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Review Article

Plant-Mediated Green Synthesis of Nanomaterials for Sustainable Energy Applications

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Research Highlights

- ❖ Demonstrated that plant-mediated synthesis offers a sustainable, low-toxicity alternative to conventional chemical methods, yielding nanoparticles with comparable stability and efficiency.
- ❖ Identified phenolics, flavonoids, and terpenoids as key reducing and capping agents driving nanoparticle formation through redox-mediated pathways.
- ❖ Established that parameters such as pH, temperature, and extract concentration significantly modulate nanoparticle morphology, with optimized conditions producing uniformly sized, highly functional particles.

- ❖ Showcased successful synthesis of metal (Ag, Au), metal oxide (ZnO, TiO₂), and carbon-based nanoparticles using plant extracts, each exhibiting distinct optical and catalytic properties.
- ❖ Demonstrated enhanced biofuel yield and catalytic efficiency when plant-derived nanoparticles were applied in transesterification and biomass conversion processes.
- ❖ Proposed scalable, green synthesis strategies integrating waste plant biomass for industrial nanoparticle production and environmental remediation.

Abstract

Nanoparticles synthesized from physical or chemical routes pose a major threat to the environment as they tend to be toxic. Thus, green production of nanoparticles using plant extract has come forward as a better and sustainable alternative. This paper focuses on plant-mediated synthesis of various nanoscale metal particles (Ag, Au, Cu), nanoscale metal oxides (ZnO, TiO₂, Fe₃O₄) as well as carbon nanomaterials (carbon nanotubes, quantum dots, graphene). Plant phytochemicals such as polysaccharides, flavonoids, enzymes, reducing sugars, steroids, proteins, terpenoids and amino acids play a key role in stabilization, capping and reduction in the biosynthetic process. The influence factors like pH, extract concentration, reaction temperature, metal salt concentration, contact time, and proportion of plant extract to metal salt is discussed. Beyond biomedical and catalytic applications, this paper highlights the significance of green nanoparticles for the production of biofuels. Despite significant advancements, plant-mediated green nanotechnology still has a long journey ahead to establish itself as a climate-resilient and sustainable solution for meeting the energy demands of a growing population. To address the pressing issue of fuel depletion, we need dedicated research and thoughtful implementation over the long term.

Keywords- green nanotechnology; biofuel production; plant mediated synthesis; metal nanoparticles; carbon nanomaterials.

1. Introduction

The domain of Nanotechnology has proven to be one of the most rapidly evolving and dynamic areas of research [1]. This scientific domain generally focuses on the creation, development, structural characterization and uses of nanomaterials which have a range of 1 to 100 nm in size. Nanomaterials have been grouped into four categories on the basis of their dimensionalities. Zero-Dimensional (0D) nanoscale materials: it includes all the nanomaterials which have all their dimensions fall within the nanoscale range, for example, fullerenes, nanoparticles and quantum dots. One-Dimensional (1D) nanoscale materials: it includes the nanomaterials which have one dimension outside the nanoscale range, for example, nanorods, nanohorns, nanotubes, nanowires and nanofibers. Two-Dimensional (2D) nanoscale materials: it consists all the nanomaterials which possess two dimensions beyond the nanoscale range, for example, nanolayers, nanosheets and nanofilms. Three-Dimensional (3D) nanoscale materials: the nanoscale materials in this group have all their dimensions outside the nanoscale, for example, bulk powders, arrays of nanowires, etc [2]. Supplementary **Table S1** summarizes this dimensional classification along with representative examples and their key structural characteristics [3-6].

In the past decade, nanomaterials and especially nanoparticles have been explored thoroughly because of their unique characteristics [7]. Nanoparticles show a variety of properties like biological interactions, mechanical stability, steric stabilization, heat and electrical conduction, fusion temperature, etc. as compared to their bulk material as a result of their minute size and increased surface area per unit mass [8]. Synthesis of nanoparticles have captured the interest of many scientists because of their broad usage in medicine, photonics, biotechnology, biofuel production, cosmetics, electronics, drug-gene delivery, catalysis, nonlinear optical devices, chemical industries, etc [9, 10].

In the literature, a number of chemical, physical as well as biological means are available to synthesize different categories of nanoscale particles. **Figure 1** illustrates the major nanoparticle synthesis methods, highlighting the biological routes through plants and microbes ¹. Nanoparticle fabrication through physical methods employs top-down approach which includes breaking down of bulk material to produce nanomaterials, these methods include laser ablation, inert gas

condensation (IGC), laser pyrolysis, electrospinning, etc. [11], whereas the chemical (etching, chemical vapor deposition, sol-gel method, etc.) and biological (green) synthesis employs bottom-up approach which includes combining tiny atoms to get nanomaterials [12]. However, physical and chemical methods unintentionally add to environmental toxicity and various related problems. They are accompanied by several limitations such as prolonged synthesis time, high production cost and complex purification steps [13], some physical methods (tube furnace) requires a huge amount of power consumption and energy to raise the environmental temperature, which in turn consumes a lot of time in achieving thermal stability, chemical techniques frequently involve the use of hazardous substances, examples include, borohydride, hydrazine hydrate, formaldehyde, etc. as reducing agents which limits their uses in pharmaceutical and clinical fields [14]. In contrast, green synthesis approaches offer a more sustainable and eco-friendly alternative. These methods minimize the use of toxic chemicals, reduce energy consumption and enhanced cost effectiveness compared to conventional techniques [1, 10, 13, 14, 15]. Researchers have understood the alarming need to avoid harmful chemicals and high energy consumption and shift towards biological methods to synthesize nanoparticles by using natural reduction, capping and stabilizing agents. Numerous biological agents, including, microbes (Molds, Unicellular Fungi, Algae, and Bacteria), Agricultural wastes and Plants (leaf, stem, fruit, root, flower, bark, seeds, etc.) have undergone extensive investigation for facilitating the eco-friendly synthesis [16]. Several studies suggest that microbes takes a short time to grow and are quite manageable which makes them suitable to synthesize specific nanoparticles [17]. However, the plant extracts are considered way more efficient because scaling up in microbial preparations are challenging and reduces the production rate [10, 18]. Plants reduce metal ions much faster than microbes [18]. It is agreed upon that plant derived nanoparticles limits the use of hazardous, toxic residues as compared to the chemically synthesized nanoparticles and can be safely implemented in farming, food sciences and technology, public health safety and biomedical engineering. Various biomolecules present in them like coenzymes, carbohydrates, phenolic acids, amino acids, alkaloids, gum, flavonoids, polysaccharides, steroids, vitamins, tannins, proteins, fats, gum, terpenoides, alcoholic compounds, etc. possess reductive capabilities and can reduce inorganic metal ions into metal nanoparticles [10].

This paper specifically emphasizes the utilization of plants as a sustainable source for producing various metal (Au, Ag) and metal oxide nanoparticles (ZnO, TiO₂) using environmental friendly green synthesis and their remarkable potential in photocatalysis and biofuel production [8]. These plant-derived NPs have begun to play a pivotal role in biofuel systems, particularly as catalysts in transesterification and biomass-conversion reactions, and as enhancers of microalgal lipid accumulation and biodiesel yield [19, 20]. This paper also addresses the various ways in which green synthesis of nanoparticles is superior to traditional chemical as well as physical methods.

2. Synthesis of NPs from Plants

2.1 Role of Plant Metabolites in Nanoparticle Synthesis

The unrefined plant extracts possess a variety of primary and secondary metabolites. Primary metabolites majorly include carbohydrates, proteins, fatty acids, nucleic acids, amino acids, etc. which play an active role in the plant's growth and progression, meanwhile conversely, secondary metabolites are synthesized by plants only during certain stress conditions. They include phenolic acid, flavonoids, alkaloids, terpenoids, alcoholic compounds, antioxidants, organic acids (oxalic acid, ascorbic acid, tartaric acid) and quinines [21]. Although they do not have a direct impact on the plant's growth or development but are ecologically important and have shown a great potential in medicinal fields including both modern and ancient medicines. Due to a wide variety of metabolites present in plants it is very difficult to pinpoint a particular compound which facilitates the formation of metallic nanoscale particles. Hence, various metabolites including flavonoids, phenolic acids, terpenoids and proteins have been credited to carry out synthesis of nanoparticles because of their reducing in addition to stabilizing potential throughout the biosynthesis [22]. These metabolites are known to mediate the reduction of metal ions, forming nanoparticles by the process known as one-step eco-friendly synthesis method [23, 24]. **Figure 2** demonstrates the typical mechanism of silver nanoparticle formation involving reduction and capping by plant-derived metabolites [25]. Several metabolites act as precursors during green synthesis of plant mediated nanoparticles. They offer numerous advantages over chemicals so that they are compatible to use in medicinal and pharmaceutical fields.

Additionally, they are cheaper and easily accessible. The biomolecules which serve as reducing and stabilizing agents includes sugars, ketones, aldehydes, carboxylic acid etc [26].

2.1.1 Phenolics

Phenolic acid belongs to the polyphenol family which is the most dominant secondary metabolite produced by plants. These compounds are biosynthesized from either polyketide acetate/malonate pathway, which produces simple phenols or the shikimate/ phenylpropanoid pathway which produces phenyl propanoids.

Gopinath et al. produced Silver, Gold and Silver-Gold dual metal nanoparticles by green synthesis from leaf extracts of *Gloriosa superba*. These nanoscale particles were analysed using XRD, FTIR spectroscopy, UV-Vis spectroscopy, AFM and TEM. They claimed that the sugar-derived compounds like glycosides and hydrophilic tannins which were present in the leaf helped in bioreduction of AgNO_3 , $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ and $\text{AgNO}_3/\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ (1:1) into the Silver, Gold and Silver-Gold dual metal nanoscale particles. This process could be visually analysed due to the changing of color from colorless to brown, yellowish white to reddish brown and yellow to dark red suggesting the successful generation of Silver, Silver-Gold dualmetal and Gold nanoparticles [27]. Hemlata et al. 2020, used the aqueous leaf extract of *Cucumis prophetarum* for the green synthesis of silver-based nanostructures. The further analysis of bioactive compounds of the leaf-derived extract showed the existence of triterpenoids, phenol, tannins as well as saponins which played a key role in reduction and capping to maintain nanoparticle's stability and inhibit their aggregation [28]. Numerous known phenolic acid such as caffeic acid and ellagic acid function as reducing substances to promote the formation of metal nanoscale particles.

The molecular framework of Phenolics includes a carboxylic acid group and a phenolic ring. The aromatic ring plays a key role in antioxidant activities and metal chelation [10]. Wang et al. 2014 demonstrated that polyphenol in combination with charged iron particles produces complex nanoparticles which have a size range of 50-90 nm. They utilised leaf extract from three plants for their experiment namely *Melaleuca nesophilia*, *Rosmarinus officinalis* and *Eucalyptus tereticornis* [29].

2.1.2 Flavonoids

Flavonoids, which are another family of secondary metabolites, are considered as the primary reducing agent in green synthesis of metal nanoparticles. To date, 7000 compounds from this family have been reported. They have low molecular weight and structurally, they consist of 15 carbon atoms with two aromatic rings (A and B) bridged by three Carbon atoms (C). They can be found as flavan-3-ols, flavones, flavonols, isoflavones, flavanones and anthocyanidins. In plants they are present as glycosides or methylated derivatives [22].

Flavonoids are biosynthesized through the phenylpropanoid metabolic route, which begins with the transformation of phenylalanine into the 4-coumaroyl-CoA. The enzyme chalcone synthase catalyzes the formation of chalcone scaffolds from 4-coumaroyl-CoA that serves as the backbone for all flavonoids [30]. Various flavonoid subclasses arise due to various enzymes, including, hydroxylases, reductases, $\text{Fe}^{2+/2-}$ oxoglutarate dependent dioxygenases and isomerases, which alter the structural framework of flavonoid [31].

Various studies have been reported in the literature regarding their ability to act as reductants which is mainly due to their nature of donating electrons and 'H' atoms [10]. Sahu et al. 2016 demonstrated the production of AgNps utilizing a range of Flavonoids- hesperidin, naringin and diosmin to reduce Ag^+ ion. Additionally, these flavonoids were also found to function as capping agents making an impact regarding the antimicrobial effects of AgNps [32]. Bose and Chatterjee et al, 2016, reduced the Ag^+ ions to silver nanoparticles utilizing the leaf decoction from *Psidium guajava* (guava plant). The authors suggested that quercetin (a flavonoid) reduces the Ag^+ to Ag^0 by liberating Hydrogen and gets oxidized to form quinone. The hydroxyl and the oxo functional group of other quercetin molecules then bring out the capping for stabilizing the silver nanoparticles [33]. Melkamu and Bitew, 2021, derived the eco-friendly synthesis of silver nanoparticles utilizing the leaf extract from *Hagenia abyssinica* plant. The phytochemical evaluation of the leaf extract indicated the presence of compounds like anthraquinone, saponins, tannins, alkaloids, phenols and flavonoids which bring out the reduction, capping and stabilization of nanoparticles throughout this process. The interaction flavonoids and metallic ions via carbonyl functional groups releases hydrogen, converting the enol form of flavonoids into the keto form, which leads to the formation of Ag^0 [34].

2.1.3 Terpenoids

Terpenoids are a class of compounds derived from terpenes, often associated with the flavor, color and aroma of numerous plants. They are derived from the essential oils of plants. About 90% part of essential oils is made up of terpenoids which are oxygenated terpenes [22].

The typical formula for terpenoids is $(C_5H_8)_n$, with 'n' indicating the number of isoprene units in the compound. On the basis of number of n, terpenoids can be classified into: hemiterpene (n=1, C₅), monoterpene (n=2, C₁₀), sesquiterpene (n=3, C₁₅), diterpene (n=4, C₂₀), sesterpene (n=5, C₂₅), triterpene (n=6, C₃₀), tetraterpene (n=8, C₄₀) and polyterpene [35].

The biosynthesis of terpenoids mainly occurs by two main pathways- the Mevalonate (MVA) Pathway which takes place in the cytosol and the 2C-methyl-d-erythritol-4-phosphate (MEP) Pathway which takes place in the plastid. Both these pathways lead to the production of isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP). DMAPP and IPP serve as building blocks to generate geranyl pyrophosphate (GPP) - a 10-Carbon molecule which gives rise to monoterpenes. On further addition of IPP units, a 15-Carbon molecule, Farnesyl pyrophosphate (FPP) and geranylgeranyl pyrophosphate (GGPP), a 20-Carbon molecule, are produced which gives rise to sesquiterpenes and diterpenes respectively [36]. These sesquiterpenes and monoterpenes are recognized as playing a crucial role in the production of silver nanoparticles [37]. They function as surface active chemicals to stabilize and reduce nanoparticles. However, their mechanism is still not clear. Shankar et al reduced silver ions into nanoparticles by using geranium leaves extract to demonstrate the role of terpenoids in biosynthesis of nanoparticles [38]. Pungle et al. 2022 demonstrated the use of *Tridax procumbens* plants' aqueous leaf extracts to derive the eco-friendly synthesis of silver nanoparticles. FTIR analysis of the leaf solution showed the presence of amines and hydroxyl groups in combination with fluoro compounds. Upon further analysis by HRLC-MS, the major capping agent was found to be fusinopril and reducing agents were found to be peptides, terpenoids, polyphenol and alkaloids [39]. According to Ahmed et al, 2010, "eugenol" plays a key role in bioreduction during fabrication of silver and gold nanoscale particles from extracts of the *C. zeylanicum* [40].

