the main focus of this study. Reagent replacement of this kind, of course, necessitates finding a new balance between reaction yield and environmental sustainability (Thunugunta et al., 2015).

8. Conclusions

This review concentrated on natural ways to make NPs, including those involving plants, fungi, algae, and other microbes. There is a need to lessen the effects of toxicity in the environment from the many chemicals employed in physico-chemical procedures because the current methods of producing NPs are expensive and produce very harmful products. Chemical synthesis by top-down and bottom-up approaches and their diverse effects on the environment by considering individual methods are discussed. Green synthesis is one of the alternative methods for creating NPs. The current review concentrates on metal nanoparticles made from plants and microorganisms versus chemical synthesis. In contrast to more traditional physical and chemical approaches, green synthesis techniques offer a safe, nontoxic, and eco-friendly alternative for synthesizing metal NPs. Numerous plant components, such as leaf and fruit extracts; seeds, fruit, and bark; and microorganisms, such as bacteria, fungi, and actinomycetes, are capable of synthesizing different metals and metal oxide nanoparticles. The determination of structural morphology by using various characterization techniques has been discussed and analysed.

Green synthesis methods are more effective than conventional synthesis techniques because they do not harm the people involved in their production or the environment. The unchecked climate change we are experiencing will lead to tragedy for humanity. It is essential to perform this critical study in an environmentally friendly manner by following the principles of green chemistry. We will be able to construct new supercomputer conductors through research into the green synthesis of nanotechnology. We will also be able to use revolutionary sensors to study space, the final frontier. Biological techniques do not require harmful or harsh chemicals because they are more sustainable than chemical methods. Plant extract waste is less hazardous and simpler to dispose of. Additionally, NPs created using the green pathway are more stable and efficient than those made using physicochemical methods. The majority of the reported greener synthesis efforts for Ag and Au NPs have been previously documented; this may be because of their significance in the field of disinfection. Capping agents and functional groups play important roles in the manufacturing of nanoparticles and make them more efficient. Various nanoparticles synthesized from chemicals, plants and microbes have been highlighted for their origin, morphology, size and broad-spectrum applications in different fields. The toxicity of metal nanoparticles and their impacts on humans and the environment have been explained in a significant manner. Future challenges, perspectives and alternative methods are considered in this study.This review is devoted to and concludes with a comparative analysis of chemical vsgreen synthesis of nanomaterials, which play an imperative role in human and environmental welfare.

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Rameshwari A. Banjara: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ashish Kumar:** Supervision, Software, Resources, Formal analysis. **Roman Aneshwari:** Visualization, Validation, Supervision, Resources. **Manmohan L. Satnami:** Visualization, Validation, Supervision, Resources, Formal analysis. **S.K. Sinha:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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