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REVIEW

Biogenic synthesis of metal nanoparticles: promoting green nanotechnology and sustainable development goals

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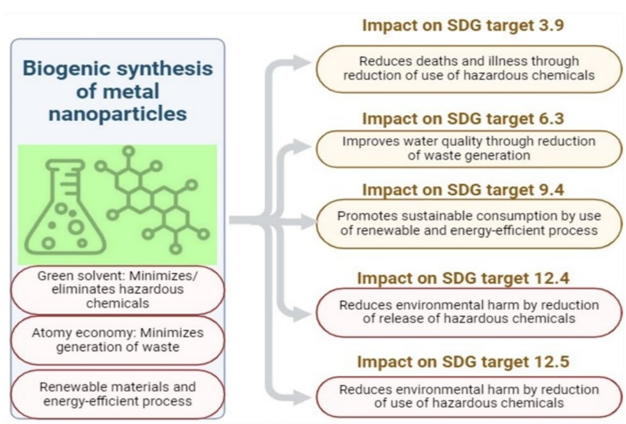
Abstract
Nanotechnology has expanded rapidly, resulting in the introduction of numerous nanomaterials for use in drug delivery, diagnostics, catalysis, environmental remediation, and the biomedical field. Though nanotechnology offers many benefits, the chemical and physical processes of producing nanomaterials are not sustainable and detrimentally affect the environment. Such processes go against the spirit of the sustainable development goals viz. sustainable development goals (SDGs) targets 3.9, 6.3, 9.4, 12.4, and 12.5 that advocate for reduction or elimination of hazardous chemicals, pollutants and contaminants to the environment; and designing sustainable, resource-use efficient industries and adoption of clean technologies. Biogenic synthesis of metal nanoparticles based on the principles of green chemistry aims to reduce or entirely eliminate the use of hazardous chemicals and minimize or possibly eliminate generation of pollutants. By use of eco-friendly solvents, maximization of atom economy to minimize waste generation and elimination of hazardous chemicals and waste to minimize impact on environment and human health, green nanotechnology substantially contributes to achieving the aforementioned SDGs targets. Integrating green nanotechnology into environmental policies can drive the adoption of eco-friendlier nanomaterials and production processes in developed and developing nations. This review focuses on the potential of biogenic synthesis of metal nanoparticles in advancing SDGs.

Graphical abstract



Keywords Green nanotechnology · Biogenic synthesis · Nanoparticles · Sustainability · SDGs

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Introduction

Nanotechnology, which involves materials being manipulated at the nanoscale, is a key enabling technologies in the twenty-first century (Bayda et al. 2019). Nanotechnology has grown tremendously leading to introduction of many nanomaterials for applications in various fields such as drug delivery, diagnostics, catalysis, environmental remediation, and biomedical field (Kanaoujiya et al. 2023). A lot has been invested in nanotechnology to drive it forward for continuous harnessing of economic and societal benefits. However, despite the numerous benefits of nanotechnology, production of nanomaterials mainly makes use of unsustainable processes such as chemical methods and physical methods that have destructive consequences on the environment. Physical and chemical methods are frequently used in nanomaterials and nanotools synthesis with higher rates of production and homogeneity (Jain et al. 2023). Physical methods include, inter alia, thermal decomposition, mechanical/ball milling and lithography. Chemical methods include; chemical reduction method, chemical vapor deposition, micro-emulsion/colloidal, pyrolysis, sonochemical, photochemical, electrochemical, sol–gel and hydrothermal methods (Chouke et al. 2022).

Materials scientists have made significant developments in the improvement of these methods. However, despite the improvements, these methods are known to consume higher amount of energy, use hazardous solvents and materials in synthesis, and generate large amounts of waste that pose negative impact on environment and humans thus rendering them destructive and unsustainable (Dehno Khalaji 2020). Reports indicate that manufacture of materials is lengthy involving use of hazardous chemicals and generation of significant waste such as contaminated solvents (Jiménez-González et al. 2004). For instance, dispersants, surfactants, or chelating agents are used in chemically synthesized nanomaterials to inhibit particle agglomeration. When used in large scale production, these reagents can be environmental pollutants. Additionally, nanomaterials from these methods may be associated with instability, bio-incompatibility, and toxicity hindering their application in the environment and human beings (Ijaz et al. 2020).

Traditional synthesis of metal nanoparticles normally use hazardous chemicals, generate significant waste and pollutants that adversely affect the environment and consume high energy (Idris and Roy 2023), making such processes to go against the spirit of the sustainable development goals (SDGs) targets 3.9, 6.3, 9.4, 12.4, and 12.5. SDG targets 3.9, 6.3, 9.4, 12.4, and 12.5 seek to achieve sound management, minimization or elimination of use of hazardous chemicals and reduction in generation of waste and pollutants (Katila et al. 2019). These suggest that minimization or eliminating the use of hazardous chemicals and reducing waste generation through green nanotechnology promotes the above-mentioned SDG targets. Additionally, SDG target 9.4 seeks to design resource-use efficient and clean processes to achieve sustainable consumption, decrease carbon footprint and reduce pollution (Katila et al. 2019).

The limitations associated with physical and chemical synthesis remain a big concern that has inspired the search for alternative sustainable synthesis methods such as green nanotechnology that align with the objectives of the aforementioned SDGs targets. Green nanotechnology, which uses eco-friendly technologies to create nanoparticles, is promising and provides impeccable solutions that support sustainable nanotechnology. By using less toxic reagents, utilizing low temperatures, and utilizing renewable energy sources whenever feasible, green synthesis expands on the twelve (12) principles of green chemistry to create nanomaterials. Thus, green synthesis is safer and eco-friendly than conventional methods (Ijaz et al. 2020). Thanks to its easy scale-up, economic viability, environmental friendliness, and simple process, the eco-friendly synthesis of nanomaterials is expanding quickly. There is also research being done on the potential for solvent-free biosynthesis of nanomaterials, albeit the research is still in its early stages, in an effort to support the principles green chemistry (Ahmed et al. 2022).

As a subset of green nanotechnology, biogenic synthesis uses biological sources—plants and microorganisms—as bioreducing, stabilizing, and capping agents (Mughal et al. 2021). Biogenic metal nanoparticle synthesis utilizes green solvents, optimizes atom economy reducing waste generation and proceeds under milder conditions room temperature thus decreasing energy consumption (Kurhade et al. 2021). Moreover, utilization of renewable and biodegradable materials such plant components promotes sustainability. The use of biogenic synthesis not only addresses the limitations of physical and chemical methods but also provides alternative sustainable and scalable processes for application in various sectors (Kisimba et al. 2023). By using biogenic synthesis to achieve sustainability, products and nanomaterials can be produced that support both the current and future generations without endangering human health and the environment (Palit and Hussain 2020). Green nanotechnology can support realization of the SDGs targets by promoting sustainable nanotechnology practices that lessen negative effects on the environment, enhance conservation efforts, and safeguard human health and resources (Aithal and Aithal 2021). Thus, strategies such as this that promote sustainable development goals are highly needed in the field of nanotechnology.

Several reviews have explored the biogenic synthesis of metal nanoparticles (Bhati 2023; Madani et al. 2022; Mughal et al. 2021; Patil and Chandrasekaran 2020; Sharma et al. 2019; Solgi and Taghizadeh 2020). Most of these reviews have focused on the procedures and biological sources used during biogenic synthesis. Despite the clarion call to document interventions that promote sustainable nanotechnology and SDGs targets, reviews that specifically cover and link the potential of biogenic synthesis to address the aforementioned SDGs targets are currently not available in literature and this review aims to fill this gap.

To address this gap, this review is not intended just to summarize biogenic synthesis of metal nanoparticles but rather its novelty lies in linking the potential of biogenic synthesis of metal nanoparticles to addressing SDG targets 3.9, 6.3, 9.4, 12.4, and 12.5. Sustainable nanotechnology themes inter alia eco-friendliness, green energy-efficient processes, green solvent, and biocompatibility that form the basis for biogenic synthesis have been discussed. Studies under each theme have been grouped and discussed with an emphasis on sustainable nanotechnology. Finally, the perspectives and recommendations on biogenic synthesis have been spelled out.

SDGs and green nanotechnology

SDGs targets 3.9. 6.3, 9.4, 12.4 and 12.5 interconnection with green nanotechnology

The pressing political, economic, and environmental problems that the society is currently facing led to the creation of the SDGs (Fallah Shayan et al. 2022). For instance, a report by GlaxoSmithKline (GSK) from a study on waste produced during production of active pharmaceutical ingredients indicated that more than 80% of their waste was solvent related (Jiménez-González et al. 2004). In another study, Dehno Khalaji (2020) indicated that use of physical methods such as thermal decomposition in production of metal nanoparticles consumed high energy (600 °C for 3 h) and generated substantial waste that caused environmental pollution making the process unsustainable. Further, a study by Sarkhosh et al. (2022) demonstrated that zinc oxide nanoparticles synthesized using chemical method detrimentally affected seed germination of *Camelina sativa* and *Brassica napus* in a dose-dependent manner.

