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GREEN SYNTHESIS OF NANOPARTICLES: A SUSTAINABLE APPROACH FOR ENVIRONMENTAL REMEDIATION

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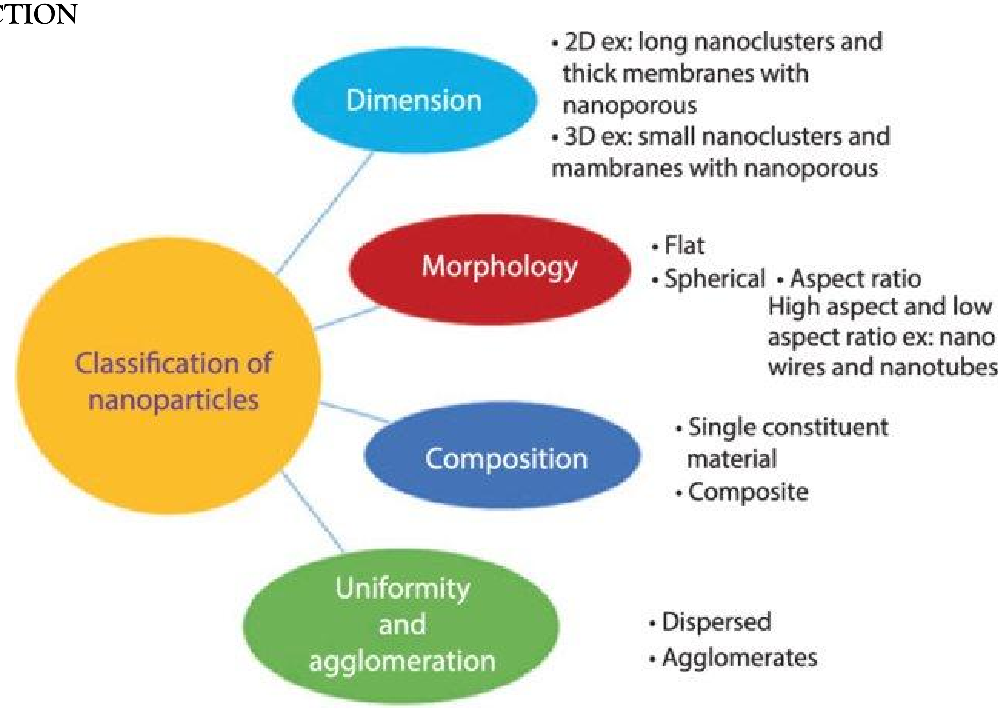
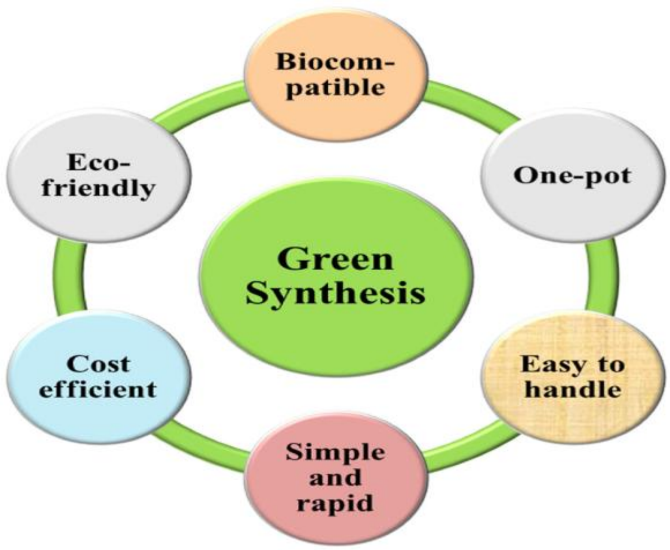
Abstract
The environmentally friendly method involving the green synthesis of nanoparticles considers biological agents like plants, microbes, algae, and fungi as reducing and stabilizing agents. Unlike previous methodologies, this processes do not use toxic reagents implying the need for more advanced environmentally friendly technology. The process of biogenic synthesis entails reduction reactions that are facilitated by phytochemicals, enzymes, and biomolecules, which gives rise to nanoparticles that are stable and possess a specific size and morphology. Their physicochemical Properties in terms of stability, shape and surface functionality are confirmed with spectroscopic characterization technique(s): UV-Vis, FTIR, TEM, SEM, XRD, and DLS. Green-synthesized nanoparticles have emerged for heavy metal removal, organic pollutant degradation, air purification with nano-catalysts, as well as for antimicrobial water treatment confirming its efficacy for environmental remediation. The identified gaps such as lack of reproducibility, large scale production, and possible toxicity fuels the advancement of technology Kalpana Rao nanotechnology to be used widely. The evaluation of long term environmental impact, optimization of synthesis parameters, and increase stability of produced nanoparticles should be studied in depth. The application of sophisticated analytical tools and machine learning together with green nanotechnology is environmentally friendly and can broaden the scope nanotechnology while accomplishing goals aligned with environmental remediation.