Scientists have suggested that the phenolic OH bond of eugenol undergoes a homolytic breakdown to yield H^+ ion in presence of sunlight which converts Ag^+ to Ag^0 [41].

2.1.4 Proteins

Proteins acts as reductants by donating electrons to the metallic ions in the course of plant mediated green synthesis of nanoscale particles. Mukherjee et al performed SDS-PAGE analysis of the leaf extracts of *Olax scandens* and concentrated supernatant of silver nanoparticles that were derived from this extract. The results indicated the existence of lightweight proteins upon examining the leaf extracts but there was no indication of their presence in the newly formed nanoparticles. This suggested the utilisation of those low molecular weight proteins during biosynthesis of nanoparticles [42]. Shukla et al. 2008, demonstrated the production of gold nanoparticles derived from soybeans by directly mixing soybeans and sodiumtetrachloroaurate ($NaAuCl_4$) in aqueous media. To explore the function of soybean proteins in the reduction of sodiumtetrachloroaurate ($NaAuCl_4$), the proteins was separated into low-molecular mass (<5 KDa) and high-molecular mass (>5 KDa) fractions through Centricon Plus-20 centrifugal filtration devices. Both protein fractions were then mixed with ($NaAuCl_4$) in aqueous media separately and both the fractions were able to produce gold nanoparticles, establishing themselves as the key component to reduce $NaAuCl_4$ [43].

Tavaf et al. 2015, effectively used reduced glycosylated adducts of whole casein fraction to serve as both reducing and stabilizing compound in the formation of nanosilver particles [44]. Using FTIR spectroscopy, a variety of C=O groups present in proteins have been proved to act as capping ligands. They associate themselves with the nanoparticle surface to ensure stability. Additionally, proteins and amino acids which contain exposed disulphide bonds and thiol group act as reductant and stabilizer during biosynthesis of nanoscale particles [41]. Bhattacharjee et al. 2005, generated gold nanoparticles by using a tripeptide sequence that has an exposed N-terminal [45].

3. Mechanism of Plant-derived Nanoparticles

The application of green chemistry to synthesize nanoparticles has been explored tremendously in the recent years. This green synthesis relies upon bottom-up approach in which nanoparticles

are assembled from a combination of smaller entities. Unlike the approaches used by traditional synthesis methods, plant-mediated synthesis mostly require an aqueous extract, normal temperature and normal air pressure which keep the energy loss in check [46]. However, careful consideration of the solvent type is essential, with water and ethanol being the most commonly employed due to their effectiveness in providing sufficient reducing and stabilizing phytochemicals and low environmental impact [47,48]. Lee et al. (2024) demonstrated that ethanol and water extracts effectively recover antioxidant and phenolic compounds with lower safety risks than more toxic organic solvent like methanol [49]. Nortjie et al. (2022) further emphasized that an ideal extraction solvent should exhibit low toxicity, appropriate volatility, good solubility for the target compounds and the ability to evaporate easily at mild temperatures. Selecting solvents such as water or ethanol, which meet these criteria and pose minimal environmental and health hazards, is therefore preferred for green synthesis approaches [47]. Compared with conventional chemical nanoparticle syntheses that often employ strong reductants (e.g., NaBH₄, hydrazine) and hazardous surfactants/solvents, the plant-based (green) approach generally reduces the use of highly toxic reagents and associated toxic by-products [50, 51].

The essential tools, processes, and materials used in nanoparticle synthesis encompass reductants, stabilizers, solvents, metal precursors, nucleation, growth, aggregation, stabilization, and characterization [1]. Plant-based nanoparticle synthesis has emerged as a better approach in large-scale industries because of their least environment impact and economical aspect as scaling them up is less expensive [23]. A systematic approach is necessary for deriving plant mediated synthesis of nanoparticles, which can be described as:

- 1) The plant should be taxonomically identified and specific plant material is selected.
- 2) Extraction process is carried out by employing an appropriate solvent/s which is followed by filtration to reduce the risk of addition of any impurities.
- 3) A metal salt solution is used as a nanoparticle precursor which is mixed with the plant extract.
- 4) Controlling physical factors (such as pH, temperature, phytochemical concentration and metal salt concentration) is necessary to ensure a successful reaction.
- 5) The nanoparticle formation is signified by a change in the solution's color.

- 6) Centrifugation is further carried out to separate nanoparticles from the solution to get rid of any remaining impurity.
- 7) Finally, the synthesized nanoparticles are characterized using a number of analytical techniques to get an idea about their size, shape, composition and physicochemical properties [10].

The process of eco-friendly plant derived nanoparticles synthesis can be summarized into three primary stages:

➤ **The Activation Phase**

Plant metabolites play a key role in extracting metal ions from their salt precursors during the activation phase. Researchers have reported that each metal has different reductive capabilities which directly influences the reduction of metals or their precursors during green synthesis process. In addition to it, the oxidation state of metal ions gets changed from monovalent or divalent to zero valent state and reduced metal atoms undergo nucleation [52]. It represents the initial stage in nanoparticle formation during plant mediated green synthesis. Nucleation results in the formation of a cluster which is termed as nuclei in wet chemistry nanoparticle synthesis. The radius of these clusters corresponds to the minimum size at which a particle can remain stable in the solution without redissolving into it. This process is really necessary to form stable clusters which upon growing give rise to nanoparticles [53].

➤ **The Growth Phase**

The growth phase follows bottom-up approach and mainly depends upon the interaction between stable nuclei and surfactants. The length and chemical nature of the surfactant should be taken into consideration too. Several studies suggest that the surface-solvent interaction can affect the dimensions and structural characteristics of the nanoparticles. Additionally, it was experimentally demonstrated that stable nuclei is observed at low concentration of surfactant, while on the other hand the nucleation and growth phases stopped in the excess of a strongly binding surfactant [53].

As the growth phase elongates, the smaller nanoparticles aggregate to form nanotubes, nano triangles, nanoprisms and a number of other irregular shapes until they achieve thermodynamic stability, this thermodynamic phenomenon is referred to as Oswald ripening [54].

➤ **The Termination Phase**

When the nanoparticles acquire the most energetically favourable conformation and a constant size and shape, the process gets terminated. Lesser the gibbs free energy of the nanoparticle, more stable the particle will be. This phase is highly dependable on plant extract to stabilize the nanoparticles. Based on FTIR analysis, some of the capacity of plant functional moieties like —C—O—C— , —C=C— , and —C=O were observed to act as protective stabilizers, aiding in nanoparticle stabilization and prevent anymore changes in their morphology [54]. The schematic in **Figure 3** outlines a typical synthesis procedure using zinc acetate and strawberry extract, showing the role of phytochemicals in reduction, Ostwald ripening and stabilization phases under controlled temperature and stirring.

4. Factors Affecting Plant-mediated Synthesis of Nanoparticles

Apart from phytochemical factors, various physicochemical factors like temperature, contact time, reaction environment, concentration, pH, composition of plant extract, amount of metal precursor, the size of raw materials, plant part, ratio of plant extract to metal solution and catalyst activity are responsible for determining the shape and dimension of the nanoparticles. In many cases, these factors also have a crucial role in shaping the application range of the resultant nanoscale particles [10]. So it is really important to control these factors during biosynthesis of nanoparticles to maintain the monodispersity, stability, morphology, rate of synthesis, and large-scale production. Optimum value of these factors was determined by studying one factor at a time for different values while keeping the other factors as constant. During experiment designing, these factors are chosen carefully in order to get the smaller sized nanoparticles [46]. It should also be noted that phytochemical composition of plant extracts can vary with factors such as season, geographic locations, growth conditions and use of fertilizers and pesticides, which may lead to inconsistencies in nanoparticle size, shape, and yield [14, 55]. Additionally, the standardization of extract preparation remains difficult, affecting reproducibility and large scale production [56].

Supplementary Table S2 summarizes the principal factors reported in previous studies, outlining how each condition affects nanoparticle characteristics such as size, shape and stability [1, 8, 57].

4.1 pH

Numerous studies have highlighted the impact of pH on biosynthesis of nanoparticles. pH can interfere with the electrical charges of metabolites essential for nanoparticle synthesis, influencing their size and morphology [58]. Muthu et al, 2017, investigated the influence of pH on the synthesis of silver nanoparticles utilizing the flower extract of *Cassia auriculata* [59]. Rajput et al, 2020, reported that neutral pH (7) at $60 \pm 2^\circ\text{C}$ results to the development of small, spherical silver nanoparticles within the size range of 5-20 nm using leaf extracts of Indian belladonna. They observed an increase in the peak of the UV-Vis spectrum of silver nanoparticles upon increasing the pH from 3 to 11 and the reaction rate was higher at the alkaline pH. However, alkaline pH leads to the fabrication of larger silver nanoparticles. Hence, balanced pH level (7) was marked as the optimum pH to derive silver nanoparticles [58]. Miranda et al, 2022, showed how pH influences the size, shape, and antimicrobial characteristics of silver nanoparticles derived from leaf-sourced extract from *Spinacia oleracea*. They highlighted the importance of pH by reporting that only those silver nanoparticles synthesized at pH 4, 5, and 9 had antimicrobial activity against *Candida albicans* and *Escherichia coli*. They used the pH level between 5-9 to carry out their experiment and observed that the particle size goes on decreasing with a rise in the pH. The nanosilver particles at pH 8 were smallest with a particle size of 91.75 nm, which was increased to 263.6 nm at pH 9. Upon TEM analysis, silver nanoparticles synthesized at pH 8 appeared spherical with rough surfaces. However, silver nanoparticles synthesized without adjusting their pH appeared as rod and spherical-shaped. Additionally, the stability of silver nanoparticles was tested by storing them for 8 weeks and further testing them on above-mentioned microbes. Only the nanosilver particles produced at pH 4 and 5 maintained their antimicrobial effectiveness, while those synthesized at pH 9 demonstrated reduced activity [60]. Jeevanandam et al. 2019, reported a study showing morphological transformation of MgO nanoparticles upon altering the pH. They prepared MgO nanoparticles using leaf extract of *Amaranthus tricolor* at 60°C and neutral pH (7) for 10 minutes. They noticed that the color changed to yellow from pale red as they altered the pH to basic, 9 and 11. Moreover, neutral pH

(7) gave rise to spherical MgO nanoparticles, which upon reducing the pH by adding hydrogen ions gets converted to hexagonal MgO nanoparticles. Their morphological characteristics were validated through TEM analysis [61]. Lee et al, 2019, also reported that nanosilver particles synthesized using fruit peel-derived extract from *Garcinia mangostana* at pH 4 had a spherical shape with an average diameter of 32.7 nm, which reduced to 7.12 nm when the pH was adjusted to 7 [62]. In 2021, Amjad et al. noted that the acidic medium with pH 5.5 supports the maximum production of copper nanoparticles than the basic medium with pH 7.5 during their experiment of green synthesis from the leaf extract of *F. margarita* [63]. Coman et al. 2024, documented the role of pH during platinum nanoparticles and experimentally concluded that optimal pH condition is necessary to carry out the reaction efficiently and faster. They set the pH at 7.5, 8, 9, and 10 while synthesizing platinum nanoparticles and found that *Quercus dalechampii* and *Quercus frainetto* contributed in the formation of platinum nanoparticles most efficiently at pH 10, while pH 9 supports the most efficient formation of platinum nanoparticles utilizing *Quercus petraea* [64]. Imade et al. in 2022 documented the fabrication of zinc oxide nanoparticles using peel derived extract from *plantain*, where they set the reaction pH to 12 for a smooth synthesis of the nanoparticles [65]. During a similar study conducted by Al Awadh et al. 2022, the effect of different pH was noted during the fabrication of ZnO nanoparticles using leaf extract from *Raphanus sativus*. They observed the characteristic peak absorption at pH 10 and 11, while there was no such observation on increasing the pH to 12-14, leading them to decide the optimal reaction pH to be 10 [66]. In a recent study conducted by Hirphaye et al. the researchers noted that a pH of 12 was highly effective in forming MgO nanoparticles from the female flower of *Hagenia abyssinica* [67]. A lower absorbance peak was observed when they adjusted the pH at 2-10, indicating the poor formation of nanoparticles.

4.2 Temperature

Temperature is another factor which influences the morphology and dimensions of nanoparticles. Many scientists have observed that the temperature has an inverse relationship with the size of nanoparticles. Lee et al. 2019, studied the impact of temperature on silver nanoparticles formation, synthesized from *Garcinia mangostana* fruit peel extract. They found that at room temperature (27° C) the nanoparticles developed an irregular spherical morphology with a mean

diameter of 49.91 nm, but as they increased the temperature to (45° C) the spherical nanoparticles appeared more uniform with their size reduced to 33.61 nm [62]. Khalil et al. 2013, also reported a similar study [68]. Rajput et al. 2020, recorded the formation of silver nanoparticles at various temperatures, including 20°C, 40°C, 60°C, and 80°C. Upon green synthesis of silver nanoparticles by using leaf extracts from *Atropa acuminata* at pH 7 for 30 minutes, they observed that the bioreduction of silver salt was higher at higher temperature, yielding small-sized silver nanoparticles, making 60°C as the optimum temperature for green synthesis of nanosilver particles [58]. Zheng et al. noted that the rate of reduction of platinum (II) ions was much higher at 90°C than that was observed at 30°C and 60°C. Herein, the smaller particle size indicates the insufficient Pt⁰ source and therefore, 90°C was identified as the optimal temperature [69]. Ansari et al. 2023, fabricated the nanosilver particles utilizing leaf extract of Neem (*Azadirachta indica*) plant. They noted that at temperature 30°C and 40°C, silver nanoparticles were not successfully produced. While upon raising the temperature range to 50-70°C, the nanoparticles started forming and the maximum production was found to be at 70°C [70]. Nagar and Devra, 2018, demonstrated the impact of temperature in the biosynthesis process while deriving copper nanoparticles using *Azadirachta indica* leaf extract [71]. Elia et al. 2014, reported that the eco-friendly synthesis of gold nanoparticles utilizing leaf derived extracts from *Salvia officinalis* as well as *Lippia citriodora* need a temperature rise to 35°C–40°C to reduce the Au(II) ions [72]. Coman et al.(2024)highlighted the role of temperature during fabrication of platinum nanoparticles utilizing the bark-derived extract from three species of *Quercus*. They noticed that the nanoparticles did not form at low temperatures. Only when they rose the temperature to 70°C did the solution exhibited a color change from light yellow to dark brown, confirming the synthesis of platinum nanoparticles [62]. In 2022, Al Awadh et al. noted the effect of temperature during the production of ZnO nanoparticles utilizing leaf-derived extracts from *Raphanus sativus*. They suggested that where no surface plasmon resonance peak was detected at 60°C as well as 70°C, that changed after increasing the temperature to 80°C and 90°C. However, the bandgap value for 80°C was closest to the theoretical value which made it as the optimal reaction temperature [66]. According to Hirphaye et al. in 2023, a temperature of 60°C was optimal for a higher yield of magnesium oxide nanoparticles derived from flower extract of *Hagenia abyssinica*. They observed a lower yield of nanoparticles upon either increasing the temperature above 60°C or lowering it below 60°C [67].

