Green Synthesis of Nanoparticles: Recent Advances and Environmental Applications

K Hariprasad[1], Dr Vustelamuri Padmavathi[2], Richa Singh[3], Pradeep Kumar Tiwari[4], Dr. Chayannika Singh[5], Madhusudhan Reddy A[6]

[1]Assistant Professor, Department of pharmaceutical chemistry, Princeton college of Pharamcy, Ghatkesar, Medchal, Hyderabad
[2]Associate Professor, Department of Chemistry (H&S), Neil Gogte Institute of Technology,Uppal,Hyderabad
[3]Department of chemistry, Thakur college of science and commerce, Mumbai
[4]Department of chemistry, Dr. Harisingh Gour Vishwavidyalaya (Central University), Sagar [M.P.]
[5]Associate Professor, Deen Dayal Upadhyaya College, University of Delhi
[6]Associate Professor, Department of Pharmacognosy, Princeton college of Pharamcy, Ghatkesar, Medchal, Hyderabad

Abstract

Green synthesis of nanoparticles has emerged as a sustainable and eco-friendly alternative to the conventional physical and chemical methods, which are associated with toxic reagents, high energy consumption and hazardous by-products. This review focuses on the recent developments in the synthesis of nanoparticles using biological sources like plant extracts, bacteria, fungi, algae, enzymes, biopolymers and waste materials, etc. These natural agents act as reducing, stabilizing and capping agents and allow the formation of nanoparticles under mild and environmentally friendly conditions. The review covers the main mechanisms such as metal ion reduction, nucleation, growth, stabilisation and capping, as well as the influence of the reaction parameters on the properties of nanoparticles such as pH, temperature, reaction time, concentration of the precursors and composition of the extracts. Different types of green synthesised nanoparticles, such as metal, metal oxide, magnetic, carbon-based and hybrid nanoparticles, are picked for their relevance to the environment. The applications in wastewater treatment, degradation of dyes, heavy metals, pharmaceutical and pesticide pollutants, antimicrobial disinfection, soil remediation, air pollution control and environmental sensing are highlighted. Although they have great potential, issues of reproducibility, toxicity testing, environmental fate, long-term stability, scale-up and life-cycle evaluation remain important. In conclusion, green synthesis is a versatile and environmentally friendly approach to nanotechnology that holds promise for sustainable production of nanomaterials and for addressing environmental challenges such as pollution control, environmental remediation, and ecological protection.

Keywords: Green synthesis; Nanoparticles; Environmental remediation; Wastewater treatment; Sustainable nanotechnology

1. Introduction

Nanotechnology is an important area in the Environmental Sciences and in Environmental Engineering due to special physicochemical and biological properties of nanoparticles. Small size, high surface area to volume ratio, tunable surface chemistry, high adsorption capacity, catalytic activity and antimicrobial activity make them useful in water purification, pollutant degradation, environmental monitoring and remediation technologies. In recent years, green nanoparticles are being seen for their vast application prospects in the field of environment, agriculture, biomedicine, energy and food which show the rising significance of green nanoparticles in sustainable material development (Osman et al., 2024).

Typical methods of producing nanoparticles fall into two categories: physical and chemical. While these methods can yield controlled size, shape and morphology of nanoparticles, they are often associated with high temperature, high pressure, expensive equipment, toxic solvents, hazardous reducing agents and non-biodegradable stabilisers. This restriction can lead to an increase in the environmental risks, and less suitability of the conventionally synthesized nanoparticles to eco-sensitive application. Hence, green synthesis has become a sustainable approach as it utilizes the biological resources and naturally derived compounds for the production of nanoparticles without creating chemical hazards (Jadoun et al., 2021).

Green synthesis is the use of plant extracts, microorganism, algae, enzymes, biopolymer and other natural reducing, stabilizing, and capping agents. The biological sources contain bioactive compounds like phenolics, flavonoids, proteins, polysaccharides, alkaloids, terpenoids and organic acids that help in the formation and stabilisation of nanoparticles in mild reaction conditions. Metallic nanoparticles which are synthesized by green methods have attracted interest, due to their applications in biotechnology, antimicrobial treatment, environmental remediation and pollution control (Salem and Fouda, 2021).

Aquatic and environmental studies are the other applications of green synthesized nanoparticles where they can be used for wastewater treatment, degradation of organic pollutants, removal of heavy metals, antimicrobial disinfection and improvement of water quality. It has been reported that green-synthesised gold, silver and iron nanoparticles are potential materials for the degradation of organic pollutants in wastewater and thus play an important role in the control of pollutants and the protection of aquatics ecosystem (Kumar, 2021). Likewise, the nanoparticles produced through biogenic synthesis have been termed as environmentally friendly options for wastewater treatment due to their eco-friendly properties and treatment efficiency (Banihashem et al., 2024).

Although nanoparticles have benefits, their use on a large scale for environmental use should be evaluated carefully.

They are small, reacting, mobile and can persist in the environment, which can lead to interactions with aquatic organisms, microorganisms, plants and other environmental species. So, the toxicity, exposure routes, fate in the environment and long term ecological impacts of nanoparticles must be taken into account together with their potential beneficial uses (Khan et al., 2019). Sustainable chemistry principles are crucial in this context since the development of nanomaterials should have a positive impact on reducing new ecological risks but also on protecting the environment (Anastas and Zimmerman, 2018).

Green synthesis has close relationship with sustainable development as it involves less chemical hazards, cleaner production, utilization of renewable biological resources and design of materials with less usage of resources. The potential of green synthesis of metals and metal oxide nanoparticles for environmental remediation is already well demonstrated, such as in the degradation of pollutants, treatment of wastewaters, and removal of contaminants (Singh et al., 2018). In addition, plant based synthesis of silver nanoparticles confirms that biological extracts can also be used to synthesize functional nanomaterials for different applications; however, many of the previous methods were more directed towards biomedical applications than towards environmental systems (Ovais et al., 2016).

In this regard, the present review focuses on summarizing the recent progress of green synthesis of nanoparticles and their use in environmental applications. It covers the major biological sources employed for the synthesis, the mechanism of nanoparticles synthesis, the factors influencing the properties of nanoparticles, various types of green synthesized nanoparticles and their applications in wastewater treatment, degradation of pollutants, remediation and environmental sensing. This review also identifies some of the most critical issues that need to be addressed, such as reproducibility, toxicity assessment, environmental fate, scale-up, environmental life cycle, and long-term stability, but with special attention to aquatic studies and environmental research.