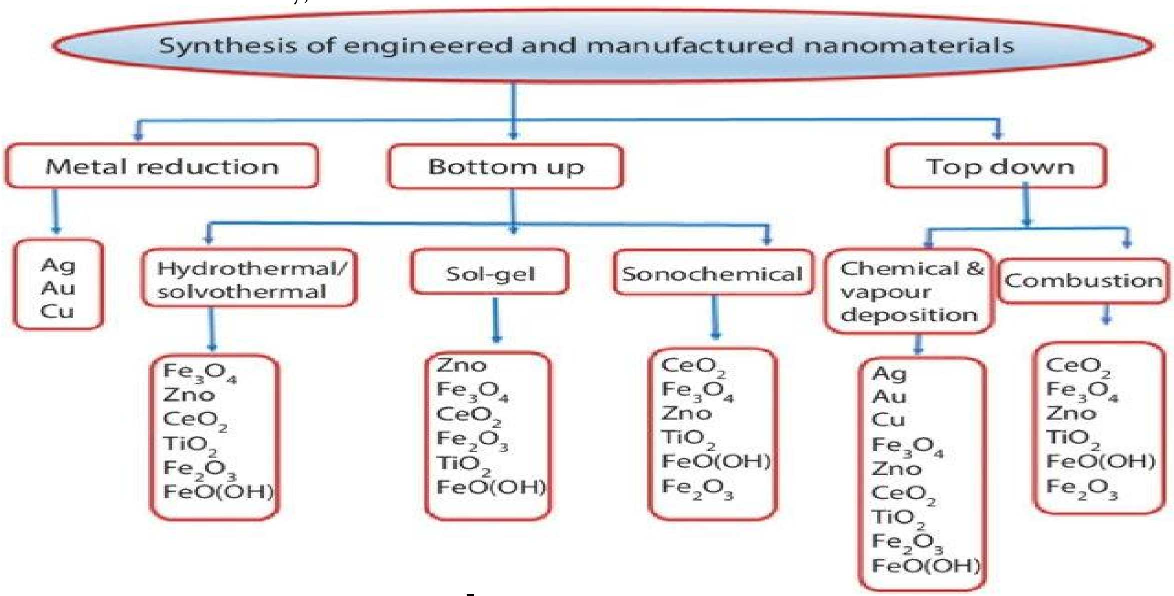
INTRODUCTION



Nanotech has transformed and improved many scientific fields on a global scale, with nanoparticles being very important in many fields such as medicine, electronics, catalysis, and environmental science (Danish et al., 2022). Historically, nanoparticles synthesis has depended on physical as well as chemical methods that consume high amounts of energy and use hazardous solvents, along with toxic reducing agents which increases the risk of environmental damage and human health complications (Sonawane et al., 2023). For these reasons, there has been a movement towards more sustainable and green methods, which make use of biological entities such as plant extracts, bacteria, fungi, and algae in the form of green synthesis (Samuel et al., 2022). This concept does not only observe the tenets of green chemistry, but also provides a novel approach in efficient nanoparticle production which produces little or no waste. The biological systems help in the reduction and stabilization of metal ions. The end result is nanoparticles with specific properties that are required (Rafique et al., 2021).



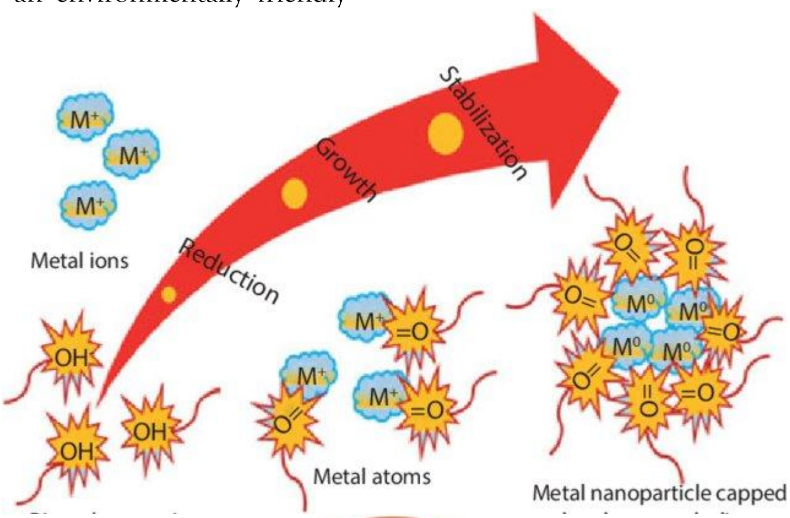
Green synthesis is largely defined by the ability of biologically active molecules derived from living organisms to reduce compounds and produce nanoparticles. For example, plants contain secondary metabolites such as flavonoids, ter-penoids, alkaloids and polyphenols, which serve as natural reducing and capping agents for the biomimetic synthesis of nanoparticles of desired size and shape (Aigbe & Osibote, 2024). The biomolecules' functional groups coordinate with metals, influencing the nucleation and growth processes and inhibiting the clustering of particles. In a similar way, microbial-assisted synthesis employs the enzymatic and protein-induced reduction of metal ions, thereby permitting the synthesis of nanoparticles under mild conditions (Tamboli et al., 2023). This approach enhances biocompatibility and provides a more eco-friendly solution by removing toxic reagents. The end product is an implantable material that does not cause the reaction of rejection by the body. Owing to the presence of these specific physicochemical features, green synthesized multifunctional nanoparticles possess high efficiency in solving many environmental

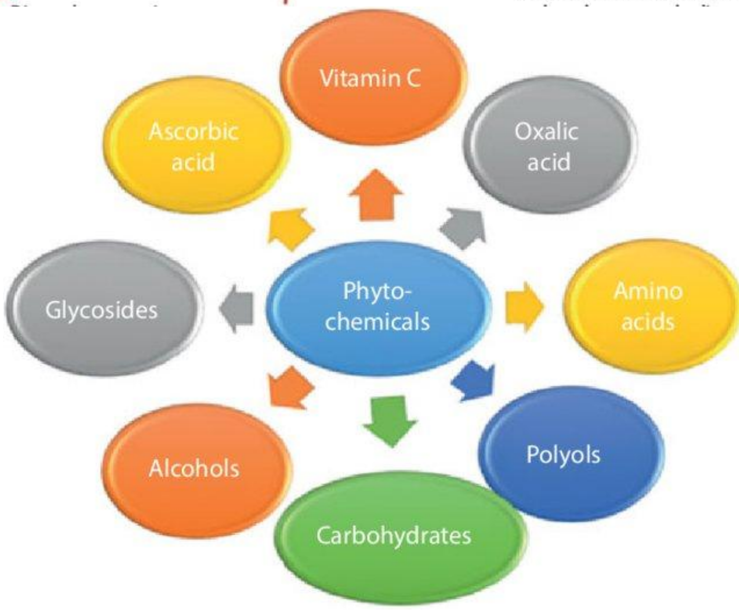


and biomedical problems (Jadoun et al., 2021).

In the range of environmentally-friendly nanoparticles, metal and metal oxide nanoparticles have exhibited a superb efficiency in the field of remediation (Kaur et al., 2022). The presence of Heavy metals, organic contaminants, and microbial pathogens are dire threats to the ecosystems and human health and therefore appropriate efficient decontamination measures must be put in place (Panhwar et al., 2021). Quaternary ammonium nanoparticles like Silver, Gold, Zinc oxide, and Iron oxide possess high catalytic and adsorption prowess rendering them useful in water purification, soil remediation, and air filtration (Nguyen et al., 2023). These nanoparticles' high surface reactivity and enhanced electron transfer allow organic pollutants to be degraded using advanced oxidation processes, while their affinity for toxic, metal ions allow removal from heavily contaminated surroundings. More so, silver and copper-based nanoparticles are very effective in disinfection and biofilm control of municipal wastewater treatment plants due to their antibacterial activities (Zelekew et al., 2023).