4.3 Contact Time

Several studies have highlighted the crucial role of contact time in nanoparticle synthesis. Rajput et al. 2020, assessed the effect of reaction duration on the synthesis of silver nanoparticles utilizing the leaf extract from *Atropa acuminata*. They measured the absorbance at various time intervals 30, 60, 120, and 180 minutes. SPR peak was observed at 424 nm after 30 minutes confirming the fabrication of silver-based nanomaterials. After allowing the mixture to rest for 180 minutes and subsequently analyzing it, no changes in the SPR peak was observed indicating that 30 minutes were enough for the complete reduction of silver salt [58]. Verma and Mehta, 2016, reported a similar study [73]. Das et al. (2019) presented a study which contradicted the result findings of Rajput et al. According to them, complete synthesis of silver nanoparticles requires a total of 2 hours of incubation time during biosynthesis using *Atropa belladonna* extract [74]. Riyanto et al. 2022, documented the role of storage time during synthesis of EO-AgNPs from the essential oil of *Cymbogoncitratrus*. The effect of storage time can be visually observed by a brownish color change. Also, the characteristic peak, which was observed at 430 nm after 24 hours, disappeared after storing them for 9-11 days [75]. Saif et al. 2016, evaluated the size of copper oxide nanostructures and observed that the size of the particles transitioned to 634.4 ± 40.2 nm following a 72 hours incubation period which was initially determined to be 212.6 ± 47.26 nm [76]. During a study conducted by Hirphaye et al. the authors noted that increasing the incubation time from 30 minutes to 120 minutes during the formation of magnesium oxide nanostructures from flower infusion of *Hagenia abyssinica* resulted in the highest absorbance, which started to fall again as the incubation time was increased further beyond 120 minutes till 240 minutes. Additionally, the size of nanoparticles got bigger, which made the authors to decide 120 minutes as the optimal incubation time to get smaller nanoparticles [67].

4.4 Metal salt concentration

Many studies reported that the type of metal salt and its concentration is directly associated with the hue of the reaction mixture and the structure of the resulting nanoparticles [77]. Rajput et al. 2020, found that increasing the concentration of AgNO_3 enhanced the synthesis of silver nanoparticles upto a concentration of 5 mM, beyond which a distorted peak was observed [58]. Saini et al. (2019) also reported a similar study when they observed that the production of silver

nanoparticles enhanced with the rise in AgNO_3 concentration [78]. Riyanto et al. 2022, evaluated the influence of AgNO_3 concentration during synthesis of EO-AgNPs by performing their experiment across varying concentrations of 2, 4, 6, 8, and 10 mM. They observed that nanoparticles synthesized from 2 mM of AgNO_3 had a lighter color, while the nanoparticles synthesized from 10 mM of AgNO_3 appeared to be much darker. The absorbances at various AgNO_3 concentrations 2, 4, 6, 8, and 10 mM were found to be 0.392, 0.472, 0.543, 0.573, and 0.663, respectively. On analyzing the different samples with UV-Vis spectrophotometer, the nanoparticles formed at 6, 8, and 10 mM AgNO_3 were found to be more stable [75]. As reported by Nagar and Devra, an increase in the size of copper nanoparticles from 48.01 to 78.51 nm when the concentration of copper chloride was increased from 6×10^{-3} M to 7.5×10^{-3} M. They suggested that high concentration of copper chloride results in the generation of higher number of nuclei [71]. Coman et al. (2024) carried out the synthesis of platinum nanoparticles at different concentrations of K_2PtCl_6 , 0.1mM, 1mM, and 5mM. The authors concluded that while 5mM concentration of K_2PtCl_6 solution inhibited the synthesis of nanoparticles altogether, a lower concentration of 1mM resulted in the most efficient reaction, making 1mM concentration of K_2PtCl_6 as the optimal concentration [64]. In a study conducted by Nadeem et al. 2024, the precursor salt concentration influenced the shape and size of nanoparticles produced. The authors stated that the copper oxide nanoparticles synthesized from 0.25 M copper (II) acetate $[\text{Cu}(\text{OAc})_2]$ had an approximate size of 34 nm and exhibited interlinking voids and pores. Upon increasing the concentration of metal salt to 0.5 M, the nanoparticle size increased to 44 nm, maintaining a spherical to irregular planar shape. Similarly, the magnesium oxide nanoparticles synthesized from 0.25 M magnesium sulfate (MgSO_4) had an average size of 30 nm. Upon increasing the concentration to 0.5 M, the average size increased to 38 nm and the Iron oxide nanoparticles synthesized from 0.25 M ferric chloride (FeCl_3) were observed to be cylindrical with an average size of 53 nm, while the nanoparticles synthesized from 0.5 M FeCl_3 had a spherical shape with a mean size of 31 nm. Also, the activities of magnesium oxide and iron oxide nanoparticles were less at 0.5 M as compared to 0.25 M concentration of their metal salt [79]. In 2023, Hirphaye et al. highlighted the role of concentration of precursor during the biosynthesis of nanoparticles. During their experiment to derive magnesium oxide nanoparticles from flower extract of *Hagenia abyssinica* and magnesium nitrate hexahydrate solution as precursor, they suggested that as the concentration of precursor salt increased from 0.5 mM to 1

mM, higher absorbance and better yield of nanoparticles were produced. However, any further increase in the concentration caused the absorbance to drop again establishing precursor concentration as an important parameter during the green synthesis of nanoparticles [67].

5. An Overview of the Different Types of Plant-Derived NPs

5.1. Metal-based Nanoparticles

Nanoparticles can be categorized as organic, inorganic and carbon-based types based on their chemical nature and structural characteristics. Organic nanoparticles includes micelles, liposomes and dendrimers, while inorganic nanoparticles, which lack carbon, includes all the metal nanoparticles which are composed of a pure metal [80]. **Figure 4** illustrates this classification. Metal nanoparticles have been the centre of attention lately because of their wide application ranging from pharmaceutical fields to various cosmetic products used in day-to-day life [81]. Metallic nanoparticles can be generated in large-scale industries by employing a downstream process optimization. Various metallic nanoparticles are derived by utilizing different metals such as silver, gold, platinum, palladium, zinc, copper, titanium, magnesium, etc. Various properties of metallic nanoparticles like unique optical characteristics, high stability, and quantum size effects enable their application across diverse fields such as food industries, farming and crop production, cosmetics, pharmaceutical sector and wastewater treatment. Based on the number of metals in their composition, they are categorized as monometallic, bimetallic, trimetallic, and polymetallic nanoparticles. As their name suggests, monometallic nanoparticles are composed of a single metal, bimetallic nanoparticles are composed of two metals, trimetallic nanoparticles are composed of three metals, and polymetallic nanoparticles are composed of more than three metals [46]. An overview of selected studies on plant-mediated synthesis of metal-based nanoparticles, along with their key characteristics and applications, is presented in Supplementary **Table S3** [58, 75, 82-105].

5.1.1. Monometallic Nanoparticles

The production of monometallic nanoparticles has garnered significant interest in recent years as they are easy to synthesize with diverse applications across various fields. Monometallic nanoparticles can be further categorized into metallic, transition, and magnetic nanoparticles on the basis of the type of metals present in them. The production of silver and gold nanoparticles is widely recognised as the most prevalent choice among researchers [46]. Various monometallic nanoparticles prepared in the recent years using various metals, including, platinum, silver, copper, palladium and gold are described below:

Silver Nanoparticles

In ancient times, various forms of silver were used as food preservatives and use of silver utensils were a common practice because of their antimicrobial properties. Silver nanoparticles have been a center of attention in the last one or two decades due to their pronounced cytotoxic activity against several pathogenic microorganisms like bacteria, protozoa, and fungi [106]. The unique characteristics of silver nanoparticles include high catalytic and antimicrobial activity, high electrical and thermal conductivity, chemical stability, etc. These nanoparticles are also employed in biomedical fields because of their use in cancer treatment, dental technology, bioimaging, etc [107]. According to Larue et al. in 2014, silver nanoparticles were considered as one of the most produced nanoparticles worldwide with a production rate of 500 tons per year [108]. Many researchers have successfully conducted the fabrication of silver nanoparticles utilizing different plant components, including, leaves, fruits, stems, roots, flowers, as well as bark, due to the phytochemicals present in them. Khosravi et al. (2023) demonstrated that silver nanoparticles synthesized by green route using *Malva sylvestris* extract effectively suppressed egg hatching and enhanced juvenile mortality of the root-knot nematode *Meloidogyne javanica* under both laboratory and greenhouse conditions, highlighting their promise as an environmentally friendly nematicidal agent [109]. Onitsuka et al, 2019, documented the production of silver nanoparticles employing black and green tea infusions derived from *Camellia sinensis*'s leaves. Upon TEM analysis, it was revealed that the nanoparticles made using green tea extracts had a dimension of 18.9 ± 4.4 nm, while nanoparticles made using black tea extracts had a bigger particle size of 34.4 ± 9.6 nm. The nanoparticles exhibited a spherical morphology and were quite stable. The nanoparticle colloidal solution was utilized to dye cotton clothes, providing them with the antimicrobial activity against *K. pneumoniae* and *S. aureus* [110]. Findings from recent work utilizing *Hyoscyamus muticus* L. extract for the green synthesis of silver nanoparticles demonstrated strong nematicidal activity against *Meloidogyne javanica* while maintaining biocompatibility with host plants. The biogenic AgNPs effectively reduced egg hatching and juvenile survival rates, thereby enhancing the plant's natural defense mechanisms without exhibiting any observable phytotoxicity. These results emphasize that green-synthesized nanoparticles, owing to their eco-friendly origin and low toxicity, hold considerable promise as replacements for hazardous synthetic agents [111]. In another study,

leaves of *Solanum nigurum* were also used to synthesize silver nanoparticles by stirring the *Solanum nigurum* leaves extract with the silver nitrate for 10 minutes as reported by Vigilvani et al., 2019. Spherical and small-sized silver nanoparticles were obtained (1.74-6.96 nm), which had a pronounced antimicrobial and catalytic activity [112]. Silver nanoparticles averaging 30 nm were synthesized using leaf-derived solution of *Ligustrum lucidum* was revealed to have antifungal properties when assessed for its effectiveness on *Setosphaeria turcica*, the half-maximal inhibitory concentration (IC₅₀) was determined to be 170.20 µg/ml, as reported by Huang et al., in 2020. Moreover, the silver nanoparticles exhibited an enhanced antifungal effect upon integration with epoxiconazole in a 9:1 and 8:2 ratio [113]. Bekhradian et al. (2024) demonstrated the potential of *Malva sylvestris* extract as a biogenic reducing and stabilizing agent for the synthesis of silver and silver oxide nanostructures. The phytochemical components of the extract, including phenolics and flavonoids, play a crucial role in reducing Ag⁺ ions and capping the resulting nanoparticles. These biosynthesized Ag/Ag₂O nanostructures exhibited notable antimicrobial and antioxidant activities, confirming the synergistic effect of the plant-derived biomolecules and the metallic core [114]. Qais et al., 2020, showed the production of silver nanoparticles utilizing seed extract of *Carum copticum* under constant stirring at ambient temperature. The obtained nanostructures predominantly exhibited a spheroidal shape with different sizes and with antivirulence and antibiofilm properties [115]. The production of silver nanoparticles was additionally documented by Odeniyi et al., 2019, using the aqueous and methanolic fruit extract of *Nauclea latifolia*. The particles were irregularly shaped with 10 nm as their size which was analyzed using SEM. The resultant nanoparticles had a broad spectrum of applications, although the nanoparticles synthesized from aqueous fruit extract were found to be much more efficient than those prepared using methanolic fruit extract. They showed antibacterial properties against most of the pathogens they were tested for (*C. Freundii*, *Staphylococcus* sp., *S. aureus*, *Escherichia coli* and *Klebsiella* sp), antifungal properties (*Rhizopus* sp. and *Candida albicans*). The nanoparticles were also used to formulate cold creams which were considered as appealing and satisfactory and also showed antimicrobial and antifungal activity against some of the tested pathogens [116]. According to Rajabi et al. (2016) Plant extracts such as those from *Suaeda Acuminata* provide bioreductants and stabilizing compounds, enabling green synthesis of silver nanostructures without surfactants or templates, thereby lowering cost and complexity [117].

Gold Nanoparticles

Gold is always considered as a symbol of wealth and prosperity. Its use in jewelry, ornaments, kings' palaces, and crowns is clearly registered in history. In India, the ashes of gold were used as an Ayurvedic medicine during ancient times. Gold, although being inactive in bulk size, found to possess unique characteristics in nanoscale. Gold nanoparticles, despite being expensive, has caught the attention of many researchers over the last few decades because of their enormous industrial application due to their least to no toxic effects against human cells, solubility, stability, catalytic properties, easy one-step green synthesis, their ability to conjugate with proteins, disease diagnostic properties, gene expression, and drug delivery [46]. Elia et al., 2014, performed the fabrication of gold nanoparticles utilizing the fruit-derived extract of *Punica granatum* and leaf-derived extracts of *Pelargonium graveolens*, *Lipia citriodora* and *Salvia officinalis*. The nanoparticles showed excellent biocompatibility and stability [72]. According to Patil et al., 2023, fruit extract of *Capsicum anuum* can be utilized in production of gold nanoparticles. This synthesis was carried out at 90°C with vigorous stirring for several minutes. The transition in mixture color from pale yellow to deep violet signified the formation of gold nanoparticles. The obtained nanoparticles, exhibited a spherical shape, ranging in size from 20 to 30 nm, with an average diameter of 25.92 nm. The nanoparticles showed dose-dependent antioxidant activity against DPPH (86.0% at 100 µg/mL), anti-inflammatory activity (IC₅₀ value=619.4 µg/ml), within a concentration range of 100 to 1200 µg/ml, and anti-angiogenic effects at concentration of 100 µg/ml [118]. Fouda et al., 2022, constructed gold nanoparticles with crystalline and spherical morphology with a size distribution ranging from 5-53 nm and average size of 15.11 ± 8.5 nm from HAuCl₄ solution and the water based extract of *Zingiber officinale* rhizome. The process took place at 8 pH and 60 °C for 60 minutes. The effective synthesis of gold nanoparticles was indicated by a color shift in the solution from pale yellow to purple. The synthesized nanoparticles showed dose-dependent antimicrobial activity towards *Bacillus subtilis*, *Escherichia coli*, *Aspergillus brasiliensis* *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Candida albicans* and *Pseudomonas aeruginosa* with the highest zone of inhibition, ZOI, at a concentration of 200 µg/ml. Antioxidant properties of gold nanoparticles against DPPH was recorded as IC₅₀ value and was around 16 µg/ml, which exhibited a slightly greater effect in comparison with ascorbic acid, which served as the standard and exhibited an

IC₅₀ value of 12.8 µg/mL. Additionally, the cytotoxic impact of gold nanoparticles on adenocarcinoma cells (MCF7) and hepatocellular carcinoma cells (HepG2) were recorded as IC₅₀ of 288.23 ± 31.39 µg/mL and 131.9 ± 9.34 µg/mL respectively, with the negligible toxicity against normal oral epithelial cells (IC₅₀ of 487.612 ± 3.53 µg/mL) [119]. In another work by Ahmad et al., 2024, crude extract of *Aconitum violacium* was utilised for the synthesis of gold nanoparticles by constant stirring at 9 pH for 50 minutes. Following SEM and TEM examination, the particles exhibited a spherical shape with below 100 nm as their size and triangular shape with near 100 nm as their size. The nanoparticles showed potent antibacterial, antioxidant, and photocatalytic activity [120].