On this basis, SDGs targets 12.4, 12.5, 3.9 and 6.3 aim to achieve sound management, minimization or elimination of use of hazardous chemicals and reduction in generation of waste and pollutants. In particular, SDG 12 target 4 talks about sound management of chemicals and generated waste throughout their life cycle. Further, the SDG 12.4 targets to significantly reduce release of chemicals and waste into environment to minimize their negative impacts on humans and the environment. SDG 12.5 targets to prevent, reduce, recycle and reuse waste to substantially decrease its generation. SDG 3 target 9 talks about reducing number of deaths and illness from hazardous chemicals, pollutants and contaminants. It is closely related to SDG 6 target 3 talks about reducing pollution and minimizing release of hazardous chemicals and pollutants into water environment to improve water quality (Katila et al. 2019). Biogenic synthesis of metal nanoparticles aims to reduce or entirely eliminate the use of hazardous chemicals and minimize or possibly eliminate generation of pollutants. By use of eco-friendly solvents, maximization of atomy economy to minimize waste generation and elimination of hazardous chemicals and waste to minimize impact on environment and human health, green synthesis substantially contributes to achieving the above-mentioned SDGs targets.

SDG 9 target 4 talks about designing sustainable and resource-use efficient industries, and adoption of clean technologies and processes (Katila et al. 2019). In context, biogenic synthesis aims to optimize resource use, use renewable and biocompatible materials, allow reactions to proceed at room temperature/milder conditions and use energy-efficient processes making the overall production process sustainable. Additionally, green synthesis optimizes atom economy reducing waste generation. Compared to high-energy consuming physical process such as pyrolysis, green synthesis occurs at milder conditions or ambient temperature thereby advancing sustainable consumption (Gupta et al. 2023). By adopting green synthesis, industries will decrease carbon footprint and reduce pollution as envisaged in SDG 9.4.

Implementation green nanotechnology by growing industries to attain SDGs targets

Growing industries are urged to embrace green nanotechnology to enable realization of SDGs targets to foster a sustainable future. The SDGs provides a framework that can adopted by growing industries to achieve sustainable processes. Some key guidelines for adopting green nanotechnology and foster SDGs implementation include: Growing industries embedding sustainability in their operations; Partnering with relevant stakeholders in the implementation process; Setting measurable SDGs targets and tracking their progress; and investing in research and development for sustainable processes, new clean technologies and approaches to overcome implementation barriers (Aithal and Aithal 2021).

By aligning and integrating their operations with eco-friendly nanotechnology solutions, these industries can progress toward SDGs targets 3.9, 6.3, 9.4, 12.4 and 12.5. For instance, Pfizer pharmaceutical industry successfully integrated green chemistry in its production of celecoxib. Pfizer's celecoxib synthesis based on green chemistry principles used benign solvents (50% aqueous isopropanol and methanol) eliminating the hazardous hexane and methylene chloride, and substantially decreased the use of hazardous hydrazine. The yield went up from 63 to 84% and waste generation went down by 35% thus reducing environment impact (Saxena et al. 2022). In this case, the shift toward green and sustainable strategies for drug synthesis through judicious selection of greener solvents contributes to eco-friendly drug production and aligns with SDGs' objectives of responsible consumption and production.

Several case studies and pilot projects have demonstrated the practical implementation of biogenic nanoparticles in sustainable technologies. For example, metal nanoparticles biogenically synthesized have been used in environmental bioremediation, effectively removing pollutants and waste (Bhardwaj et al. 2023). Use of biogenic metal nanosorbents in treatment of wastewater demonstrates practical application of biogenic nanoparticles in a sustainable manner. For instance, silver nanoparticles synthesized using *P. thonningii* leaf extract have been successfully utilized in removal of heavy metals from wastewater (Tailor et al. 2020). Goutam and co-workers produced titanium dioxide nanoparticles by use of *Jatropha curcas* leaf extract and applied the biogenic nanoparticles to remove 74.5% chromium and 82.3% chemical oxygen in wastewater (Goutam et al. 2018). In the pharmaceutical field, green synthesized platinum nanoparticles exhibited activity against *P. aeruginosa* and *S. pyogenes* and anticancer activity on SKO-3 and SK-GT-4 cell lines (Ali and Mohammed 2021).

A comparative study by Sharma et al. (2022a, b) employed green synthesis using biocompatible *Zingiber officinale* leaf extract as a reducing and capping agent to synthesis silver nanoparticles. Similarly, NaBH4 was used as reducing agent in the chemical synthesis process. The results demonstrated that silver nanoparticles produced by green approach had a superior antibacterial activity. Additionally, the plant-mediated nanoparticle synthesis offers a sustainable synthesis route and reduces environmental pollution since the plant extract is easily disposed without environmental harm compared to NaBH4. In another case study, Mahaya et al. (2023) looked at the implementation of SDGs in a pasteurized milk industry. The study indicated that implementing SDGs in this growing industry involved reducing, recycling and reusing it safely.

To implement the SDGs, growing industries would have to prioritize and align relevant SDGs targets with their operational process. Through adoption of green synthesis and integration of green nanotechnology into environmental policies, developed and developing nations can drive the adoption of eco-friendlier nanomaterials and production processes as they commit to sustainable consumption, clean energy and reduction of pollution.

Limitations of green nanotechnology in achieving SDGs targets

Green nanotechnology adoption, while holding benefits of long-term sustainability, it is in infancy stage and does face limitations such economic feasibility, scalability, technological difficulties, cost, inconsistent regulations, toxicity concerns and industry unacceptance that hinder its implementation by growing industries (Gupta et al. 2023; Kisimba et al. 2023). Integration of green nanotechnology requires careful considerations of these limitations to ensure successful and wider implementation in growing industries. Moreover, investing in green nanotechnology research, promoting education of green nanotechnology and SDGs, developing appropriate guidelines on implementing green nanotechnology to foster attainment of SDGs targets, and conducting a comprehensive assessment of nanotoxicity and environment impact can unlock the potential of green nanotechnology and progress toward achieving SDGs targets.

Green chemistry principles

The foundation of green chemistry consists of the twelve principles put forth by Paul Anastas and John Warner in their attempt to characterize a more environmentally friendly (or greener) chemical process or product (Chen et al. 2020). The development of green chemistry principles aimed to prevent pollution at its source by minimizing the use of hazardous chemicals and optimizing product yield in the preparation of nanomaterials (Madani et al. 2022). Though no reaction can be entirely green, by applying the following 12 green chemistry principles wherever appropriate, the overall detrimental effects of nanotechnology research and industry can be lessened (Ameta and Ameta 2023). Table 1 highlights the twelve principles of green chemistry, their interpretation and consideration in biogenic synthesis of metal nanoparticles to promote sustainable and green nanotechnology.

Promoting sustainable nanotechnology through biogenic synthesis of nanoparticles

Developing nanomaterials through easy, affordable, environmentally friendly, and green methods is the cornerstone of sustainable nanotechnology. The process of creating nanomaterials through biogenic synthesis is one such technique that is safe, economical, ecologically friendly, and clean (Ravikumar and Prakash 2022). The production of nanoparticles through biogenic synthesis is becoming a viable, affordable, sustainable, biocompatible, and alternative method to chemical and physical methods (Chauhan et al. 2023). This production of safe, non-toxic, economical, energy-efficient, and metallic nanoparticles using plants and microbes like viruses, bacteria, fungi, and algae has been extensively studied, increasing significantly in the recent years. Green synthetic technology undoubtedly has a significant impact on improving biological compatibility and lowering environmental toxicity and pollution (Chopra et al. 2022).