The self-redox reaction and surface chemistry of nanoparticles produced through green methods are essential for their environmental uses. The electrons of metal nanoparticles are so dense that they can engage in redox processes that catalyze the decomposition of organic pollutants such as dyes, pesticides and pharmaceutical waste (El Messaoudi et al., 2024). Magnetite (Fe_3O_4) iron oxide nanoparticles have been extensively used in magnetic separation processes because of superparamagnetic ability. This characteristic makes the separation of heavy metal ions like lead (Pb), cadmium (Cd) and mercury (Hg) from industrial wastewater extremely fast and easy (Bhandari et al., 2023). The modification of composite and hybrid systems with green synthesized nanomaterials makes these processes more effective by increasing their stability, dispersability, and reuse in removing contaminants from composite materials. Green synthesis of nanomaterials presents an environmentally friendly and highly efficient solution for global environmental problems through the exploitation of the unique electronic and structural features of nanoparticles (Ying et al., 2022).





The adoption of green synthesis techniques is extremely useful in alleviating the obstacles faced during the fabrication of nanoparticles. Indeed, chemical synthesis approaches are very effective only when using reducing agents such as sodium borohydride, and hydrazine which are extremely harmful to the environment because of their toxicity (Rafeeq et al., 2022). The processes involved in the traditional techniques of producing nanoparticles also incorporate high-temperature and high-pressure which ultimately means that a lot of energy is used and a lot of greenhouse gases produced (Anees et al., 2024). On the other hand, synthesized nanoparticles can be innocuously produced through utilizing ambient temperature and relying on water or ethanol-based solvents and biological reducing agents which means that the production of nanomaterials becomes more carbon friendly (García-Quintero & Palencia, 2021). Green synthesis is eco-friendly which makes it compliant with many sustainable development goals, but the fact that it can also be easily scaled makes it economically beneficial for large scale industrial implementations. Moreover, the modification of nanoparticles using biological approaches expands their use even more for catalysis, energy storage, and biomedical engineering (Mahesh, 2024).

Many benefits come with green synthesized nanoparticles, yet there are several things that can be done to increase their practicality and efficiency (Alprol et al., 2023). Issues like pH, temperature, and precursor concentration can alter the yield, size distribution, and stability (Shobana et al., 2025). Additionally, the reproducibility and scalability of green synthesis methods need advanced characterization techniques and controlled experimental conditions. Biogenic nanoparticle formation is one of the molecular mechanisms that must be better understood (Malik et al., 2023). In the future, advancements in green synthesis procedures should be complemented by novel analytical techniques, such as in situ spectroscopy and computational modeling, which are among the next generation of tools in nanotechnology. With improvements in synthesis techniques and biomaterials being used, green nanotechnology can substantially transform environmental cleanup efforts and contribute to a circular economy (Malik et al., 2023).

Problem Statement

Standard methods of synthesizing nanoparticles usually require toxic chemicals which have dangerous side effects. There is an increasing requirement to develop a green alternative that uses biological agents to create this alternative. That said, there are still issues that need to be worked on such as the reproducibility, stability, and large-scale production of these nanoparticles for their use in environmental remediation.

Significant of the Study

Nanoparticle synthesis using green methods proves to be less toxic, cheaper, and an environmentally friendly way to deal with pollution. As these methods rely on natural reducing as well as stabilizing agents, it generates less harmful waste while improving compatibility with living organisms. It can also be used for the remediation of contaminated water, air, and other pollutants, proving to be much more effective environmentally.

Aim of Study

The study intends to study the mechanism, characterization, and application of environmentally friendly synthesized nanoparticles and their ability to remediate the environment. This research attempts to determine the degree of effectiveness of these nanoparticles in the removal of heavy metals, degradation of organic pollutants, and microbial activities in order to prove nanotechnology as an alternative solution. Also, this research intends to solve the problems of stability, scalability, and toxicity in the development of green nanotechnology.

Green Synthesis as a sustainable approach for environmental remediation

The green approach for synthesizing nanoparticles using biological active agents like proteins, polyphenols, alkaloids, and flavonoids during the chemical reduction process is what green synthesis chemistry focuses on. In this, the metal precursor salts like chloroauric acid, zinc acetate, or silver nitrate are reduced in a redox reaction which forms nanoparticles. For instance, while using plant extracts to synthesize silver nanoparticles (*AgNPs*), the bioactive molecules in the extract participate in electron transfer, reducing Ag^+ to Ag^0 (Ghaffar et al., 2021).

$$AgNO_3 \rightarrow Ag^+ + NO_3^-$$

$$Ag^+ + \text{(reducing agent)} \rightarrow Ag^0 \text{ (nanoparticles)}$$

In a similar manner, the reduction of Au^{3+} ions from $HAuCl_4$ or chloroauric acid is also done with plant polyphenols to obtain gold nanoparticles (*AuNPs*) (Alprol et al., 2023).

$$HAuCl_4 + 3e^- \rightarrow Au^0 + 4Cl^-$$

When synthesizing zinc oxide (*Zn*O) nanoparticles, the reduction of Zn ions accompanied with the hydrolysis and condensation reactions happen to form the oxide.

$$Zn(CH_3COO)^2 + H_2O \rightarrow Zn(OH)^2 + 2CH_3COOH$$

$$Zn(OH)_2 \rightarrow ZnO + H_2O$$

The synthesized nanoparticles can be effectively utilized for eliminating pollutants. For example, silver and zinc oxide nanoparticles can photocatalytically degrade organic contaminants like methylene blue in UV and visible light.

$$MB + h\nu \rightarrow \text{Degradation products } (CO_2, H_2O, \text{etc.})$$

Moreover, Heavy metals can be adsorbed using metal nanoparticles like Fe_3O_4 by applying electrostatic forces and complexation.

$$Mn^{+} + Fe_3O_4 \rightarrow M - Fe_3O_4 \text{ (adsorbed complex)}$$

Switching hydrazine (N_2H_4) and sodium borohydride ($NaBH_4$) for bio-based reducing agents minimizes toxicity and energy usage while increasing biocompatibility and making the process greener. This approach is sustainable as it follows green chemistry principles, which allows for the environmentally friendly and cost-effective production of nanoparticles for managing pollution, purification of water, and removal of heavy metals (Alprol et al., 2023).