Copper Nanoparticles

Copper has long been used in medical and dental fields because of its antimicrobial, inflammation-reducing, and low-toxicity characteristics [121]. In the literature, a huge data is available on the plant-mediated biosynthesis of copper nanoparticles and their wide-ranging applications. Copper nanoparticles are obtained by the reduction of Cu²⁺ ions in the presence of a salt solution of the same metal to Cu⁰ form. The bioactive compounds found in plant extracts provide them with good stability [122]. The size and morphology of copper nanostructures are largely influenced by the concentration of the precursor salt as demonstrated by Nagar and Devra in 2018 during synthesis of copper nanoparticles through leaf extracts of *Azadirachta indica* [71]. Mehdizadeh et al., 2020, carried out the synthesis of copper nanoparticles using cellulosic walnut shell as a base material. The process was first conducted at 50°C for duration of 2 hours. In the subsequent step, reduction of Cu²⁺ ions was accomplished by adding the ethanol solution of NaBH₄ and stirring it for another 3 hours. The nanoparticles were found to be stable up to 200°C. Upon TEM analysis, three different kinds of nanoparticles were appeared, CuNPs with size ranging from 15-22 nm, CuNPs with size ranging from 60-80 nm and non-supported CuNPs. The nanoparticles exhibited antimicrobial properties against *Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus*, antioxidant properties for DPPH and cytotoxic properties for K562 (erythroleukemia) cell line with IC₅₀ value of 25.24 ± 5 µg/ml in a dose-dependant manner [123]. Mali et al., 2020, constructed copper nanoparticles with spherical shapes from CuSO₄.5H₂O solution and the aqueous leaf extract from *Celastraspaniculatus*. The reaction pH was adjusted to 7.0. The obtained particles were 2-10 nm in size with a mean

diameter of 5 nm. The nanoparticles exhibited good photocatalytic property and antifungal activity against *Fusarium oxysporum*. At different concentrations of Copper nanoparticles, 0.24, 0.18, and 0.12%, the mycelial growth inhibition was found to be 76.29 ± 1.52 , 73.70 ± 1.52 , and 59.25 ± 0.57 , respectively [124]. According to Amjad et al. in 2021, the copper nanoparticles can be synthesized from leaves extract of *Fortunella margarita* and $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ solution at 70°C and 5.5 pH for 30 minutes. The transition in color from dark green to bluish green represented the successful formation of nanoparticles. The nanoparticles appeared spherical but were agglomerated, exhibiting size ranging from 51.26-56.66 nm under SEM [63]. Sharma et al., 2018, synthesized copper nanoparticles utilizing the leaf-derived extracts of *Tinosporacardifolia* and CuCl_2 solution at 85°C for 20 minutes. The particles had a spherical shape with the size ranging from 50-130 nm. The synthesized nanoparticles showed excellent catalytic degradation towards reactive dye, eosin yellowish, safranin and direct dye [125]. Mali et al, 2020, utilized the secondary metabolites of leaf extract of *Celastrus paniculatus* to derive copper nanoparticles and the particles morphology as shown in SEM and TEM images, the structures exhibit a spherical shape with a size range of 2–10 nm. The copper nanoparticles synthesized from plants demonstrates effective catalytic degradation of MB (methylene blue) and notable antifungal potential against *Fusarium oxysporum*, 76.29 ± 1.52 mycelial growth inhibition at 0.24% copper nanoparticles concentration [124].

Palladium Nanoparticles

Palladium nanoparticles have a broad applicability in bioscience, biomedicine, and pharmacy. These nanoparticles have drawn great attention due to their large surface area relative to volume, which enables them to act as highly efficient and specific catalysts based on their morphology, as reported by Cheong et al [96]. A number of phytochemicals from plant carry out the green synthesis of palladium nanoparticles by facilitating the reduction the Pd(II) ions present in metal (Pd) salts [1]. Petla et al produced palladium nanoparticles utilizing leaf-derived extracts from Glycine Max. The leaf extract has various polyols, terpenoids, and reducing sugar, which worked as reducing agents to synthesize palladium nanoparticles which had a FCC crystalline framework with a dimension of 15 nm [96]. Vinodhini et al., 2022, conducted the plant-mediated fabrication of palladium nanoparticles using the leaf extract from *Allium fistulosum*, *Basella alba*, and *Tabernaemontana divaricate*, with the size of 500 nm, 2 μm , and 2 μm respectively. The

obtained nanoparticles were spherical. The nanoparticle formation was indicated by a color transition from mild brown to dark brown in case of *T. divaricata* and *A. fistulosum*, while pale brown to green in case of *Basella alba*. The nanoparticles were further evaluated for their biomedical application. They showed highly effective antibacterial efficacy for *Bacillus cereus*, *Bacillus subtilis*, *Escherichia coli* and *Staphylococcus aureus*, with the greatest antibacterial effect noted at a concentration of 100 μl . They were also found to be antifungal against *Aspergillus flavus*, *Penicillium sp.*, and *Candida albicans* at three different diameters, 150, 100 and 50 nm, respectively. Palladium nanoparticles synthesized from *Basella alba* also exhibited highest antioxidant activity at 1000 μg concentration as compared to others. The nanoparticles also showed dose-dependent anti-diabetic properties by repressing alpha-amylase enzyme. Additionally, the nanoparticles possessed a good photocatalytic activity too [99]. Sattar et al., 2024, utilized root extract of *Curcuma longa* for the biosynthesis of palladium nanoparticles. The mixture was continuously stirred at 70°C for a duration of 3 hours. The generated nanoparticles were characterized by a spherical structure, with sizes varying between 50-150 nm. Palladium nanoparticles showed dose-dependent antioxidant activity, antifungal activity towards *Candida sp.* with the highest zone of inhibition was reported as 17 ± 0.28 mm at 130 $\mu\text{g/mL}$. Similar results were noted while evaluating their antibacterial efficiency against *Staphylococcus aureus* and *Escherichia coli* with the maximum inhibitory zone reported to be 17 ± 0.28 and 27 ± 0.22 mm, respectively at the concentration of 130 $\mu\text{g/ml}$. The palladium nanoparticles also inhibited MCF7 (breast cancer) cell line in a concentration-dependent fashion with the highest inhibition observed at 130 $\mu\text{g/ml}$, which was $26.53\% \pm 2.45$ in comparison with untreated breast cancer cells [126]. Bathula et al., 2020, used leaf extracts of *Coleus amboinicus* to derive palladium nanoparticles ultrasonically. The transformation of the precursor solution from brown to black indicated the successful formation of palladium nanoparticles. Upon further exploring their morphology using HRTEM and TEM, the nanoparticles were confirmed to have a spherical and crystalline structure with dimensions ranging from 16-23 nm and an average diameter of 20 nm. The palladium nanoparticles were found to act as an exceptional catalyst in ultrasound-assisted Suzuki-Miyaura coupling reactions [127].

Platinum Nanoparticles

Platinum nanoparticles have been extensively researched, especially in relation to their utilization in the biomedical sector. Patel et al investigated the potential of platinum nanoparticles in nanomedicine and for their antibacterial properties [128]. In another study by Sahin et al., 2016, *Punica granatum*-mediated platinum nanoparticles were studied for their cytotoxic effects against the human breast cancer cell line, MCF-7 as evaluated using the MTT assay. Platinum nanoparticles showed a dose-dependent inhibition in proliferation of MCF7 cells by inducing cell apoptosis during G0/G1 phase [129]. Zhang et al., 2022, performed the green synthesis of platinum nanoparticles utilizing floral extract of *Nymphaea tetragona*, in the $H_2PtCl_6/N.tetragona$ floral extract ratio of 1:4 and 1:1, and confirmed the average particle size of formed nanoparticles as 2.01 ± 0.80 nm and 4.04 ± 1.31 nm, respectively. The authors evaluated the use of platinum nanoparticles in anti-aging and skin lightening. Upon culturing the human melanogenic cell line (A375) with platinum nanoparticles, it was revealed that both types of nanoparticles exhibit dose-dependent inhibition of melanin production by inhibiting tyrosinase enzyme. They also inhibit the synthesis of UVB-induced melanin. Upon studying their effects on human skin fibroblast cell line (HFF-1), it was confirmed that the nanoparticles act as anti-aging agents by increasing the production of collagen I by promoting the underlying molecular mechanism (TGF-beta pathway and Smad pathway) responsible for collagen I synthesis [105]. In another study, Eltaweil et al., 2021, prepared platinum nanoparticles using leaf extracts of *Atriplex halimus*. The reaction was carried out at 9.6 pH, 95 °C, by constant stirring for around an hour, subsequently a color transition from dark yellow to black was noticed. The prepared nanoparticles possessed the particle size ranging from 1-3 nm and predominantly displayed a spherical shape. The nanoparticles exhibited excellent catalytic, antioxidant, and antibacterial activity [100]. In a similar work by Coman et al. in 2024, platinum nanoparticles were synthesized utilizing bark-derived extract from *Quercus petraea*, *Quercus frainetto* and *Quercus dalechampii* with the average diameter of 41 ± 5.3 nm, 41.6 ± 4.4 nm and 58.5 ± 7.6 nm, respectively. The synthesized nanoparticles had a spherical morphology and showed superb antioxidant properties, with Nanoparticles synthesized from *Q. petraea* having the maximum DPPH (539 mg GAE/g dw), FRAP (783 mg GAE/g dw), and CUPRAC (573 mg GAE/g dw) free radical scavenging activity while nanoparticles synthesized from *Q. dalechampii* showed highest ABTS free radical scavenging activity (605 mg GAE/g dw). The nanoparticles also had

potent antimicrobial activities against certain bacteria and fungi, especially against *Escherichia coli*, *Enterococcus faecalis*, *Candida krusei* and *Candida auris* [64].

5.1.2. Bimetallic Nanoparticles

The bimetallic nanoparticles resulted because of the discovery of hybrid nanoparticle synthesis in which two distinct metals are combined in a reaction vessel under carefully controlled conditions [130]. They can be of two types, first, where both the metals are mixed homogeneously in the same particle and second, where one metal (shell) encapsulates the other metal (core). **Figure 5** illustrates the green synthesis of Ag–Cu bimetallic nanoparticles using *Salvia officinalis* leaf extract, where phytochemicals act as reducing and capping agents during nanoparticle formation [131]. These nanoparticles are considered to be more significant as they overcome the shortcomings of corresponding monometallic nanoparticles and enhance their properties [46]. Bimetallic nanoparticles display distinct physical attributes, including high surface area, quantum effects, enhanced mobility, thermal, catalytic, magnetic, mechanical, chemical and optical characteristics, which makes them superior than the individual monometallic nanoparticles [130]. As reported by Fahmy et al. in 2021, that platinum–palladium (Pt-Pd) bimetallic nanoparticles synthesized from seed extract of *Peganum harmala* at 60°C for 24 hours were more functionally efficient than the individual platinum and palladium nanoparticles. Upon investigating their antioxidant activities by FRAP assay, it was found that platinum–palladium nanoparticles ($843 \pm 60 \mu\text{M TE/mg}$) showed about 4 times more antioxidant activity than harmala alkaloid fraction, ($33.91 \pm 5.82 \mu\text{M TE/mg}$), platinum nanoparticles ($277.3 \pm 13.5 \mu\text{M TE/mg}$), and palladium nanoparticles ($167.6 \pm 4.8 \mu\text{M TE/mg}$). Upon investigating their cytotoxic activity against human breast cancer cells, MCF-7 and lung cancer cells, A549, it was found that platinum–palladium nanoparticles were much more cytotoxic against MCF7 and A549 cells (IC_{50} of 3.6 and 8.8 $\mu\text{g/ml}$ respectively) in comparison with platinum nanoparticles (IC_{50} of 6.7 and 10.9 $\mu\text{g/ml}$ respectively) and palladium nanoparticles (IC_{50} of 10.8 and 31 $\mu\text{g/ml}$ respectively) [84]. A study presented by Ashishie et al., 2018, documented the eco-friendly synthesis of Ag-Cu bimetallic nanoparticles utilizing the aqueous infusion of *Kigelia africana* fruits at 120°C under reflux for 6 hours. The resultant nanoparticles appeared to be crystalline in nature with 10 nm as their size and demonstrated greater effectiveness against both gram-positive and gram-negative bacteria compared to antibiotics (Augmentin, Meropenem, Ofloxacin, Ciprofloxacin and

Racinef) they were tested against [132]. *Moringa oleifera* leaf extract was used to synthesize Ni/Fe₃O₄ MNPs at 70 °C by Prasad et al., 2017. The nanoparticles exhibited a spherical morphology with their diameter ranging from 16-20 nm. Ni/Fe₃O₄ nanoparticles functioned as a magnet adsorbent for the removal of Malachite green dye from an aqueous solution [133]. Luo et al., 2016, also documented the fabrication of Fe/Pd bimetallic nanoparticles utilizing the aqueous extract of grape leaf. The process was conducted at ambient temperature for a duration of 30 minutes. The synthesized nanoparticles exhibited a spherical shape with sizes ranging from 20-100 nm [134]. A study by Mamatha et al., 2020, reported the fabrication of Ag-Cu nanoparticles on cotton fabrics utilizing aloe vera leaf extract by constant stirring for 24 hours. These cotton fabrics incorporated with nanoparticles were used in medical fields for dressing wounds [135].