Table 1 Twelve principles of green chemistry, their interpretation and consideration in synthesis to promote green nanotechnology

Green chemistry principle	Interpretation of principle	Consideration of principle in biogenic synthesis
1. Prevent waste generation	Formulate innovative, environmentally friendly chemical nanomaterials by reducing or eliminating waste production and the creation of unusable byproducts (Lancaster 2020)	To prevent production of unwanted products during the fabrication of nanoparticles, strategies, such as morphological control, can be considered (Zhao et al. 2020). Plant extracts are easily disposed without any harm to the environment
2. Design safer materials	Create less toxic or non-toxic nanomaterials. Reduce the amount of contaminants that might be hazardous to people or the ecosystem (Khan 2020)	Utilizing modern purification techniques can be helpful in retaining the impurities (Din and Rani 2018)
3. Less harmful chemical processes	Work on creating synthesis methods that create compounds with little to no toxicity to people or the environment by using environmentally friendly reagents and solvents (Khan 2020)	Utilizing naturally occurring substances, like plant extract, to reduce metal precursors to nanoparticles is an illustration of environmentally friendly processes using safe reactants (Madani et al. 2022)
4. Utilize renewable feedstocks	Make use of environmentally friendly, sustainable energy sources and raw materials (Khan 2020)	Utilizing renewable resources like sunlight and renewable materials like cellulose, chitin, starch, and glycerol to create nanoparticles (Yanat and Schroën, 2023)
5. Utilize catalysts	Through the reduction of activation energy, improved raw material utilization, and waste minimization, the appropriate catalyst selection can improve process efficiency overall (Falsini et al. 2018)	For instance, polyoxometalates can function as photocatalysts in the production of metallic nanoparticles, enabling the reactions to occur in a matter of minutes at room temperature (Gu et al. 2021)
6. Reduction of chemical derivatives	Derivatization procedures like blocking, protecting, and substance alteration ought to be avoided since they add more chemicals, use more energy, and produce more waste (Ivanković et al. 2017)	Using biopolymers like chitosan can reduce the requirement for capping agents when synthesizing metallic nanoparticles (Verma et al. 2021)
7. Maximize atom economy	Design and develop synthesis so that the finished product contains the maximum amount of the precursors and raw ingredients (Khan 2020)	Using fewer reactants by choosing reagents that serve double roles (e.g., using polysaccharides as both capping and reducing agents) improves the atom economy of reactions (Madani et al. 2022)
8. Safer solvents	Hazardous solvents and chemicals should be avoided (Ameta and Ameta 2023)	Synthesis of nanoparticles can be done with non-toxic solvents like glycerol or water, or with safer methods like solventless systems (Piermatti 2021)
9. Energy efficiency	Develop techniques for synthesis that can, if feasible, be performed at room temperature and pressure (Ameta and Ameta 2023)	Reducing energy consumption through lowering the activation energy by choosing suitable precursors that allow for conversion to occur at room temperature
10. Degradability	Chemical products should readily break down into simpler, non-toxic molecules without staying long in the environment (Ameta and Ameta 2023)	Stabilizing nanoparticles with biodegradable polymers guarantees a brief product life after environmental release (Sharma and Pathania 2022)
11. Real-time monitoring of pollutants	The synthetic process must be continuously monitored in order to avoid unwanted byproduct production and to conserve energy (Ivanković et al. 2017)	Real-time monitoring of nanoparticles synthesis to avoid formation of unwanted pollutants (Ivanković et al. 2017)
12. Safer chemistry	To minimize risks and hazards like toxicity, flammability, explosivity and to prevent accidents, materials needed for synthesis should be chosen carefully (Khan 2020)	Eliminating flammable and hazardous materials such as dimethyl formamide, sodium borohydride, carbon monoxide and hydrazine from nanoparticle synthesis process (García-Ruiz et al. 2021)

Typically, the synthesis of nanoparticles requires the use of multiple reagents, such as solvents, reducing and stabilizing agents, precursors, and in certain situations, energy to attain the ideal temperature for reduction (Shafey 2020). Thus, green reagents and green energies have been investigated in an effort to develop a green approach. Scholars have explored a variety of phytochemical constituents in plants and plant extracts that can function as solvents, stabilizers, or capping agents as alternatives to the hazardous reagents (Sharma et al. 2022a, b). Furthermore, studies on the use of microwave, gamma, and ultraviolet radiation have shown that these methods can both reduce and produce uniform heating in nanoparticle synthesis (Guo et al. 2020). Table 2 summarizes studies on biogenic synthesis of metal nanoparticles with emphasize on the green solvent used, green energy-efficient process and biocompatible reagents used as reducing, capping or stabilizing agents. These studies are reviewed in the subsequent sections based on the green solvent, green energy-efficient process, and biocompatible biological components used as reducing, stabilizing and capping agents.

Sustainable nanotechnology through use of safer solvents in biogenic synthesis

The use of solvent systems is an essential step in any synthesis process. The green solvent method employs green solvents, e.g., distilled water instead of organic solvents during the synthesis of nanoparticles. In addition to their low toxicity and ability to be renewed, these green solvents have the advantage of not harming human health or ecosystems (Tilahun Bekele et al. 2021). The best solvent is none at all, and water is the perfect solvent if one is required. Water is always thought to be the best, affordable, widely available and most appropriate solvent system. Water has been used as a solvent for the synthesis of several metal nanoparticles such as silver, copper, gold, palladium, iron, platinum, etc. Supercritical fluids, ionic liquids and liquid polymers such as PEG are also green solvents that can be considered in synthesis of metal nanoparticles. However, studies using these solvents are scanty, pointing a gap that needs to be explored in future studies. In this subsection, we review metal nanoparticles that have been synthesized using water as a green solvent.

Silver nanoparticles have been synthesized by many researchers using water as a green solvent at room temperature (Cardoso-Avila et al. 2021; Gharari et al. 2023; Odeniyi et al. 2020; Razavi et al. 2020; Rodríguez-Félix et al. 2021; Suganya et al. 2020; Tamilarasi & Meena 2020; Wang et al. 2018a, b; Zangeneh et al. 2019a, b). For instance, Wang and co-workers synthesized and characterized silver nanoparticles in aqueous medium. The average size of the AgNPs was 25–35 nm with a zeta potential of – 20.17 mV, indicating good stability. Additionally, the AgNPs exhibited high scavenging activity and strong inhibition against selected bacteria (Wang et al. 2018a, b). In another study, Rodríguez-Felix and co-workers synthesized silver nanoparticles in water at room temperature using safflower aqueous extract rich in proteins, polysaccharides and polyphenols. They obtained uniform and spherical nanoparticles with mean size of 8.67 nm which demonstrated antimicrobial properties (Rodríguez-Félix et al. 2021). Additionally, Tamilarasi and Meena synthesized silver nanoparticles with enhanced antibacterial activity using *Gomphrena globosa* leaf aqueous extract as a reducing agent and stabilizer in water medium at room temperature (Tamilarasi and Meena 2020).

Gold nanoparticles have also been synthesized using water as a green solvent at ambient temperature (Cardoso-Avila et al. 2021; Fadaka et al. 2021; Rajeshkumar et al. 2021; Shakerimanesh et al. 2022). For instance, Shakerimanesh and co-workers synthesized spherical gold nanoparticles in water using *Haplophyllum obtusifolium* aqueous extract, characterized and tested their cytotoxicity against breast cancer cell line (Shakerimanesh et al. 2022).

Palladium nanoparticles have also been synthesized at room temperature using water as the solvent medium (Bathula et al. 2020; Razavi et al. 2020). Bathula and co-workers employed ultrasonically driven production of palladium nanoparticles using *Coleus amboinicus* aqueous extract at room temperature for 30 min. This novel process was simple and fast producing spherical palladium nanoparticles with a mean size of 45 nm (Bathula et al. 2020).

Iron nanoparticles too have been synthesized at room temperature in a water medium (Jamzad and Kamari Bidkorpeh 2020; Salem et al. 2019; Zangeneh et al. 2019a, b). For instance, Salem and co-workers used water to produce iron oxide nanoparticles biogenically at room temperature with the use of algae species. The spherical nanoparticles had a size of between 11.24 and 33.71 nm and possessed a wide spectrum of antimicrobial activity (Salem et al. 2019). Similarly, Jamzad and Bidkorpeh synthesized iron nanoparticles using *Laurus nobilis* leaves aqueous extract. The nanoparticles were spherical and hexagonal with antibacterial and antifungal activity (Jamzad and Kamari Bidkorpeh 2020).

Copper nanoparticles have also been synthesized utilizing water as green solvent at room temperature (Nzilu et al. 2023; Razavi et al. 2020). For instance, Nzilu and co-workers synthesized copper nanoparticles at room temperature using an aqueous extract of *Parthenium hysterophorus* as a reducing, capping and stabilizing agent. The nearly spherical copper nanoparticles had a mean size of 59.99 nm and possessed an ability to degrade rifampicin antibiotic (Nzilu et al. 2023). Figure 1 illustrates the biogenic synthesis of copper oxide nanoparticles in aqueous medium. Similarly, Jothiramalingam and co-workers synthesized copper nanoparticles utilizing aqueous extract of lemon flower at 60°.