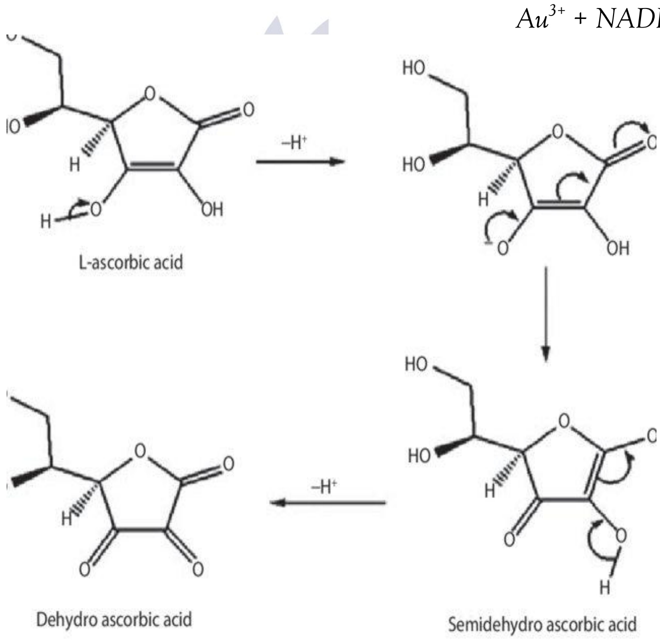
Mechanisms of Green Synthesis

Green synthesis of nanoparticles involves the use of biological agents such as plants, microbes, algae, and fungi, which serve as natural reducing and stabilizing agents. These organisms possess phytochemicals, enzymes, proteins, and secondary metabolites such as flavonoids, alkaloids, terpenoids, and polyphenols capable of reducing metal ions into nanoparticles (García-Quintero & Palencia, 2021). For example, in the plant mediated synthesis, silver nitrate ($AgNO_3$) is reduced by polyphenolic plant extracts to form stable silver nanoparticles (AgNPs). This reduction follows a general reduction mechanism:

$$Ag^{+} + \text{Phytochemicals} \rightarrow Ag^{0} + \text{Oxidized phytochemicals}$$

In a similar fashion, in microbial synthesis, biomolecules such as reductase enzymes are secreted to catalyze the reduction of the metal ions (Zulfiqar et al., 2024). In the bacterial or fungal mediated synthesis of gold nanoparticles (AuNPs), gold ions (Au^{3+}) are enzymatically reduced to initiate the formation of the nanoparticles:

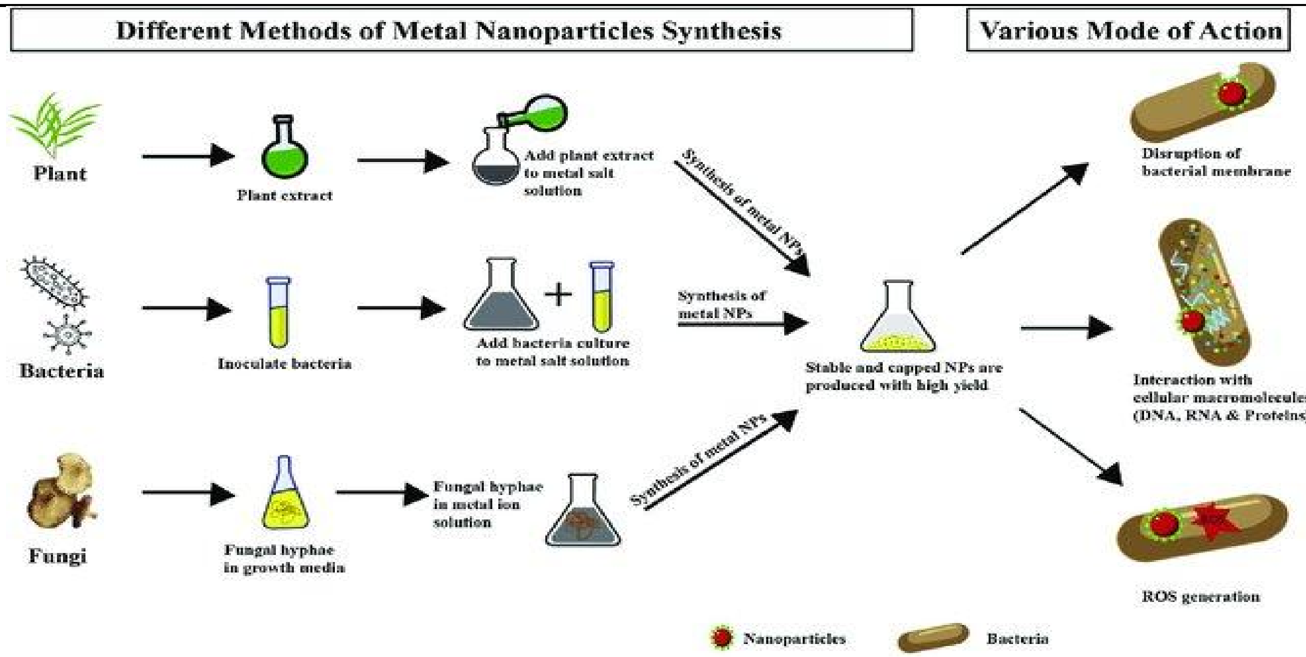
$$Au^{3+} + NADH \rightarrow Au^{0} + NAD^{+}$$



$$Zn^{+2} + 2e^{-} \longrightarrow Zn(0) + Air(O_2) \longrightarrow ZnO$$

Stabilization and capping of nanoparticles serve to agglomerate the particles, thus sustaining their size, shape, and disparity (Mahesh, 2024). Biological agents act as capping agents by coating the surface of the nanoparticles and thus increase their stability. Nanoparticles sourced from microbes serve as stabilizers through the proteins and polysaccharides while plants provide flavonoid and tannin steric stabilizers (Alprol et al., 2023). For example, ZnO NP_s are synthesized when zinc acetate reacts with plant flavonoids, causing reduction of Zn^{2+} and formation of stable ZnO NP_s:

$$Zn2^{+} + \text{Flavonoid} \rightarrow ZnO + \text{Oxidized flavonoid}$$



The green synthesis mechanism enables production of nanoparticles with reduced environmental consequences by avoiding the use of toxic chemicals while exploiting biological systems' chemical pathways (Shobana et al., 2025). It is noteworthy that the process is efficient, scalable, and results in the production of functionalized surfaces nanoparticles ideal for environmental remediation's heavy metal removal, pollutant degradation, and even antimicrobial activities (Nzilu et al., 2023).

Approaches in Green Synthesis of Nanoparticles

Bottom-Up Approach

In the green synthesis bottom-up approach self-assembling of atoms or molecules into nanoparticles is enabled through chemical or biological processes (Kumar et al., 2021). Hence, nucleation and controlled growth processes are utilized, which aid in facilitative processes through natural reducing and stabilizing agents such as plant extracts, microbial enzymes, and biomolecules. In green synthesis, Ag^+, Au^{3+}, or Zn^{2+} metallic precursor ions reduction is done through bioactive compounds in the form of flavonoids, phenolics, or proteins, which leads to the formation of nanoparticles. The reaction consists of several steps: reduction of metal ions, nucleation, and the growth and stabilization of the resultant particles (Rafique et al., 2021). As an illustration, in the use of plant extracts for the synthesis of silver nanoparticles, the polyphenols reduce nanoparticles of silver Ag^+ ions to Ag^0 and stable colloidal silver nanoparticles is produced. This method of synthesis is safe for our environment, as toxic reducing agents like sodium borohydride $NaBH_4$ have been eliminated (Ghaffar et al., 2021). This alone makes it a favorable option for nanomaterial production. The bottom-up approach facilitates better control of nanoparticle size, shape, and crystallinity, improving catalyzed environmental remediation, heavy metal adsorption, photo-catalysis, and pollution degradation (Kumar et al., 2021).