2. Principles and Mechanisms of Green Nanoparticle Synthesis

Green synthesis of nanoparticles involves the synthesis of nanomaterials using biological or natural resources, such as microorganisms or plant extracts, which are free of toxic chemicals used for reducing and stabilising the nanoparticles. This is done according to the principles of sustainability, environmental safety and cleaner production. Green synthesis often involves mild reaction conditions and the use of biological compounds, which can reduce metal ions and stabilise the nanoparticles produced in the process. These benefits make green synthesis an important approach to the production of nanomaterials for environmental and aquatic applications.

The overall process of green synthesis of nanoparticles can be divided into a few major steps: reduction of metal ions, nucleation, growth, stabilisation, and capping. Step 1 involves the reduction of metal ions to neutral atoms using bioactive compounds available in plant extract, microorganisms, enzymes or biopolymers. The atoms after reduction start to clump together and to produce small nuclei. These nuclei then become larger, forming nanoparticles, as additional reduced atoms are added. The final size, shape and stability of the nanoparticles would rely on the balance between the nu green synthesis of nanoparticles are summarised in Figure 1.

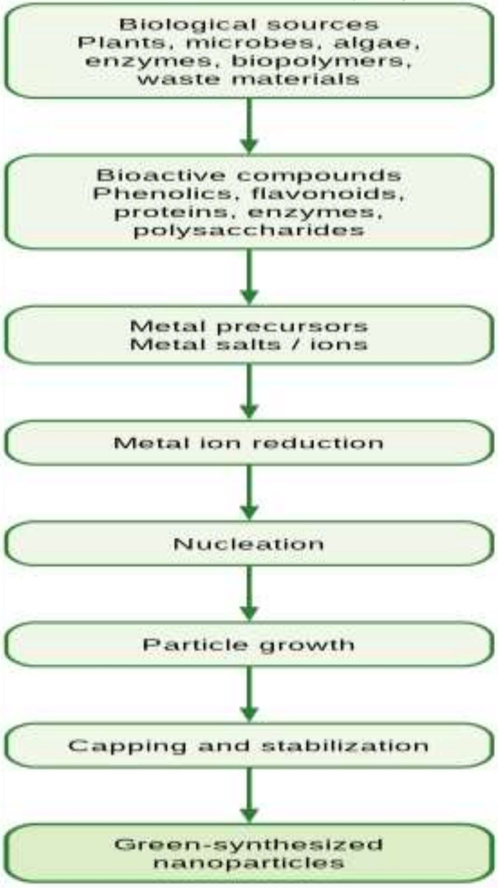


Figure 1. Schematic mechanism of green nanoparticle synthesis showing the role of biological sources, bioactive compounds, metal precursors, reduction, nucleation, growth, and capping and stabilisation in nanoparticle formation

Biological compounds are very important in this process. The metabolites of plants, microbial enzymes, protein, polysaccharide, phenolics and organic acids can be used as reducing, stabilizing and capping agents. Metal ions or nanoparticle surfaces can be functionalized by hydroxyl, carbonyl, amine and carboxyl groups, which can influence the formation of particles. These biomolecules also help to prevent aggregation of the nanoparticles in an uncontrolled manner by creating a protective layer on the surface of the nanoparticles. The nanoparticles are therefore more stable and are more appropriate for subsequent use in the removal of pollutants, in the treatment of antimicrobials and in environmental monitoring.

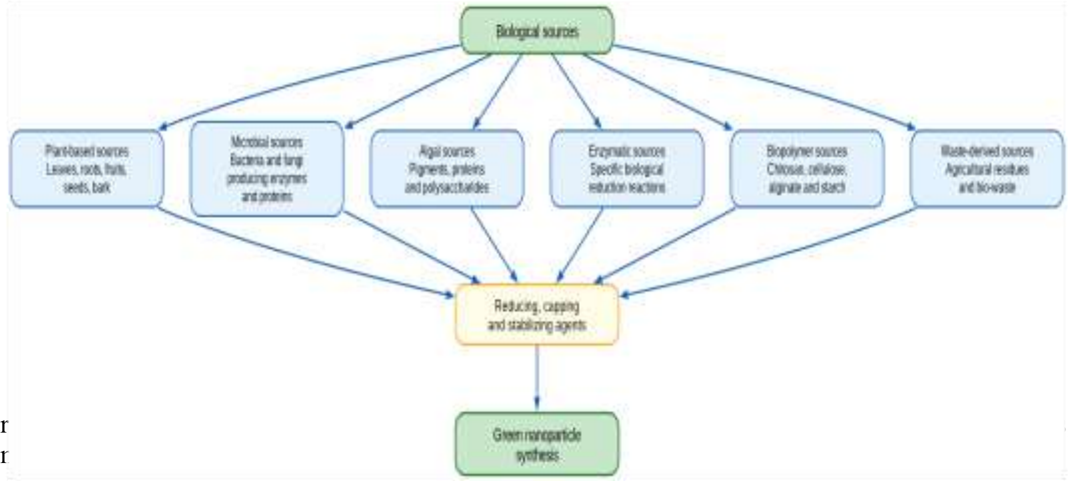
The process of green synthesis is regarded as a sustainable process as it minimizes the use of toxic solvents, potent reducing agents and non-biodegradable stabilizers. Other functional applications of naturally derived nanomaterials have been investigated, such as biosensing and delivery systems (Noah and Ndangili, 2022), demonstrating the diverse applications of biologically derived nanomaterials (BDNM). While physical and chemical methods are available, green synthesis offers an alternative that is environmentally friendly but can sometimes be hindered by the inability to replicate, control particle size and batch-to-batch variation. Comparisons of chemical, physical and green synthesis approaches have highlighted the increased preference for green synthesis as both environmentally friendly and suitable for practical synthesis of nanoparticles (Ijaz et al., 2020).

Plant-based synthesis is one of the most popular green synthesis methods, as phytochemicals present in the plant extracts are readily available. These extracts can also reduce the metal ions and stabilise the nanoparticles without the use of any other toxic chemicals. The synthesis of metal nanoparticles using plants has been identified as a green method of nanotechnology that is simple, low-cost and scalable (Makarov et al., 2014). Likewise, the green synthesis of nanoparticles has demonstrated potential applications in the field of antimicrobial, catalysis and environmental applications, which has reinforced the concept that green synthesis is not just a method of preparation, but also a tool for the synthesis of functional materials for sustainable utilisation (Hussain et al., 2016).