Table 2 Summary of studies on biogenic synthesis of metal nanoparticles utilizing green solvent, green energy-efficient process and biocompatible materials as reducing, capping or stabilizing agents

Sustainable nanotechnology theme/green chemistry principle			Nanoparticle	Key characteristics	References
Green solvent	Energy efficient process	Biocompatible stabilizer/ Capping agent			
Water	Synthesis at room temperature within 30 min	Polyphenols in aqueous *P. guajava* leaf extract	Ag NPs	Particle size: 20–35 nm	(Wang et al. 2018a, b)
Water	Synthesis at room temperature within 2 h	Seaweeds (*Colpomenia sinuosa*) and (*Pterocladia capillacea*) aqueous extracts	Fe_3O_4 NPs	Spherical NPs, 11.24–33.71 nm	(Salem et al. 2019)
Water	Synthesis at room temperature	Fucoidan	Au NPs	Particle size: 21–44 nm	(Rajeshkumar et al. 2021)
Water	Synthesis at room temperature Gamma irradiated synthesis	Chitosan	Ag NPs	Cubic NPs, 40–50 nm	(Beden et al. 2022)
Water	Synthesis at room temperature Ultrasonic-assisted Synthesis within 30 min	*Coleus amboinicus* extract	Pd NPs	Cubic NPs, 40–50 nm	(Bathula et al. 2020)
Water	Synthesis at room temperature	*Haplophyllum Obtusifolium* water extract	Au NPs	Spherical NPs, 12 nm	(Shakerimanesh et al. 2022)
Water	Synthesis at room temperature UV-irradiated synthesis Synthesis within 1 h	Glycyrrhiza	Au NPs	Particle size: 20–50 nm	(Cai et al. 2019)
Water	Synthesis at room temperature	Flavonoids in *Scutellaria multicaulis* aqueous extract	Ag NPs	Spherical particles Size: 31–58 nm	(Gharari et al. 2023)
Water	Synthesis at room temperature Synthesis within 15 min	Phenolic compounds in aqueous *Rose canina* extract	Au NPs Ag NPs	Quasi-spherical, 33 ± 5 nm	(Cardoso-Avila et al. 2021)
Water	Synthesis at 15 °C Synthesis within 30 min	Gallic acid, ascorbate, terpenoids, and amino acids in olive leaf extract	Pt NPs	Particle size: 9.2 nm	(Mohammed et al. 2022)
Water	Synthesis at room temperature	Aqueous extract of whole *Parthenium hysterophorus* plant	CuO NPs	Nearly spherical Particle size: 59.99 nm	(Nzilu et al. 2023)
Water	Synthesis at room temperature UV-irradiated synthesis	Polyphenols in *Premna integrifolia* leaf aqueous extract	Ag NPs	Spherical NPs, 9–35 nm	(Singh et al. 2019a, b)
Water	Synthesis at room temperature Synthesis within 10 min	Aqueous extract of *Pimenta dioica* leaves	Au NPs	Spherical shaped Size: 11.48 nm	(Fadaka et al. 2021)
Water	Synthesis at room temperature UV-irradiated synthesis Synthesis within 1 h	Flavones, terpenoids and polysaccharides in Moringa oleifera extract	Ag NPs	Particle size, 9–11 nm	(Moodley et al. 2018)
Ionic medium	Synthesis at room temperature Microwave-assisted synthesis	*Asparagus racemosus* root extract	Ag–Au NPs	Spherical NPs, 10–50 nm	(Amina et al. 2020)
Water	Synthesis at room temperature	Hydroxyl, phenols, carboxyl, amines, alkyl halides, amides and carbonyl groups in Nauclea latifolia fruit extract	Ag NPs	Irregular-shaped NPs, 12 nm	(Odeniyi et al. 2020)

Table 2 (continued)

Sustainable nanotechnology theme/green chemistry principle			Nanoparticle	Key characteristics	References
Green solvent	Energy efficient process	Biocompatible stabilizer/ Capping agent			
Water	Ultrasonic-assisted synthesis	Polysaccharides in red algae, *Pterocladia capillacea* extract	CuO NPs	Particle size: 62 nm	(Aboeita et al. 2022)
Water	Synthesis at room temperature	Proteins, polysaccharides & polyphenols in aqueous safflower extract	Ag NPs	Spherical NPs 8.67 ± 4.7 nm	(Rodríguez-Félix et al. 2021)
Water	Synthesis at room temperature	Alkaloids, phenol, flavonoids and tannins in *Withania somnifera* leaf aqueous extract	Se NPs	Spherical NPs, 45–90 nm	(Alagesan and Venugopal 2019)
Water	Synthesis at room temperature	Aqueous extract of mulberry fruit	Ag NPs Cu NPs Pd NPs	Particle size: 80–150 nm Particle size: 50–200 nm Particle size: 50–100 nm	(Razavi et al. 2020)
Glycerol	Microwave irradiation-assisted synthesis	Corn starch	Ag NPs	Particle size: 11.5 ± 6.9 nm	(Strapasson et al. 2021)
Water	Microwave irradiation-assisted synthesis	*Cynomorium songaricum* polysaccharide	Pd NPs	Particle size: 4.2 nm	(Wang et al. 2018a, b)
Water	Microwave irradiation-assisted synthesis	Proteins and phenolics in *Myristica fragrans* leaf aqueous extract	Au NPs	Hexagonal, triangular and spherical NPs, 18.72 nm	(Punnoose et al. 2021)
Water	Ultrasonic and microwave-assisted synthesis Synthesis within 1 h	Aqueous extract of *Cynara scolymus* leaves	Ag NPs	Average particle size: 98.47 ± 2.04 nm	(Erdogan et al. 2019)
Water	UV radiation-assisted synthesis Synthesis within 30 min	Proteins, flavonoids, tannins, & phenolics in aqueous extract of *Dunaliella salina*	Au NPs	Nearly spherical NPs, 22.4 nm	(Singh et al. 2019a, b)
Water	Synthesis at room temperature Within 3 h	Amino acids and polysaccharides in *Sargassum wightii* aqueous extract	Ag NPs	Spherical NPs, 80–100 nm	(Suganya et al. 2020)
Water	Synthesis at room temperature Within 2.5 h	Presence of OH-containing polyphenols in aqueous *Laurus nobilis* leaf extract	Fe_2O_3 NPs	Spherical and hexagonal NPs, 8.03 ± 8.99 nm	(Jamzad and Kamari Bidkorpeh 2020)
Water	Synthesis at room temperature Within 1 h	Polyphenols and proteins in *Gomphrena globosa* leaf aqueous extract	Ag NPs	Particle size: 15–22 nm	(Tamilarasi & Meena 2020)
Water	Synthesis at room temperature Within 2 h	Terpenoids, flavones and polysaccharides in *Stachys lavandulifolia* aqueous extract	Ag NPs	Nearly spherical NPs, 20–40 nm	(Zangeneh et al. 2019a, b)
Water	Synthesis at room temperature	Polysaccharides and proteins in *Falcaria vulgaris* leaf aqueous extract	Fe NPs	Spherical NPs, 25 nm	(Zangeneh et al. 2019a, b)
Water	Synthesis at room temperature	*Punica granatum* peel and coffee ground extracts	ZnO NPs	Hexagonal, 111.2 – 118.6 nm	(Abdelmigid et al. 2022)
Water	Synthesis at ambient temperature under stirring	*Cocos nucifera* leaf aqueous extract	ZnO NPs	Flower-shaped, particle size of 15 nm	(Rahman et al. 2022)
Water	Synthesis at 40 °C for 70 min	*Viola betonicifolia* leaf aqueous extract	MnO NPs	Spherical; 10.5 ± 0.85 nm	(Lu et al. 2021)

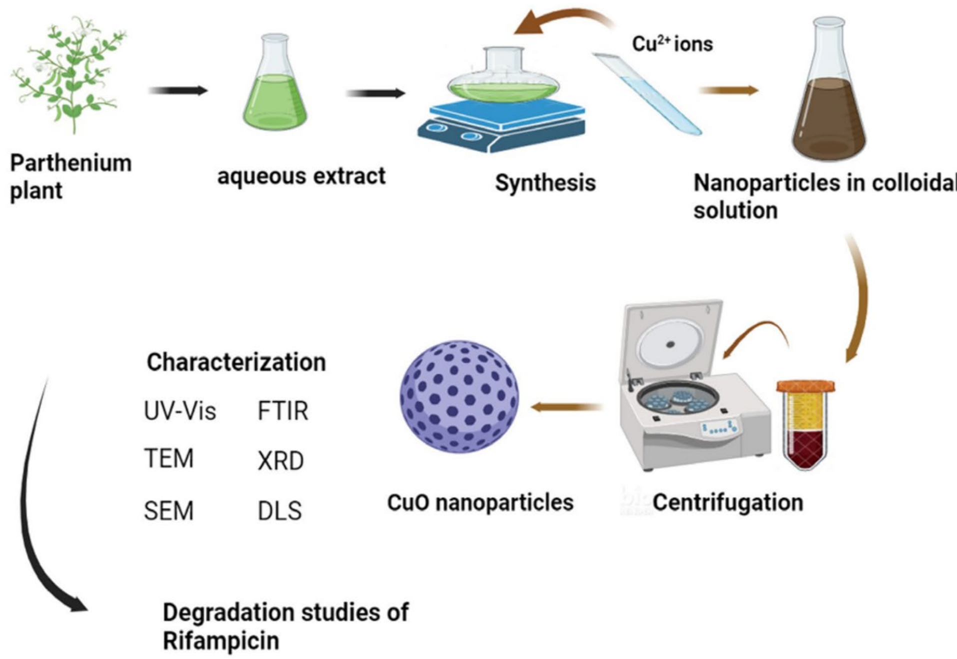

Fig. 1 Synthesis of copper nanoparticles in aqueous medium and characterization. Reproduced with permission from Nzilu et al. (2023)

The nanoparticles were spherical with promising potential to inhibit *E-coli, S typhi* and *S.aureus* (Jothiramalingam et al. 2022).