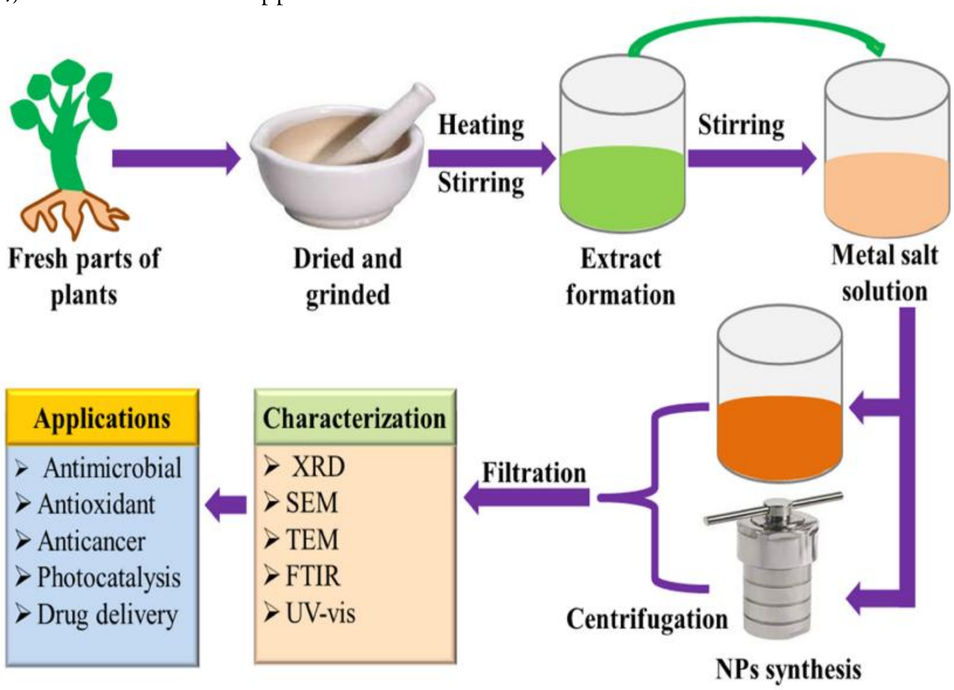
Top-Down Approach

A top-down strategy refers to the process of material synthesis that begins with bulk materials and converts them into nano-sized particles using mechanical, chemical, or physical processes. The top-down processes may comprise ball milling, laser ablation, and green assisted etching, which are already familiar for bulk metals or metal oxides decomposition into nanoparticles (García-Quintero & Palencia, 2021). Green synthesis incorporates biotechnological or eco-friendly approaches for greater sustainability. For example, in biogenic milling, nanoparticles are etched and refined using plant extracts or microbial metabolites to minimize the adverse effects associated with conventional top down approaches. A top-down method differs from the bottom-up strategy of nanomaterial synthesis where nanostructures are constructed atom by atom. In a top-down method (Zulfiqar et al., 2024), nanostructures are derived from a bulk structure by size reduction while keeping its physicochemical properties intact. It is easier to produce larger quantities of nanoparticles with this method, but it is harder to maintain uniformity and stability. Still, this technique is effective for generating functionalized nanomaterials for environmental uses such as water purification, heavy metal sequestration, and organic pollutants' biodegradable catalysis, which provide a sustainable method for the nanoparticle fabrication (Alprol et al., 2023).

Characterization of Green Synthesized Nanoparticles

Characterization of green-synthesized nanoparticles is crucial to gaining insights into their physicochemical characteristics, structural constituents, and associated functionalities (Nzilu et al., 2023). Several analytical methods are adopted to verify nanoparticle formation and evaluate their optical, morphological, and crystallographic properties. One of the foremost practices used to confirm nanoparticle synthesis is evaluating surface plasmon resonance (SPR) for which UV-Vis spectroscopy is often preferred (Mahesh, 2024). The surface appearance of nanoparticles during synthesis is indicative of their size and distribution. For example, silver nanoparticles (AgNPs) customarily exhibit a resonance absorption peak between 400-450nm, while gold nanoparticles (AuNPs) capture the attention between 500-600nm (Shobana et al., 2025). Fourier-transform infrared (FTIR) spectroscopy is another critical technique which assists in evaluating the functional groups responsible for the stabilization of the nanoparticles. The role biomolecules such as phenols, flavonoids, and proteins that aid in capping and stabilizing the nanoparticles is confirmed by the observation of characteristic peaks in FTIR spectra. The changes in position of peaks provides information on the interaction of molecules due to the presence of metal ions and the reducing agents during green synthesis (Tamboli et al., 2023).

A lot of researchers in these areas have also started using transmission electron microscopy (TEM) and scanning electron microscopy (SEM) in order to observe the planar and 3D features of the samples. In contrast to SEM, which provides lower magnification images, TEM is able to image particles at atomic resolution, thus enabling estimation of the nanoparticle's size, shape, and dispersion (Alprol et al., 2023).



In the case of SEM method, it provides the topographical and structural details to assess the presence of nanoparticle agglomerates or diplodocus uniformity in synthesis (Rafique et al., 2021). The assessment of nanoparticle crystallinity is done by X-ray diffraction analysis (XRD), which informs about the crystalline phase and purity of nanoparticles. The characteristic diffraction peaks were allocated to the specific lattice planes of metal nanoparticles, confirming their crystalline nature. For instance, strong diffraction peaks of silver nanoparticles at 2θ are 38.1°, 44.3°, 64.4°, 77.5° corresponding to FCC structure of Silver Metal (Nzilu et al., 2023). XRD patterns also help in determining the average crystallite size using Scherrer equation.

$$D=K\lambda / \beta\cos\theta$$

Where D is the crystallite size, K is the shape factor (commonly set to 0.9), λ is the X-ray wavelength, β is the full width at half maximum (FWHM) of center minus the diffraction peak, and θ is the Bragg angle. Dynamic light scattering (DLS) is used to assess the hyro-dynamic diameter of the nanoparticles in colloidal suspensions to further confirm size distribution and stability. DLS is particularly useful in determining particle size and poly-dispersity index (PDI), an index of size uniformity (Panhwar et al., 2021). High size homogeneity is indicated with lower PDI value. Furthermore, the analysis of zeta potential is carried out to measure surface charge and assess the stability of the nanoparticles; those exceeding a zeta potential of ±30 mV tend to have a high stability due to electrostatic repulsion suppressing aggregation (Kumar et al., 2021). These characterization techniques guarantee that the green synthesized nanoparticles have the necessary physicochemical properties for fabrication and environmental remediation, as well as biomedical and catalysis applications (Ghaffar et al., 2021).