3. Biological Sources Used for Green Synthesis

Biological source is the major contributor to applying the green method in the synthesis of nanoparticles as they provide reducing, stabilizing and capping agents in a natural way. Biological synthesis: Utilisation of renewable materials like plants, bacteria, fungi, algae, enzymes, biopolymers and waste-originated resources, which is different from the conventional chemical approach. The materials are rich in bioactive molecules which can transform metal ions to nanoparticles and regulate their growth, surface properties and stability. These properties, such as size, shape, surface charge, aggregation behaviour, and application potential of nanoparticles, are significantly influenced by the choice of biological source. Figure 2 shows the major biological sources used for green synthesis of nanoparticles.

Figure 2. Biological sources used for green nanoparticle synthesis, including plant-based, microbial, algal, enzymatic, biopolymer, and waste-derived sources that provide reducing, capping and stabilising agents



Plant extr , their active cor

Table 1. Biological sources used for green synthesis of nanoparticles

Biological source	Major active compounds or agents	Role in nanoparticle synthesis	Common nanoparticles produced	Environmental relevance
Plant extracts	Phenolics, flavonoids, tannins, alkaloids, terpenoids, proteins and carbohydrates	Act as reducing, stabilising and capping agents	Ag, Au, Cu, Fe and ZnO nanoparticles	Wastewater treatment, dye degradation and antimicrobial disinfection
Bacteria	Enzymes, proteins, metabolites and extracellular polymeric substances	Support intracellular or extracellular reduction and stabilisation	Ag, Au, Fe and metal oxide nanoparticles	Bioremediation, pollutant transformation and wastewater treatment

Fungi	Extracellular enzymes, proteins and organic acids	Reduce metal ions and stabilise nanoparticles	Ag, ZnO, Fe and CuO nanoparticles	Pollutant degradation, antimicrobial treatment and environmental remediation
Algae	Pigments, polysaccharides, proteins and phenolic compounds	Function as biological reducing and stabilising agents	Ag, Au, ZnO and Fe nanoparticles	Aquatic pollution control, water treatment and ecological protection
Enzymes	Reductases, oxidases and proteins	Provide specific biological reduction under mild conditions	Metal and metal oxide nanoparticles	Controlled synthesis, sensing and environmental monitoring
Biopolymers	Chitosan, cellulose, starch, alginate and proteins	Improve capping, stabilisation and biocompatibility	Cu, Ag, ZnO and hybrid nanoparticles	Sustainable remediation, adsorption and antimicrobial activity
Waste-derived materials	Fruit peels, agricultural residues, plant waste and bio-waste	Provide low-cost reducing agents and support waste valorisation	Ag, Fe, ZnO and CuO nanoparticles	Circular economy, sustainable resource management and wastewater treatment

Plants have phytochemicals like flavonoids, phenolic acids, tannins, alkaloids, terpenoids, proteins and carbohydrates in various parts that include leaves, roots, fruits, seeds, bark, flowers and peels. These compounds will help reduce metal ions and form protective surface films to stabilise nanoparticles. Biological synthesis of silver nanoparticles has been given special attention because the prepared nanoparticles have a high antimicrobial, catalytic and environmental potential (Dhaka et al., 2023).

Some microorganisms are also helpful in the synthesis of nanoparticles. Nanoparticles can be synthesised intracellularly or extracellularly with the help of enzymes, proteins and metabolic products of bacteria. Fungi are good biological factories since they release extracellular enzymes and proteins that can decrease the metal ions and stabilise the metal particles. Microbial synthesis is particularly important for environmental biotechnology as microorganisms are already used in bioremediation, nutrient cycling and transformation of pollutants. So, microbial nanoparticle synthesis can be seen to be a potential interface between nanotechnology and biological remediation.

Some biological metabolites may be used to promote the formation of nanoparticles as well. Natural compounds like usnic acid and thymol have been utilised in the biosynthesis of silver nanoparticles and copper nanoparticles, respectively, and have been demonstrated to be antibacterial against MDR bacteria (Alavi and Karimi, 2019). This means that the biological molecules can not only affect the synthesis process, but also the functional activity of the nanoparticles. Thus, it is crucial to understand the chemical nature of the biological source to be able to establish the final properties and applications of the nanomaterial.

Another group of materials obtained by green synthesis are biopolymer. Stabilising and capping agents can be chitosan, cellulose, starch, alginate and proteins. These polymers can be used to enhance the dispersion of particles, inhibit aggregation and enhance compatibility with biological and environmental systems. Biopolymer-based nanoparticles can also be used in sustainable agriculture and the environment with their potential application in improving defence responses and plant growth in maize (Choudhary et al., 2017).

Capping agents are especially relevant due to their influence on the stability and activity of the nanoparticles. However, it is found that surface stabilisation is important during the synthesis of ZnO nanocrystals as capping agents influence the physical, optical and biological characteristics of nanocrystals (Javed et al., 2016). Other good synthesis pathways include algae and waste products. The relevance of algae for aquatic systems lies in the pigments, proteins and polysaccharides they produce, as well as in waste materials, which can be utilised to create valuable nanomaterials and help to implement circular economy principles. Overall, using biological sources as a base to produce nanoparticles for environmental remediation and aquatic protection is a sustainable approach.

4. Factors Affecting Green Nanoparticle Synthesis

There are multiple physicochemical and biological parameters which play a significant role in the synthesis of green nanoparticles and subsequently the properties of the nanomaterials. The pH, the temperature, the reaction time, the concentration of the precursor, the concentration of the biological extract and the composition of reducing and stabilising compounds are important parameters. These factors impact the rate of reduction, nucleation, growth, aggregation, particle size, morphology, surface charge and long-term stability. Thus, optimisation of the synthesis is a prerequisite to achieve reliable quality and environmental characteristics of nanoparticles. Table 2 shows the significant synthesis parameters that can affect the green synthesis of nanoparticles and their environmental performance.