Multiple nanoparticles have been synthesized using a biocompatible reducing and stabilizing agent (Nguyen et al. 2018; Razavi et al. 2020). For instance, Razavi and co-workers synthesized silver, copper and palladium nanoparticles using mulberry aqueous extract at room temperature. The synthesized AgNPs, CuNPs, and PdNPs were of spherical morphology and possessed antibacterial activity (Razavi et al. 2020). In another study, gum karaya extract in aqueous medium was used to synthesize gold, silver, platinum, copper oxide and palladium nanoparticles. The nanoparticles were stable over 6 months and exhibited biocidal and antimicrobial properties (Nguyen et al. 2018).

In conclusion, the use of safer solvents in the biogenic synthesis of metal nanoparticles is a growing area of interest and these studies collectively underscore the potential of biogenic synthesis using safer solvents such as water in the production of metal nanoparticles.

Sustainable nanotechnology by use of biocompatible materials in biogenic synthesis

Plants contain a wide variety of biocompatible phytochemical compounds that are used in the synthesis of nanomaterials. These compounds include flavonoids, alkaloid compounds, tannins, saponins, and others (Mohammadzadeh et al. 2022). Scholars have explored a variety of phytochemical constituents and plant extracts that can function as solvents, stabilizers, or capping agents as alternatives to the hazardous reagents (Sharma and Pathania 2022). In this subsection, we review studies that have used some of these biocompatible phytochemical compounds such as fucoidan, glycyrrhiza, cannabidiol, and other plant extracts in synthesis of metal nanoparticles.

Fucoidan, a polysaccharide, was used by Rajeshkumar et al. (2021) to serve as a reducing agent and stabilizer in synthesis of gold nanoparticles at room temperature using water as a solvent. Crystalline Au NPs of mean size of 31 nm were obtained and tested against cancer using HepG2 cell line. Figure 2 illustrates the biogenic synthesis of Au NPs using fucoidan as a reducing agent and stabilizer.

Glycyrrhiza, a hydrophilic polysaccharide extracted from licorice, was employed in photo-induced production of silver nanoparticles. The obtained glycyrrhiza stabilized silver nanoparticles with a size between 20 and 50 nm were incorporated into biopolymeric film and tested for their antibacterial activity (Cai et al. 2019). In another study, cannabidiol was utilized in reducing and capping of silver and gold nanoparticles in a microwave-assisted process. Both AgNPs and AuNPs were spherical, monodispersed with potential cytotoxic effect on human keratinocyte cells (Josiah et al. 2021).

Both silver and gold nanoparticles were synthesized by Cardoso-Avilla and co-workers using water as a solvent and phenolic compounds in aqueous *Rose canina* extract as reducing and capping agents at ambient temperature for 15 min. Stable, quasi-spherical nanoparticles of size between 26 and 34 nm were formed (Cardoso-Avila et al. 2021). In another study, Mohammed and co-workers synthesized platinum nanoparticles using olive leaf extract enriched with ascorbic and gallic acids, terpenoids, and amino acids in

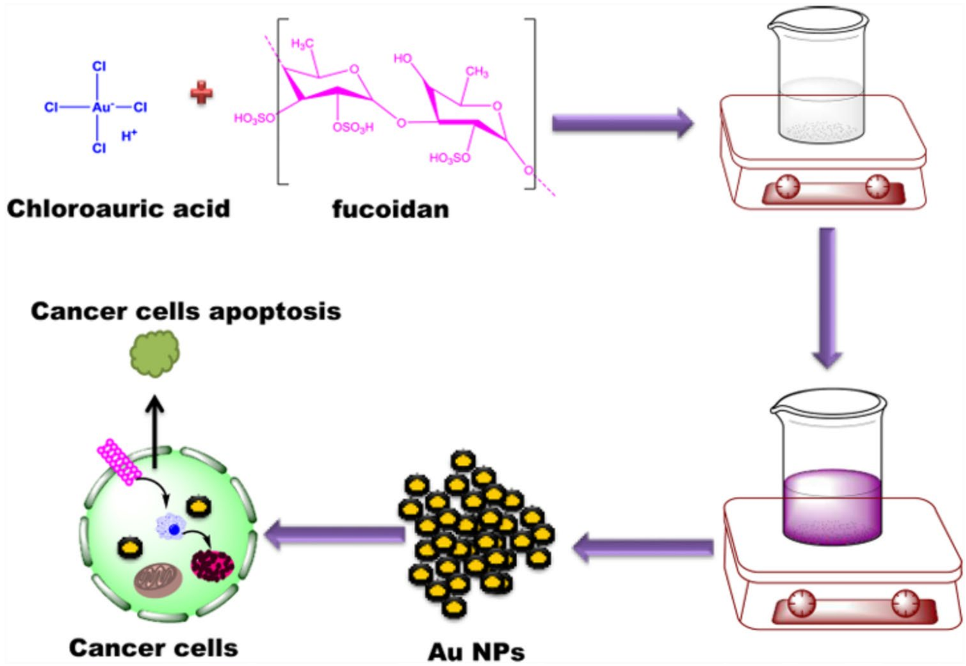

Fig. 2 Gold nanoparticle synthesis using fucoidan reducing agent and stabilizer. Reproduced with permission from Rajeshkumar et al. (2021)

aqueous medium at room temperature. Spherical and compact nanoparticles with mean size of 9.2 nm were produced and their effects tested on aspartate aminotransferase activity (Mohammed et al. 2022).

In summary, the biogenic synthesis of metal nanoparticles utilizing biocompatible plant phytochemicals and extracts is a promising area of research, offering environmentally friendly and cost-effective methods for nanoparticle production. These studies collectively highlight the promising potential of plant phytochemicals in biogenic synthesis, emphasizing their ability to reduce and stabilize metal nanoparticles.

Sustainable nanotechnology by use of efficient green energy in biogenic synthesis

A range of studies have explored the biogenic synthesis of metal nanoparticles at room temperature, utilizing efficient green energies (Amina et al. 2020; Beden et al. 2022; Erdogan et al. 2019; Punnoose et al. 2021; Singh et al. 2019a, b; Strapasson et al. 2021; Wang et al. 2018a, b). The ability of biological processes to produce stable chemical nanoparticles with a spherical morphology and compact size with high energy efficiency is widely recognized (Rana et al. 2020). For instance, synthesis is carried at ambient temperature and/or by use of green energies such as microwave, UV or gamma radiation, and ultrasound. By using these modern energy transfer techniques instead of conventional methods, less energy is needed, making it a greener approach. Additionally, because this energy transfer techniques causes the constituents to heat quickly and uniformly, they offer uniform nucleation and growth conditions for nanomaterials. In this subsection, we discuss various studies that have employed green energy-efficient techniques such as gamma, UV, microwave energies in biogenic synthesis of metal nanoparticles.

Using gamma radiation energy, Beden and co-workers synthesized silver nanoparticles chitosan composite in aqueous medium at room temperature. The Gamma irradiation-assisted synthesis produced Ag NPs with a narrow sized distribution (Beden et al. 2022). In another study, instead of using gamma radiation, Singh and co-workers utilized *Dunaliella salina* aqueous extract to reduce and stabilize gold nanoparticles in presence of UV light for 75 min. The spherical AuNPs had an average size of 22.4 nm and demonstrated anticancer activity when tested on MCF7 cell line (Singh et al. 2019a, b).