Application in Environmental Remediation

Through the years, it has been observed that people have sought for green-synthesized nanoparticles due to its ability to single-handedly aid in recovering the environment, especially in cleaning heavy metals out of water (Tamboli et al., 2023). Several other known nanoparticles are silver *AgNPs*, Iron oxide Fe_3O_4 NP_s, and Zinc oxide *ZnO NPs*. These elements have proven to have the highest adsorption capacitive owing to the enormous surface area, high reactivity, and the presence of other metals bound to their surfaces making metal ion binding easier (Panhwar et al., 2021). The toxic and dangerous metals include lead Pb^{2+}, cadmium, and arsenic which are eliminated from water solutions by undergoing surface complexation, electrostatic interactions, and redox reactions. A good example would be Fe_3O_4 nanoparticles, the ones with carboxyl and amine groups (Mahesh, 2024). They bind with metals which help in the chelation process forming complex stables such as:

$$Fe_3O_4 - COO^- + Pb^{2+} \rightarrow Fe_3O_4 - COO\text{-}Pb$$

As the other biosynthesized silver nanoparticles possess the same features making them behave as efficient adsorbents, they tend to reduce pollution owing to ion-exchange and surface binding, thus making water purification safe and easier (García-Quintero & Palencia, 2021). These nanoparticles play a significant part of controlling air pollution as they serve as nano-catalysts helping in circumvention oxidation of chemical processes AOPs for gaseous pollutants. These active Titanium dioxide TiO2 and cerium oxide CeO2 nanoparticles photo-catalyze organic volatiles and nitrogen oxides NOx to non-hazardous or less toxic substances under ultra-violet or visible light (Alprol et al., 2023). The reaction of the catalytic TiO2 nanoparticles under UV light is:

$$TiO_2 + h\nu \rightarrow e^- + h^+$$

$$h^+ + H_2O \rightarrow {}^{\cdot}OH$$

$$\cdot OH + VOCs \rightarrow CO_2 + H_2O$$

The ideal candidate for purifying the air for long periods of time is these nanoparticles because they do not lose effectiveness in multiple reaction cylces, making them ideal for long-term usage. The destruction of complex organic structures arising from pollutants such as pharmaceuticals, synthetic dyes, and pesticides relies heavily on green-synthesized nanoparticles (Shobana et al., 2025). In the oxidative photo-degradation process, ZnO, CuO, and Fe203 nanoparticles serve the dual purpose of catalysts as well as being the main active parts for creating reactive oxygen species (ROS) such as hydroxyl radicals (˙OH) which, in turn, contribute to the breakdown of big structures into smaller constituents and hydroxyls capable of easily undergoing further decomposition (Alprol et al., 2023). The process of oxidation in color dyes for example methylene blue (MB) dye is performed by using.

$$MB + {}^{\cdot}OH \rightarrow \text{Degraded Products}$$

This breakdown of compounds not only assists the elimination of color from the waste water but also assists in the removal of toxic chemicals that are likely to harm living organisms in water (Zulfiqar et al., 2024). Hence, serving as a form of ecofriendly treatment. Green-synthesized nanoparticles lead to greater efficiency in these processes of degradation without inducing secondary pollution via traditional chemical processes.

$$AgNPs + O_2 \rightarrow Ag^{+} + \cdot O_2^{-}$$

$$\cdot O_2^{-} + H_2O_2 \rightarrow \cdot OH + O_2$$

Another contribution that significantly aids in the treatment of water is in the antimicrobial activity of [Ag] and [Cu] nanoparticles. The antibacterial action of these metals consists in breaking the internal and external membrane of pathogenic microorganisms by oxidative stress together with release of metallic ions resulting in destruction of the bacterial cells (Rafique et al., 2021). The action of such contaminations is based on the emission of active toxic forms of oxygen that attack proteins, fats, and other nuclei, represented by these toxic forms sap the oxidative stamina of bacterial cells and hence charging green-synthesized nanoparticles with great efficacy towards bacteria free previously discussed pathogens is easy such as E-coli (Panhwar et al., 2021), Pseudomonas Aeruginosa and Salmonella. Integrating them into filtration membranes and disinfection systems provides a clean, green water treatment option that is less harmful than traditional chlorine methods of purification (Kumar et al., 2021).

Advantages over the conventional Method

The green synthesis of nanoparticles saves a lot of time and money over the traditional physical and chemical methods since these are mostly based on the inexpensive biological resources that are non-toxic and renewable (Tamboli et al., 2023). The synthesis of nanoparticles typically depends on using lethal chemical reducing agents like sodium borohydride ($NaBH_4$) and hydrazine (N_2H_4) which are very toxic as well as dangerous due the environmental damage that they can cause with harmful byproducts. But in contrast, green synthesis uses plant extracts, microbial enzymes, and biopolymers for reduction and stabilizing processes and therefore, no chemicals that are hazardous are needed (Nzilu et al., 2023). Natural phytochemicals such as flavonoids, polyphenols, alkaloids, and others provide the reducing power to facilitate the formation of the nanoparticles through redox reactions:

$$\text{Flavonoid} + Mn^{+} \rightarrow M^{0} + \text{Oxidized Flavonoid}$$

Where M^{n+} denotes the metal ions that are in the form of zero valence level and thus can be classified as nanoparticles. This eco-friendly method assures that synthesis process is not only sustainable but also does not contribute to secondary pollution (Panhwar et al., 2021).

The green synthesis of nanoparticles is more affordable in economic terms due to the significant reduction in production costs (Mahesh, 2024). Now instead of additional costs, the money that used to go into process deeper into technology can be centered and used for more future innovations. The traditional methods make unnecessary and relaxed economical spends on high temperature evocation and impact for over destruction strongly to clean the rest of the money resource waste. But with these new ideas everything becomes very low, ultra-handle and easy energy use, also no specialized use of green means which delay impact in high environmental costs (Rafique et al., 2021).

For instance, the room temperature biosynthesis of silver nanoparticles (AgNPs) using plant extracts takes place biomolecules simultaneously perform the double function of reduction along with preventing agglomeration to ensure stable colloidal dispersions. The removal of poisonous reagents and highly energy consuming treatments renders the green synthesis economically competitive with conventional methods and suitable for large scale industrial use (Ghaffar et al., 2021).