Table 2. Factors affecting green nanoparticle synthesis and nanoparticle properties

Synthesis factor	Effect on the synthesis process	Influence on nanoparticle properties	Relevance to environmental application
pH	Alters the ionisation of biomolecules and affects metal ion reduction	Controls particle size, surface charge, aggregation and stability	Important for wastewater systems with variable water chemistry

Temperature	Influences the reaction rate, nucleation and growth	Affects crystallinity, particle size, yield and morphology	Determines synthesis efficiency and functional performance
Reaction time	Controls the completion of reduction and particle growth	Influences yield, size distribution and aggregation	Helps optimise stable nanoparticles for treatment systems
Precursor concentration	Determines the availability of metal ions for reduction	Affects nucleation density, particle size and final concentration	Important for scalable and reproducible synthesis
Biological extract concentration	Provides reducing, stabilising and capping compounds	Controls size, morphology and colloidal stability	Supports greener synthesis with reduced chemical use
Extract composition	Depends on source type, plant part, season and extraction method	Influences surface chemistry and functional activity	Affects reproducibility and environmental performance
Stirring and mixing	Improves contact between precursor and bioactive compounds	Promotes uniform particle formation	Useful for scale-up and process optimisation
Light exposure	May activate photochemical reduction in some systems	Can influence nucleation and photocatalytic behaviour	Relevant for photocatalytic nanoparticles used in pollutant degradation

One of the major parameters of the reaction medium influencing the formation of the nanoparticles is the pH of the medium. Can affect the metal ion binding ability and/or ionisation of functional groups found in biological extracts. Biomolecules like phenolics, proteins, enzymes and organic acids may exhibit varying reducing and stabilising properties under varying pH. In certain systems, the formation of smaller particles and/or accelerated reduction reaction may be favoured under alkaline conditions, and the reaction may be slower, or the particles may aggregate under acidic conditions. It is crucial to optimise the pH of the water for environmental applications as nanoparticles used in wastewater treatment need to be stable at variable water chemistry (Banihashem et al., 2024).

Temperature is also very important in the green synthesis of nanoparticles. A higher temperature can increase the rate of reduction of metal ions, thus increasing the rate of nucleation and potentially reducing particle size and increasing yield. But, when the temperature is too high, the sensitive biomolecules from plant or microbial extracts might be affected, which may lead to their diminished ability to stabilise the nanoparticles. Cooler temperatures can aid in controlled growth and reaction time. Iron oxide nanoparticles synthesis through a biogenic route using Moringa oleifera leaf extract has revealed that the reaction parameters can influence the formation of nanoparticles and their functional properties; therefore, the synthesis parameters need to be controlled (Aisida et al., 2020).

Another important factor is reaction time. A reaction time that is too brief can lead to incomplete reduction of metal ions, which can yield low yields of nanoparticles or unstable nanoparticles. Long reaction times, on the other hand, can encourage particle growth, aggregation and/or morphology changes. Hence, it is required to have an appropriate reaction time for the balance of nucleation and growth. Likewise, the concentration of precursors will influence the size distribution and stability of nanoparticles. A high concentration of precursors can lead to a higher number of produced nanoparticles, but if the stabilisers used in the biological reactor are not enough to prevent the nanoparticles from aggregating, this can be the case.

Synthesis efficiency will also depend on the concentration and chemical composition of the biological extract. These phytochemicals are complex mixtures, and the composition of these mixtures may differ depending on the plant species, part of the plant, extraction process, maturity stage and storage process. Silver nanoparticles (AgNPs) can be synthesised using plant extracts, and it has been shown that leaf extract of Salvia officinalis can be used for the synthesis of silver nanoparticles with biological activity, but further characterisation is required to confirm the properties of the synthesised nanoparticles (Okaiyeto et al., 2021). Likewise, several studies on the synthesis of silver nanoparticles using plant extracts have revealed that the properties of these nanoparticles are unique and depend on the reaction conditions and the phytochemical constituents used (Ullah et al., 2017). In summary, it is crucial to standardise the synthesis conditions for greater reproducibility, scalability and applicability in aquatic and environmental remediations.

5. Types of Green-Synthesised Nanoparticles

There are several different nanoparticle types that can be synthesized using the green route, and these have various compositions, structures and environmental functions. The major types include metal nanoparticles, metal oxide nanoparticles, magnetic nanoparticles, carbon-based nanoparticles and hybrid nanomaterials. The properties of each class are ideally suited for environmental uses like wastewater treatment, pollutant degradation, antimicrobial disinfection, sensing and remediation. The type of nanoparticles is a function of the specific pollutant to be treated, the treatment conditions, recovery method and desired stability. A summary of the main types of green-synthesised nanoparticles and their applications in the environment is provided in Table 3.

Table 3. Types of green-synthesised nanoparticles and their environmental applications

Nanoparticle type	Common examples	Main properties	Major environmental applications
Metal nanoparticles	Ag, Au, Cu and Fe nanoparticles	Antimicrobial, catalytic, optical and reactive properties	Disinfection, pollutant degradation and environmental sensing
Metal oxide nanoparticles	ZnO, TiO_2, Fe_2O_3 and CuO nanoparticles	Photocatalytic, oxidative, antimicrobial and adsorptive properties	Dye degradation, wastewater treatment and pharmaceutical pollutant removal
Magnetic nanoparticles	Fe_3O_4, iron oxide composites and magnetic hybrids	Magnetic recovery, reusability and high adsorption capacity	Heavy metal removal, dye adsorption and wastewater purification
Carbon-based nanoparticles	Carbon dots, graphene-based materials, carbon nanotubes and biochar-based nanomaterials	High surface area, adsorption ability and sensing performance	Pollutant adsorption, environmental sensing and water quality monitoring
Hybrid nanoparticles	MOF/GO, MOF/CNT, metal oxide-carbon hybrids and polymer-based hybrids	Multifunctional, stable and highly reactive	Emerging contaminant removal, catalytic degradation and combined remediation
Biopolymer-based nanoparticles	Chitosan, alginate, cellulose and starch-supported nanoparticles	Biocompatible, stable and biodegradable	Sustainable remediation, antimicrobial treatment and pollutant adsorption

Among the extensively studied green-synthesised nanomaterials, metal nanoparticles stand out. The most frequently used plant extracts, microorganisms and other biological resources for the synthesis of silver, gold, copper and iron nanoparticles are found. Due to their high surface activity, optical properties, catalytic and antimicrobial properties, they have potential applications in pollution and water treatment. The relevance of green synthesis of gold, silver and iron nanoparticles in the degradation of organic pollutants in aqueous waste has been reported (Kumar, 2021). From the general principles of nanotechnology, it is also known that the properties of nanoparticles are very sensitive to size, morphology, surface charge and composition, which determines their behaviour in environmental systems (Nasrollahzadeh et al., 2019).

