Advancements in Green Chemistry: Strategies for Sustainable Nanoparticle Synthesis and Environmental Impact Reduction

Ms. Hitendra Kaur Sidhwani[1], Dr. Preeti Jain[1]

Department of Chemistry, Medi-Caps University, Pigdamber, Rau, Indore-453331, Madhya Pradesh, India Email: hitendrak.sidhwani@medicaps.ac.in, preeti.jain@medicaps.ac.in

Abstract
Chemistry plays a pivotal role in enhancing the quality of human life, whether it is in the field of environmental science, pharmaceuticals, polymer industry, agriculture, or material science. Every domain of research has a responsibility to adopt sustainable practices due to its significance in environmental footprint. This review explores the latest developments in green chemistry with respect to the synthesis of nanoparticles, due to their importance in various fields such as biomedical, agriculture, electronics, pharmacy, drug delivery, diagnostics, bioremediation, theragnostic, etc. It also highlights green route strategies aimed at boosting sustainability and minimizing harmful environmental impact during the synthesis of nanoparticles and nanocomposites. Key areas of focus include innovative green synthetic methods, such as the use of green solvents, sustainable or renewable resources for synthesis, and energy-efficient technologies. Further, the role of nanoparticles synthesized via green synthetic route, is examined for their contributions to more sustainable research. Additionally, the review explores various ways of reducing the use of harmful chemicals, and presents a summary of their successful practical implementations. Lastly, the various applications of green synthesized nanoparticles are summarized. This review aims to offer a thorough overview of how green chemistry is transforming synthesis of nanoparticles, offering insights into both current achievements and future opportunities for enhancing sustainability in this critical sector.
Keywords:
Green synthesis, Nanoparticles, Nanotechnology, Synthesis methods, Nanoparticles applications

1. Introduction

The concept of "Green Chemistry" introduced by "Paul Anastas and John Warner" aims to promote eco-friendly chemical processes and products.[1], [2], [3] It consists of the designing of chemical routes and procedures, for reduction or removal of the use of harmful chemicals and generation of harmful products and by-products. Recently, green chemistry has attracted considerable attention because of its emerging application in nanotechnology. This concept, has facilitated development of functional nanomaterials with minimal waste. By utilizing greener approaches, such as the use of renewable resources, researchers have discovered effective reducing agents, capping agents and solvents that can be used for carrying out the synthesis via a green route. The most important and key step in synthesis is selection of stabilizing agent/capping agent/ reducing agent and the solvent.[4] Stabilizing agent or capping agents are the compounds that prevent the aggregation or coagulation of the nanoparticles during their synthesis thereby stabilizing them and inhibiting their over growth. These are responsible for stabilization of the interface between nanoparticles and their medium of synthesis. Reducing agents are the chemical compounds responsible for reduction of ionic species/salt during nanoparticle synthesis. These can be either a chemical agent such as $NaBH_4$, DMSO; a plant extract; a biological agent or some irradiation source.

Nanoparticles have gained significant attention these days because of their distinctive properties that differ from their bulky counterparts. These particles have their dimension in the range of 1-100 nm (1nm=10^{-9}m). Due to their minute size, these particles possess large surface area-to-volume ratio. This in turn is responsible for its extremely high reactivity, exceptional physiochemical, optical, mechanical, optical, catalytic properties. Their transformative role in everyday life in different domains cannot be overlooked. They have a vast contribution in fields such as medical-target drug delivery,[5] improved diagnostics,[6] catalyzing various chemical reaction,[7] environment remediation like water purification,[8] pollution control,[9] consumer products like advanced cosmetics, production of sunscreen glasses,[10] automobile industries,[11] enhancements in energy storage,[12] agriculture,[13], [14] construction[15] etc. With advancements in research, the potential of nanoparticles continues to grow. There are different ways in which nanoparticles can be synthesized. Conventionally, their synthesis can be broadly categorized under two approaches: Top-Down approach and Bottom's up approach.[16], [17] In top-down approach, the synthesis starts from a bulky source that is reduced to the size of particles in nanometer range. Bottom's up approach assembles single atoms and molecules into larger nanostructures. Both these approaches either involve a physical method (like Milling, Arc discharge, Thermal/Laser Ablation, Sputtering, etc.) or chemical method (like Condensation, Vapor deposition, Electrochemical deposition, Spray pyrolysis, Sol-gel method, Chemical etching, co-precipitation)[18], [19] (Figure_1). The major limitations of these processes are: 1) Utilization of toxic chemicals, 2) Generation of harmful by-products, 3) High energy consumption during the process.[17] Thus, focus on biological or green routes of synthesis is gaining traction. These methods make use of renewable or environmental-friendly sources such as plants[20], or microbial synthesis using fungi,[20] algae,[21] bacteria,[22] and yeast.[23] These biological sources are called "biofactories" which are used either intracellularly (i.e. within the cell) or extracellularly (i.e, outside the cell; non-cellular component), for the synthesis of nanoparticles.[24] The metabolites present naturally in these sources fulfill the purpose of stabilizing/capping agent and also as reducing agent. This minimizes the use of chemicals that are added additionally as reducing and stabilizing/capping agent.[25]

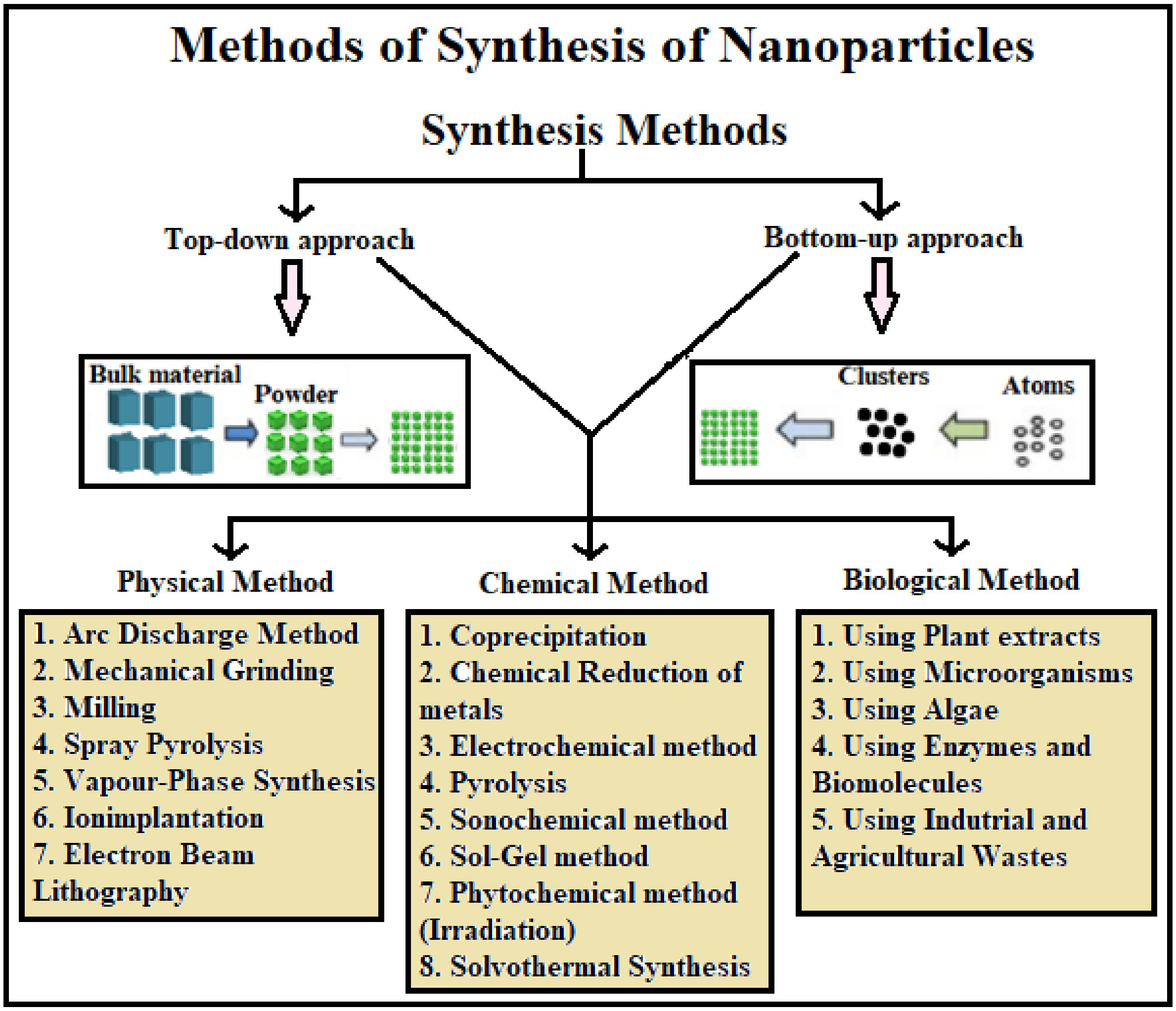

Figure_1: Methods for Nanoparticles Synthesis

Over the past few decades, various nanoparticles have been identified and studied for their potential applications. Based on the composition, these particles can be either inorganic nanoparticles such as metal and metal oxide nanoparticles, organic nanoparticles like polymers, dendrimers, micelles, ferritin, liposomes, etc. or carbon-based nanoparticles such as fullerenes and quantum carbon dots. Inorganic nanoparticles have distinctive properties such as hydrophilic nature, non-toxicity, biocompatibility and also higher stability than organic nanoparticles.[26], [27], [28] Their distinct properties enable them to be used in imaging and diagnosis (medical), optical sensors, polymer composites.[29], [30], [31], [32] Organic nanoparticles are non-toxic and biodegradable in nature, but are susceptible to thermal and electromagnetic degradation. Most common area of application of organic nanoparticles is thus for target drug delivery[26] and cancer therapy.[33] Carbon based nanoparticles due to their unique shape and diverse properties are utilized in various sectors. They hold a potential application in energy storage and production, waste treatment, water treatment, biological fields, etc.[10] All these have been thoroughly researched for their properties and other possible applications.

