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Plant-Waste-Mediated Green Synthesis of Nanomaterials: A Mini Review

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Abstract : *Agricultural residues and plant-based wastes are increasingly recognized as valuable resources for sustainable nanomaterial synthesis because of their rich phytochemical content. Fruit peels, seeds, husks, leaves, stems, roots, shells, floral residues and other agro-wastes contain phenolics, flavonoids, tannins, terpenoids, proteins and sugars that can act as reducing, complexing and stabilizing agents.*

This mini review highlights recent advances in the green synthesis of metallic, metal-oxide, carbon-based and composite nanomaterials using plant-derived wastes, with emphasis on phytochemical-mediated synthesis, key phytochemicals involved, and characterization techniques. Their applications in photocatalysis, environmental remediation, antimicrobial activity, agriculture, food preservation and biomedical fields are discussed. Such approaches simultaneously support nanomaterial production and waste valorization, contributing to circular-resource utilization. Overall, plant-waste-mediated synthesis offers a promising route toward sustainable nanotechnology and effective utilization of renewable biological resources.

Key Words: Plant waste, Green synthesis, Nanomaterials, Agricultural waste, Phytochemicals, Green chemistry.

I. INTRODUCTION

Nanotechnology has developed into an important multidisciplinary field because materials at the nanoscale exhibit physicochemical properties that can differ substantially from their bulk counterparts. High surface area, tunable optical characteristics, enhanced catalytic activity, distinctive electronic properties and size-dependent biological interactions make nanomaterials useful in environmental remediation, catalysis, sensing, agriculture, food technology, medicine and energy-related applications [1,2]. However, many conventional nanoparticle synthesis routes involve toxic reducing agents, organic solvents, high temperatures, elevated pressures and energy-intensive processing [3,4].

Green synthesis has consequently attracted considerable interest as an alternative approach. Biological resources such as microorganisms, algae, plants and plant-derived wastes can provide reducing, complexing and stabilizing molecules for nanoparticle formation. Recent reviews have emphasized that biomass and waste materials can serve as sustainable feedstocks for nanomaterial synthesis while simultaneously addressing waste-management problems [5].

Plant-derived waste is particularly attractive because it is abundant, inexpensive and renewable. Large quantities of fruit peels, seeds, shells, leaves, stems, husks, agricultural residues and processing by-products are generated every year. Instead of treating these materials exclusively as waste, their phytochemical content can be exploited for the production of value-added nanomaterials [6,7,8].

Agricultural waste has been increasingly investigated as a sustainable source of phytochemicals for the biosynthesis of metal and metal-oxide nanoparticles. Extracts obtained from agro-food residues can provide phenolic compounds, flavonoids, terpenoids, proteins and other bioactive constituents that participate in the reduction, capping and stabilization of nanoparticles, enabling their use in antimicrobial, catalytic, environmental and biomedical applications [9]. Consequently, the utilization of plant-derived waste offers a dual environmental advantage by converting low-value

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biomass into value-added nanomaterials while reducing dependence on conventional chemical reducing and stabilizing agents used in nanoparticle synthesis [8,9].

The objective of this mini review is to summarize the current state of plant-waste-mediated green synthesis of nanomaterials, with emphasis on: major sources of plant waste; phytochemicals involved in nanoparticle formation; synthesis mechanisms; important synthesis parameters, characterization techniques; major classes of nanomaterials with emerging applications.

II. PHYTOCHEMICAL BASIS OF NANOPARTICLE FORMATION

The major advantage of plant waste is its phytochemical composition. These compounds can act simultaneously as reducing agents, complexing agents and stabilizing/capping agents [10].

Important groups include:

2.1 Phenolic compounds

Phenolic compounds possess hydroxyl groups capable of interacting with metal ions. Depending on their redox properties, phenolics can participate in the reduction of metal ions and subsequently remain associated with nanoparticle surfaces [10].

2.2 Flavonoids

Flavonoids are important secondary metabolites containing hydroxyl and carbonyl functionalities. They can participate in electron transfer and metal-ion complexation and therefore influence nanoparticle nucleation and growth [11].

2.3 Tannins

Tannins contain numerous phenolic groups and can contribute to both reduction and stabilization of nanoparticles [10,12].

2.4 Proteins and amino acids

Proteins may interact with nanoparticle surfaces through amino, carboxyl and other functional groups. Such interactions can influence aggregation and colloidal stability [13].

2.5 Sugars and carbohydrates

Reducing sugars may contribute to metal-ion reduction, while polysaccharides can act as natural stabilizing or templating materials [14].