Microwave irradiation has been employed as a green energy process in nanoparticle synthesis (Amina et al. 2020; Erdogan et al. 2019; Punnoose et al. 2021; Strapasson et al. 2021; Wang et al. 2018a, b). For instance, Punnoose and co-workers used microwave energy to synthesis gold nanoparticles together with *Myristica fragrans* aqueous extract to reduce and cap the nanoparticles. The nanoparticles had average size of 18.72 nm with catalytic potential to degrade environmental pollutants (Punnoose et al. 2021). Similarly, Amina and co-workers successfully synthesized silver and gold alloy nanoparticles using microwave irradiation in presence of *Asparagus racemosus* aqueous extract. Both nanoparticles were of spherical morphology and showed antimicrobial and immunomodulatory potential (Amina et al. 2020). Similarly, Strapasson and co-workers produced silver

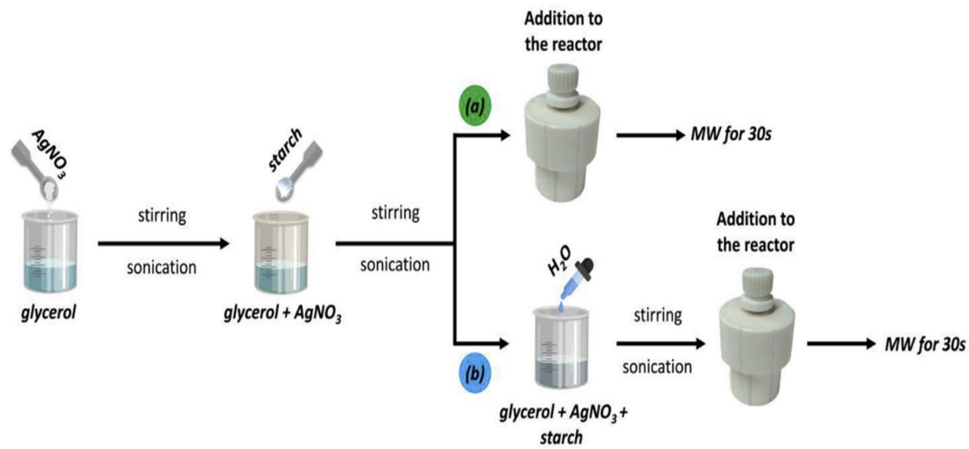

Fig. 3 Microwave-assisted synthesis of AgNPs using glycerol or glycerol/water as green solvent and starch as a biocompatible reducing agent and stabilizer. Reused with permission from Strapasson et al. (2021)

nanoparticles using glycerol or glycerol/water as green solvent, starch as reducing and stabilizing agent and microwave irradiation and green energy (Strapasson et al. 2021). They produced highly stable nanoparticles for photogeneration as illustrated in Fig. 3. This novel approach combines the use of green solvent, biocompatible starch and microwave irradiation for the rapid biosynthesis of silver nanoparticles.

In conclusion, the biogenic synthesis of metal nanoparticles utilizing green energy methods has gained significant attention due to its eco-friendly and efficient nature. These green energy processes offer several advantages, including low energy requirements, cost-effectiveness, and minimal environmental impact. These studies collectively underscore the potential of biogenic synthesis, particularly in combination with green energy sources such as microwave irradiation, for the production of metal nanoparticles.

Summary and future perspective of biogenic synthesis and sustainable nanotechnology

Nanotechnology, as a key enabling technology, has grown tremendously leading to introduction of many nanomaterials for applications in various fields such as in drug delivery, diagnostics, catalysis, environmental remediation, and biomedical field. However, despite the numerous benefits of nanotechnology, production of nanomaterials makes use of unsustainable processes such as chemical methods and physical methods that have destructive consequences on the environment. Such processes go against the spirit of the sustainable development goals number viz. SDG 3.9, 6.3, 9.4, 12.4, and 12.5 that advocate for reducing number of deaths and illness from hazardous chemicals, pollutants and contaminants; reducing pollution and minimizing release of hazardous chemicals and pollutants into water environment to improve water quality; designing sustainable and resource-use efficient industries, and adoption of clean technologies and processes; reducing release of chemicals and waste into environment to minimize their negative impacts on humans and the environment; and preventing, reducing, recycling and reusing waste to substantially decrease its generation, respectively.

Green nanotechnology, which emphasizes sustainability and uses eco-friendly technologies, is promising and provides impeccable solutions that support realization of the sustainable development goals. Green synthesis of metal nanoparticles based on the principles of green chemistry aims to reduce or entirely eliminate the use of hazardous chemicals and minimize or possibly eliminate generation of pollutants. By use of eco-friendly solvents, maximization of atom economy to minimize waste generation and elimination of hazardous chemicals and waste to minimize impact on environment and human health, green synthesis substantially contributes to achieving the above-mentioned SDGs targets. Through adoption of green synthesis and integration of green nanotechnology into environmental policies, developed and developing nations can drive the adoption of eco-friendlier nanomaterials and production processes as they commit to sustainable consumption, clean energy, reduction of pollution and creation of a more sustainable future.

The future of biogenic synthesis of metal nanoparticles is promising, with a focus on green and sustainable nanotechnologies. However, biogenic synthesis and green nanotechnology solutions are still in the nascent phase which underscores the importance of continued research and development in this field. Additional research is needed to evaluate how nanotechnologies perform in actual production conditions, as well as to determine their effectiveness and long-term sustainability. It is also important to compare nanomaterials with current technologies to ensure their validity. Nevertheless, we believe that using biogenic synthesis and green nanotechnology to achieve sustainability, products and nanomaterials can be produced that support both the current and future generations without endangering human health or the environment.

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Declarations

Conflict of interests The authors declare no competing interests.

References

Abdelmigid HM, Hussien NA, Alyamani AA, Morsi MM, AlSufyani NM, Kadi HA (2022) Green synthesis of zinc oxide nanoparticles using pomegranate fruit peel and solid coffee grounds versus chemical method of synthesis, with their biocompatibility and antibacterial properties investigation. Molecules 27(4):1236

Aboeita NM, Fahmy SA, El-Sayed MM, Azzazy HME-S, Shoeib T (2022) Enhanced anticancer activity of nedaplatin loaded onto copper nanoparticles synthesized using red algae. Pharmaceutics 14(2):418

Ahmed SF, Mofijur M, Rafa N, Chowdhury AT, Chowdhury S, Nahrin M, Islam AS, Ong HC (2022) Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. Environ Res 204:111967

Aithal S, Aithal P (2021) Green nanotechnology innovations to realize UN sustainable development goals 2030. Int J Appl Eng Manage Lett (IJAEML) 5(2):96–105

Alagesan V, Venugopal S (2019) Green synthesis of selenium nanoparticle using leaves extract of withania somnifera and its biological applications and photocatalytic activities. Bionanoscience 9:105–116

Ali NH, Mohammed AM (2021) Biosynthesis and characterization of platinum nanoparticles using Iraqi Zahidi dates and evaluation of their biological applications. Biotechnol Rep 30:e00635

Ameta SC, Ameta R (2023) Green chemistry: fundamentals and applications. CRC Press, Florida

Amina M, Al Musayeib NM, Alarfaj NA, El-Tohamy MF, Al-Hamoud GA (2020) Antibacterial and immunomodulatory potentials of biosynthesized Ag, Au, Ag-Au bimetallic alloy nanoparticles using the Asparagus racemosus root extract. Nanomaterials 10(12):2453

Bathula C, Subalakshmi K, Kumar A, Yadav H, Ramesh S, Shinde S, Shrestha NK, Mallikarjuna K, Kim H (2020) Ultrasonically driven green synthesis of palladium nanoparticles by Coleus amboinicus for catalytic reduction and Suzuki-Miyaura reaction. Colloids Surf B 192:111026

Bayda S, Adeel M, Tuccinardi T, Cordani M, Rizzolio F (2019) The history of nanoscience and nanotechnology: from chemical–physical applications to nanomedicine. Molecules 25(1):112

Beden SA, Ati AA, Fayadh Alimarah KA, Saihood SK, Abdulnabi RK, Mejbel MK (2022) Green Synthesis and characterization of silver nanoparticles/CM-Chitosan-isopropanol by gamma irradiations method. J Compos Adv Mater/revue Des Compos Et Des Matér Av 32(4):173–180

Bhardwaj T, Khanna K, Sharma P, Bakshi P, Devi K, Madaan I, Kaushik S, Sirhindi G, Mir BA, Kaur R (2023) Nanobioremediation: a novel technology with phenomenal clean up potential for a sustainable environment. Environmental applications of microbial nanotechnology. Elsevier, pp 315–331

Bhati M (2023) Biogenic synthesis of metallic nanoparticles: principles and applications. Mater Today Proceed 81:882–887

Cai Z, Dai Q, Guo Y, Wei Y, Wu M, Zhang H (2019) Glycyrrhiza polysaccharide-mediated synthesis of silver nanoparticles and their use for the preparation of nanocomposite curdlan antibacterial film. Int J Biol Macromol 141:422–430

Cardoso-Avila PE, Patakfalvi R, Rodríguez-Pedroza C, Aparicio-Fernández X, Loza-Cornejo S, Villa-Cruz V, Martínez-Cano E (2021) One-pot green synthesis of gold and silver nanoparticles using *Rosa canina* L. extract. RSC Adv 11(24):14624–14631