5.1.3. Trimetallic Nanoparticles

Trimetallic nanoparticles are made by combining three different metals or metal oxides. They possess a "triple core-shell architecture", where a specific element serves as the core, which is surrounded by a second element and forms an interlayer, the interlayer is further surrounded by a third element which acts as a shell [136]. **Figure 6** depicts the eco-friendly synthesis of Cu–Co–Ni trimetallic nanoparticles utilizing *Origanum vulgare* extract, highlighting the bio-reduction and stabilization mechanisms mediated by plant-derived phytochemicals [137]. Polymetallic or Trimetallic nanoparticles have been a center of attention for many years as they are much more efficient in terms of their biological properties in comparison with single-metal and dual-metal nanoparticles [138]. When compared with mono or bimetallic nanoparticles, they demonstrate enhanced stability with a higher diversity in shape, have better catalytic and antibacterial properties, and other therapeutic activities [139]. Their optical, magnetic, electronic, and catalytic properties arise from the combined effects of each metal present in them, which widens their area of application, such as catalysis, antimicrobial, antibiofilm, biomedicine, sensing, and catalysis. Trimetallic nanoparticles are also incorporated in food packaging, as reported by several studies [140]. To date, plant-mediated fabrication of trimetallic nanoparticles has been scarcely explored, as highlighted in the literature. A recent study by Farooq et al. (2025) highlighted the effectiveness of green synthesized Co-Fe-ZnS nanocomposites prepared from plant extract of *Avena fatua*, which demonstrated remarkable multifunctional activity including

the photocatalytic degradation of amoxicillin, hydrogen generation and CO₂ reduction. The study further optimized reaction conditions through response surface methodology (RSM), confirming the material's potential for sustainable and scalable photocatalytic applications. Such findings emphasize how combining multiple metal ions within a single nanosystem can significantly improve photocatalytic performance while adhering to environmentally friendly synthesis principles [141]. Vaseghi et al., 2018, synthesized the Cu-Cr-Ni oxide trimetallic nanoparticles using the aqueous infusion of leaves from *Eryngium campestre* and *Froriepia subpinnata* as reducing as well as capping agents. The process was conducted for 3 minutes at 34°C with the addition of all three precursor salts (Cr(NiO₃)₃.9H₂O, Ni(NiO₃)₂.6H₂O and CuSO₄.5H₂O) along with the leaf-derived extracts from *E. campestre* while, for *F. subpinnata* leaf extract, the temperature was set at 40°C. The transformation from transparent brown to colloidal brown confirmed the synthesis of trimetallic oxide nanoparticles. Upon FESEM analysis, the nanoparticles were revealed to have a nanoplate shape with average thickness of 14.15 nm, 10.96 nm and 18.73 nm for mixed leaf extract, *F. Subpinnata* and *E. campestre*, respectively. The nanoparticles exhibited strong antibacterial properties against *Staphylococcus aureus* and *Escherichia coli* [142]. Kannaiyan et al., 2021, documented the fabrication of trimetallic oxide Ni-Cr-Cu nanoparticles utilizing leaf-derived extract from *Coriander sativum*. Cr(NO₃)₃.9H₂O, Ni(NO₃)₂.6H₂O, and CuSO₄.5H₂O acted as precursor salts. The process was conducted for 45 minutes using a water bath at 40°C. The synthesized nanoparticles exhibited dose-dependent antibacterial and antifungal activity, where the highest zone of inhibition, ZOI, was calculated at 1000 µg/mL, i.e., 27 mm, 24 mm, 23 mm and 15 mm for *E. coli*, *Staphylococcus aureus*, *A. flavus* and *Penicillium sp.*, respectively [143]. In a similar study by Hussein et al., 2022, the authors investigated the fabrication of Ru/Ag/Pd nanoparticle employing the aqueous extract of leaves from garlic tunicate. The obtained nanoparticles exhibited a spherical morphology with sizes varying between 50 and 90 nm. The nanoparticles displayed significant antimicrobial effects against all examined microbes, i.e., *B. cereus*, *A. niger*, *C. glabrata*, *A. Flavus*, *E. coli*, and *C. albicans*, which had higher efficiency than individual palladium nanoparticles, silver nanoparticles, and ruthenium nanoparticles. The nanoparticles also exhibited cytotoxic properties for K562, HepG2, and Caco-2 cell line with an IC₅₀ values of 35.87 ± 2.0, 68.8 ± 3.9 and 47.35 ± 2.7 µg/ml respectively, which were further improved upon UV exposure and found to be 28.32 ± 1.6, 46.77 ± 2.6 and 9.32 ± 0.52 µg/ml respectively [144]. Radhakrishnan and Subramaniam

prepared Cu-Ag-Ru trimetallic nanoparticles using *Andrographis paniculata* leaf extract. The reaction was set at 70°C for 1 hour and the 0.1N copper sulfate, silver nitrate, and ruthenium chloride were utilized as precursor solution. The TEM image showed that the synthesized nanoparticles were spherical, exhibited an agglomerated structure, and had a mean size of 22 nm. The nanoparticles demonstrated exceptional photocatalytic activity, strong antibacterial properties for *E. coli*, *S. pyogenes*, *S. aureus*, and *K. pneumoniae*, with the highest zone of inhibition noted at 75 µL, anticancer activities against breast cancer line in humans and antioxidant activities [145]. Mohammed and Idrees, 2024, performed the synthesis of Co-Zn-Ni Trimetallic Oxide nanoparticles from the leaf extracts of *Cicer arietinum*. The produced nanoparticles exhibited a spherical shape with a diameter of 25.72 nm. Additionally, the nanoparticles showed stronger anti-biofilm activity against *Staphylococcus aureus*, than the commonly used antibiotic, ciprofloxacin [140].

5.2. Metal Oxide-based Nanoparticles

Metal oxide nanoparticles represent a distinct class of inorganic nanomaterials. A range of metal oxide nanoparticles, including, copper oxide, zinc oxide, cerium oxide, cobalt oxide, titanium dioxide, calcium oxide, silicon oxide, manganese oxide, iron oxide nanoparticles, etc. have been cited in scholarly literature. Till date, their application in renewable energy conversion, chemical reactions, detection systems, data storage technologies and electronics has already been studied [146]. Recent studies have demonstrated the green synthesis of metal oxide nanoparticles, such as γ -Al₂O₃, using plant extracts like *Oxystelma esculentum*, which exhibit excellent photocatalytic efficiency for both pollutant degradation and CO₂ photoreduction. The biogenic approach not only reduces the reliance on hazardous chemical precursors but also enhances surface reactivity and stability, highlighting the potential of such nanomaterials in environmental remediation and renewable energy applications [147]. A similar study by Farooq et al. (2025) also explored the green synthesis of cerium oxide (CeO₂) for their remarkable photocatalytic and environmental remediation potential. They synthesized CeO₂ nanoparticles using *Ammi visnaga* plant extract, achieving 96.19% methylene blue degradation within 1 hour and CO₂ photoreduction efficiency of 109.27 µmol·g⁻¹·h⁻¹ under optimized conditions [148]. Although the plant mediated fabrication of metal oxide nanoparticles is more complicated than metal-based nanoparticles since a high-temperature treatment is needed to derive nanoparticles from metal

oxides as they tend to be more unstable. So, to remove oxygen from the metal oxides, treatments like annealing or calcination are employed which requires temperatures beyond 300°C [149]. The main purpose to synthesize them is because they can enhance the properties of their corresponding metal nanoparticles [80]. Metal oxide nanoparticles offer a wide range of unique features regarding their optical, magnetic, and electrical characteristics which have led to their wide exploration to investigate their application in various fields [146]. Represented studies on plant mediated synthesis of metal oxide nanoparticles are summarized in Supplementary **Table S4** [52, 65-67, 79, 104, 150-180].

Copper Oxide Nanoparticles

Due to the magnetic, optical, and electrical properties of copper oxide, there has been an accelerated growth in the synthesis of their nanoparticles with a broad spectrum of application. In the existing literature, copper oxide nanoparticles derived from various plants have undergone exploration for their antimicrobial efficacy, photocatalytic activity and cytotoxic properties [150]. Alhalili Z, 2022, documented the fabrication of copper oxide nanoparticles utilizing leaf-derived extract of *Eucalyptus globoulus*. The obtained nanoparticles exhibited a spherical shape with an average diameter of 88 nm. Furthermore, its potential as an adsorbent was investigated by utilizing the nano-copper oxide for the removal of methyl orange from aquatic environments. Their study suggested the highest absorption capacity was 92.2 mg/g by regulating different factors such as keeping the weight of the adsorbent to be 0.045 g, pH-6 and temperature-25°C [150]. In another study by Nasrollahzadeh et al., 2015, Copper Oxide nanoparticles were synthesized using the flower-based extracts of *Anthemis nobilis* and used as catalysts in the aldehyde-amine-alkyne (A³) coupling reaction [181]. According to Andualam et al., (2020), Copper Oxide nanoparticles were synthesized from *Catha edulis*, which was employed as stabilizing and reducing agents and copper nitrate trihydrate as precursor. The reaction mixture was stirred constantly by keeping the temperature as 80°C until the solution's color shifted from deep green to deep brown. The biosynthesized nanoparticles appeared to be spherical upon SEM and TEM analysis. The authors investigated the nanoparticles for their antibacterial activity and concluded that the nanoparticles prepared by using leaf extract and precursor salt in the ratio of 1:2 had the highest antibacterial activity with ZOI of 29 ± 0.03 mm, 32 ± 0.02 mm, 24 ± 0.02

mm, 22 ± 0.01 mm for *Klebsiella pneumonia*, *Escherichia coli*, *S. pyogenes* and *Staphylococcus aureus*, respectively [182]. Similarly, a study conducted by Abosedo et al., (2022), utilized leaf-derived extract from *Justicia carnea* to produce copper oxide nanoparticles from copper sulfate pentahydrate as precursor salt. The formation of a brown solid precipitate after a total of 40 minutes confirmed the formation of nanoparticles [183]. Another study by Afzal et al., (2022) documented the production of copper oxide nanoparticles by employing leaf extracts from *Aerva javanica* and copper sulfate pentahydrate. The process was conducted at pH 11 and the temperature was kept as 60°C for 2 hours under constant stirring. The nanoparticles showed an agglomerated structure and had promising potential as antifungal and antibacterial agents [184]. Sukumar et al., (2020), discovered that the seed extract of *Caesalpinia bonducella* can serve as an effective agent for synthesizing copper oxide nanoparticles. The antibacterial potential of the obtained nanoparticles was assessed against *Staphylococcus aureus* and *Aeromonas* [185]. Atri et al., (2023), observed the octahedral crystal clusters of copper oxide nanoparticles synthesized using the aerial parts of *Ephedra alata*. The reaction took place at a temperature of 90°C over a period of 2 hours. The obtained nanoparticles also exhibited photocatalytic activity, antimicrobial potential against *C. albicans* (ZOI=16.2 mm), *S. cerevisiae* (ZOI=18.4 mm), *B. Subtilis* (ZOI=16 mm) and *S. aureus* (ZOI=20.4 mm) respectively. Additionally, biosynthesized copper nanoparticles were found to be much more efficient than chemically synthesized ones [186].

Zinc Oxide Nanoparticles

Zinc oxide, an N-type semiconductor, features a strong binding energy and broad band gap, which makes it suitable to use in the fields of photocatalytic, light-emitting diode, electrochemicals, sensors, and solar cells [149]. Plant-extracted Zinc oxide nanoparticles have found widespread applications in the pharmaceutical fields owing to their antimicrobial, anti-larvicidal, anti-inflammatory, anti-tumorous properties and their potential in drug delivery and imaging applications. Their low toxicity and cost-effectiveness has also garnered a considerable amount of attention from the researchers [187]. Manojkumar et al., (2023), observed hexagonal wurtzite structure in nano- zinc oxide synthesized by leaf extract of *Brassica oleracea* var. *botrytis* with their mean size calculated to be 52 nm. The nanoparticles displayed good antimicrobial potential against *Escherichia coli* (inhibition zone of 9 mm), *Klebsiella pneumonia*

(inhibition zone of 13 mm), *Staphylococcus aureus* (inhibition zone of 13 mm) and *Bacillus subtilis* (inhibition zone of 16 mm) respectively, effective photocatalytic breakdown of methylene blue and larvicidal activity against the larva of *Culex quinquefasciatus* with the LC50 and LC90 value being 76.03 and 190.03 ppm, respectively [188]. Idris et al., (2024) successfully prepared zinc oxide nanoparticles from leaf extract of *Mariposa christia vespertioni*, they showed an agglomerated and irregular structure with the particle size varying from 38–65 nm. The nanoparticles exhibited excellent potential to be used as anode materials in Sodium-Ion Batteries, SIBs [189]. Al-Radadi et al., 2022, produced zinc oxide nanoparticles using underground stem extract from *Zingiber officinale*. The reaction was carried out at 60 °C temperature, 11 pH, 60 minutes of incubation time, and 2.0 mg of metal salt concentration. The authors also revealed that the obtained nanoparticles improved the antibacterial potential of various antibiotics like Ciprofloxacin, Imipenem, Vancomycin, and Amoxilin-Clavulanic acid against *Echerichia coli* and *Staphylococcus aureus*. The nanoparticles were also identified as possessing hemo-compatible, antioxidant and anti-inflammatory properties. Additionally, the nanoparticles exhibited anti-diabetic properties by inhibiting alpha-amylase and anti-Alzheimer's properties by inhibiting acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) [91]. Al-Awadh et al., (2022), obtained spherical structured nanoparticles with the particle size of 66.47 nm synthesized from leaf extract of *Raphanus sativus* and zinc acetate solution ($\text{Zn}(\text{O}_2\text{CCH}_3)_2(\text{H}_2\text{O})_2$) as precursor salt. The synthesis of nanoparticles were found to be highly efficient at 12 pH and 80°C and showed good cytotoxicity in inhibiting human breast cancer cells [66]. Karimzadeh et al., (2020), reported spherical ZnO nanoparticles with the particle range of 20-80 nm synthesized using aerial parts of *Acantholimon serotinum* at 60°C and 8 pH for 6 hours. The development of a yellowish brown hue signifies the successful formation of nanoparticles. The nanoparticles were further investigated for their anti-cancerous activity against HEK-293 (IC50: 60 µg/ml), MDA-MB-231 (IC50: 24 µg/ml), SH-SY5Y (IC50: 42 µg/ml) and Caco-2 (IC50: 61 µg/ml) [190]. A study by Sana et al., 2020, documented the formation of ZnO nanoparticles utilizing leaf extract of *Crotalaria verrucosa*. The biogenic nanoparticles appeared hexagonal in structure, the size varying between 16-38 nm and displayed potential as an effective antimicrobial substance against *Klebsiella pneumonia*, *P. vulgaris*, *S. aureus* and *Escherichia coli* and anti-cancerous agent for DU145 as well as HeLa cell lines [191].