2. Green Synthesis of Nanoparticles

Green synthesis means synthesis of nanoparticles using a biological route. This synthesis can be mediated by using aqueous extracts from plant materials, bacteria, fungi, algae, or yeast. This area has been widely explored by researchers for carrying out nanoparticle synthesis due to their advantages, such as their eco-friendly nature, cost efficiency of the overall process, biocompatibility, feasibility and better control on size and uniformity.[34] Ghorbani et. al. [35] explored different biological route and non-biological routes for synthesizing silver nanoparticles. The researchers tried to enlist the advantages and disadvantages in selection of biological and non-biological routes.[35]

Numerous literature sources[34], [36], [37], [38], [39] have elaborated on the attempts made for synthesizing nanoparticles in biofactories a summary of which has been described in this review.

2.1 Synthesis using plants and their extracts

The synthesis of nanoparticles using plants (Figure_2) involves the use of aqueous plant extract as a reducing and stabilizing/capping agent and a metallic salt solution. Various metal-based nanoparticles have been synthesized using this approach[40]. Siti et. al. explored the use of plant extract via microwave assisted method for producing silver nanoparticles.[41] This study leverages the waste from pineapple leaves, which are typically discarded, as a natural reducing and stabilizing agent during the synthesis process. Ag nanoparticles (AgNPs) were synthesized by reduction of silver nitrate ($AgNO_3$) using aqueous leaf extract as source of reducing and capping agent. 4 mL leaf extract was used and optimal concentration of silver nitrate required for the formation of Ag nanoparticles was investigated by altering its concentration from 5 to 25 mM. Effect of variation in different parameters such as incubation time, sample volume was also studied along with effect of varying concentration of silver nitrate. Formation of the silver nanoparticles was confirmed using UV-Visible spectrophotometer, Fourier- transform infra-red Spectroscopy (FTIR), Field Emission Scanning Electron Microscopy (SEM), X-Ray diffraction (XRD). The synthesized AgNPs demonstrated antimicrobial activity against E. coli, B. subtilis, and S. aureus, with a minimum inhibitory concentration of 60 µg/mL for bacterial growth, serving as a promising alternative to antiseptic agents in pharmaceutical field.[41] In yet another study, dragon fruit peel extract was used for the synthesis of silver nanoparticles. The formation of particles was confirmed by spectroscopic techniques and XRD. The information about the charge on the surface of the particle and their stability in solution was furnished by zeta potential values. Zeta potential values are the measure of the magnitude of electrostatic attraction or repulsion between the particles in a dispersed system.[42] Shashank Shekhar et al. synthesized titanium oxide nanoparticles using leaves' extract from Azadirachta Indica (commonly known as neem tree).[43] X ray studies confirmed the formation of polycrystalline titanium oxide nanoparticles. SEM furnished the data concerning the shape and size of the particles and elucidated that the phytochemicals present in plant extract worked as capping agent for stabilizing the particles. Further, a number of studies prove that flavonoids and alkanoids present in plant extract work as reducing and capping agent respectively during formation of nanoparticles.[30], [37], [44]

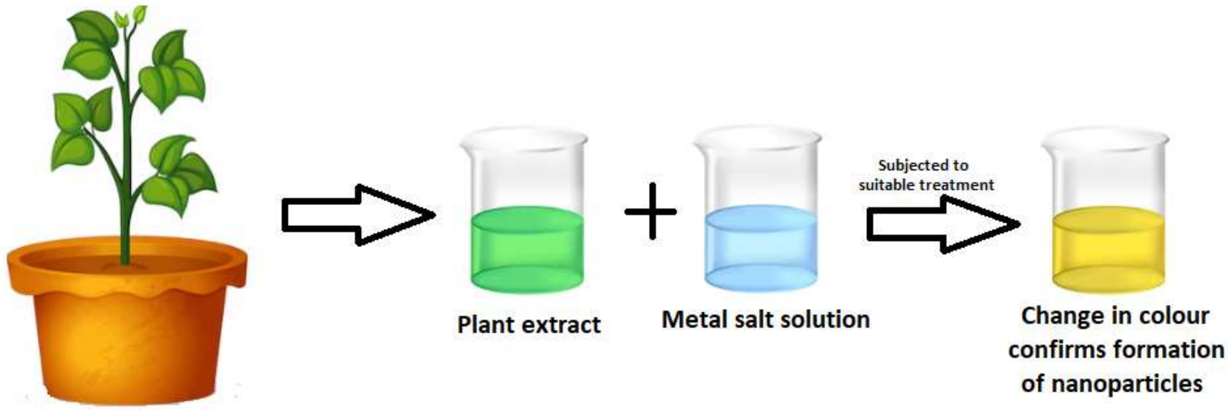

Figure_2: Overview of nanoparticles synthesis using plant extract

2.2 Microbial synthesis of nanoparticles

Biological agents such as yeast, fungi, bacteria and algae have extensively been used as biofactories for the nanoparticle's synthesis. Numerous studies elaborate various attempts made for synthesis using these biofactories. These biofactories serve as a cleaner, non-toxic and environment-friendly method for synthesizing nanoparticles with high biocompatibility. These biological entities function as templates for stabilization of nanostructures produced. The natural polymeric compounds (biopolymers) present in the cells of these biofactories, prevent the aggregation of nanoparticles produced. A study conducted by Riti T. Kapoor et al.[45] enlists various metallic nanoparticles synthesized via microbial route and their possible mechanism of synthesis. Their review elaborately discusses the synthesis of metallic nanoparticles using marine microorganisms, virus, actinomycetes, bacteria,[22] algae,[46] yeast[23], and fungi[47] along with the conditions and method of synthesis. It also discusses areas of applications of biogenic nanoparticles. Jaison Jeevanandam et al.[48] published their findings on synthesis of metal and metal oxide nanoparticles using microbial extracts emphasizing the advantages of biological routes over conventional synthetic routes. The authors reported that the biomolecules and phytochemicals present in microbes and plants respectively are the active compounds work as stabilizing and reducing agents during synthesis of nanoparticles via greener route. Their study implies that greener biosynthetic methods can significantly energy inputs and production costs in comparison to the traditional routes of synthesis. They also identified various plant and microbial sources that can work as effective reducing and stabilizing agents for nanoparticle synthesis. Bhupendra Koul et al.[49] described the synthesis of silver, gold, nickel nanoparticles using species of bacteria's such as *Bacillus sp.*, *Pseudomonas sp., Acinetobacter sp., etc.* Extracellular and intracellular fabrication strategies of microbial synthesis of nanoparticles have been discussed. In the intracellular process, metal ions are absorbed by microbial cells and transformed into nanoparticles (NPs) by cellular enzymes within the cells. In contrast, during the extracellular process, metal ions are captured on the cell surface, where cellular enzymes reduce them to create NPs outside the cells. Vast literature survey[49] of the attempts made so far, based on these strategies have been discussed.

The plant-based method, in comparison to the microbial synthesis, offers a significant advantage, as it avoids the need for separate, complex procedures like isolation, development and preservation of culture. Additionally, it is quicker, cost-effective and easier for scaling up to manufacture the nanoparticles in bulk.[50], [51]

3. Choice of reducing agent, capping agent and solvent for synthesis

3.1 Reducing agent

In the bottoms'-up approach, nanoparticles are formed through nucleation and growth processes. The initial step involves reducing the metal ion precursors using a reducing agent. This process is called as reduction reaction. It initiates the nucleation of metal atoms and subsequently promotes the growth of these nuclei into metal nanoparticles. Hydrazine, amino borane complexes,[52], [53] sodium borohydride,[54] dimethyl sulfoxide,[55] formaldehyde,[24] etc. are commonly used reducing agents in synthesis of nanoparticles. Owing to their toxicity concerns, these can be substituted by less hazardous reducing agents such as sodium citrate, polysaccharides, vitamin C, citric acid, ascorbic acid[56] etc. These reducing agents are mild, cost effective and non-toxic in nature.

3.2 Capping agent

Capping agents play a very crucial role in nanoparticles synthesis as the stability of particle is dependent on them. These are basically amphiphilic molecules with a polar head and a non-polar tail. The polar head coordinates with the metal atoms of the nanocrystals, whereas the tail interacts with the surrounding medium. Commonly employed capping agents include ionic and non-ionic surfactants and polymers. The assembly of nanoparticles is facilitated by various forces, such as Van der Waals interactions, capillary forces, surface tension, hydrophobic interactions, and hydrogen bonding.[46] Capping agents are used during colloidal synthesis (involves dispersion of solid in liquid medium resulting in formation of a colloidal solution) to control the morphology of the particle and also to prevent its aggregation, once it is formed. Utilization of non-toxic and energy efficient capping agent, thus is an important step towards green revolution. Long chain hydrocarbons with heteroatoms, such as oleic acid, linoleic acid, oleyl amine, etc. work as a great capping agent due to strong binding with nanoparticles, but are less eco-friendly.[24] A disadvantage of capping agent is that extensive procedure is required for its removal while extraction of the desired nanoparticle. Thus, instead of using such capping agents, other agents such as polymers, dendrimers, polysaccharides can be used.[24] The polymers can bind weakly with synthesized nanoparticles, thereby reducing the complexities of cleaning of capping agent for extraction of nanoparticles. Dendrimers, highly branched macromolecules can help in controlling size distribution of synthesized nanoparticles.[24] Polysaccharides, being water soluble can act as a potential capping agent, in presence of water as a solvent.[24] The weak interaction of polysaccharides with nanoparticles, facilitate easy removal of capping agent post production. This makes the process more energy efficient.[24]