Unlike chemically synthesized nanoparticles which often retain toxic residues, green synthesized nanoparticles encapsulating nontoxic biomolecules demonstrate remarkably low cytotoxic effects making them ideal for use in biomedical and environmental fields. The -OH, -COOH, and -NH2 functional groups from bio-molecular capping agents not only improve the stability of the nanoparticles, but also enable interaction with biological systems so they can be safely used in drug delivery, water purification, and antimicrobial coatings (Tamboli et al., 2023). These nanoparticles serve best for multiple applications without endangering human health or ecosystems due to the improved colloidal stability and controlled surface functionalization. One of the primary benefits of green synthesis is the extra waste disposed of because it is the usual concern in standard nanoparticle engineering (Rafique et al., 2021). Strong acids, alkalis, and organic solvents are frequently utilized in chemical synthesis methods, producing toxic leftovers that necessitate expensive waste disposal processes (Nzilu et al., 2023).

On the other hand, green synthesis creates biodegradable wastes that are safe to throw away and can be recycled in other industrial applications (Kumar et al., 2021). For example, the left over plant extracts from the synthesis of nanoparticles can be used as bio-fertilizers or as a means of inhibiting the growth of bacteria. The removal of harmful substances and byproducts that are toxic in nature is what unifies green synthesis and green chemistry. This guarantee's green chemistry's core concept of sustainability in the field of nanomaterial development (Alprol et al., 2023).

Challenges and Future Perspectives

The green synthesis of nanoparticles faces the challenge of reproducibility across multiple synthesis batches. Plant extracts, microbial cultures, and biopolymers are biological agents that contain complex and diverse mixtures of biomolecules (Panhwar et al., 2021). Variability in growth conditions, extraction methods, and seasonal changes can affect biomolecule class. These variations lead to inconsistencies in nanoparticle size, shape, and surface properties due to their effect on the reduction, nucleation, and stabilization processes (Alprol et al., 2023). In addition, the precise control over numerous synthesis parameters that need to be mastered makes the uniformity and predictability of the characteristics of the nanoparticles extremely challenging (Shobana et al., 2025). This is especially problematic for applications that require extreme rigidity, like catalysis and biomedicine. Development of a robust in situ monitoring system or optimization of reaction conditions and protocol standardization can help address the reproducibility issues by identifying key biomolecule responsible for reduction and capping (Nzilu et al., 2023).

An additional important restriction is the industrial applicability of green synthesis techniques. While lab-scale biological extracts synthesis is fairly simple, the challenge is enlarging the process and still retaining the nanoparticles' physicochemical properties (Zulfiqar et al., 2024). Issues in large scale production include batch-to-batch inconsistency, poor reaction yield, long synthesis time, and difficulties related to purification and separation. Conventional physical and chemical methods are relatively easy to implement because they are fast and yield a large amount of product, unlike green synthesis that takes longer and needs stabilization after reaction to prevent nanoparticles from merging (Ghaffar et al., 2021). Increasing the practicality of large scale production can be achieved by developing continuous flow bioreactors, optimizing reaction kinetics, and improving extraction methods for bio-reducing agents (Alprol et al., 2023).

Even though green nanoparticles are eco-friendly, their possible risks, toxicity, and application in biomedicine and environment systems are still of concern (Kumar et al., 2021). Plant and microbial origin synthesized nanoparticles are believed to be biocompatible, but the adverse biological interactions and the ecological consequences are not well known. Bioaccumulation, cytotoxicity, and ecological impacts are affected by the bio-functional groups on the surface, particle size, and surface charge (Mahesh, 2024). The introduction of nanoparticles in the land and water ecosystems could cause unknown biological consequences which require thorough toxicity analysis. In vitro and in vivo toxicological tests, computational models, and life cycle analyses are some of the advanced technologies needed to assess safety and set regulations for the use of these products (Shobana et al., 2025).

Further studies should attend to maximizing the effectiveness of green synthesis methods, augmenting the stability of nanoparticles, and increasing their actual and potential uses in different disciplines (Alprol et al., 2023). The combination of nanotechnology and AI or ML will enable predictive modeling and process optimization, making green synthesis processes more reproducible. The use of new biological materials, including extremophiles microorganisms and marine algae, can serve as more stable and functional thesauruses and capping agents (Alprol et al., 2023). In addition, hybrid green methods that integrate biological green methods with chemical ones could also be developed to provide options to some of the biological methods while being fully green. Solving these problems with interdisciplinary research and technological innovations will lead to viable nanotechnology options that consider environmental and industrial needs (García-Quintero & Palencia, 2021).

Conclusion

The environmentally friendly synthesis of nanoparticles is a promising solution in comparison to the synthetic methods which are both chemical and physical. This alternative is beneficial as it is inexpensive, environmentally friendly, and ideal for biological use especially in the field of environmental protection. Biological agents like plant extracts, microbes, algae, and fungi can serve as the reducing and stabilizing agents, and this eliminates the need for hazardous chemicals. Along with this, it ensures the production of nanoparticles with customized physicochemical properties. The use of environmentally friendly nanoparticles in the removal of heavy metals, destruction of organic pollutants, as well as in the purification of water and air illustrate their great potential in combating environmental pollution. Nevertheless, issues concerning stability, scalability, and possible toxicity can be detrimental in implementing these and need to be addressed. The further research in optimization of synthesis, toxicity evaluation, and their mass production will be impactful for the economic advantages of green nanotechnology and will help establish a sustainable future.

REFERENCES

Aigbe, U. O., & Osibote, O. A. (2024). Green synthesis of metal oxide nanoparticles, and their various applications. *Journal of hazardous materials advances*, *13*, 100401. Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., Eltaweil, A. S., Abd El-Monaem, E. M., ... & Yap, P. S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environmental Chemistry Letters*, *22*(2), 841-887.

Alprol, A. E., Mansour, A. T., Abdelwahab, A. M., & Ashour, M. (2023). Advances in green synthesis of metal oxide nanoparticles by marine algae for wastewater treatment by adsorption and photocatalysis techniques. *Catalysts*, *13*(5), 888.

Alprol, A. E., Mansour, A. T., El-Beltagi, H. S., & Ashour, M. (2023). Algal extracts for green synthesis of zinc oxide nanoparticles: promising approach for algae bioremediation. *Materials*, *16*(7), 2819.

Anees, A., Gupta, R., Phanindra, P. V., Fabiyi, O. A., Thera, U. K., Bello, T. T., & Ahmad, F. (2024). Green synthesis of nanoparticles and applications. In *Advanced Nanotechnology in Plants* (pp. 89-122). CRC Press.