Iron Oxide Nanoparticles

Iron, which is one of the most common elements present in Earth's crust, has been of major interest to derive nanoparticles. Its oxides have four crystalline structures, α -Fe₂O₃, β -Fe₂O₃, γ -Fe₂O₃ and ϵ -Fe₂O₃. α -Fe₂O₃, β -Fe₂O₃ and γ -Fe₂O₃ are also termed as hematite, magnetite and maghemite. Among all these structures, α -Fe₂O₃ (hematite) is much more stable and shows interesting characteristics such as low toxicity, chemical inert nature, biocompatibility, etc., which motivated researchers for an extensive study to derive its nanoparticles and their application in various fields [192]. To date, many methods have been employed to derive α -Fe₂O₃ nanoparticles, including Sol-gel reactions, co-precipitation, microwave, and microemulsion. However, green synthesis is currently being preferred over them. Aida et al., (2023), described the production of hematite (α -Fe₂O₃) nanoparticles using floral extract of hibiscus and FeCl₃ solution, yielding a mean size of 20 nm [193]. Earlier, Miri et al. (2019) described the fabrication of α -Fe₂O₃ nanoparticles using a bark extract of *Salvadora persica*. The reaction took place at a temperature of 70°C for the time period of 2 hours and the pH was set at 7 and 11. The nanoparticles synthesized at pH 7 and calcinated at 350°C maghemite (γ -Fe₂O₃) nanoparticles were dominant while at 450°C hematite (α -Fe₂O₃) nanoparticles were dominant, which exhibited a spherical shape with dimensions ranging from 15–20 nm. The study also revealed the supermagnetic property of the biosynthesized nanoparticles [161]. Desalegn et al., (2019), carried out the synthesis of iron nanoparticles by utilizing peel extract of *Mangifera indica* [194]. Rostamizadeh et al., (2020), documented the production of Fe₂O₃ nanoparticles by using *Cornus mas* L. fruit extract. The nanoparticles were spherical with dimensions varying between 20–40 nm. The study indicated the potential of Fe₂O₃ nanoparticles for the production of nanofertilizers [195]. Jamzad et al., (2020), also successfully produced Fe₂O₃ nanoparticles using leaves extract of *Laurus nobilis* L. The nanoparticles displayed a predominantly spherical shape and with partial hexagonal features, averaging between 8.03 ± 8.99 nm. The nanoparticles exhibited remarkable antibacterial and antifungal activity [196]. Buarki et al., (2022), assessed the antibacterial inhibition efficacy against various bacterial strains, including, *Escherichia coli*, *Klebsiella pneumonia*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus* using almost spherical Fe₂O₃ nanoparticles synthesized from *Hibiscus rosa sinensis* flower extract and FeCl₂.4H₂O in the ratio of 2:1. The nanoparticles exhibited an average diameter of 51 nm.

However, nanoparticles synthesized by using 1:1 ratio of flower extract and precursor salt showed better antibacterial activity with inhibition zones of 5 mm (*Escherichia coli*), 6 mm (*Klebsiella pneumonia*), 4 mm (*Pseudomonas aeruginosa*), and 3 mm (*Staphylococcus aureus*) respectively [156]. Shabbir et al., (2023), successfully synthesized uniformly spherical Fe₂O₃ nanoparticles by using *Madhuca indica* leaves extract and FeSO₄ solution at 37°C for 24 hours. The nanoparticles exhibited a size range between 50 and 60 nm. The synthesized nanoparticles showed effective free radical scavenging potential at a 1000 µg/ml concentration, anti-inflammatory activity, and anti-diabetic effects through the inhibition of the α-amylase enzyme in a concentration-responsive manner, (IC₅₀: 73.3% at 1000 µl/ml) [155]. Lakshminarayanan et al., (2021), conducted a study utilizing the leaf extract from *Bauhinia tomentosa* to produce cluster-like Fe₂O₃ nanoparticles possessing an average diameter of 70 nm. The obtained nanoparticles were utilized for the production of 1, 3-diolein [157].

Titanium Dioxide Nanoparticles

Titanium dioxide, a white-colored inorganic substance, has been immensely used in purification of water bodies due to their catalytic properties. Titanium dioxide or titania nanoparticles are known for their optical, dielectric, chemical stability, non-toxicity, and oxidation strength. Titania has three different types of polymorphs, namely anatase, rutile, and brookite, among which anatase is more preferred in green synthesis because of its high stability [197]. Bopape et al., (2023), prepared titanium dioxide nanoparticles using different concentrations of *Commelina benghalensis* plant extract, 10-30 g, and reported that on increasing the plant extract's concentration, much smoother and distinct spherical nanoparticles were observed with the size range of 30–200 nm. They also noted their photodegradation efficiency for MB (65%) and SSX (82.4%) [167]. Rathi et al., (2023), produced spherical (15–28 nm) TiO₂ nanoparticles from flower extract of *Caesalpinia pulcherrima*, irregular and near-spherical TiO₂ nanoparticles using peel extract from *Manihot esculenta*, and agglomerated quasi-spherical TiO₂ nanoparticles utilizing leaf extract from *Nervila aragona*, which were effectively utilized as catalysts for the breakdown of methylene blue and displayed antimicrobial potential against *P. Aeruginosa*, *Escherichia coli*, *Candida albicans* and *Staphylococcus aureus* [198]. Mbenga et al., (2023), recently described the production of TiO₂ nanoparticles utilizing leaf extract of *Tulbhagia violacea*. The nanoparticles turned out to be rectangular and irregular shaped and showed

moderate antioxidant and cytotoxic activities against HEK 293 and HeLa cell lines [168]. Sethy et al., (2020), prepared titanium dioxide nanoparticles by utilizing *Syzygium cumini*'s leaf-derived extract for the stabilization and capping of nanoparticles at room temperature for 8 hours and employed them as catalysts for the photocatalytic removal of lead (Pb) from water bodies near industrial area [199]. Aravind et al., (2021), reported that titanium dioxide nanoparticles produced using flower extracts of jasmine showed superior photodegradation of methylene blue (92%) as compared to the titanium dioxide nanoparticles prepared using hydrothermal (chemical) method [200]. Balaraman et al., (2022), reported plant-synthesized titanium dioxide nanoparticles using aqueous extract of *Sargassum myriocystum* to yield nanoparticles possessing cubic, square, and spherical morphology with particle size distribution of 50-90 nm, which were found to be pretty effective as antibiofilm agents against *P. vulgaris*, *S. epidermis*, *S. aureus*, *E. coli*, *P. aeruginosa* and *K. pneumonia*, larvicidal activities against *Aedes aegypti* and *Culex quinquefasciatus* and photodegradation activity against methylene blue [201]. Mohany et al., (2023), synthesized spherically shaped titanium dioxide nanoparticles using plant extract of *Solanum surattense* with dimensions varying between 10-80 nm. The shift in color of the reaction mixture from light green to whitish brown after continuous stirring under ambient temperature for a full day confirmed the formation of nanoparticles, which were quite effective in reducing the duration of seizures as investigated by maximal electroshock-induced epileptic (MESE) and pentylene tetrazole (PTZ) models. Additionally, the nanoparticles showed significant cytotoxic activity for THP-1 cell line at concentration of 80 µg/ml [173].

Magnesium Oxide Nanoparticles

Magnesium oxide nanoparticles are amongst the most widely studied metal oxide nanoparticles because of their high stability, low cost, and wide band gap. To date, they have been employed in a number of applications including water purification, fuel additives, sensing, absorbance, and antimicrobial applications [180]. MgO nanoparticles have been extensively utilized in biomedical applications for the treatment of stomach pain, in blood collection vessels, to relieve heartburn, coating capsules, bone regeneration, and many more [202]. Muhaymin et al., (2024), utilized the fruit extract from *Hyphaene thebaica* for the production of magnesium oxide nanoparticles with spherical morphology and an average diameter of 32.6 ± 5 nm. The nanoparticles showcased remarkable photocatalytic activity of methylene blue dye (98% after

110 minutes) [180]. Younis et al., (2021), synthesized MgO nanoparticles by employing flower extracts of *Rosa floribunda* charisma and obtained polyhedral-shaped particles of 35.25–55.14 nm size range as confirmed by HR-TEM images. The obtained nanoparticles exhibited antioxidant activity against xanthine oxidase (IC₅₀: 15.9 µg/ml), hydroxyl radical (IC₅₀: 31.9 µg/ml), nitric oxide (IC₅₀: 52.9 µg/ml) and superoxide (IC₅₀: 26.2 µg/ml) in comparison with ascorbic acid which was used as control. The nanoparticles also exhibited anti-aging activity in dose-dependent manner by inhibition of enzymes like tyrosinase (IC₅₀: 158.6 ± 5.20 µg/ml), hyaluronidase (IC₅₀: 191.4 ± 5.68 µg/ml), elastase (IC₅₀: 82.5 ± 2.93 µg/ml), hyaluronidase (IC₅₀: 191.4 ± 5.68 µg/ml) and collagenase (IC₅₀: 58.7 ± 1.66 µg/ml). Moreover, the nanoparticles were found to be antibacterial against three skin pathogens *P. aeruginosa* (MIC: 31.25 µg/ml), *Streptococcus pyogenes* (MIC: 7.81 µg/ml) and *Staphylococcus epidermis* (MIC: 15.63 µg/ml). Additionally, the nanoparticles also showed anti-biofilm activity against the above-mentioned bacterial strains with the minimal concentration required to inhibit biofilm formation of 7.81, 1.95 and 1.95 µg/ml respectively [175]. Hirphaye et al., (2023), demonstrated the production of MgO nanoparticles utilizing *Hagenia abyssinica* female flower. The process was conducted pH 12 and 60 °C for 120 minutes. Upon SEM analysis, the biogenic nanoparticles appeared to be sphere-like, exhibiting the particle size ranging from 10-40 nm. Authors also discussed how different parameters such as duration of reaction, concentration of precursor salt, temperature, volume of plant extract, and pH play an important role in the biogenic formation of MgO nanoparticles and showcased the antimicrobial potential of the obtained nanoparticles against *Escherichia coli* and *Staphylococcus aureus* with their zone of inhibition recorded to be 15 ± 0 mm and 27 ± 0.28 mm, respectively [67]. A study by Abinaya et al., (2023), described the synthesis of magnesium oxide nanoparticles utilizing leaf extract of *Psidium guajava* with the spherical morphology and the size of 85.8 nm. The nanoparticles were analyzed regarding their larvicidal as well as antibacterial properties [177]. Likewise, Dinga et al., (2022), reported magnesium oxide nanoparticles synthesized from seed extract of *Melia azadarach* at varying volumes of 20, 10 and 5 mL. The authors observed that while all the nanoparticles were spherical in shape, the edges become more definite upon increasing the volume of the seed extract and particle size reduced in size from 73.29 nm to 62.4 nm and 44.29 nm with the addition of 5, 10 and 20 mL of seed extract, respectively. Moreover, these nanoparticles found to be effective as larvicidal and antioxidant agents [174].

5.3. Carbon-based Nanoparticles

The emergence of carbon nanoparticles have gained a significant interest due to their extensive utilization in modern technologies such as water purification, energy storage materials, catalysis, electronics, biofuels, and bioimaging. Carbon nanoparticles include several types of nanomaterials including nanodiamonds (NDs), graphene and its derivatives, carbon nanotubes (CNTs), carbon nanohorns (CNHs), carbon nanofibers (CNFs), carbon-based quantum dots (CQDs), graphene oxides and fullerenes [203, 204]. Carbon nanotubes are categorized into single-walled and multi-walled types depending on the number of graphene layers in their composition. The dimensions and morphology of CNTs can be altered by altering the conditions like reaction gas, temperature, precursor and catalyst during the biosynthesis. With the rising of popularity of carbon nanotubes in biomedical fields, green synthesis is required in their cost-effective commercial production. This one-step synthesis process checks the use of chemical catalysts which are limited and replace them with plant extracts. Quantum dots (QDs) possess high luminescent 204, high photostability, low toxicity, chemical inertness, and biocompatibility when compared to other carbon nanomaterials which give them an upper hand in biomedical fields [205]. Carbon quantum dots can play the role of nano-carriers and an imaging tool simultaneously during drug delivery as reported by Ross (2020) [206]. Nanodiamonds were discovered accidentally during detonation process. Their core lattice has sp^3 hybridization while sp^2 hybridization is seen at the surface. Nanodiamonds, because of their low toxicity and fluorescence emitting property make them an ideal tool in diagnostics and bioimaging. Nanodiamonds include nanocrystalline diamonds (NCD) with a particle size measuring below 100 nm and ultrananocrystalline diamond (UNCD) with a particle size measuring below 10 nm [205]. Liu et al., administered the nanodiamonds into preadipocyte fibroblast line (3T3-L1) and lung adenocarcinoma epithelial cell line (A549). Cell imaging revealed that the nanodiamonds did not cause any harm to the cells even after a long period of time and did not interfere with the cell processes like division, differentiation, or gene expression, which makes them suitable to be used for tracking and identifying stem as well as cancer cells [207]. In another similar work by Perevedentseva et al., the uptake of nanodiamonds by both non-cancerous and cancerous cells, including HFL1 fibroblast-like human fetal lung cells, Beas-2b non-tumorigenic human bronchial epithelial cells and LH adenocarcinoma cells (A549) cells, was examined and

evaluated [208]. However, generating nanodiamonds through green synthesis remains very limited till date. Graphene, which appears to have a honeycomb-like structure, is also a subject of interest in green chemistry due to several studies reporting its production from biological agents as described by Kim et al., Ruan et al., and Gurunathan et al [209-211]. Graphene nanomaterials, due to the existence of a carboxyl group ($-\text{COOH}$) on its surface, makes a strong bond with nuclear bases, and acts effectively as biosensors for the DNA and RNA. Its applications as nanocarriers for anti-cancer drugs have also been explored [205]. Qu et al., (2016), described the green fabrication of carbon nanotubes using *Brassica juncea*'s extracts. Upon further analysis, the carbon nanotubes appear to have a hollow core with the outer diameter as 80 nm [212]. Recently, Singh et al., (2024), synthesized carbon nanoparticles utilizing different plants, including *Azadirachta indica*, *Pisidium guajava*, *Mangifera indica*, *Bergera koenigii* and *Syzygium cumini* leaves extract. Based upon SEM analysis, all the nanoparticles were found to have a quasi-spherical shape with different sizes. The average size distribution was around 23.5 nm, 32 nm, 33 nm, 42.5 nm, and 37 nm for nanoparticles synthesized from *Syzygium cumini*, *Mangifera indica*, *Azadirachta indica*, *Bergera koenigii*, and *Pisidium guajava*, and *Holy basil*, respectively. The obtained nanoparticles exhibited remarkable antioxidant properties [213]. Tripathi et al., (2017), observed the hollow rectangular cross-section carbon nanobelts and single-walled nanotubes by utilizing several plants like *Cynodon dactylon*, *Rosa*, *Azadirachta indica*, and *Juglans regia* leaf extracts. The nanomaterials were further characterized by using HR-TEM, Raman and IR spectroscopy [214]. However, green route to synthesize carbon nanomaterials require a very high temperature and long reaction time. To overcome this issue of high energy consumption, Arizaga et al., (2022), fabricated carbon nanomaterials utilizing extracts from tomato. The tomato pulp was mixed with aluminum ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) and magnesium salt ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) at 8.5 pH, followed by calcination at 60 °C. FESEM analysis confirmed the semi-spherical structure of the nanoparticles, which were later investigated for their fluorescent response against metal cations and photothermal activity [215]. Nadeem et al., (2022), obtained spherical carbon nanoparticles with particle size of 57 nm, 24 nm, and 18 nm by utilizing linseed, olive and mustard's seed oils, respectively. The produced nanoparticles were assessed for their antibacterial efficacy against *Staphylococcus aureus*, *Proteus refrigere*, *Streptococcus haemolyticus* and *Pseudomonas aeruginosa*, and showed excellent outcome [216]. Damera et al., (2020), described the production of carbon nanoparticles utilizing Eucalyptus

twigs and ammonium chloride. The nanoparticles were multi-emissive and referred to as light blue, blue, green, and red carbon nanoparticles. Light blue carbon nanoparticles showed remarkable sensing of Brilliant Blue (BB), a toxic, synthetic food colorant [217].