3.3 Solvent

Selection of correct solvent is one of the most vital aspects in synthesis of nanoparticles. The ideal solvent for synthesis via green route should be non-toxic. In this regard, water can be considered as the most ideal solvent. Due to its wide availability, universal solvent properties and high dielectric constant, water is the most preferred solvent in green synthesis of nanoparticles. It is the preferred choice where solubilization of polar compounds is considered.[57], [58], [59] It also plays a crucial role in nucleation and growth phases of synthesis of nanoparticles.[57], [58], [59] Literature suggests use of other eco-friendly solvents as well like ionic liquids, supercritical fluids, eutectic solvents, etc.[60], [61] Other commonly used green solvents are ionic liquids and supercritical liquids. Ionic liquids are composed of ions that have melting points less than 100°C. Advantages of using ionic solvents as secondary solvents, for the sub phases of synthesis are: 1) good solubility for metal catalysts and polar organic compounds, thereby supporting biocatalysts, 2) work over wide temperature range due to constructive thermal stability, 3) modulation in

solubility properties feasible by change of ions associated with them, 4) do not evaporate easily, 5) possess dual functionality.[57] Supercritical fluids are highly compressed fluids possessing combined properties of liquids and gases. These possess densities equivalent to liquids and diffusion equivalent to gases. They have also contributed significantly to the nanoparticle's synthesis. K. Byrappa et al.[62] reported use of supercritical fluids for the synthesis of metal and metal oxide nanoparticles. Supercritical carbon dioxide (CO_2) is another universal solvent for synthesis of nanoparticles. It can either be used in liquid form or in the form of supercritical CO_2. It exists in a gaseous state at lower pressures and can turn into a liquid upon increasing the pressure. When subjected to a temperature of 31°C and pressure of 7.38 kPa, it forms a supercritical fluid.[60] Supercritical water (sc H_2O) and supercritical CO_2 are most commonly employed supercritical fluids for nanoparticle synthesis.[24]
Further, Eutectic solvents can be a good alternative for ionic solvents. These solvents are formed by mixing two or three components bonded by a hydrogen bond. The final eutectic mixture has melting temperatures lower than the individual components from which it is formed. It has a donor and an acceptor of hydrogen bond.[63] Owing to their cost effectiveness, biodegradability, non-toxic nature and easy synthesis, various attempts have been made for their use as green solvent in synthesizing nanoparticles. Dr. Hong-Gang Liao et al.[64] reported using deep eutectic solvent (DES) for synthesis of gold nanoparticles. DES are mixtures of Lewis/Bronsted acids and bases that can form a eutectic mixture. It can be composed of different types of cations or anions. In another study by Ying Huang et al.,[65] cuprous chloride (CuCl) nanoparticles were synthesized using eutectic solvent. Lorenzo Gontrani et al.[66] have described the synthesis of zinc oxide nanoparticles using deep eutectic solvents. The list of other common green solvents for synthesis is represented in Figure_3.

Figure_3: Choice of Green Solvents

4. Applications of nanoparticles

Green synthesized nanoparticles are gaining significant attention due to their potential in contribution to wide-range of applications. From water treatment[67], [68] to agriculture[30], [69],

[70] and medicinal field,(Balan et al., 2016; Haseeb et al., 2017) reinforcement for composites,(T. Mishra et al., 2022) their sustainable role is very well studied. Few important applications, aligning towards sustainability and achieving green chemistry goals are discussed below:

4.1 Antimicrobial activity: Several research groups have explored the antimicrobial property of nanoparticles.[22], [73], [74], [75] Studies carried out by L. Wang et. al.[73] suggested use of nanoparticles against traditional antibiotics for targeting bacteria. Excessive use of antibiotics has led to emergence of bacterial strains with multi-drug resistance.[73] The exact antibacterial mechanism of nanoparticles is yet to be explored. The most accepted mechanism includes oxidative stress, releasing metal ions, and employing non-oxidative methods.[73] Because these multiple mechanisms act simultaneously against microbes, developing antibacterial resistance would necessitate several concurrent gene mutations within the same bacterial cell. This makes it challenging for bacteria to become resistant to NPs. A number of other studies have reported synthesis of metal nanoparticles possessing antibacterial, antifungal, antiviral activity. For example, Jain et al.[76] and Ahmed et al.[77] reported antimicrobial activity of green synthesized nanoparticles. In another study carried out by S. kazemi et al.[78] antimicrobial activity of various metal and metal oxide nanoparticles, like iron nanoparticles (FeNPs), selenium nanoaprticles (SeNPs), zinc oxide nanoaprticles (ZnONPs), cuprous oxide nanoparticles (CuONPs), titanium dioxide nanoparticles (TiO_2NPs) were elaborated. B. Buszewski et. al.[79] synthesized biogenic AgNPs using an actinobacteria strain and studied its antimicrobial properties. They observed synergistic effects when biogenic silver nanoparticles were used in combination with ampicillin, tetracycline, against *K. pneumoniae*, *S. aureus*, and *P. aeruginosa.* Maiti et. al.[80] synthesized silver nanoparticles via green synthetic route. The synthesized particles were tested for their antimicrobial activity against E. coli strain of bacteria at varying concentrations of 0.2 to 100 μg/ml. With increase in concentration of AgNPs, the bacterial concentration was found to decrease. The growth of bacteria was completely inhibited at a concentration of 50 μg/ml.

4.2 Agriculture: The use of nanoparticles, particularly those synthesized via green routes, has garnered significant attention in recent years for their contribution in the sustainable development of agriculture. They have provided a means of replacing or reducing use of harmful chemicals for enhancing growth of crops,(Zheng et al., 2005) insect and pest management,(Jiang et al., 2022) increasing shelf life of the produce, preventing plant disease,(Jiang et al., 2022) improving the yield,[82] and quality of the produce.[70] Zheng et. al.[69] compared the effect of titanium oxide nanoparticles (TiO_2 NPs) and bulk TiO_2 on growth and development of Spinacia oleracea seeds. The seeds treated with the NPs resulted in higher rate of photosynthesis, enhanced chlorophyll a content, and 73% increase in dry weight. With decrease in size of the nanoparticles, the rate of germination was found to improve. Optimal concentration of NPs required for growth promotion was identified. Y. Jiang et. al.[81] reviewed the synthesis of metal-based nanoparticles and summarized their use in field of agriculture. Use of metal NPs for seed priming, alleviating heavy metal stress, antibacterial agents, plant growth have been summarized.

Afzal et. al.[82] synthesized iron oxide nanoparticles (FeONPs) using flower extracts of *Cassia occidentalis L.* and studied their use for promoting rice seed germination, whereby the total soluble sugar content was found to increase by 24% in the seedings as compared to the untreated seedings. Rice seeds primed with FeO NPs at concentration of 20mg/L and 40mg/L showed a significant improved seed germination and vigor. The study was compared to priming with ferrous sulphate ($FeSO_4$) and hydro-primed control. Seeds treated with 20mg/L NPs also exhibited 50% increase in biophysical factors like root length and dry weight. In a study, Kasote et. al.[83] synthesized iron nanoparticles (FeNPs) using onion extract. They studied the impact of seed priming with varying concentrations of FeNPs such as 20mg/L, 40mg/L, 80mg/L and 160mg/L on growth parameters, photosynthetic pigments and metabolites profile of watermelon seeds (*Citrullus lanatus*). The findings suggests that FeNPs treatment enhance antioxidant potential and also induce jasmonic acid related defense mechanism in watermelon seeds. The treatment also modulated the OPDA 12-oxo phytodienoic acid (OPDA) level in watermelon seedlings. OPDA accumulates under stress condition and promotes seed dormancy. FeNPs priming helps to break seed dormancy and promote growth. The level of OPDA decreases with increase in concentration of FeNPs priming treatment.

Phosphorus, as essential element for plant growth, is available in soil but at times in form that cannot be utilized. Use of nanoparticles for improving this uptake have received tremendous attention in recent years. Sana Ullah et. al.[84] investigated impact of titanium oxide nanoparticles (TiO_2 NPs) on phytoavailable phosphorus in soil. The study revealed a significant increase of 63.3% in plant available phosphorus on treatment with 50mg/kg of TiO_2 NPs. The treatment also enhances root and shoot length by 63 and 26%. In another study, Pratibha Acharya et. al.[85] synthesized silver (AgNPs) and gold (AuNPs) suing onion extract. Their study compared the impact of synthesized nanoparticles on seed germination, emergence and growth of onion seeds with unprimed (i.e. untreated seeds, control) and hydroprimed seeds (i.e. water-soaked seeds, followed by drying to control germination metabolism). Primed seeds showed a significant change in emergence % in comparison to the control. There was an increase of 23.9% in average yield in treated onion in comparison to the unprimed ones.

Nanoparticles are also known to regulate the expression of genes related to hormone synthesis in plants. Wu et. al.[86] reported that nanoparticles can improve the plant antioxidant system effectiveness. They can also eliminate excess reactive oxygen species (ROS), thereby alleviating stress and supporting biological growth. Their study demonstrates use of cerium oxide nanoparticles (CeO_2) nanoparticles for scavenging ROS and enhancing chloroplast photosynthetic performance in *Arabidopsis thaliana* plant.[86]

4.3 Treatment of wastewater: Use of nanoparticles for treatment of wastewater is yet another widely explored domain. Material scientists have reported their use for the degradation of dyes and heavy metals present in wastewater, thereby improving the quality of water. Chanchal Das et al.[67] synthesized magnetite nanoparticles (Fe_3O_4NPs) using *Jatropha curcas* latex and *Cinnamomum tamala* leaves, and studied its effect on wastewater treatment and for dye adsorption. K. Rambabu et al.[68] synthesized zinc oxide (ZnONPs) nanoparticles using waste of *Phoenix dactylifera* (date palm fruit) and studied its dye degradation properties in wastewater treatment.[68] Photocatalytic degradation of hazardous dyes, methylene blue and eosin yellow was studied. With use of ZnONPs, 90% degradation efficiency was achieved. The synthesized particles were also studied for their antibacterial property against pathogenic bacteria. They showed strong antibacterial property, evidenced by disc assay. Thus, these can be a potential candidate for treatment of wastewater.