Another class of green-synthesised materials are the metal oxide nanoparticles. These can be zinc oxide, titanium dioxide, iron oxide and copper oxide nanoparticles. The photocatalytic, antimicrobial, adsorptive and oxidative properties make these materials useful. The Zinc oxide nanoparticles have been given attention as they can be synthesised in a variety of ways and are found to be highly functional. But before expanding their use, their potential health and environmental hazards need to be taken into consideration (Singh et al., 2020). Metal oxide nanoparticles can be used to treat wastewater, where they can be used as photocatalysts for the degradation of dyes, pharmaceuticals and other organic pollutants.

Magnetic nanoparticles are interesting for environmental remediation because they can be removed from the water after the treatment by applying an external magnetic field. This enhances the recovery, reuse and post-treatment management, thereby minimising the risk of nanoparticles being released into the environment. Sorption properties of iron oxide magnetic nanoparticles for the removal of organic contaminants from wastewater and water sources have been investigated, and it is expected that a practical remediation system could be developed.

Advanced oxidation processes are also important for photocatalytic nanoparticles. Photocatalysts are materials that under illumination will produce reactive oxygen species capable of degrading organic pollutants into less harmful compounds. It can be used for dye-contaminated wastewater, pharmaceutical residues and pesticide pollutants. Photocatalysis has been proven to be a very effective advanced oxidation process (AOP) for wastewater treatment due to its ability to degrade persistent contaminants (Ameta et al., 2018).

New classes of environmental potential that emerge are the nanoparticles made of carbon and hybrid nanomaterials. Carbon dots, graphene-based materials, carbon nanotubes, & Biochar based nanomaterials are useful in adsorption, sensing and detecting pollutants. Multicomponent nanoparticles are those that consist of two or more materials, which can be engineered to exhibit improved stability, catalytic properties and multifunctionality. Overall, the variety of green-synthesised nanoparticles offers a range of possibilities for sustainable environmental remediation and protection of aquatic ecosystems.

6. Environmental Applications of Green-Synthesised Nanoparticles

The Green synthesised nanoparticles have received an enormous interest in environmental science due to their capacity to remove, degrade, detect and control various pollutants. They possess several desirable properties such as high surface area, reactive surface groups, catalytic activity, adsorption and antimicrobial properties which make them useful in wastewater treatment, pollutant degradation, environmental sensing and ecological protection. Advances have been made in the use of biogenic nanomaterials and photocatalysts to assist wastewater treatment, enhancing the treatment of organic contaminants, dyes, pathogens and other pollutants, but there are still challenges related to cost, recovery, stability, and field-scale application (Sanni et al., 2024). The significant applications of green-synthesised nanoparticles in the environment are presented in Figure 3.

Figure 3. Environmental applications of green-synthesised nanoparticles in wastewater treatment, pollutant degradation, antimicrobial disinfection, environmental remediation, sensing and ecological protection

The most important environmental application of the green-synthesised nanoparticles is wastewater treatment. These nanoparticles can be used to bind, photocatalyze, oxidise, reduce, precipitate and inhibit the growth of microorganisms. One of the most significant applications of the biosynthetic route of nanoparticles is the ability of microorganisms to create functional nanoparticles and transform pollutants and bioremediation processes as well (Koul et al., 2021). This renders biologically synthesised nanoparticles useful for sustainable wastewater treatment systems and protection of aquatic ecosystems.

Another application of green nanoparticles is in the detection and removal of pollutants. Systems that rely on nanotechnology will be able to identify low concentrations of heavy metals, dyes, pesticides, pharmaceuticals and microbial contamination. It is beneficial for water quality monitoring and for avoiding ecological damage. Nanotechnology is a subject of discussion which can be used to ensure Eco-sustainability both by pollutant sensing and by pollutant remediation (Yadav et al., 2021). Inorganic nanomaterials, like gold nanoparticles, iron nanoparticles, silica nanoparticles, and quantum dots, also have properties that are useful for sensing, interaction with pollutants, and functioning in the environment (Cruz and Reyes, n.d.).

Another issue of concern in aquatic environments is emerging contaminants. Pharmaceuticals, personal care products, endocrine-disrupting chemicals and pesticide residues can remain in wastewater and be discharged into the waters of the rivers, lakes and other water bodies. Conventional treatment processes may not completely remove these pollutants. The enhanced removal of emerging contaminants from wastewater using adsorption, degradation and mixed processes has been demonstrated with the use of nanomaterials in recent years (Ahmed et al., 2021).

The use of green synthesized nano particles is also important for extended environmental remediation. The application of nanotechnology to the treatment of contaminated water, contaminated soil, and contaminated industrial effluent is of interest here, as the interaction between the small size of the nanomaterials and their high reactivity allows them to be effective in the treatment of contaminated materials (Thomas et al., 2022). For environmental monitoring applications, the use of carbon-based sensors and the related nanomaterial platforms can be used to detect pollutants and enhance water quality assessment (Manjunatha, 2025).

In addition, antimicrobial disinfection is an important application. The biological molecules present on the surface of nanoparticles can modify their interaction with microorganisms, which makes them highly effective against microorganisms. High antimicrobial activity of green-synthesised silver nanoparticles is due to the biomolecules present on the surface of NPs, which can modify their interactions with microorganisms (Roy et al., 2019). Hybrid nanocomposites also exhibit great potential for pollutant removal. As an illustration, MOF/graphene oxide and MOF/CNT-based materials have been shown to possess high adsorption capacity for bisphenol A removal from water and thus have been found promising for the treatment of persistent organic pollutants (P.O.Ps) (Ahsan et al., 2019). In general, green-synthesised nanoparticles are promising and sustainable water treatment agents, pollutant removers, eco-sensors, and water protectors.

7. Role in Pollution Remediation and Ecological Protection

The ecologic protection and pollution remediation is one of the important applications of green-synthesised nanoparticles as they can be used for removing, degrading and monitoring pollutants in water, soil and air. They have high surface reactivity, adsorption capacity, catalytic capability and antimicrobial activity, which makes them a good choice for lowering the polluting levels in aquatic and terrestrial environment. Untreated wastewater, industrial effluents and agricultural runoffs are of direct concern to aquatic ecosystems involving rivers, lakes, wetlands or coastal ecosystems; hence, green nanomaterials are very relevant to aquatic field research and environmental sustainability.

Green nanomaterials can be used as adsorbents, catalysts, photocatalysts and antimicrobial agents in wastewater and soil treatment. They can remove heavy metals, dyes, pesticides, as well as residues of micro-organisms and pharmaceuticals from polluted systems. A number of green nanomaterials have been reviewed for the treatment of wastewater and soils and have exhibited their sustainability as a substitute to the conventional remediation materials

(Nakum and Bhattacharya, 2022). They are also beneficial for environmentally sensitive applications due to their biological origin and less chemical burden.