2.6 Terpenoids and other secondary metabolites

Terpenoids and related compounds may contribute to metal-ion reduction and surface stabilization depending on their chemical structures [10,14].

Thus, plant waste should not be regarded simply as a source of a single reducing compound. Instead, it represents a complex phytochemical reaction system in which several components may act synergistically.

III. MECHANISM OF PLANT-WASTE-MEDIATED NANOPARTICLE SYNTHESIS

Plant-waste-mediated nanoparticle synthesis involves extraction of phytochemicals followed by their interaction, complexation and/or reduction of metal ions. These processes promote nucleation and subsequent nanoparticle growth, while adsorbed phytochemicals help stabilize the particles and control their morphology. For metal oxides, hydrolysis, precipitation and thermal treatment may also contribute to formation. The overall process can be represented as plant-waste phytochemicals → metal-ion interaction → nucleation → growth → stabilization. The exact mechanism is system-dependent and should be established using appropriate spectroscopic and surface-characterization techniques rather than inferred solely from colour changes [15].

IV. TYPES OF NANOMATERIALS SYNTHESIZED USING PLANT WASTE

4.1 Silver nanoparticles

Pomegranate and orange peels have been successfully used for AgNP production, with phenolic constituents contributing to the reduction and stabilization process [16,17]. Agro-waste from Pithecellobium dulce fruit peel has

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also been employed for AgNP synthesis [18]. Similarly, potato peels and coriander stems have been demonstrated as vegetable-waste substrates for AgNP formation [19].

4.2 Gold nanoparticles

Pomegranate, banana, pineapple and passion-fruit peels have been successfully employed as plant-waste substrates for AuNP synthesis, with phenolics, flavonoids and other phytochemicals contributing to the reduction of Au^{3+} and stabilization of the nanoparticles [20]. Grape and other fruit-processing wastes have also been explored as sustainable sources for AuNP formation [21]. These examples demonstrate the potential of fruit and agro-industrial wastes as low-cost phytochemical feedstocks for AuNP production while simultaneously promoting waste valorization.

4.3 Silica nanoparticles

Rice husk and other silica-rich agricultural residues have been explored as sustainable feedstocks for the production of silica nanoparticles. Rice husk is particularly attractive because of its high silica content and abundant availability. Silica nanoparticles derived from agricultural residues have demonstrated potential in adsorption, catalysis, sensing, drug delivery, water treatment and composite materials. Thus, converting agricultural residues into silica nanomaterials provides an effective approach for waste valorization and the sustainable production of value-added materials [22].

4.4 Carbon-based nanoparticles

Carbon-rich agricultural wastes such as banana peels, rice residues, sugarcane bagasse, orange peels, wheat straw and coconut husks can be converted into activated carbon, carbon dots, porous carbon and graphene-like materials. Biomass-derived carbon dots exhibit photoluminescence and tunable surface properties, making them promising for sensing, bioimaging and environmental applications, while promoting sustainable waste valorization [23].

In this way, ZnONPs, CuONPs, Fe_2O_3 and Fe_3O_4, etc., are also reported.

V. CHARACTERIZATION OF PLANT-WASTE-DERIVED NANOMATERIALS

Comprehensive characterization is essential to confirm nanoparticle formation and establish structure–property relationships. UV–Vis and FTIR spectroscopy provide information on optical properties and phytochemical functional groups, while XRD determines crystalline phase and crystallite size. SEM/TEM reveal morphology and particle dimensions, whereas EDS/EDX confirms elemental composition. DLS and zeta potential provide information on hydrodynamic size, size distribution and colloidal stability, enabling reliable evaluation of plant-waste-derived nanomaterials [24].

VI. APPLICATIONS OF PLANT-WASTE-DERIVED NANOMATERIALS

6.1 Environmental remediation

Environmental remediation is a major application of plant-waste-derived nanomaterials, particularly for dye degradation, antibiotic removal, adsorption and photocatalytic treatment of wastewater. For example, banana flower waste has been used as a template for Fe_2O_3 and CuO nanoparticles, which demonstrated efficient degradation of textile dyes and antibiotics. Plant-mediated CuO and ZnO nanomaterials have also shown promising photocatalytic and adsorptive performance against dyes and pharmaceutical pollutants [25].