Ramakrishnan et. al.[87] used *Ocimum tenuiforum* leaf extract for the synthesis of silver nanoparticles. Degradation of sulforhodamine B, an organic carcinogen, was studied in dark, using the synthesized silver nanoparticles. The synthesized particles were found to be stable for a period of two months from the date of synthesis. Their degradation activity against Rhodamine dye was also explored and was found to be effective.[87] Yazdi et. al.[88] synthesized silver nanoparticles using shoot of H. graveolens. In this work, the researchers evaluated AgNPs for treatment of wastewater. They demonstrated significant capacity of AgNPs for removal of pollutants comprising of heavy metals and organic contaminants. Photocatalytic activity of AgNPs was estimated through degradation study of methyl orange under visible light.[88]

Katata-Seru et. al.[89] used moringa oleifera leaves and seeds for the synthesis of iron nanoparticles (FeNPs). A comparative study was carried out for removal of nitrate ions from surface water and ground water using the prepared nanoparticles. A water-soluble substance present in seeds of moringa oleifera makes it an ideal candidate for water treatment due to its coagulation properties. Results showed that the removal efficiency increased at lower pH value. The efficacy of (moringa oleifera seed-MOS) MOS-FeNPs outperforms the MOS extract alone, achieving a removal rate of 85% compared to 43% for MOS. (Moringa oleifera leaves-MOL) MOL-FeNPs exhibited a lower removal efficiency of 26% for groundwater and 70% for surface water. Overall, MOS-FeNPs demonstrated promising potential for treating NO_3^- contaminated water, suggesting that both MOS-FeNPs and MOL-FeNPs could be effective alternatives for various aqueous media.[89]

Punia et. al.[90] made a detailed comparison of different nanoparticles that have been so far used for the removal of organic contaminants and heavy metals on the basis of removal efficiency, pH, temperature, optimal concentration of the nanoparticles required and exposure time. A detailed comparison of efficacy of various nanoparticles (such as ZnO, TiO_2, SiO_2, MgO, Ag, $CoFe_2O_4$ & $NiFe_2O_4$ etc.) for removal of different pathogens was also done.[90]

4.4 Biomedical applications: Various studies carried out by researchers suggests use of nanoparticles in biomedical field for drug delivery,[91] cancer treatment,[26], [75], [92], [93], [94] theranostic agents,[91] gene delivery,[26], [27] bioimaging[95], [96] and cancer therapy.[28], [37], [57], [97]

Zia Ul Haq Khan et. al.[94] evaluated effect of green synthesized gold nanoparticles (AuNPs) for their toxicity against breast cancer cells MCF-7. The analysis was done using various concentration of gold nanoparticles: 6, 3, 1.5, 0.75, and 0.375 µL/mL. After two days of treatment with 3 and 6 µL/mL of the green-synthesized AuNPs. The cancer cells appeared rounded and exhibited signs of cell death.[94] The cell membranes displayed a swollen appearance at various points, indicating necrosis. The results revealed that approximately 50% of the cells died at a concentration of 1.5 µL/mL of AuNPs. Direct relationship between cytotoxicity and concentration of synthesized nanoparticles used was observed. At a concentration of 100 µg/mL, the highest cytotoxic effect (75%) was observed and the viability of MCF-7 cells was reduced to 25% at this concentration.

Mukherjee et. al.[91] summarized the theranostic (therapeutic and diagnostic) applications of green synthesized nanoparticles for treatment of various diseases. The use of AuNPs is highly appealing for biomedical applications because of their unique physicochemical properties, ease of synthesis and surface modification at the nanoscale, biocompatibility, and various other benefits.[91]

Rajesh Kotcherlakota et. al.[98] explored the applications of nanoparticles synthesized via greener routes, for disease therapy and diagnostics. Green synthesized silver nanoparticles (AgNPs) have been identified as an effective in various roles: anticancer agent,[92], [99], [100], [101] antiangiogenesis i.e. suppression of cell proliferation,[99], [100], [102] wound healing i.e. restoration of injured tissues[71], [103] and antidiabetic agents i.e. that acts on suppression of secretary level of enzymes responsible for insufficient production of insulin and cause abrupt increase in blood sugar levels.[72] Their use for bioimaging i.e. visualization of cellular compartments for accurate disease diagnosis and biosensing[95], [96] have been widely explored. The production of reactive oxygen species (ROS) was identified as the primary cause of the cytotoxic effects of biosynthesized AgNPs.

Akintelu et. al.[104] in their review, described the synthesis of copper oxide nanoparticles (CuONPs) by physical, chemical and biological routes. Green synthesis using plant extract was elaborated along with effects of experimental parameters on synthesis such as pH, temperature, time. The anticancer activity of CuONPs synthesized by use of different copper salt was summarized.[104] P.C. Nagajyothi et. al.[105] studied anticancer potency of CuONPs biosynthesized from black bean extract, using the sulforhodamine-B assay. Alterations in mitochondrial structure was observed upon incubation with CuONPs. Additionally, the growth of cervical carcinoma cells was significantly inhibited when treated with these nanoparticles.

4.5 Catalysis: M. J. Ndolomingo et al.[106] described the use of various metal nanoparticles with catalytic activity for various reactions. They explored the use of metal nanoparticles, in particular, gold, copper, palladium, platinum, silver, cobalt, nickel, ruthenium, for oxidation and hydrogenation reactions. The quantum size effect i.e. size induced metal-insulator transition, is responsible for the characteristic property of particles in nano range. With the reduction in size of particles in nano range, percentage of atoms increase on the surface than bulk, subsequently increasing surface to volume ratio. This in turn is responsible for providing higher number of active sites on surface and hence the catalytic capacity increases. Effective use of copper nanoparticles for oxidation of methylene blue,[7], [107] gold nanoparticles for liquid phase oxidation of benzyl alcohol to benzaldehyde,[7], [108] platinum nanoparticles for catalyzing hydrogen evolution reactions in fuel cells,[109] etc. have been reported.

Srinivasarao Sunkari et. al.[110] carried synthesis of AuNPs using papaya leaf extract and chloroauric acid ($HAuCl_4$). Catalytic activity of synthesized AuNPs for reduction of 4-nitrophenol to 4-aminophenol was studied. The rate of reaction was found to increase with increase in concentration of AuNPs.[110]

Jinhui Wei et. al.[111] studied catalytic degradation of organic pollutants by use of metal organic frameworks (MOFs) was explored. MOFs comprises of assemble of metal ions and ligands. These are crystalline materials with extremely high porosity and high surface areas. Thus, these act as very good adsorbent. Presence of numerous active sites in MOFs makes them potential agent to catalyze the degradation of organic pollutants. Use of MOFs for the degradation of pollutants in dye and pharmaceuticals was reported.[111] H. Kolya et. al.[112] synthesized AgNPs by reduction of silver nitrate using Amaranthus Gangeticus Linn (Chinese red spinach) leaf extract. Degradation of a non-biodegradable, toxic azo dye, Congo red was studied using the synthesized silver nanoparticles. The progress of the degradation was monitored using UV-Visible Spectrophotometer. The absorption peak was found to gradually decrease with time and ultimately vanishes on treating with the AgNPs. The time of degradation was significantly got reduced due to AgNPs and got complete within few minutes of treatment.[112]

In another study, Sulaiman A. Alsalamah et. al.[113] created CuONPs using Zygnema moss. Photocatalytic role of the synthesized copper oxide nanoparticles was studied for degradation of reactive red (RR195) and reactive blue dyes. Optimal degradation was found to be 84.66% and 90.82% respectively at 40°C and 75 minutes.[113]

Neel Narayan et. al.[114] in their comprehensive review discussed the role of noble-metal nanoparticles (like Au, Pt, Ag) and non-noble-metal nanoparticles (such as Fe, Cu, Ni, Co) as efficient catalysts. Studies by Haruta and Hutchings,[115] demonstrating the effectiveness of gold nanoparticles for CO oxidation marks a notable breakthrough in catalytic research. It prompted additional research onto various metal supported catalysts. However, the high cost and toxicity of noble metals have driven research toward non-noble-metal alternatives, which are abundant, environmentally friendly, and stable. The authors also highlighted the importance of developing robust and eco-friendly catalysts for achieving green chemistry goals. They also differentiated homogeneous and heterogeneous catalysts, concluding that heterogeneous catalysts are generally more effective. This is due to superior dispersion and greater active site availability. However, separating them after reactions poses challenges.[115] Figure_4 illustrates applications of nanoparticles in varied domains.