6. Application in Energy

With the rapid rise in the world population, the exhaustion of fossil fuel resources has become a major global challenge. Simultaneously, the harm done to the ecosystem by emission of fossil fuels has motivated the scientists to come up with a substitute, which is climate resilient and can meet the demand of growing population. Amidst the global petroleum crisis, bioenergy has come up as a clean energy source with low carbon impression [218]. Biofuels are derived from biomass and can be divided into four according to their source, including first-generation biofuels, sourced from consumable food crops and contains biodiesel, biogas, and bioalcohols. Second-generation biofuels are produced using non-edible feedstocks, including lignocellulosic biomass and contain cellulosic ethanol, dimethylfurane, etc. Third-generation biofuels or "algae fuel" or "oilage" are made from algae as their name suggests and contains biodiesel, butanol and propanol. Lastly, genetically modified algae are utilized to produce fourth-generation biofuels and contain biobutanol, biohydrogen, biomethane, etc [219]. A shift towards renewable biofuel has significantly lowered greenhouse gas emissions and carbon footprint. Biofuels, including biodiesel, biogas, bioethanol, biomethane, and biohydrogen have been largely investigated to minimize the dependency on petroleum derivatives [218]. The conversion of biomass into biofuel is primarily carried out by processes like fermentation, transesterification, thermochemical, and biochemical conversion. Although the production of biofuels is quite costly, which limits its commercialization, implementation of cutting-edge technologies in biofuel production to lower its cost and enhance its yield is necessary to ensure a carbon-free economy. To tackle this problem, many researchers have applied nanotechnology to accelerate the cost-efficient and sustainable production of bioenergy and biofuel. Although several studies report that plant mediated synthesis reduces reagent use, simplifies processing and lowers laboratory energy consumption, there is a scarcity of rigorous techno-economic analyses or cost comparisons that directly quantify overall cost benefits versus chemically synthesized catalysts or conventional processes at scale. Therefore, while green synthesis is promising for reducing

certain material and energy inputs, its true impact on total production cost and commercialization feasibility remains to be demonstrated by dedicated techno-economic analyses and scale-up studies [10, 19, 220]. Nanomaterials, because of their exceptional and unique properties like chemical reactivity, high thermal and electrical conductivity, large surface area, optical activity, and chemical strength has proved to be promising devices to enhance biofuel creation [219]. Nanoparticles like calcium oxide and magnesium oxide can be used as heterogeneous catalysts in transesterification to generate biodiesel, as reported by Zhang et al [221]. Or they can be used as carriers to immobilize enzymes to enhance their catalytic properties. Utilization of nanocatalysts in transesterification to generate biodiesel have garnered massive attention due to their decreased size, high reactivity, low toxicity, and significant reusability, as demonstrated by Qiu et al [222]. Some of the examples of such nanocatalysts include MgO, SrO, ZnO and CaO, while substances like Al₂O₃ are employed to enhance the catalytic properties. In a study from Saka et al., 2022, ZnO nanoparticles were employed for the transesterification of *Mangifera indica* seed oil for biofuel production and they observed the maximum biodiesel yield of 85% at 10 ml nanocatalyst, temperature of 50°C, 7:2 M/O molar ratio and over a period of 1 hour [223]. Despite a huge amount of work done in the implementation of different types of nanoparticles in biofuel production processes, there are still some drawbacks, as these nanoparticles are derived from the chemical routes like sonochemical, sol-gel, chemical precipitation, and solid-state thermal decomposition. These processes result in a huge environment impact due to their demand for longer reaction time, high temperature, and pressure. So, the synthesis of nanoparticles through a green route and their utilization in bioenergy production is the need of the hour. However, this research is still in its initial stage with very few studies reported over the past couple of years. In a newly conducted study published by Arun et al., (2023), copper oxide nanoparticles was derived from the flower extracts of *Bombax ceiba* and was successfully used as reusable heterogeneous catalyst to produce biodiesel from *Bombax ceiba* oil feedstock. The findings validated a 95.6% yield of biodiesel by keeping the concentration of obtained nanoparticles as 3.5 wt%, reaction time as 50 minutes, reaction temperature as 60°C and methanol to oil ratio as 11:1. The produced fuel also has considerably low harmful emissions [224]. As Cholapandian et al., (2022), described, calcium oxide nanoparticles were produced utilizing the leaf-derived extract of *Acalypha indica* and also investigated their role as catalyst to produce biodiesel. They confirmed 94.74% yield of biodiesel at a temperature of 63.7°C, 11.8:1

M/O molar ratio, 2.4 wt% concentration of the catalyst for over a period of 70 minutes [225]. Similarly, Changmai et al., (2021), prepared magnetic nanoparticles from the *Citrus sinensis* peel ash to generate biodiesel from waste cooking oil. They achieved a 98% biodiesel yield under optimal conditions, including a period of 3 hours, a 6:1 M/O molar-ratio, a temperature of 65°C and 6% of catalyst. Moreover, the nanocatalysts (CSPA@Fe₃O₄) were found to be reusable and reactive up to nine consecutive cycles, adding it to its sustainability [226]. Yildirim and Ozkaya (2024), investigated the production of biohydrogen through plant-mediated synthesized nickel and cobalt ferrite nanoparticles. The nanoparticles were synthesized using olive leaves and Fe(NO₃)₃.9H₂O and NiCl₂.6H₂O as precursors for nickel ferrite nanoparticles and Fe(NO₃)₂.9H₂O and Co(NO₃)₂.6H₂O as precursors for the cobalt ferrite nanoparticles. The process took place for over a period of 2 hours at 200°C temperature. Upon SEM analysis, the measured mean particle sizes were 292 nm and 385 nm for CoFe₂O₄ and NiFe₂O₄ nanoparticles, respectively. The authors observed that both nanoparticles were capable of enhancing the yield of dark fermentation, with nickel ferrite nanoparticles improving the biohydrogen yield by 47%, while cobalt ferrite nanoparticles improved it by 41% [218]. Subramani et al., (2024), synthesized silver nanoparticles using the *Azadirachta indica* leaf extract and silver nitrate solution by constant stirring at 70°C until the colorless reaction mixture turned brown. The synthesized nanoparticles exhibited a spherical shape with an average size of 13 nm. The *chlorella* sp. when treated with these nanoparticles showed a higher growth rate with the higher yield of biohydrogen (10.8 mmol L⁻¹). On the other hand, the untreated cells had a low growth rate with low yield of biohydrogen (0.003 mmol L⁻¹) [227].

7. Conclusion and future prospect

Due to the rising energy needs and declining fossil fuels, scientists have established biofuels as a strong contender to maintain the global bioeconomy. However, the biofuel production has its own drawbacks which can be eliminated by using nanotechnology. Nanotechnology has emerged as a valuable approach to improve biofuel production, and among various strategies, the use of plant-extract-mediated nanocatalysts has gained considerable attention for being both effective and eco-friendly. Plant extracts contain diverse phytochemicals, including flavonoids and polyphenols, which can reduce and stabilize metal ions during nanoparticle synthesis [228, 220].

These green-synthesized nanoparticles have shown excellent catalytic properties, particularly metallic (Ag, Cu, Ni) and metal oxide nanoparticles (TiO₂, ZnO, Fe₃O₄), which have enhanced processes such as biodiesel transesterification, bioethanol production, and biogas upgrading [19, 228]. Optimal synthesis parameters- such as reaction temperature, pH, extract-to-metal precursor ratio and reaction time- play critical roles in tuning nanoparticle characteristics that directly influence catalytic efficiency. In addition to their role in bioenergy, these nanomaterials have also exhibited versatility in biomedical, environmental, and agricultural applications [220]. Therefore, plant-based nanocatalysts provide a promising route for developing sustainable and multifunctional materials that can support the transition toward a greener bioeconomy.

Despite these encouraging advances, significant research gaps persist. The lack of standardized synthesis protocols leads to inconsistent nanoparticle properties and limited reproducibility across studies. Moreover, mechanistic understanding of phytochemical interactions during nanoparticle nucleation and growth remains inadequate. Comprehensive studies on the toxicity, biocompatibility and environmental impact of these nanomaterials are still scarce, hindering their safe translation to large-scale use [55]. Furthermore, the scalability of green synthesis processes and their integration into real-world biofuel production systems require deeper exploration [229]. Further studies can be carried out on developing standardized extraction and synthesis protocols to ensure reproducibility and scalability; elucidating phytochemical-mediated reaction mechanisms through in situ analytical and computational methods; and bridging the gap between laboratory-scale catalytic performance and industrial-level biofuel applications. Detailed life-cycle and toxicity assessments are essential to ensure the environmental and human safety of these nanomaterials. Research should also explore invasive or toxic plants as alternative bioresources for nanoparticle synthesis, reducing dependence on edible or medicinal species. Furthermore, improving reusability, catalytic stability, and active-site density will be key to maximizing performance and ensuring long-term sustainability of nanotechnology-assisted biofuel production.

List of Abbreviations:

- 0D – Zero Dimensional
- AFM – Atomic Force Microscopy
- AChE – Acetylcholinesterase

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- AgNPs – Silver nanoparticles
 - BB – Brilliant Blue
 - CNTs – Carbon nanotubes
 - CQDs – Carbon quantum dots
 - CNFs – Carbon nanofibers
 - CNHs – Carbon nanohorns
 - DPPH – 2,2-Diphenyl-1-picrylhydrazyl
 - DMAPP – Dimethylallyl pyrophosphate
 - FCC – Face-centered cubic
 - FESEM – Field Emission Scanning Electron Microscopy
 - FRAP – Ferric Reducing Antioxidant Power
 - FPP – Farnesyl pyrophosphate
 - FTIR – Fourier transform infrared spectroscopy
 - GAE – Gallic acid equivalents
 - GGPP – Geranylgeranyl pyrophosphate
 - GPP – Geranyl pyrophosphate
 - HFF-1 – Human foreskin fibroblast cell line
 - HR-TEM – High Resolution Transmission Electron Microscopy
 - HRLC–MS – High-resolution liquid chromatography–mass spectrometry
 - IGC – Inert gas condensation
 - MB – Methylene Blue
 - MCF-7 – Human breast cancer cell line
 - MNPs – Magnetic nanoparticles
 - MEP – 2-C-Methyl-D-erythritol-4-phosphate pathway
 - MVA – Mevalonate pathway
 - NDs – Nanodiamonds
 - NPs – Nanoparticles
 - PdNPs – Palladium nanoparticles
 - PtNPs – Platinum nanoparticles
 - QDs – Quantum dots
 - RSM – Response Surface Methodology
 - SEM – Scanning Electron Microscopy
 - SIBs – Sodium-ion batteries
 - SSX – Sulfasalazine
 - SDS-PAGE – Sodium dodecyl sulphate–polyacrylamide gel electrophoresis
 - SPR – Surface plasmon resonance
 - TEM – Transmission electron microscopy
 - UV–Vis – Ultraviolet–visible spectroscopy
 - XRD – X-ray diffraction

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AI-declaration:

The authors confirm that no AI tools were used to generate any content of this manuscript. No AI-based tools has been used for figure creation. The image has been created by using M.S. powerpoint and Canva.

Supplementary Material

Supplementary material associated with this article has been published online and is available at: [Link to the DOI](#)

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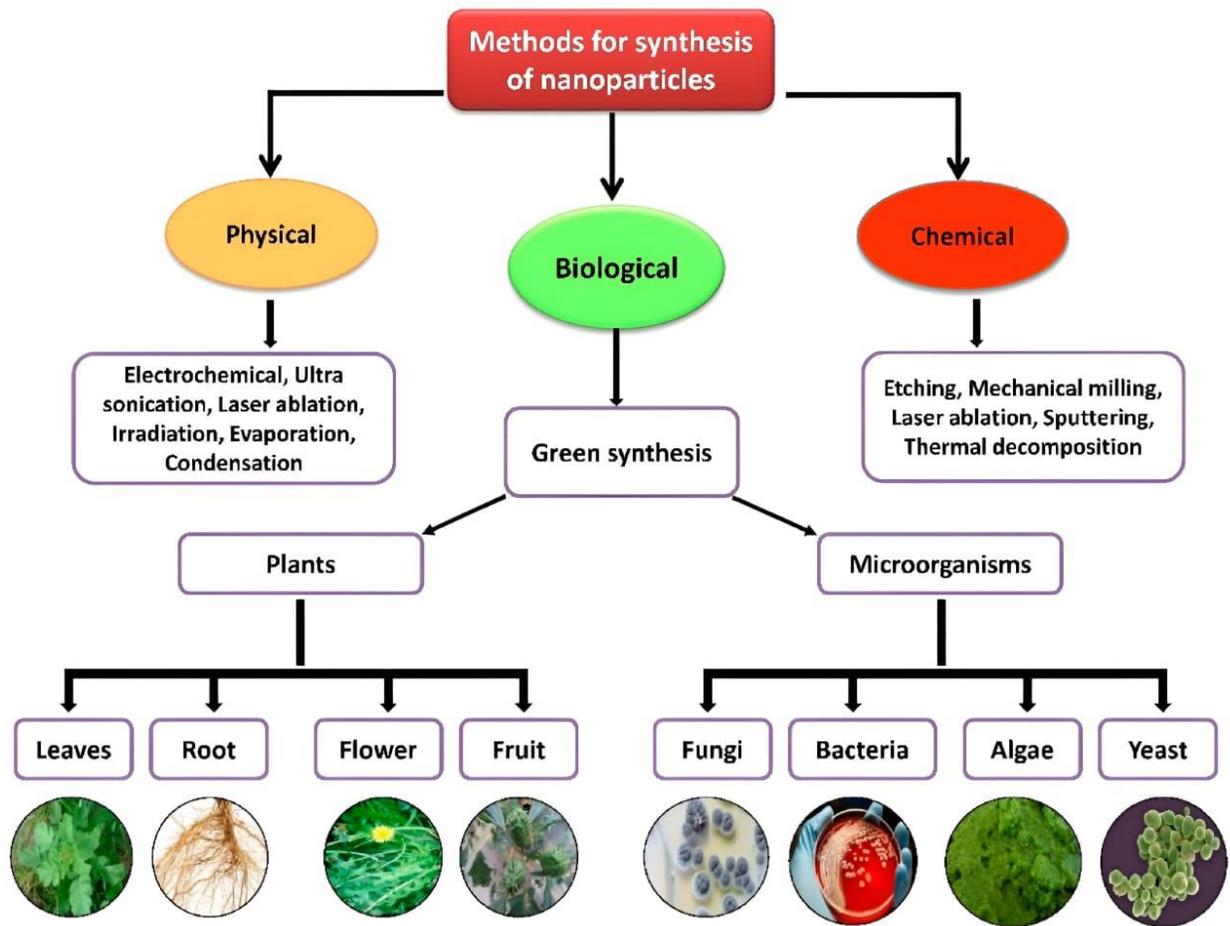


Figure 1: Overview of physical, chemical and biological methods for nanoparticle synthesis, highlighting the comparative advantages of eco-friendly biological routes. The diagram emphasizes the growing preference for plant-mediated synthesis due to its simplicity, cost-effectiveness and reduced environmental impact. (Adapted from Khan et al. 2022 [1] under the license [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/).)