Textile and industrial effluents are a major environmental problem with regards to dye pollution. Synthetic dyes can cause a decrease in light penetration in water, impact photosynthesis and addict harmful compounds in the water. The advantage of green magnetic nanoparticles is that they can absorb dyes and then be removed via the magnetic force from the treated water. The sorption of malachite green dye using 3-mercaptopropionic acid functionalized magnetic nanoparticles indicates that the plant-based magnetic nanomaterials are a potential approach in treating wastewater contaminated with dyes (Ali et al., 2018).

Nanotechnology also can contribute to all-round environmental cleanup with materials that can be used for adsorption, catalysis, oxidation-reduction reaction and pollutant sensing. Nanomaterials can be designed to react with certain contaminants, increase degradation efficiency, and increase the removal from complex environmental matrices. The studies on nanotechnology for pollutant remediation emphasize the need for selecting appropriate materials and application methods for effective and safe pollutant removal (Guerra et al., 2018).

The use of biobased nanomaterials in sustainable water treatment is particularly relevant for their potential to be developed using renewable resources and to be used in pollutant removal, membrane modification, antimicrobial treatment, and environmental monitoring. Advances in biobased nanomaterials for water treatment technologies demonstrate the possibility of achieving sustainability and remediation efficiency in the future.Future water treatment systems combining sustainability and treatment efficiency are attainable thanks to advances in biobased nanomaterials for water treatment technologies. (Saud et al., 2024) This will help produce new technologies that will create greener solutions to protect aquatic ecosystems and enhance water quality.

Green nanotechnology can also play a part in resource recovery and environmental management based on a circular economy. In addition to eliminating pollutants, advanced green nanomaterials could enable the recovery of nutrients, metals and other valuable resources from wastewater and contaminated systems. Recent studies on "green nanotechnology for sustainable ecosystems" highlight its potential in the field of pollution control and resource recovery, suggesting that future research could include both contaminant removal and sustainable resource management (Abdel-Fatah and Ewies, 2025). In general, green-synthesised nanoparticles offer great potential as a tool to mitigate pollution, safeguard ecosystems and enable sustainable environmental engineering.

8. Challenges, Toxicity, Environmental Fate, and Future Perspectives

The application of green-synthesised nanoparticles for the remediation of the environment shows great potential, but there are still several significant challenges. These include scale-up and life cycle evaluation, recovery after treatment, long-term stability, toxicity assessment and reproducibility. Many of the green synthesis methods are dependent on biological extracts, leading to differences in the size, shape, surface chemistry, and activity of the resulting nanoparticles, depending on the plant species, microbial strain, extraction method, pH, temperature, and storage conditions. This gives rise to batch-to-batch variations and requires standardisation before use in the environment on a large scale. The challenges and future research opportunities for the green-synthesised nanoparticles are summarised in Table 4.

Table 4. Challenges and future perspectives of green-synthesised nanoparticles

Challenge	**Main problem**	**Possible environmental risk**	**Future recommendation**
Reproducibility	Biological extracts vary by species, season, extraction method and storage	Inconsistent nanoparticle size, shape and activity	Develop standardised synthesis protocols
Toxicity	Green nanoparticles may still affect living organisms	Possible impacts on algae, bacteria, invertebrates and fish	Conduct detailed aquatic and terrestrial ecotoxicity testing
Environmental fate	Nanoparticles may transform after release into water, soil or sediment	Unknown mobility, persistence, bioavailability and accumulation	Study long-term fate under real environmental conditions
Aggregation and stability	Nanoparticles may clump or lose activity	Reduced treatment efficiency and unpredictable behaviour	Improve capping, stabilisation and surface modification
Recovery and reuse	Nanoparticles may remain in treated water after use	Possible secondary contamination	Develop magnetic, immobilised or reusable nanoparticle systems
Scale-up	Laboratory synthesis may not translate easily to industrial production	High cost, quality variation and low process control	Conduct pilot-scale and field-scale studies
Life-cycle assessment	Total environmental impact is often unknown	Green synthesis may still have hidden environmental costs	Apply full life-cycle assessment from synthesis to disposal
Regulatory acceptance	Lack of standard guidelines for environmental use	Uncontrolled application and uncertain risk management	Establish safety standards and application guidelines

One of the major concerns is toxicity. Although nanoparticles are manufactured using green technology, they can interact with living organisms because of their small size and high reactivity and surface area. Nanoparticles can induce oxidative stress and damage to membranes and/or cause bioaccumulation or disruption of cellular processes in aquatic algae, bacteria, invertebrates, fish and other organisms. There is a need for assessing the effects of nanomaterials in both terrestrial and aquatic environments, before their wider use in environmental systems, as was highlighted in a systematic review about nanomaterial ecotoxicology (Gambardella and Pinsino, 2022).

Special care should be taken for aquatic ecosystems, as nanoparticles released in aquatic environments can undergo aggregation, sedimentation, dissolution and transformation as a function of various environmental factors such as pH, ionic strength, water chemistry, and organic matter. These changes can affect their mobility, bioavailability and toxicity. Studies on aquatic exposure to nanomaterials have pointed towards the need for better ecotoxicity testing, the need for harmonised methods and more precise research priorities to better understand the environmental risk of nanomaterials (Selck et al., 2016).

Another significant one is environmental fate. After application, the nanoparticles can be transferred from water, sediment, soil to organisms and vice versa. They exhibit particle size, surface coating, charge, solubility and natural organic matter interaction dependency. Another transformation of nanoparticles can be oxidation, sulfidation, photochemical or biological processes. Studies of the behaviour, fate, bioavailability and risk of nanomaterials indicate that environmental factors have a significant impact on the risk and long-term performance of nanomaterials (Lead et al., 2018).

The potential of green nanoparticles may also be used in remediation processes, such as the reduction of toxic metals. In the case of hexavalent chromium-contaminated effluents, for instance, the effluents need to be treated to convert the highly toxic form of chromium, Cr (VI), to less harmful forms. Bio reduction of hexavalent chromium is reported to be an effective wastewater treatment method, and the use of nanoparticles in wastewater remediation can be a better option (Pradhan et al., 2017).