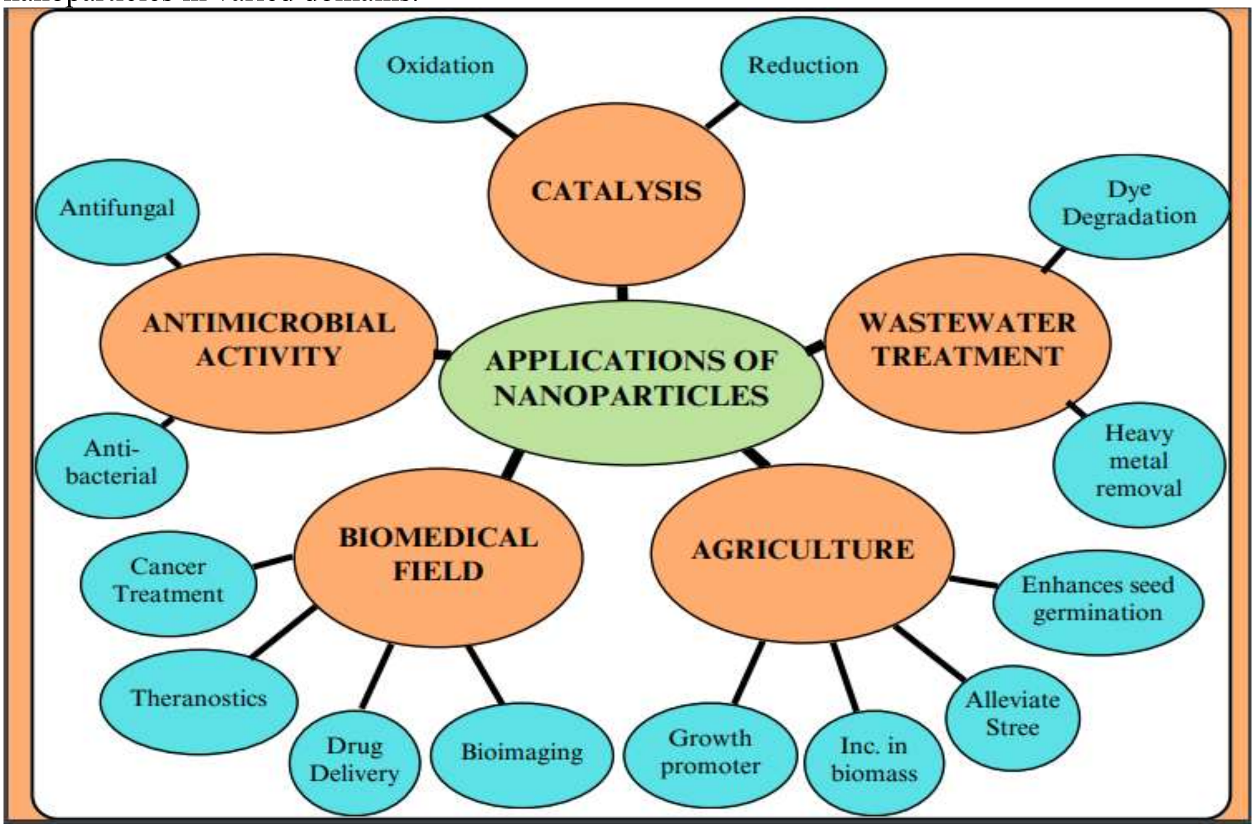

Figure_4: Applications of Nanaoparticles

5. Conclusion and Future Outlook

To summarize, different biological or environment-friendly methods for nanomaterials synthesis and their applications in different domains was discussed. Although a number of physical and chemical methods are available for the nanomaterial production, at present, biological methods are preferred more. This is because of their non-hazardous nature in comparison to the other methods involving excess use of chemicals. Few key factors (like expensive chemicals, higher energy consumption and toxicity) makes the use of chemically produced nanomaterials unfavorable. Therefore, there arises a need for biocompatible, greener and economical approaches for the production of NPs.[34] Use of plants-based extracts, naturally obtained polysaccharides and microbes are the preferred resources for meeting the demand for sustainability.

Synthesis of nanoparticles via green chemistry techniques is an important emerging area towards sustainable nanotechnology. It will not only help in achieving the sustainable goals but can open new areas where the potential applications of the synthesized particles can be explored. Though green synthesis provides a promising path towards sustainability, it does have few challenges for the researchers to overcome in future. The major challenge with adopting the green synthesis is selection of starting material for synthesis, complexity in its processing, product optimization, and providing the necessary conditions for growth (in case microbial route is adapted) during scale up. It gives better opportunity for future researchers for carrying detailed investigations regarding sources which can be utilized for synthesis of nanoparticles via green route, ways of optimizing the process for mass production of particles without compromising the efficacy of the process, optimizing microbial pathways for synthesis and studying the long-term impact of green synthesized nanoparticles on environment. Further research efforts should be made on grasping the concepts and mechanisms related to biological and economic production of nano systems utilizing plant sources and microorganisms.[52]

Acknowledgement

I would like to express my sincere gratitude to Dr. Preeti Jain, whose invaluable insights and feedback greatly enhanced the quality of this review. Special thanks to Medi-Caps University, Department of Chemistry for providing the necessary resources and facilities.

I acknowledge that no financial support was received from any of the organization for writing this review.

Additionally, I am thankful to my colleagues for their constructive discussions and encouragement throughout the review process.

Author Contributions

Both authors contributed to the study conception and design. The first draft of manuscript was written by Hitendra Kaur Sidhwani. Dr. Preeti Jain contributed to improvising the article. Both the authors gave final approval of the version to be published. Both also agree to be accountable for every aspect of the work.

Funding Sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interests

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

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used ChatGPT in order to provide structure to the review and for paraphrasing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Orcid Id

Hitendra Kaur Sidhwani: https://orcid.org/my-orcid?orcid=0009-0007-3009-5919

Dr. Preeti Jain: https://orcid.org/my-orcid?orcid=0000-0003-3849-6606

References

[1] P. T. Anastas and T. C. Williamson, *Green chemistry-designing chemistry for the environment*, vol. 626. Washington, DC: American Chemical Society, 1996. doi: 10.1021/bk-1996-0626.

[2] P. Anastas and N. Eghbali, 'Green Chemistry: Principles and Practice', *Chem. Soc. Rev.*, vol. 39, no. 1, pp. 301–312, 2010, doi: 10.1039/B918763B.

[3] István T. Horváth6 and P. T. Anastas, 'Introduction: Green Chemistry', *Chem Rev*, vol. 107, no. 6, pp. 2167–2168, Jun. 2007, doi: 10.1021/cr0783784.

[4] M. Madani *et al.*, 'Green synthesis of nanoparticles for varied applications: Green renewable resources and energy-efficient synthetic routes', *Nanotechnol Rev*, vol. 11, no. 1, pp. 731–759, Feb. 2022, doi: 10.1515/ntrev-2022-0034.

[5] W. Park and K. Na, ‘Advances in the synthesis and application of nanoparticles for drug delivery’, *WIREs Nanomedicine and Nanobiotechnology*, vol. 7, no. 4, pp. 494–508, Jul. 2015, doi: 10.1002/wnan.1325.

[6] M. Youns, J. D. Hoheisel, and T. Efferth, ‘Therapeutic and Diagnostic Applications of Nanoparticles’, *Curr Drug Targets*, vol. 12, no. 3, pp. 357–365, Mar. 2011, doi: 10.2174/138945011794815257.

[7] M. J. Ndolomingo, N. Bingwa, and R. Meijboom, ‘Review of supported metal nanoparticles: synthesis methodologies, advantages and application as catalysts’, *J Mater Sci*, vol. 55, no. 15, pp. 6195–6241, May 2020, doi: 10.1007/s10853-020-04415-x.

[8] B.-M. Jun *et al.*, ‘Applications of metal-organic framework based membranes in water purification: A review’, *Sep Purif Technol*, vol. 247, p. 116947, Sep. 2020, doi: 10.1016/j.seppur.2020.116947.

[9] Mojtaba Taran, Mohsen Safaei, Naser Karimi, and Ali Almasi, ‘Benefits and Application of Nanotechnology in Environmental Science: an Overview’, *Biointerface Res Appl Chem*, vol. 11, no. 1, pp. 7860–7870, Jul. 2020, doi: 10.33263/BRIAC111.78607870.

[10] Y. Khan *et al.*, ‘Classification, Synthetic, and Characterization Approaches to Nanoparticles, and Their Applications in Various Fields of Nanotechnology: A Review’, *Catalysts*, vol. 12, no. 11, p. 1386, Nov. 2022, doi: 10.3390/catal12111386.

[11] M. Nasrollahzadeh, S. M. Sajadi, M. Sajjadi, and Z. Issaabadi, ‘Applications of Nanotechnology in Daily Life’, 2019, pp. 113–143. doi: 10.1016/B978-0-12-813586-0.00004-3.

[12] H. Yu *et al.*, ‘Nature-resembled nanostructures for energy storage/conversion applications’, *Journal of Industrial and Engineering Chemistry*, vol. 129, pp. 53–68, Jan. 2024, doi: 10.1016/j.jiec.2023.08.041.

[13] C. Parisi, M. Vigani, and E. Rodríguez-Cerezo, ‘Agricultural Nanotechnologies: What are the current possibilities?’, *Nano Today*, vol. 10, no. 2, pp. 124–127, Apr. 2015, doi: 10.1016/j.nantod.2014.09.009.

[14] R. J. B. Peters *et al.*, ‘Nanomaterials for products and application in agriculture, feed and food’, *Trends Food Sci Technol*, vol. 54, pp. 155–164, Aug. 2016, doi: 10.1016/j.tifs.2016.06.008.

[15] A. Mohajerani *et al.*, ‘Nanoparticles in Construction Materials and Other Applications, and Implications of Nanoparticle Use’, *Materials*, vol. 12, no. 19, p. 3052, Sep. 2019, doi: 10.3390/ma12193052.

[16] J. A. Kumar *et al.*, ‘A focus to green synthesis of metal/metal based oxide nanoparticles: Various mechanisms and applications towards ecological approach’, *J Clean Prod*, vol. 324, p. 129198, Nov. 2021, doi: 10.1016/j.jclepro.2021.129198.

[17] A. Rastogi, P. Singh, F. A. Haraz, and A. Barhoum, ‘Biological synthesis of nanoparticles: an environmentally benign approach’, in *Fundamentals of Nanoparticles*, Elsevier, 2018, pp. 571–604. doi: 10.1016/B978-0-323-51255-8.00023-9.

[18] M. Naghdi *et al.*, ‘A green method for production of nanobiochar by ball milling-optimization and characterization’, *J Clean Prod*, vol. 164, pp. 1394–1405, Oct. 2017, doi: 10.1016/j.jclepro.2017.07.084.

[19] R. K. Ajeel, K. Sopian, and R. Zulkifli, ‘Thermal-hydraulic performance and design parameters in a curved-corrugated channel with L-shaped baffles and nanofluid’, *J Energy Storage*, vol. 34, p. 101996, Feb. 2021, doi: 10.1016/j.est.2020.101996.

[20] A. Ryaidh and M. A. J. Al-Qayim, 'Bio-Synthesis and Characterizations of Magnetic Iron Oxide Nanoparticles Mediated By Iraq Propolis Extract', *IOSR Journal of Pharmacy and Biological Sciences (IOSR-JPBS*, vol. 12, no. 6, pp. 65–73, doi: 10.9790/3008-1206056573.

[21] T. Kathiraven, A. Sundaramanickam, N. Shanmugam, and T. Balasubramanian, 'Green synthesis of silver nanoparticles using marine algae Caulerpa racemosa and their antibacterial activity against some human pathogens', *Appl Nanosci*, vol. 5, no. 4, pp. 499–504, Apr. 2015, doi: 10.1007/s13204-014-0341-2.

[22] A. Deljou and S. Goudarzi, 'Green Extracellular Synthesis of the Silver Nanoparticles Using Thermophilic Bacillus Sp. AZ1 and its Antimicrobial Activity Against Several Human Pathogenetic Bacteria', *Iran J Biotechnol*, vol. 14, no. 2, pp. 25–32, Jun. 2016, doi: 10.15171/ijb.1259.