6.2 Antimicrobial applications

Plant wastes from species such as Punica granatum (pomegranate peel), Citrus sinensis (orange peel), Solanum tuberosum (potato peel) and Coriandrum sativum (coriander stems) have been used as feedstocks for AgNP synthesis. These waste-derived AgNPs demonstrated antifungal activity against Alternaria solani and antibacterial activity against several bacterial pathogens, highlighting their potential for agricultural disease management and antimicrobial applications [16].

6.3 Photocatalysis

Plant wastes have been explored as sustainable feedstocks for producing photocatalytic nanomaterials for water purification. Banana peel (Musa acuminata) has been used to synthesize ZnO nanoparticles exhibiting visible-light-driven degradation of methylene blue and other organic dyes [26]. Rice husk (Oryza sativa) has served as a silica

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source for TiO_2/SiO_2-based photocatalysts, which have been applied to the degradation of methylene blue in aqueous systems[27]. Similarly, orange peel (Citrus sinensis) has been utilized for the green synthesis of SnO_2 nanoparticles for photocatalytic methylene-blue degradation [28], while recent work has reported ZnO and Ag-doped ZnO prepared from the same waste for dye degradation. These examples demonstrate how plant-waste valorization can be integrated with nanomaterial-based photocatalysis for wastewater treatment [29].

6.4 Food packaging and preservation

Plant-derived waste streams are gaining attention as renewable resources for developing nanostructured food-packaging materials with antimicrobial, antioxidant, barrier, and mechanical functions. Banana peel (Musa spp.) residues, for instance, have been used as a biomass source for bacterial nanocellulose, which was subsequently combined with in-situ synthesized AgNPs to fabricate antimicrobial films for mushroom preservation [30]. Wastes from olive (Olea europaea) processing have also been investigated as sources of bioactive compounds for food-packaging films, providing antioxidant and UV-blocking functionality [31]. In addition, cellulose nanomaterials obtained from agricultural residues have been explored as nanofillers in biodegradable packaging matrices, where they can improve mechanical strength and barrier properties [32,33]. These approaches illustrate how plant-processing residues can be converted into value-added nanostructured packaging materials while simultaneously contributing to food preservation and agricultural-waste valorization..

6.6 Agricultural applications

Plant-waste-derived nanomaterials are emerging as sustainable inputs for crop nutrition, seed treatment, and stress management. Rice husk (Oryza sativa)-derived silica nanoparticles improved germination, physiological traits, and nutrient-related responses in Eruca sativa, while also showing antifungal activity against Fusarium oxysporum and Aspergillus niger [34]. More recently, rice-husk-derived nanosilica improved biomass and micronutrient accumulation in hybrid maize (Zea mays) under drought stress [35]. Similarly, banana-peel (Musa spp.)-derived ZnO nanoparticles enhanced germination and seedling vigour of chilli (Capsicum annuum) at an optimized concentration [36]. These studies demonstrate the potential of agricultural-waste-derived nanomaterials for nanofertilization, seed priming, crop growth, and stress management, although concentration-dependent phytotoxicity and environmental safety require careful assessment.

6.7 Biomedical applications

Plant-waste-derived nanomaterials are being explored for antimicrobial, antioxidant, wound-care, and anticancer applications. Pithecellobium dulce fruit-peel-mediated AgNPs exhibited broad antibacterial activity, antioxidant effects, and cytotoxicity against MG-63 osteosarcoma cells, demonstrating their potential for biomedical research [18]. Similarly, Garcinia mangostana fruit-peel-derived Fe_3O_4 nanoparticles have been investigated for hyperthermia and anticancer applications [37]. AgNPs synthesized from green tomato (Solanum lycopersicum) agricultural waste have also demonstrated antimicrobial and wound-healing activity in experimental models [38]. These findings illustrate the potential of converting plant-processing residues into value-added nanomaterials for biomedical applications. However, dose, particle size, surface chemistry, ion release, residual phytochemicals, and long-term cytotoxicity must be systematically evaluated before therapeutic application.

VII. CONCLUSION

Plant-waste-mediated synthesis provides a sustainable strategy for converting agricultural and plant residues into value-added nanomaterials. Phytochemicals present in fruit peels, seeds, husks, leaves, shells, and other wastes can facilitate the formation and stabilization of metallic, metal-oxide, carbon-based, and composite nanomaterials. Recent studies demonstrate their diverse applications in photocatalysis, environmental remediation, antimicrobial systems, agriculture, food preservation, and biomedical research. Future research should focus on mechanistic understanding, standardized synthesis, safety evaluation, and life-cycle assessment. Overall, valorizing plant waste for nanomaterial production can promote resource efficiency, circularity, and more sustainable nanotechnology.

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