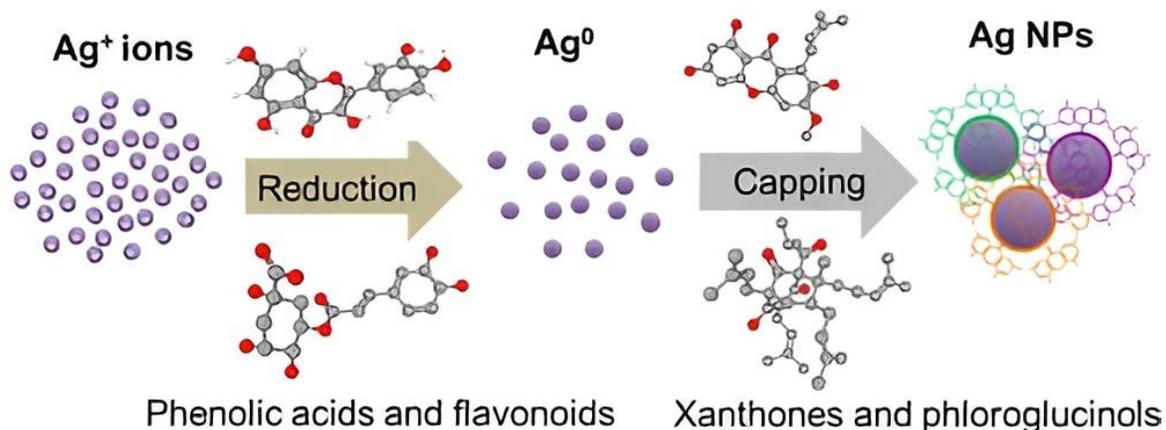


Figure 2: Proposed mechanism of silver nanoparticle (AgNP) synthesis mediated by plant extracts. The figure illustrates the reduction of Ag^+ ions to Ag^0 nanoparticles facilitated by plant-derived metabolites such as phenolics and flavonoids, followed by stabilization through capping agents. This mechanism underpins the green synthesis approach discussed in this review ¹¹. (Adapted from Pradeep et al, 2021 [25] under the license of [CC BY-NC-ND 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/))

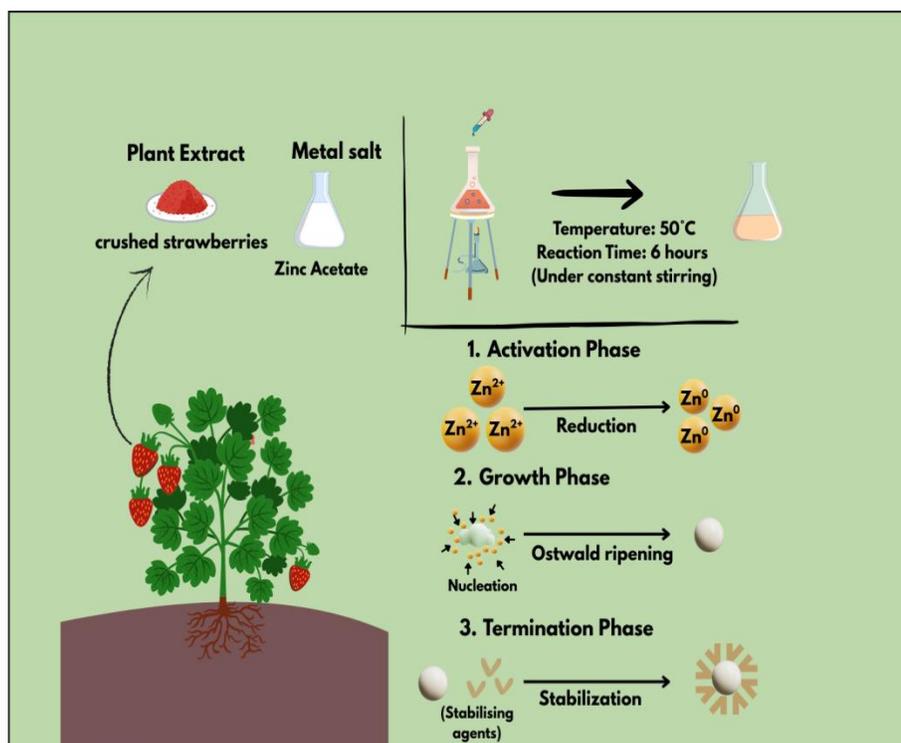


Figure 3: Schematic representation of the green synthesis of ZnO nanoparticles using crushed strawberry fruit extract as a reducing and stabilizing agent. The process demonstrates how plant-derived biomolecules contribute to the controlled formation of ZnO nanoparticles with enhanced biocompatibility and catalytic potential.

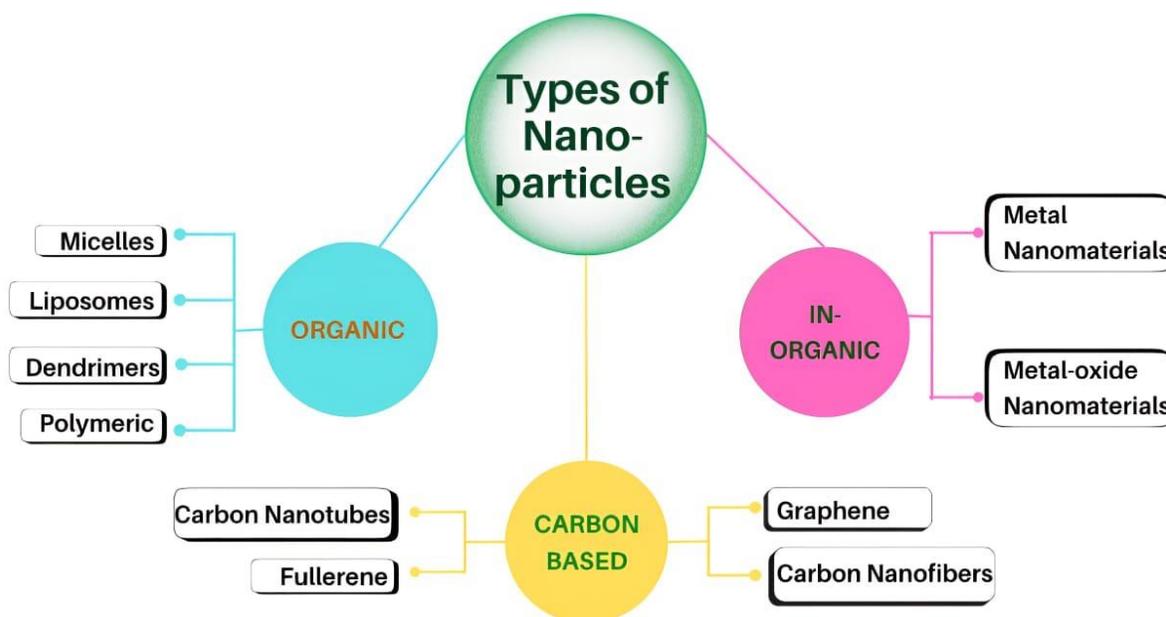


Figure 4: Classification of nanoparticles based on their composition into organic, inorganic and carbon-based categories. Organic nanoparticles include micelles, liposomes, dendrimers and polymeric forms; inorganic nanoparticles comprise metal and metal-oxide nanomaterials; while carbon-based nanoparticles include fullerenes, carbon nanotubes, graphene and carbon nanofibers. This classification highlights the structural diversity and broad functional applications of nanomaterials across biological and industrial fields.

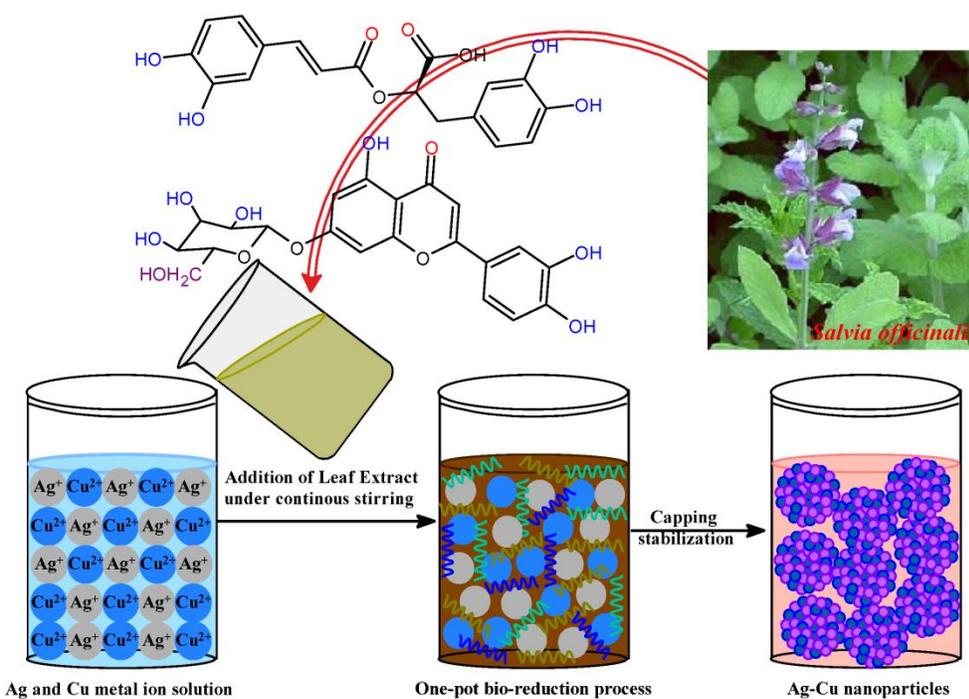


Figure 5: Schematic representation of the green synthesis of Ag–Cu bimetallic nanoparticles using *Salvia officinalis* leaf extract. The bio-reduction and capping processes are mediated by phytochemicals such as polyphenols and flavonoids present in the extract, leading to the stabilization of Ag–Cu nanoparticles. (Adapted from Malik et al, 2023 [131] **under the license of [CCBY 4.0](https://creativecommons.org/licenses/by/4.0/)**)

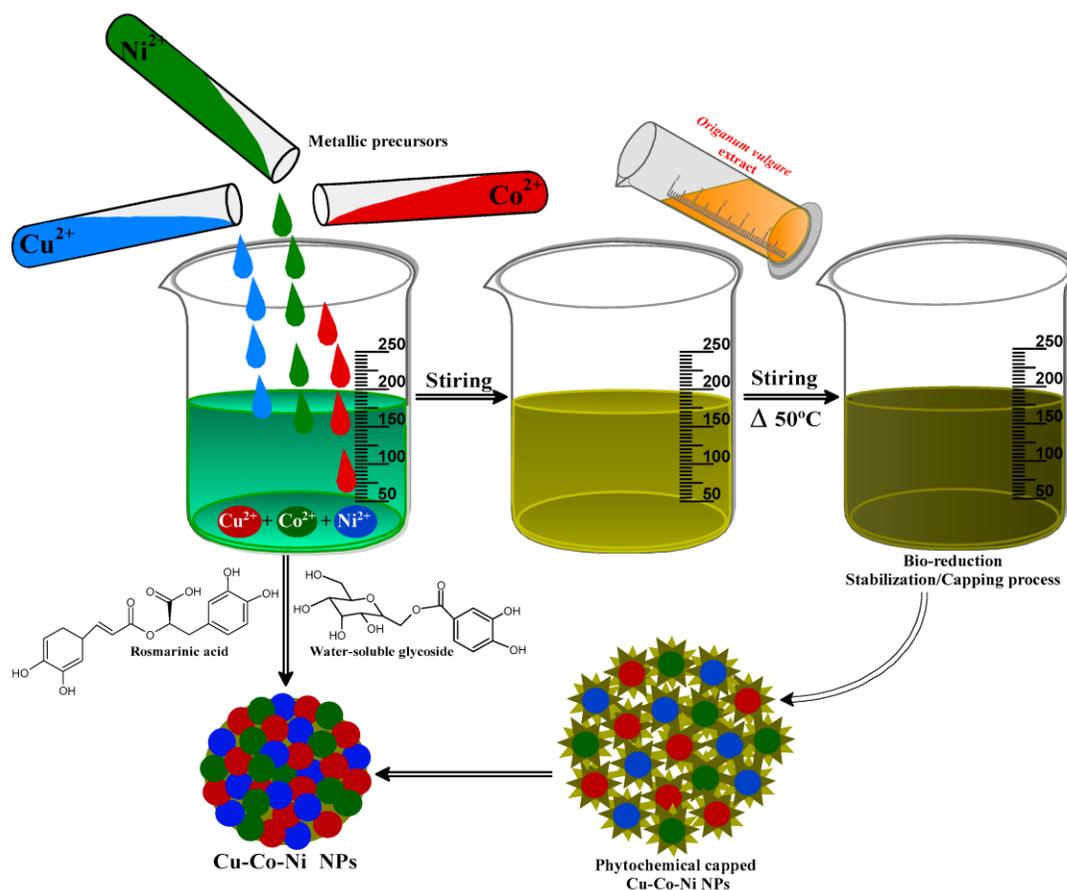


Figure 6: Illustrates the eco-friendly synthesis of Cu–Co–Ni trimetallic nanoparticles using *Origanum vulgare* extract. The phytochemical constituents, including rosmarinic acid and glycosides, act as reducing and stabilizing agents during the bio-reduction and capping process. (Adapted from Alshehri et al, 2020 [137] under the license of [CCBY 4.0](https://creativecommons.org/licenses/by/4.0/))