[23] F. Niknejad, M. Nabili, R. Daie Ghazvini, and M. Moazeni, 'Green synthesis of silver nanoparticles: Another honor for the yeast model Saccharomyces cerevisiae', *Curr Med Mycol*, vol. 1, no. 3, pp. 17–24, Sep. 2015, doi: 10.18869/acadpub.cmm.1.3.17.

[24] H. Duan, D. Wang, and Y. Li, 'Green chemistry for nanoparticle synthesis', *Chem Soc Rev*, vol. 44, no. 16, pp. 5778–5792, 2015, doi: 10.1039/C4CS00363B.

[25] Sean Drummer, Tafirenyika Madzimbamuto, and Mahabubur Chowdhury, 'Green Synthesis of Transition-Metal Nanoparticles and Their Oxides: A Review', 2021.

[26] E. Calzoni, A. Cesaretti, A. Polchi, A. Di Michele, B. Tancini, and C. Emiliani, 'Biocompatible Polymer Nanoparticles for Drug Delivery Applications in Cancer and Neurodegenerative Disorder Therapies', *J Funct Biomater*, vol. 10, no. 1, p. 4, Jan. 2019, doi: 10.3390/jfb10010004.

[27] S. Naahidi, M. Jafari, F. Edalat, K. Raymond, A. Khademhosseini, and P. Chen, 'Biocompatibility of engineered nanoparticles for drug delivery', *Journal of Controlled Release*, vol. 166, no. 2, pp. 182–194, Mar. 2013, doi: 10.1016/j.jconrel.2012.12.013.

[28] M. S. Kang, S. Y. Lee, K. S. Kim, and D.-W. Han, 'State of the Art Biocompatible Gold Nanoparticles for Cancer Theragnosis', *Pharmaceutics*, vol. 12, no. 8, p. 701, Jul. 2020, doi: 10.3390/pharmaceutics12080701.

[29] A. D'Souza and R. Shegokar, 'Polymer: Lipid Hybrid Nanostructures in Cancer Drug Delivery: Successes and Limitations', in *Nanoarchitectonics for Smart Delivery and Drug Targeting*, Elsevier, 2016, pp. 431–463. doi: 10.1016/B978-0-323-47347-7.00016-1.

[30] D. Mishra, M. K. Chitara, S. Negi, J. Pal singh, R. Kumar, and P. Chaturvedi, 'Biosynthesis of Zinc Oxide Nanoparticles via Leaf Extracts of Catharanthus roseus (L.) G. Don and Their Application in Improving Seed Germination Potential and Seedling Vigor of Eleusine coracana (L.) Gaertn', *Advances in Agriculture*, vol. 2023, pp. 1–11, Jan. 2023, doi: 10.1155/2023/7412714.

[31] R. D. A. A. Rajapaksha, U. Hashim, S. C. B. Gopinath, N. A. Parmin, and C. A. N. Fernando, 'Nanoparticles in electrochemical bioanalytical analysis', in *Nanoparticles in Analytical and Medical Devices*, Elsevier, 2021, pp. 83–112. doi: 10.1016/B978-0-12-821163-2.00006-6.

[32] T. Mishra, P. Mandal, A. K. Rout, and D. Sahoo, 'A state-of-the-art review on potential applications of natural fiber-reinforced polymer composite filled with inorganic nanoparticle', *Composites Part C: Open Access*, vol. 9, p. 100298, Oct. 2022, doi: 10.1016/j.jcomc.2022.100298.

[33] N. Joudeh and D. Linke, ‘Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists’, *J Nanobiotechnology*, vol. 20, no. 1, p. 262, Jun. 2022, doi: 10.1186/s12951-022-01477-8.
[34] B. Bhardwaj, P. Singh, A. Kumar, S. Kumar, and V. Budhwar, ‘Eco-Friendly Greener Synthesis of Nanoparticles’, *Adv Pharm Bull*, vol. 10, no. 4, pp. 566–576, Aug. 2020, doi: 10.34172/apb.2020.067.
[35] H. R. Ghorbani, A. A. Safekordi, H. Attar, and S. M. Rezayat Sorkhabadi, ‘Biological and Non-biological Methods for Silver Nanoparticles Synthesis’.
[36] M. Ovais, A. T. Khalil, M. Ayaz, I. Ahmad, S. K. Nethi, and S. Mukherjee, ‘Biosynthesis of Metal Nanoparticles via Microbial Enzymes: A Mechanistic Approach’, *Int J Mol Sci*, vol. 19, no. 12, p. 4100, Dec. 2018, doi: 10.3390/ijms19124100.
[37] M. Ovais *et al.*, ‘Green Synthesis of Silver Nanoparticles Via Plant Extracts: Beginning a New Era in Cancer Theranostics’, *Nanomedicine*, vol. 11, no. 23, pp. 3157–3177, Dec. 2016, doi: 10.2217/nnm-2016-0279.
[38] T. Yari, H. Vaghari, M. Adibpour, H. Jafarizadeh-Malmiri, and A. Berenjian, ‘Potential application of Aspergillus terreus, as a biofactory, in extracellular fabrication of silver nanoparticles’, *Fuel*, vol. 308, p. 122007, Jan. 2022, doi: 10.1016/j.fuel.2021.122007.
[39] A. C. Bogas, S. Henrique Rodrigues, M. O. Gonçalves, M. De Assis, E. Longo, and C. Paiva De Sousa, ‘Endophytic Microorganisms From the Tropics as Biofactories for the Synthesis of Metal-Based Nanoparticles: Healthcare Applications’, *Frontiers in Nanotechnology*, vol. 4, Feb. 2022, doi: 10.3389/fnano.2022.823236.
[40] K. Suvardhan and S. Ahmed, *Green Metal Nanoparticles*. Wiley, 2018. doi: 10.1002/9781119418900.
[41] S. N. S. Anis, W. C. Liew, A. Mohd Marsin, I. I. Muhamad, S. H. Teh, and A. Z. Md Khudzari, ‘Microwave-assisted green synthesis of silver nanoparticles using pineapple leaves waste’, *Clean Eng Technol*, vol. 15, p. 100660, Aug. 2023, doi: 10.1016/j.clet.2023.100660.
[42] S. Phongtongpasuk, S. Poadang, and N. Yongvanich, ‘Environmental-friendly Method for Synthesis of Silver Nanoparticles from Dragon Fruit Peel Extract and their Antibacterial Activities’, *Energy Procedia*, vol. 89, pp. 239–247, Jun. 2016, doi: 10.1016/j.egypro.2016.05.031.
[43] S. Shekhar, S. Singh, N. Gandhi, S. Gautam, and B. Sharma, ‘Green chemistry based benign approach for the synthesis of titanium oxide nanoparticles using extracts of Azadirachta Indica’, *Clean Eng Technol*, vol. 13, p. 100607, Apr. 2023, doi: 10.1016/j.clet.2023.100607.
[44] S. Shamaila *et al.*, ‘A cost effective and eco-friendly green route for fabrication of efficient graphene nanosheets photocatalyst’, *J Environ Chem Eng*, vol. 5, no. 6, pp. 5770–5776, Dec. 2017, doi: 10.1016/j.jece.2017.11.009.
[45] R. T. Kapoor, M. R. Salvadori, M. Rafatullah, M. R. Siddiqui, M. A. Khan, and S. A. Alshareef, ‘Exploration of Microbial Factories for Synthesis of Nanoparticles – A Sustainable Approach for Bioremediation of Environmental Contaminants’, *Front Microbiol*, vol. 12, Jun. 2021, doi: 10.3389/fmicb.2021.658294.
[46] D. Chugh, V. S. Viswamalya, and B. Das, ‘Green synthesis of silver nanoparticles with algae and the importance of capping agents in the process’, *Journal of Genetic Engineering and Biotechnology*, vol. 19, no. 1, p. 126, Dec. 2021, doi: 10.1186/s43141-021-00228-w.
[47] Z. Molnár *et al.*, ‘Green synthesis of gold nanoparticles by thermophilic filamentous fungi’, *Sci Rep*, vol. 8, no. 1, p. 3943, Mar. 2018, doi: 10.1038/s41598-018-22112-3.