The other problem is where the nanoparticles will be after their usage. Nanoparticles can be released into the environment at the time of their synthesis, application, disposal and/or accidental release. They can spread in the environment, going from one environmental compartment to another, and interact with the organisms when they are released. Research on the origin, transport and destination of nanoparticles highlights the importance of improving exposure assessment, environmental monitoring and regulatory control (Bundschuh et al., 2018). Safe-by-design synthesis, recovery and reuse, testing with real wastewater, long-term ecotoxicity, life-cycle assessment and field-scale testing and validation should therefore be focused on future research.

9. Conclusion

Green synthesis of nanoparticles offers an environmentally sustainable and eco-friendly means of fabrication of functional nanoparticles with significant environmental applications. The biological route relies on the use of natural sources like plant extracts, microorganisms, algae, enzymes, biopolymers and waste materials to minimise toxic chemical use and promote environmentally friendly nanoparticle manufacturing. It is revealed that bioactive compounds found in these natural sources function as reducing, stabilising and capping agents, which allows for the formation of nanoparticles under mild conditions. The green synthesised nanoparticles, such as metal, metal oxide, magnetic, carbon, hybrid and biopolymer-based nanoparticles, can be used in wastewater treatment, dye degradation, heavy metal removal, remediation of pharmaceutical and pesticide pollutants, antimicrobial disinfection, soil remediation, air pollution control, and environmental sensing with considerable potential. The applications are very significant in relation to aquatic ecosystems and the protection of the environment, as they can lower the pollutant load and enhance water quality. But for field-scale application, attention to reproducibility, toxicity, nanoparticle recovery, environmental fate, long-term stability and regulatory acceptance must be paid. Synthetic approaches need to be standardised, real wastewater trials should be conducted, aquatic ecotoxicity evaluation should be done, and safe-by-design nanomaterials and full life-cycle assessments should be addressed in future studies. In summary, the use of green-synthesised nanoparticles is a potential platform for sustainable technologies in the field of environmental pollution remediation, protection of the environment and managing resources in ways that are environmentally friendly.

References

1. Abdel-Fatah, M.A. and Ewies, E.F. (2025) ‘Green nanotechnology for sustainable ecosystems: innovations in pollution remediation and resource recovery’, Egyptian Journal of Chemistry, 68(10), pp. 621–633.
2. Ahmed, S.F., Mofijur, M., Nuzhat, S., Chowdhury, A.T., Rafa, N., Uddin, M.A., Inayat, A., Mahlia, T.M.I., Ong, H.C., Chia, W.Y. and Show, P.L. (2021) ‘Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater’, Journal of Hazardous Materials, 416, p. 125912.
3. Ahsan, M.A., Jabbari, V., Islam, M.T., Turley, R.S., Dominguez, N., Kim, H., Castro, E., Hernandez-Viezcas, J.A., Curry, M.L., Lopez, J. and Noveron, J.C. (2019) ‘Sustainable synthesis and remarkable adsorption capacity of MOF/graphene oxide and MOF/CNT based hybrid nanocomposites for the removal of Bisphenol A from water’, Science of the Total Environment, 673, pp. 306–317.
4. Aisida, S.O., Madubuonu, N., Alnasir, M.H., Ahmad, I., Botha, S., Maaza, M. and Ezema, F.I. (2020) ‘Biogenic synthesis of iron oxide nanorods using Moringa oleifera leaf extract for antibacterial applications’, Applied Nanoscience, 10(1), pp. 305–315.
5. Alavi, M. and Karimi, N. (2019) ‘Biosynthesis of Ag and Cu NPs by secondary metabolites of usnic acid and thymol with biological macromolecules aggregation and antibacterial activities against multi drug resistant (MDR) bacteria’, International Journal of Biological Macromolecules, 128, pp. 893–901.
6. Ali, I., Peng, C., Ye, T. and Naz, I. (2018) ‘Sorption of cationic malachite green dye on phytogenic magnetic nanoparticles functionalized by 3-mercaptopropionic acid’, RSC Advances, 8(16), pp. 8878–8897.
7. Ameta, R., Solanki, M.S., Benjamin, S. and Ameta, S.C. (2018) ‘Photocatalysis’, in Advanced Oxidation Processes for Waste Water Treatment. Academic Press, pp. 135–175.
8. Anastas, P.T. and Zimmerman, J.B. (2018) ‘The United Nations sustainability goals: How can sustainable chemistry contribute?’, Current Opinion in Green and Sustainable Chemistry, 13, pp. 150–153.
9. Banihashem, S.M., Moradi, A., Evazzadeh, B., Namvar, F. and Fang, Z.N. (2024) ‘Biogenically synthesized

nanoparticles in wastewater treatment; a greener approach: a review', Clean Technologies and Environmental Policy, 26(6), pp. 1731–1754.