Chauhan A, Anand J, Parkash V, Rai N (2023) Biogenic synthesis: a sustainable approach for nanoparticles synthesis mediated by fungi. Inorg Nano-Metal Chem 53(5):460–473

Chen T-L, Kim H, Pan S-Y, Tseng P-C, Lin Y-P, Chiang P-C (2020) Implementation of green chemistry principles in circular economy system towards sustainable development goals: challenges and perspectives. Sci Total Environ 716:136998

Chopra H, Bibi S, Singh I, Hasan MM, Khan MS, Yousafi Q, Baig AA, Rahman MM, Islam F, Emran TB (2022) Green metallic nanoparticles: biosynthesis to applications. Front Bioeng Biotechnol 10:874742

Chouke PB, Shrirame T, Potbhare AK, Mondal A, Chaudhary AR, Mondal S, Thakare SR, Nepovimova E, Valis M, Kuca K (2022) Bioinspired metal/metal oxide nanoparticles: a road map to potential applications. Mater Today Adv 16:100314

Dehno Khalaji A (2020) Copper oxide nanoparticles: synthesis, characterization, optical property and its application for the removal of methyl green dye. *J Nanoanal*, *500*(1), 0

Din MI, Rani A (2018) Selection of optimum strategies for the fabrication of plant-mediated metal nanoparticles: emerging problems in sustainability. Crit Rev Anal Chem 48(5):406–415

Erdogan O, Abbak M, Demirbolat GM, Birtekocak F, Aksel M, Pasa S, Cevik O (2019) Green synthesis of silver nanoparticles via Cynara scolymus leaf extracts: the characterization, anticancer potential with photodynamic therapy in MCF7 cells. PLoS ONE 14(6):e0216496

Fadaka A, Aluko O, Awawu S, Theledi K (2021) Green synthesis of gold nanoparticles using Pimenta dioica leaves aqueous extract and their application as photocatalyst, antioxidant, and antibacterial agents. J Multidiscip Appl Nat Sci 1(2):78–88

Fallah Shayan N, Mohabbati-Kalejahi N, Alavi S, Zahed MA (2022) Sustainable development goals (SDGs) as a framework for corporate social responsibility (CSR). Sustainability 14(3):1222

Falsini S, Bardi U, Abou-Hassan A, Ristori S (2018) Sustainable strategies for large-scale nanotechnology manufacturing in the biomedical field. Green Chem 20(17):3897–3907

García-Ruiz DL, Granados-Martínez FG, Gutiérrez-García CJ, Ambriz-Torres JM, de Jesús J, Contreras-Navarrete NFR, Méndez F, Domratcheva-Lvova L (2021) Synthesis of carbon nanomaterials by chemical vapor deposition method using green chemistry principles. Handbook of greener synthesis of nanomaterials and compounds. Elsevier, pp 273–314

Gharari Z, Hanachi P, Sadeghinia H, Walker TR (2023) Eco-friendly green synthesis and characterization of silver nanoparticles by Scutellaria multicaulis leaf extract and its biological activities. Pharmaceuticals 16(7):992

Goutam SP, Saxena G, Singh V, Yadav AK, Bharagava RN, Thapa KB (2018) Green synthesis of TiO2 nanoparticles using leaf extract of *Jatropha curcas* L. for photocatalytic degradation of tannery wastewater. Chem Eng J 336:386–396

Gu J, Chen W, Shan G-G, Li G, Sun C, Wang X-L, Su Z (2021) The roles of polyoxometalates in photocatalytic reduction of carbon dioxide. Mater Today Energy 21:100760

Guo K, Baidak A, Yu Z (2020) Recent advances in green synthesis and modification of inorganic nanomaterials by ionizing and non-ionizing radiation. J Mater Chem A 8(44):23029–23058
Gupta D, Boora A, Thakur A, Gupta TK (2023) Green and sustainable synthesis of nanomaterials: recent advancements and limitations. Environ Res 231:116316
Idris DS, Roy A (2023) Synthesis of bimetallic nanoparticles and applications—an updated review. Crystals 13(4):637
Ijaz I, Gilani E, Nazir A, Bukhari A (2020) Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. Green Chem Lett Rev 13(3):223–245
Ivanković A, Dronjić A, Bevanda AM, Talić S (2017) Review of 12 principles of green chemistry in practice. Int J Sustain Green Energy 6(3):39–48
Jain S, Kumar N, Tahir M, Garg S (2023) Nanoparticle synthesis, characterization and applications. The impact of nanoparticles on agriculture and soil. Elsevier, pp 13–40
Jamzad M, Kamari Bidkorpeh M (2020) Green synthesis of iron oxide nanoparticles by the aqueous extract of *Laurus nobilis* L. leaves and evaluation of the antimicrobial activity. J Nanostruct Chem 10(3):193–201
Jiménez-González C, Curzons AD, Constable DJ, Cunningham VL (2004) Cradle-to-gate life cycle inventory and assessment of pharmaceutical compounds. Int J Life Cycle Assess 9:114–121
Josiah AJ, Pillai SK, Cordier W, Nell M, Twilley D, Lall N, Ray SS (2021) Cannabidiol-mediated green synthesis, characterization, and cytotoxicity of metal nanoparticles in human keratinocyte cells. ACS Omega 6(43):29078–29090
Jothiramalingam R, Devasanan S, Lohedan H, Muthumareeswaran M, Alqahtani H, Abdalnaser K (2022) Green chemistry method prepared effective copper nanoparticles by lemon flower (citrus) extract and its antimicrobial activity. Dig J Nanomater Biostr 17:145–151
Kanaoujiya R, Saroj SK, Rajput VD, Alimuddin, Srivastava S, Minkina T, Igwegbe CA, Singh M, Kumar A (2023) Emerging application of nanotechnology for mankind. Emerg Mater 6(2):439–452
Katila P, Colfer CJP, De Jong W, Galloway G, Pacheco P, Winkel G (2019) Sustainable development goals. Cambridge University Press, Cambridge
Khan SH (2020) Green nanotechnology for the environment and sustainable development. Green Mater Wastewater Treat. https://doi.org/10.1007/978-3-030-17724-9_2
Kisimba K, Krishnan A, Faya M, Byanga K, Kasumbwe K, Vijayakumar K, Prasad R (2023) Synthesis of metallic nanoparticles based on green chemistry and their medical biochemical applications: synthesis of metallic nanoparticles. J Renew Mater 11(6):2575–2591
Kurhade P, Kodape S, Choudhury R (2021) Overview on green synthesis of metallic nanoparticles. Chem Pap 75(10):5187–5222
Lancaster M (2020) Green chemistry: an introductory text. Royal society of chemistry, London
Lu H, Zhang X, Khan SA, Li W, Wan L (2021) Biogenic synthesis of MnO2 nanoparticles with leaf extract of Viola betonicifolia for enhanced antioxidant, antimicrobial, cytotoxic, and biocompatible applications. Front Microbiol 12:761084
Madani M, Hosny S, Alshangiti DM, Nady N, Alkhursani SA, Alkhaldi H, Al-Gahtany SA, Ghobashy MM, Gaber GA (2022) Green synthesis of nanoparticles for varied applications: green renewable resources and energy-efficient synthetic routes. Nanotechnol Rev 11(1):731–759
Mahaya ETK, Amalia I, Wafiroh LA, Zulfa SR, Fajrin M (2023) The implementation of SDGs program on liquid waste processing for the pasteurized milk industry. Formosa J Sci Technol 2(6):1589–1608
Mohammadzadeh V, Barani M, Amiri MS, Yazdi MET, Hassanisaadi M, Rahdar A, Varma RS (2022) Applications of plant-based nanoparticles in nanomedicine: a review. Sustain Chem Pharm 25:100606
Mohammed SH, Rheima A, Al-jaafari F, Al-Marjani MF (2022) Green-synthesis of platinum nanoparticles using olive leaves extracts and its effect on aspartate aminotransferase activity. Egypt J Chem 65(4):377–382
Moodley JS, Krishna SBN, Pillay K, Sershen F, Govender P (2018) Green synthesis of silver nanoparticles from Moringa oleifera leaf extracts and its antimicrobial potential. Adv Natur Sci Nanosci Nanotechnol 9(1):015011
Mughal B, Zaidi SZJ, Zhang X, Hassan SU (2021) Biogenic nanoparticles: synthesis, characterisation and applications. Appl Sci 11(6):2598
Nguyen NH, Padil VVT, Slaveykova VI, Černík M, Ševců A (2018) Green synthesis of metal and metal oxide nanoparticles and their effect on the unicellular alga Chlamydomonas reinhardtii. Nanoscale Res Lett 13:1–13
Nzilu DM, Madivoli ES, Makhanu DS, Wanakai SI, Kiprono GK, Kareru PG (2023) Green synthesis of copper oxide nanoparticles and its efficiency in degradation of rifampicin antibiotic. Sci Rep 13(1):14030
Odeniyi MA, Okumah VC, Adebayo-Tayo BC, Odeniyi OA (2020) Green synthesis and cream formulations of silver nanoparticles of Nauclea latifolia (African peach) fruit extracts and evaluation of antimicrobial and antioxidant activities. Sustain Chem Pharm 15:100197
Palit S, Hussain CM (2020) Green nanomaterials: a sustainable perspective. In: Ahmed S, Ali W (eds) Green nanomaterials: processing, properties, and applications. Springer Singapore, Singapore, pp 23–41
Patil S, Chandrasekaran R (2020) Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges. J Genet Eng Biotechnol 18(1):67
Piermatti O (2021) Green synthesis of Pd nanoparticles for sustainable and environmentally benign processes. Catalysts 11(11):1258
Punnoose MS, Bijimol D, Mathew B (2021) Microwave assisted green synthesis of gold nanoparticles for catalytic degradation of environmental pollutants. Environ Nanotechnol Monitor Manage 16:100525
Rahman F, Majed Patwary MA, Bakar Siddique MA, Bashar MS, Haque MA, Akter B, Rashid R, Haque MA, Royhan Uddin A (2022) Green synthesis of zinc oxide nanoparticles using Cocos nucifera leaf extract: characterization, antimicrobial, antioxidant and photocatalytic activity. Royal Soc Open Sci 9(11):220858
Rajeshkumar S, Malarkodi C, Al Farraj DA, Elshikh MS, Roopan SM (2021) Employing sulphated polysaccharide (fucoidan) as medium for gold nanoparticles preparation and its anticancer study against HepG2 cell lines. Mater Today Commun 26:101975
Rana A, Yadav K, Jagadevan S (2020) A comprehensive review on green synthesis of nature-inspired metal nanoparticles: mechanism, application and toxicity. J Clean Prod 272:122880
Ravikumar A, Prakash KS (2022) Green and sustainable approaches of nanoparticles. In: Mallakpour S, Hussain CM (eds) Handbook of consumer nanoproducts. Springer, Singapore, pp 1433–1453
Razavi R, Molaei R, Moradi M, Tajik H, Ezati P, Shafipour Yordshahi A (2020) Biosynthesis of metallic nanoparticles using mulberry fruit (*Morus alba* L.) extract for the preparation of antimicrobial nanocellulose film. Appl Nanosci 10:465–476
Rodríguez-Félix F, López-Cota AG, Moreno-Vásquez MJ, Graciano-Verdugo AZ, Quintero-Reyes IE, Del-Toro-Sánchez CL, Tapia-Hernández JA (2021) Sustainable-green synthesis of silver nanoparticles using safflower (*Carthamus tinctorius* L.) waste extract and its antibacterial activity. Heliyon. https://doi.org/10.1016/j.heliyon.2021.e06923