[48] J. Jeevanandam *et al.*, 'Green approaches for the synthesis of metal and metal oxide nanoparticles using microbial and plant extracts', *Nanoscale*, vol. 14, no. 7, pp. 2534–2571, 2022, doi: 10.1039/D1NR08144F.
[49] B. Koul, A. K. Poonia, D. Yadav, and J.-O. Jin, 'Microbe-Mediated Biosynthesis of Nanoparticles: Applications and Future Prospects', *Biomolecules*, vol. 11, no. 6, p. 886, Jun. 2021, doi: 10.3390/biom11060886.
[50] M. S. Samuel *et al.*, 'A Review on Green Synthesis of Nanoparticles and Their Diverse Biomedical and Environmental Applications', *Catalysts*, vol. 12, no. 5, p. 459, Apr. 2022, doi: 10.3390/catal12050459.
[51] S. A. Fahmy, E. Preis, U. Bakowsky, and H. M. E.-S. Azzazy, 'Platinum Nanoparticles: Green Synthesis and Biomedical Applications', *Molecules*, vol. 25, no. 21, p. 4981, Oct. 2020, doi: 10.3390/molecules25214981.
[52] B. Bhattarai, Y. Zaker, and T. P. Bigioni, 'Green synthesis of gold and silver nanoparticles: Challenges and opportunities', *Curr Opin Green Sustain Chem*, vol. 12, pp. 91–100, Aug. 2018, doi: 10.1016/j.cogsc.2018.06.007.
[53] B. Bhattarai, Y. Zaker, A. Atnagulov, B. Yoon, U. Landman, and T. P. Bigioni, 'Chemistry and Structure of Silver Molecular Nanoparticles', *Acc Chem Res*, vol. 51, no. 12, pp. 3104–3113, Dec. 2018, doi: 10.1021/acs.accounts.8b00445.
[54] S. M. Roopan and G. Elango, 'Self-assembly of transition metal nanoparticles using marine sources**The authors declare that there is no conflict of interests regarding the publication of this chapter.', in *Fabrication and Self-Assembly of Nanobiomaterials*, Elsevier, 2016, pp. 459–483. doi: 10.1016/B978-0-323-41533-0.00015-5.
[55] J. Németh, G. Rodríguez-Gattorno, D. Díaz, A. R. Vázquez-Olmos, and I. Dékány, 'Synthesis of ZnO Nanoparticles on a Clay Mineral Surface in Dimethyl Sulfoxide Medium', *Langmuir*, vol. 20, no. 7, pp. 2855–2860, Mar. 2004, doi: 10.1021/la035097s.
[56] L. Suber, I. Sondi, E. Matijević, and D. V. Goia, 'Preparation and the mechanisms of formation of silver particles of different morphologies in homogeneous solutions', *J Colloid Interface Sci*, vol. 288, no. 2, pp. 489–495, Aug. 2005, doi: 10.1016/j.jcis.2005.03.017.
[57] D.-M. Radulescu, V.-A. Surdu, A. Ficai, D. Ficai, A.-M. Grumezescu, and E. Andronescu, 'Green Synthesis of Metal and Metal Oxide Nanoparticles: A Review of the Principles and Biomedical Applications', *Int J Mol Sci*, vol. 24, no. 20, p. 15397, Oct. 2023, doi: 10.3390/ijms242015397.
[58] Y. Jin *et al.*, 'Water-based green and sustainable extraction protocols for value-added compounds from natural resources', *Curr Opin Green Sustain Chem*, vol. 40, p. 100757, Apr. 2023, doi: 10.1016/j.cogsc.2023.100757.
[59] D. Prat *et al.*, 'CHEM21 selection guide of classical- and less classical-solvents', *Green Chemistry*, vol. 18, no. 1, pp. 288–296, 2016, doi: 10.1039/C5GC01008J.
[60] L. Soltys, O. Olkhovyy, T. Tatarchuk, and Mu. Naushad, 'Green Synthesis of Metal and Metal Oxide Nanoparticles: Principles of Green Chemistry and Raw Materials', *Magnetochemistry*, vol. 7, no. 11, p. 145, Oct. 2021, doi: 10.3390/magnetochemistry7110145.
[61] L. Castillo-Henríquez, K. Alfaro-Aguilar, J. Ugalde-Álvarez, L. Vega-Fernández, G. Montes de Oca-Vásquez, and J. R. Vega-Baudrit, 'Green Synthesis of Gold and Silver Nanoparticles from Plant Extracts and Their Possible Applications as Antimicrobial Agents in the Agricultural Area', *Nanomaterials*, vol. 10, no. 9, p. 1763, Sep. 2020, doi: 10.3390/nano10091763.

[62] K. Byrappa, S. Ohara, and T. Adschiri, 'Nanoparticles synthesis using supercritical fluid technology – towards biomedical applications', *Adv Drug Deliv Rev*, vol. 60, no. 3, pp. 299–327, Feb. 2008, doi: 10.1016/j.addr.2007.09.001.

[63] X. Xiong Chang *et al.*, 'A review on the properties and applications of chitosan, cellulose and deep eutectic solvent in green chemistry', *Journal of Industrial and Engineering Chemistry*, vol. 104, pp. 362–380, Dec. 2021, doi: 10.1016/j.jiec.2021.08.033.

[64] H. Liao, Y. Jiang, Z. Zhou, S. Chen, and S. Sun, 'Shape-Controlled Synthesis of Gold Nanoparticles in Deep Eutectic Solvents for Studies of Structure–Functionality Relationships in Electrocatalysis', *Angewandte Chemie International Edition*, vol. 47, no. 47, pp. 9100–9103, Nov. 2008, doi: 10.1002/anie.200803202.

[65] Y. Huang *et al.*, 'Synthesis and Characterization of CuCl Nanoparticles in Deep Eutectic Solvents', *Particulate Science and Technology*, vol. 31, no. 1, pp. 81–84, Jan. 2013, doi: 10.1080/02726351.2011.648823.

[66] L. Gontrani, D. T. Donia, E. Maria Bauer, P. Tagliatesta, and M. Carbone, 'Novel Synthesis of Zinc Oxide Nanoparticles from Type IV Deep Eutectic Solvents', *Inorganica Chim Acta*, vol. 545, p. 121268, Jan. 2023, doi: 10.1016/j.ica.2022.121268.

[67] C. Das *et al.*, 'Green Synthesis, Characterization and Application of Natural Product Coated Magnetite Nanoparticles for Wastewater Treatment', *Nanomaterials*, vol. 10, no. 8, p. 1615, Aug. 2020, doi: 10.3390/nano10081615.

[68] K. Rambabu, G. Bharath, F. Banat, and P. L. Show, 'Green synthesis of zinc oxide nanoparticles using Phoenix dactylifera waste as bioreductant for effective dye degradation and antibacterial performance in wastewater treatment', *J Hazard Mater*, vol. 402, p. 123560, Jan. 2021, doi: 10.1016/j.jhazmat.2020.123560.

[69] L. Zheng, F. Hong, S. Lu, and C. Liu, 'Effect of Nano-TiO₂ on Strength of Naturally Aged Seeds and Growth of Spinach', *Biol Trace Elem Res*, vol. 104, no. 1, pp. 083–092, 2005, doi: 10.1385/BTER:104:1:083.

[70] S. Shende *et al.*, 'Metal-Based Green Synthesized Nanoparticles: Boon for Sustainable Agriculture and Food Security', *IEEE Trans Nanobioscience*, vol. 21, no. 1, pp. 44–54, Jan. 2022, doi: 10.1109/TNB.2021.3089773.

[71] M. T. Haseeb *et al.*, 'Linseed hydrogel-mediated green synthesis of silver nanoparticles for antimicrobial and wound-dressing applications. International Journal of Nanomedicine', *Int J Nanomedicine*, 2017.

[72] K. Balan *et al.*, 'Antidiabetic activity of silver nanoparticles from green synthesis using Lonicera japonica leaf extract', *RSC Adv*, vol. 6, no. 46, pp. 40162–40168, 2016, doi: 10.1039/C5RA24391B.

[73] L. Wang, C. Hu, and L. Shao, 'The antimicrobial activity of nanoparticles: present situation and prospects for the future', *Int J Nanomedicine*, vol. Volume 12, pp. 1227–1249, Feb. 2017, doi: 10.2147/IJN.S121956.

[74] N. A. Rosli, Y. H. Teow, and E. Mahmoudi, 'Current approaches for the exploration of antimicrobial activities of nanoparticles', *Sci Technol Adv Mater*, vol. 22, no. 1, pp. 885–907, Dec. 2021, doi: 10.1080/14686996.2021.1978801.

[75] H. Chandra, P. Kumari, E. Bontempi, and S. Yadav, 'Medicinal plants: Treasure trove for green synthesis of metallic nanoparticles and their biomedical applications', *Biocatal Agric Biotechnol*, vol. 24, p. 101518, Mar. 2020, doi: 10.1016/j.bcab.2020.101518.

[76] A. S. Jain, P. S. Pawar, A. Sarkar, V. Junnuthula, and S. Dyawanapelly, 'Bionanofactories for Green Synthesis of Silver Nanoparticles: Toward Antimicrobial Applications', *Int J Mol Sci*, vol. 22, no. 21, p. 11993, Nov. 2021, doi: 10.3390/ijms222111993.

[77] S. Ahmed, M. Ahmad, B. L. Swami, and S. Ikram, 'A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise', *J Adv Res*, vol. 7, no. 1, pp. 17–28, Jan. 2016, doi: 10.1016/J.JARE.2015.02.007.

[78] S. kazemi *et al.*, 'Recent advances in green synthesized nanoparticles: from production to application', *Materials Today Sustainability*, vol. 24, p. 100500, Dec. 2023, doi: 10.1016/j.mtsust.2023.100500.

[79] B. Buszewski *et al.*, 'Antimicrobial activity of biosilver nanoparticles produced by a novel Streptacidiphilus durhamensis strain', *Journal of Microbiology, Immunology and Infection*, vol. 51, no. 1, pp. 45–54, Feb. 2018, doi: 10.1016/j.jmii.2016.03.002.

[80] S. Maiti, D. Krishnan, G. Barman, S. K. Ghosh, and J. K. Laha, 'Antimicrobial activities of silver nanoparticles synthesized from Lycopersicon esculentum extract', *J Anal Sci Technol*, vol. 5, no. 1, p. 40, Dec. 2014, doi: 10.1186/s40543-014-0040-3.

[81] Y. Jiang *et al.*, 'Green synthesis of metal-based nanoparticles for sustainable agriculture', *Environmental Pollution*, vol. 309, p. 119755, Sep. 2022, doi: 10.1016/j.envpol.2022.119755.

[82] S. Afzal, D. Sharma, and N. K. Singh, 'Eco-friendly synthesis of phytochemical-capped iron oxide nanoparticles as nano-priming agent for boosting seed germination in rice (Oryza sativa L.)', *Environmental Science and Pollution Research*, vol. 28, no. 30, pp. 40275–40287, Aug. 2021, doi: 10.1007/s11356-020-12056-5.

[83] D. M. Kasote, J. H. J. Lee, G. K. Jayaprakasha, and B. S. Patil, 'Seed Priming with Iron Oxide Nanoparticles Modulate Antioxidant Potential and Defense-Linked Hormones in Watermelon Seedlings', *ACS Sustain Chem Eng*, vol. 7, no. 5, pp. 5142–5151, Mar. 2019, doi: 10.1021/acssuschemeng.8b06013.

[84] S. Ullah *et al.*, 'Physiological and biochemical response of wheat (Triticum aestivum) to TiO2 nanoparticles in phosphorous amended soil: A full life cycle study', *J Environ Manage*, vol. 263, p. 110365, Jun. 2020, doi: 10.1016/j.jenvman.2020.110365.

[85] P. Acharya, G. K. Jayaprakasha, K. M. Crosby, J. L. Jifon, and B. S. Patil, 'Green-Synthesized Nanoparticles Enhanced Seedling Growth, Yield, and Quality of Onion (*Allium cepa* L.)', *ACS Sustain Chem Eng*, vol. 7, no. 17, pp. 14580–14590, Sep. 2019, doi: 10.1021/acssuschemeng.9b02180.