10. Bundschuh, M., Filser, J., Lüderwald, S., McKee, M.S., Metreveli, G., Schaumann, G.E., Schulz, R. and Wagner, S. (2018) 'Nanoparticles in the environment: where do we come from, where do we go to?', Environmental Sciences Europe, 30(1), p. 6.
11. Choudhary, R.C., Kumaraswamy, R.V., Kumari, S., Sharma, S.S., Pal, A., Raliya, R., Biswas, P. and Saharan, V. (2017) 'Cu-chitosan nanoparticle boost defense responses and plant growth in maize (Zea mays L.)', Scientific Reports, 7(1), p. 9754.
12. Cruz, J.C. and Reyes, L.H. (n.d.) 'Inorganic nanocarriers: Gold nanoparticles, iron nanoparticles, silica nanoparticles, quantum dots', in Nanocarriers for Nucleic Acids and Proteins. CRC Press, pp. 105–140.
13. Dhaka, A., Mali, S.C., Sharma, S. and Trivedi, R. (2023) 'A review on biological synthesis of silver nanoparticles and their potential applications', Results in Chemistry, 6, p. 101108.
14. Gambardella, C. and Pinsino, A. (2022) 'Nanomaterial ecotoxicology in the terrestrial and aquatic environment: a systematic review', Toxics, 10(7), p. 393.
15. Guerra, F.D., Attia, M.F., Whitehead, D.C. and Alexis, F. (2018) 'Nanotechnology for environmental remediation: materials and applications', Molecules, 23(7), p. 1760.
16. Gutierrez, A.M., Dziubla, T.D. and Hilt, J.Z. (2017) 'Recent advances on iron oxide magnetic nanoparticles as sorbents of organic pollutants in water and wastewater treatment', Reviews on Environmental Health, 32(1–2), pp. 111–117.
17. Hussain, I., Singh, N.B., Singh, A., Singh, H. and Singh, S.C. (2016) 'Green synthesis of nanoparticles and its potential application', Biotechnology Letters, 38(4), pp. 545–560.
18. Ijaz, I., Gilani, E., Nazir, A. and Bukhari, A. (2020) 'Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles', Green Chemistry Letters and Reviews, 13(3), pp. 223–245.
19. Jadoun, S., Arif, R., Jangid, N.K. and Meena, R.K. (2021) 'Green synthesis of nanoparticles using plant extracts: a review', Environmental Chemistry Letters, 19(1), pp. 355–374.
20. Javed, R., Usman, M., Tabassum, S. and Zia, M. (2016) 'Effect of capping agents: structural, optical and biological properties of ZnO nanoparticles', Applied Surface Science, 386, pp. 319–326.
21. Khan, I., Saeed, K. and Khan, I. (2019) 'Nanoparticles: Properties, applications and toxicities', Arabian Journal of Chemistry, 12(7), pp. 908–931.
22. Koul, B., Poonia, A.K., Yadav, D. and Jin, J.O. (2021) 'Microbe-mediated biosynthesis of nanoparticles: Applications and future prospects', Biomolecules, 11(6), p. 886.
23. Kumar, B. (2021) 'Green synthesis of gold, silver, and iron nanoparticles for the degradation of organic pollutants in wastewater', Journal of Composites Science, 5(8), p. 219.
24. Lead, J.R., Batley, G.E., Alvarez, P.J., Croteau, M.N., Handy, R.D., McLaughlin, M.J., Judy, J.D. and Schirmer, K. (2018) 'Nanomaterials in the environment: behavior, fate, bioavailability, and effects—an updated review', Environmental Toxicology and Chemistry, 37(8), pp. 2029–2063.
25. Makarov, V.V., Love, A.J., Sinitsyna, O.V., Makarova, S.S., Yaminsky, I.V., Taliansky, M.E. and Kalinina, N.O. (2014) '"Green" nanotechnologies: synthesis of metal nanoparticles using plants', Acta Naturae, 6(1), pp. 35–44.
26. Manjunatha, J.G. (2025) Handbook of Carbon Sensors.
27. Nakum, J. and Bhattacharya, D. (2022) 'Various green nanomaterials used for wastewater and soil treatment: a mini-review', Frontiers in Environmental Science, 9, p. 724814.
28. Nasrollahzadeh, M., Sajadi, S.M., Sajjadi, M. and Issaabadi, Z. (2019) 'An introduction to nanotechnology', in Interface Science and Technology. Vol. 28. Elsevier, pp. 1–27.
29. Noah, N.M. and Ndangili, P.M. (2022) 'Green synthesis of nanomaterials from sustainable materials for biosensors and drug delivery', Sensors International, 3, p. 100166.
30. Okaiyeto, K., Hoppe, H. and Okoh, A.I. (2021) 'Plant-based synthesis of silver nanoparticles using aqueous leaf extract of Salvia officinalis: characterization and its antiplasmodial activity', Journal of Cluster Science, 32(1), pp. 101–109.
31. Osman, A.I., Zhang, Y., Farghali, M., Rashwan, A.K., Eltaweil, A.S., Abd El-Monaem, E.M. and Yap, P.S. (2024) 'Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: a review', Environmental Chemistry Letters, 22(2), pp. 841–887.
32. Ovais, M., Khalil, A.T., Raza, A., Khan, M.A., Ahmad, I., Islam, N.U., Saravanan, M., Ubaid, M.F., Ali, M. and Shinwari, Z.K. (2016) 'Green synthesis of silver nanoparticles via plant extracts: beginning a new era in cancer theranostics', Nanomedicine, 11(23), pp. 3157–3177.
33. Pradhan, D., Sukla, L.B., Sawyer, M. and Rahman, P.K. (2017) 'Recent bioreduction of hexavalent chromium in wastewater treatment: a review', Journal of Industrial and Engineering Chemistry, 55, pp. 1–20.
34. Roy, A., Bulut, O., Some, S., Mandal, A.K. and Yilmaz, M.D. (2019) 'Green synthesis of silver nanoparticles: biomolecule-nanoparticle organizations targeting antimicrobial activity', RSC Advances, 9(5), pp. 2673–2702.
35. Salem, S.S. and Fouda, A. (2021) 'Green synthesis of metallic nanoparticles and their prospective biotechnological applications: an overview', Biological Trace Element Research, 199(1), pp. 344–370.
36. Sanni, S.E., Oni, B.A., Okoro, E.E. and Pandya, S. (2024) 'Recent advances in the use of biogenic nanomaterials and photocatalysts for wastewater treatment: challenges and future prospects', Frontiers in Nanotechnology, 6, p. 1469309.
37. Saud, A., Gupta, S., Allal, A., Preud'Homme, H., Shomar, B. and Zaidi, S.J. (2024) 'Progress in the sustainable development of biobased (nano) materials for application in water treatment technologies', ACS Omega, 9(27), pp. 29088–29113.
38. Selck, H., Handy, R.D., Fernandes, T.F., Klaine, S.J. and Petersen, E.J. (2016) 'Nanomaterials in the aquatic

environment: A European Union–United States perspective on the status of ecotoxicity testing, research priorities, and challenges ahead', Environmental Toxicology and Chemistry, 35(5), pp. 1055–1067.

39. Singh, J., Dutta, T., Kim, K.H., Rawat, M., Samddar, P. and Kumar, P. (2018) '"Green" synthesis of metals and their oxide nanoparticles: applications for environmental remediation', Journal of Nanobiotechnology, 16(1), p. 84.
40. Singh, T.A., Das, J. and Sil, P.C. (2020) 'Zinc oxide nanoparticles: a comprehensive review on its synthesis, anticancer and drug delivery applications as well as health risks', Advances in Colloid and Interface Science, 286, p. 102317.
41. Thomas, S., Thomas, M.S. and Pothen, L.A. (eds.) (2022) Nanotechnology for Environmental Remediation. John Wiley & Sons.
42. Ullah, M.N., Umer, A., Aadil, M.A., Rehman, F. and Ramzan, N. (2017) 'Plant-based synthesis of silver nanoparticles and their characteristic properties', Bioinspired, Biomimetic and Nanobiomaterials, 6(1), pp. 20–36.
43. Yadav, N., Garg, V.K., Chhillar, A.K. and Rana, J.S. (2021) 'Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: a review', Chemosphere, 280, p. 130792.