Bhandari, G., Dhasmana, A., Chaudhary, P., Gupta, S., Gangola, S., Gupta, A., ... & Slama, P. (2023). A perspective review on green nanotechnology in agro-ecosystems: opportunities for sustainable agricultural practices & environmental remediation. *Agriculture*, *13*(3), 668.

Danish, M. S. S., Estrella-Pajulas, L. L., Alemaida, I. M., Grilli, M. L., Mikhaylov, A., & Senjyu, T. (2022). Green synthesis of silver oxide nanoparticles for photocatalytic environmental remediation and biomedical applications. *Metals*, *12*(5), 769.

El Messaoudi, N., Ciğeroğlu, Z., Şenol, Z. M., Kazan-Kaya, E. S., Fernine, Y., Gubernat, S., & Lopicic, Z. (2024). Green synthesis of CuFe2O4 nanoparticles from bioresource extracts and their applications in different areas: a review. *Biomass Conversion and Biorefinery*, 1-22.

García-Quintero, A., & Palencia, M. (2021). A critical analysis of environmental sustainability metrics applied to green synthesis of nanomaterials and the assessment of environmental risks associated with the nanotechnology. *Science of the Total Environment*, *793*, 148524.

Ghaffar, A., Kiran, S., Rafique, M. A., Iqbal, S., Nosheen, S., Hou, Y., ... & Aimun, U. (2021). Citrus paradisi fruit peel extract mediated green synthesis of copper nanoparticles for remediation of Disperse Yellow 125 dye. *Desalination and Water Treatment*, *212*, 368-375.

Jadoun, S., Arif, R., Jangid, N. K., & Meena, R. K. (2021). Green synthesis of nanoparticles using plant extracts: A review. *Environmental Chemistry Letters*, *19*(1), 355-374.

Kaur, M., Gautam, A., Guleria, P., Singh, K., & Kumar, V. (2022). Green synthesis of metal nanoparticles and their environmental applications. *Current Opinion in Environmental Science & Health*, *29*, 100390.

Kumar, S. A., Jarvin, M., Sharma, S., Umar, A., Inbanathan, S. S. R., & Lalla, N. P. (2021). Facile and green synthesis of MgO nanoparticles for the degradation of victoria blue dye under UV irradiation and their antibacterial activity. *ES Food & Agroforestry*, *5*(12), 14-19.

Mahesh, B. (2024). A comprehensive review on current trends in greener and sustainable synthesis of ferrite nanoparticles and their promising applications. *Results in Engineering*, *21*, 101702.

Malik, A. Q., Mir, T. U. G., Kumar, D., Mir, I. A., Rashid, A., Ayoub, M., & Shukla, S. (2023). A review on the green synthesis of nanoparticles, their biological applications, and photocatalytic efficiency against environmental toxins. *Environmental Science and Pollution Research*, *30*(27), 69796-69823.

Malik, A. Q., Mir, T. U. G., Kumar, D., Mir, I. A., Rashid, A., Ayoub, M., & Shukla, S. (2023). A review on the green synthesis of nanoparticles, their biological applications, and photocatalytic efficiency against environmental toxins. *Environmental Science and Pollution Research*, *30*(27), 69796-69823.

Nguyen, N. T. T., Nguyen, L. M., Nguyen, T. T. T., Tran, U. P., Nguyen, D. T. C., & Van Tran, T. (2023). A critical review on the bio-mediated green synthesis and multiple applications of magnesium oxide nanoparticles. *Chemosphere*, *312*, 137301.

Nzilu, D. M., Madivoli, E. S., Makhanu, D. S., Wanakai, S. I., Kiprono, G. K., & Kareru, P. G. (2023). Green synthesis of copper oxide nanoparticles and its efficiency in degradation of rifampicin antibiotic. *Scientific reports*, *13*(1), 14030.

Panhwar, S., Buledi, J. A., Mal, D., Solangi, A. R., Balouch, A., & Hyder, A. (2021). Importance and analytical perspective of green synthetic strategies of copper, zinc, and titanium oxide nanoparticles and their applications in pathogens and environmental remediation. *Current Analytical Chemistry*, *17*(8), 1169-1181.

Rafeeq, H., Hussain, A., Ambreen, A., Waqas, M., Bilal, M., & Iqbal, H. M. (2022). Functionalized nanoparticles and their environmental remediation potential: a review. *Journal of Nanostructure in Chemistry*, *12*(6), 1007-1031.

Rafique, M. A., Kiran, S., Javed, S., Ahmad, I., Yousaf, S., Iqbal, N., ... & Rani, F. (2021). Green synthesis of nickel oxide nanoparticles using Allium cepa peels for degradation of Congo red direct dye: an environmental remedial approach. *Water Science and Technology*, *84*(10-11), 2793-2804.

Samuel, M. S., Ravikumar, M., John J, A., Selvarajan, E., Patel, H., Chander, P. S., ... & Chandrasekar, N. (2022). A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. *Catalysts*, *12*(5), 459.

Shobana, N., Prakash, P., Samrot, A. V., Saigeetha, S., Dhiva, S., Thirumurugan, A., ... & Abirami, S. (2025). Natural biopolymer mediated green synthesis of silver nanoparticles and its applications in environmental remediation. *Biomass Conversion and Biorefinery*, *15*(1), 531-544.

Sonawane, S. S., Thakur, P. P., Malika, M., & Ali, H. M. (2023). Recent advances in the applications of green synthesized nanoparticle based nanofluids for the

ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 3, Issue 3, 2025

environmental remediation. *Current Pharmaceutical Biotechnology*, *24*(1), 188-198.

Tamboli, Q. Y., Patange, S. M., Mohanta, Y. K., Sharma, R., & Zakde, K. R. (2023). Green synthesis of cobalt ferrite nanoparticles: an emerging material for environmental and biomedical applications. *Journal of Nanomaterials*, *2023*(1), 9770212.

Ying, S., Guan, Z., Ofoegbu, P. C., Clubb, P., Rico, C., He, F., & Hong, J. (2022). Green synthesis of nanoparticles: Current developments and limitations. *Environmental Technology & Innovation*, *26*, 102336.w

Zelekew, O. A., Haitosa, H. H., Chen, X., & Wu, Y. N. (2023). Recent progress on plant extract-mediated biosynthesis of ZnO-based nanocatalysts for environmental remediation: Challenges and future outlooks. *Advances in Colloid and Interface Science*, *317*, 102931.

Zulfiqar, Z., Khan, R. R. M., Summer, M., Saeed, Z., Pervaiz, M., Rasheed, S., ... & Ishaq, S. (2024). Plant-mediated green synthesis of silver nanoparticles: synthesis, characterization, biological applications, and toxicological considerations: a review. *Biocatalysis and Agricultural Biotechnology*, 103121.