Salem DM, Ismail MM, Aly-Eldeen MA (2019) Biogenic synthesis and antimicrobial potency of iron oxide (Fe3O4) nanoparticles using algae harvested from the Mediterranean Sea. Egypt Egypt J Aquat Res 45(3):197–204

Sarkhosh S, Kahrizi D, Darvishi E, Tourang M, Haghighi-Mood S, Vahedi P, Ercisli S (2022) Effect of zinc oxide nanoparticles (ZnO-NPs) on seed germination characteristics in two brassicaceae family species: *Camelina sativa* and *Brassica napus* L. J Nanomater 2022(1):1892759

Saxena N, Srivastav N, Kumar A, Anjali A (2022) Adoption of green methodology in industry for the synthesis of Sildenafil citrate & Celecoxib: a case study. Mater Today Proceed 60:1021–1025

Shafey AME (2020) Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: a review. Green Process Synth 9(1):304–339

Shakerimanesh K, Bayat F, Shahrokhi A, Baradaran A, Yousefi E, Mashreghi M, Es-Haghi A, Yazdi MET (2022) Biomimetic synthesis and characterisation of homogenouse gold nanoparticles and estimation of its cytotoxity against breast cancer cell line. Mater Technol 37(13):2853–2860

Sharma S, Pathania AR (2022) Biodegradable polymers green synthesis of nanoparticle–an overview. Mater Today Proceed 62:3827–3831

Sharma D, Kanchi S, Bisetty K (2019) Biogenic synthesis of nanoparticles: a review. Arab J Chem 12(8):3576–3600

Sharma AK, Rana K, Shrestha S, Oli HB, Bhattarai DP (2022a) A comparative study on synthesis, characterization and antibacterial activity of green vis-a-vis chemically synthesized silver nanoparticles. Amrit Res J 3(01):75–83

Sharma D, Gulati SS, Sharma N, Chaudhary A (2022b) Sustainable synthesis of silver nanoparticles using various biological sources and waste materials: a review. Emergent Mater 5(6):1649–1678

Singh AK, Tiwari R, Singh VK, Singh P, Khadim SR, Singh U, Srivastava V, Hasan S, Asthana R (2019a) Green synthesis of gold nanoparticles from Dunaliella salina, its characterization and in vitro anticancer activity on breast cancer cell line. J Drug Deliv Sci Technol 51:164–176

Singh C, Kumar J, Kumar P, Chauhan BS, Tiwari KN, Mishra SK, Srikrishna S, Saini R, Nath G, Singh J (2019b) Green synthesis of silver nanoparticles using aqueous leaf extract of Premna integrifolia (L.) rich in polyphenols and evaluation of their antioxidant, antibacterial and cytotoxic activity. Biotechnol Biotechnol Equip 33(1):359–371

Solgi M, Taghizadeh M (2020) Biogenic synthesis of metal nanoparticles by plants. In: Ghorbanpour M, Bhargava P, Varma A, Choudhary DK (eds) Biogenic nano-particles and their use in agro-ecosystems. Springer Singapore, Singapore, pp 593–606

Strapasson GB, Assis M, Backes CW, Corrêa SA, Longo E, Weibel DE (2021) Microwave assisted synthesis of silver nanoparticles and its application in sustainable photocatalytic hydrogen evolution. Int J Hydrog Energy 46(69):34264–34275

Suganya S, Dhanalakshmi B, Dinesh Kumar S, Santhanam P (2020) Cytotoxic effect of silver nanoparticles synthesized from Sargassum wightii on cervical cancer cell line. Proceed Natl Acad Sci India Sect B Biol Sci 90:811–818

Tailor G, Yadav B, Chaudhary J, Joshi M, Suvalka C (2020) Green synthesis of silver nanoparticles using Ocimum canum and their anti-bacterial activity. Biochem Biophys Rep 24:100848

Tamilarasi P, Meena P (2020) Green synthesis of silver nanoparticles (Ag NPs) using Gomphrena globosa (Globe amaranth) leaf extract and their characterization. Mater Today Proceed 33:2209–2216

Tilahun Bekele E, Gonfa BA, Sabir FK (2021) Use of different natural products to control growth of titanium oxide nanoparticles in green solvent emulsion, characterization, and their photocatalytic application. Bioinorg Chem Appl 2021:6626313

Verma DK, Malik R, Meena J, Rameshwari R (2021) Synthesis, characterization and applications of chitosan based metallic nanoparticles: a review. J Appl Natur Sci 13(2):544–551

Wang F, Niu X, Wang W, Jing W, Huang Y, Zhang J (2018a) Green synthesis of Pd nanoparticles via extracted polysaccharide applied to glucose detection. J Taiwan Inst Chem Eng 93:87–93

Wang L, Wu Y, Xie J, Wu S, Wu Z (2018b) Characterization, antioxidant and antimicrobial activities of green synthesized silver nanoparticles from Psidium guajava L. leaf aqueous extracts. Mater Sci Eng C 86:1–8

Yanat M, Schroën K (2023) Advances in chitin-based nanoparticle use in biodegradable polymers: a review. Carbohyd Polym 312:120789

Zangeneh MM, Joshani Z, Zangeneh A, Miri E (2019a) Green synthesis of silver nanoparticles using aqueous extract of Stachys lavandulifolia flower, and their cytotoxicity, antioxidant, antibacterial and cutaneous wound-healing properties. Appl Organomet Chem 33(9):e5016

Zangeneh MM, Zangeneh A, Pirabbasi E, Moradi R, Almasi M (2019b) Falcaria vulgaris leaf aqueous extract mediated synthesis of iron nanoparticles and their therapeutic potentials under in vitro and in vivo condition. Appl Organomet Chem 33(12):e5246

Zhao X, Bian F, Sun L, Cai L, Li L, Zhao Y (2020) Microfluidic generation of nanomaterials for biomedical applications. Small 16(9):1901943