[86] H. Wu, N. Tito, and J. P. Giraldo, 'Anionic Cerium Oxide Nanoparticles Protect Plant Photosynthesis from Abiotic Stress by Scavenging Reactive Oxygen Species', *ACS Nano*, vol. 11, no. 11, pp. 11283–11297, Nov. 2017, doi: 10.1021/acsnano.7b05723.

[87] R. Jayakrishnan, A. Joseph, and V. Thomas, 'Efficacy in degradation of carcinogenic pollutant sulforhodamine B by green synthesized silver nanoparticles', *Micro and Nano Systems Letters*, vol. 9, no. 1, p. 12, Dec. 2021, doi: 10.1186/s40486-021-00138-z.

[88] M. E. Taghavizadeh Yazdi *et al.*, 'Green Synthesis of Silver Nanoparticles Using Helichrysum graveolens for Biomedical Applications and Wastewater Treatment', *Bionanoscience*, vol. 10, no. 4, pp. 1121–1127, Dec. 2020, doi: 10.1007/s12668-020-00794-2.

[89] L. Katata-Seru, T. Moremedi, O. S. Aremu, and I. Bahadur, 'Green synthesis of iron nanoparticles using Moringa oleifera extracts and their applications: Removal of nitrate

from water and antibacterial activity against Escherichia coli', *J Mol Liq*, vol. 256, pp. 296–304, Apr. 2018, doi: 10.1016/j.molliq.2017.11.093.

[90] P. Punia *et al.*, 'Recent advances in synthesis, characterization, and applications of nanoparticles for contaminated water treatment- A review', *Ceram Int*, vol. 47, no. 2, pp. 1526–1550, Jan. 2021, doi: 10.1016/j.ceramint.2020.09.050.

[91] S. Mukherjee, S. K. Nethi, and C. R. Patra, 'Green Synthesized Gold Nanoparticles for Future Biomedical Applications', in *Particulate Technology for Delivery of Therapeutics*, Singapore: Springer Singapore, 2017, pp. 359–393. doi: 10.1007/978-981-10-3647-7_11.

[92] L. Fageria *et al.*, 'Biosynthesized Protein-Capped Silver Nanoparticles Induce ROS-Dependent Proapoptotic Signals and Prosurvival Autophagy in Cancer Cells', *ACS Omega*, vol. 2, no. 4, pp. 1489–1504, Apr. 2017, doi: 10.1021/acsomega.7b00045.

[93] N. Jain, P. Jain, D. Rajput, and U. K. Patil, 'Green synthesized plant-based silver nanoparticles: therapeutic prospective for anticancer and antiviral activity', *Micro and Nano Systems Letters*, vol. 9, no. 1, p. 5, May 2021, doi: 10.1186/s40486-021-00131-6.

[94] Z. U. H. Khan *et al.*, 'Biomedical applications of green synthesized Nobel metal nanoparticles', *J Photochem Photobiol B*, vol. 173, pp. 150–164, Aug. 2017, doi: 10.1016/j.jphotobiol.2017.05.034.

[95] K. Farhadi, M. Forough, R. Molaei, S. Hajizadeh, and A. Rafipour, 'Highly selective Hg2+ colorimetric sensor using green synthesized and unmodified silver nanoparticles', *Sens Actuators B Chem*, vol. 161, no. 1, pp. 880–885, Jan. 2012, doi: 10.1016/j.snb.2011.11.052.

[96] S. Pandey, G. K. Goswami, and K. K. Nanda, 'Green synthesis of biopolymer–silver nanoparticle nanocomposite: An optical sensor for ammonia detection', *Int J Biol Macromol*, vol. 51, no. 4, pp. 583–589, Nov. 2012, doi: 10.1016/j.ijbiomac.2012.06.033.

[97] M. J. Molaei, 'Carbon quantum dots and their biomedical and therapeutic applications: a review', *RSC Adv*, vol. 9, no. 12, pp. 6460–6481, 2019, doi: 10.1039/C8RA08088G.

[98] R. Kotcherlakota, S. Das, and C. R. Patra, 'Therapeutic applications of green-synthesized silver nanoparticles', in *Green Synthesis, Characterization and Applications of Nanoparticles*, Elsevier, 2019, pp. 389–428. doi: 10.1016/B978-0-08-102579-6.00017-4.

[99] V. Sabaratnam, S. Gurunathan, J. Raman, S. N. Abd Malek, and P. John, 'Green synthesis of silver nanoparticles using Ganoderma neo-japonicum Imazeki: a potential cytotoxic agent against breast cancer cells', *Int J Nanomedicine*, p. 4399, Nov. 2013, doi: 10.2147/IJN.S51881.

[100] S. Gurunathan, K.-J. Lee, K. Kalishwaralal, S. Sheikpranbabu, R. Vaidyanathan, and S. H. Eom, 'Antiangiogenic properties of silver nanoparticles', *Biomaterials*, vol. 30, no. 31, pp. 6341–6350, Oct. 2009, doi: 10.1016/j.biomaterials.2009.08.008.

[101] M. J. Firdhouse and P. Lalitha, 'Biosynthesis of Silver Nanoparticles and Its Applications', *J Nanotechnol*, vol. 2015, pp. 1–18, 2015, doi: 10.1155/2015/829526.

[102] S. Sheikpranbabu, K. Kalishwaralal, D. Venkataraman, S. H. Eom, J. Park, and S. Gurunathan, 'Silver nanoparticles inhibit VEGF-and IL-1β-induced vascular permeability via Src dependent pathway in porcine retinal endothelial cells', *J Nanobiotechnology*, vol. 7, no. 1, p. 8, Oct. 2009, doi: 10.1186/1477-3155-7-8.

[103] S. Shankar, L. Jaiswal, R. S. L. Aparna, R. G. V Prasad, G. P. Kumar, and C. M. Manohara, 'Wound healing potential of green synthesized silver nanoparticles prepared from *Lansium domesticum* fruit peel extract', *Materials Express*, vol. 5, no. 2, pp. 159–164, Mar. 2015, doi: 10.1166/mex.2015.1225.

[104] S. A. Akintelu, A. S. Folorunso, F. A. Folorunso, and A. K. Oyebamiji, 'Green synthesis of copper oxide nanoparticles for biomedical application and environmental remediation', *Heliyon*, vol. 6, no. 7, p. e04508, Jul. 2020, doi: 10.1016/j.heliyon.2020.e04508.

[105] P. C. Nagajyothi, P. Muthuraman, T. V. M. Sreekanth, D. H. Kim, and J. Shim, 'Green synthesis: In-vitro anticancer activity of copper oxide nanoparticles against human cervical carcinoma cells', *Arabian Journal of Chemistry*, vol. 10, no. 2, pp. 215–225, Feb. 2017, doi: 10.1016/j.arabjc.2016.01.011.

[106] M. J. Ndolomingo, N. Bingwa, and R. Meijboom, 'Review of supported metal nanoparticles: synthesis methodologies, advantages and application as catalysts', *J Mater Sci*, vol. 55, no. 15, pp. 6195–6241, May 2020, doi: 10.1007/s10853-020-04415-x.

[107] M. J. Ndolomingo and R. Meijboom, 'Kinetic analysis of catalytic oxidation of methylene blue over γ-Al2O3 supported copper nanoparticles', *Appl Catal A Gen*, vol. 506, pp. 33–43, Oct. 2015, doi: 10.1016/j.apcata.2015.08.036.

[108] M. J. Ndolomingo and R. Meijboom, 'Selective liquid phase oxidation of benzyl alcohol to benzaldehyde by tert-butyl hydroperoxide over γ-Al2O3 supported copper and gold nanoparticles', *Appl Surf Sci*, vol. 398, pp. 19–32, Mar. 2017, doi: 10.1016/j.apsusc.2016.12.020.

[109] C. Wang, H. Daimon, T. Onodera, T. Koda, and S. Sun, 'A General Approach to the Size- and Shape-Controlled Synthesis of Platinum Nanoparticles and Their Catalytic Reduction of Oxygen', *Angewandte Chemie*, vol. 120, no. 19, pp. 3644–3647, Apr. 2008, doi: 10.1002/ange.200800073.

[110] S. Sunkari, B. R. Gangapuram, R. Dadigala, R. Bandi, M. Alle, and V. Guttena, 'Microwave-irradiated green synthesis of gold nanoparticles for catalytic and anti-bacterial activity', *J Anal Sci Technol*, vol. 8, no. 1, p. 13, Dec. 2017, doi: 10.1186/s40543-017-0121-1.

[111] J. Wei *et al.*, 'Recent advances in metal organic frameworks for the catalytic degradation of organic pollutants', *Collagen and Leather*, vol. 5, no. 1, p. 33, Dec. 2023, doi: 10.1186/s42825-023-00140-8.

[112] H. Kolya, P. Maiti, A. Pandey, and T. Tripathy, 'Green synthesis of silver nanoparticles with antimicrobial and azo dye (Congo red) degradation properties using Amaranthus gangeticus Linn leaf extract', *J Anal Sci Technol*, vol. 6, no. 1, p. 33, Dec. 2015, doi: 10.1186/s40543-015-0074-1.

[113] S. A. Alsalamah, M. I. Alghonaim, M. M. Bakri, and T. M. Abdelghany, 'Zygnema sp. as creator of copper oxide nanoparticles and their application in controlling of microbial growth and photo-catalytic degradation of dyes', *Appl Biol Chem*, vol. 67, no. 1, p. 47, May 2024, doi: 10.1186/s13765-024-00891-w.

[114] N. Narayan, A. Meiyazhagan, and R. Vajtai, 'Metal Nanoparticles as Green Catalysts', *Materials*, vol. 12, no. 21, p. 3602, Nov. 2019, doi: 10.3390/ma12213602.

[115] G. J. Hutchings and M. Haruta, 'A golden age of catalysis: A perspective', *Appl Catal A Gen*, vol. 291, no. 1–2, pp. 2–5, Sep. 2005, doi: 10.1016/j.apcata.2005.05.044.