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Green Synthesis of Zinc Oxide Nanoparticles Using Plant and Agricultural Waste Resources - A Review

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Abstract: Zinc oxide nanoparticles (ZnO NPs) have attracted considerable attention owing to their unique optical, catalytic, antimicrobial, and semiconductor properties. Conventional synthesis methods often involve hazardous chemicals, high energy consumption, and environmentally undesirable reaction conditions. Consequently, green synthesis approaches have emerged as sustainable alternatives for ZnO nanoparticle production. Plant extracts and agricultural wastes contain diverse phytochemicals such as polyphenols, flavonoids, tannins, proteins, and carbohydrates that can function as reducing, stabilizing, and capping agents during nanoparticle synthesis. Recent studies have demonstrated the successful utilization of coconut wastes, banana peels, citrus peels, rice husk, tea waste, coffee waste, and medicinal plant extracts for the green synthesis of ZnO nanoparticles. These biologically synthesized nanoparticles exhibit promising applications in photocatalytic degradation of pollutants, antimicrobial activity, wastewater treatment, agriculture, and energy related technologies. This mini review summarizes recent developments in plant and agricultural waste mediated synthesis of ZnO nanoparticles, discusses the underlying formation mechanisms, highlights major characterization techniques, and evaluates key environmental and technological applications. The review also identifies current challenges related to reproducibility, standardization, and large scale production. Green synthesis offers a sustainable pathway for the development of environmentally friendly ZnO nanomaterials and supports the principles of circular bioeconomy and green chemistry.
Keywords: Zinc oxide nanoparticles, Green synthesis, Agricultural waste, Plant extracts, Photocatalysis, Nanotechnology

I. INTRODUCTION

Zinc oxide nanoparticles (ZnO NPs) are among the most extensively investigated metal oxide nanomaterials because of their unique optical, catalytic, antimicrobial, semiconducting, and photocatalytic properties. Their wide band gap (3.37 eV), high exciton binding energy, chemical stability, and environmental compatibility have enabled applications in environmental remediation, agriculture, biomedicine, sensors, and energy technologies. Recent advances in nanotechnology have significantly increased the demand for ZnO nanoparticles with controlled size, morphology, and surface properties.

Conventional methods for ZnO nanoparticle synthesis include physical and chemical approaches such as sol gel synthesis, hydrothermal synthesis, chemical precipitation, and vapor deposition techniques. Although these methods provide good control over nanoparticle properties, they frequently involve toxic chemicals, high energy consumption, and environmentally undesirable reaction conditions. These limitations have encouraged the development of green synthesis approaches that align with the principles of sustainable chemistry. Green synthesis utilizes biological resources including plant extracts, agricultural wastes, algae, fungi, and microorganisms as natural reducing and stabilizing agents. Among these approaches, plant mediated synthesis has emerged as one of the most attractive methods because plant materials are inexpensive, renewable, readily available, and rich in phytochemicals such as flavonoids, phenolics, tannins, alkaloids, proteins, and carbohydrates. These compounds facilitate nanoparticle formation while minimizing environmental impact.

This mini review summarizes the green synthesis of ZnO nanoparticles using plant and agricultural waste resources, discusses the underlying synthesis mechanisms, highlights major characterization techniques, and presents important environmental and technological applications.

II. GREEN SYNTHESIS MECHANISM OF ZNO NANOPARTICLES

Plant mediated synthesis of ZnO nanoparticles generally involves three major stages: complexation of zinc ions, formation of zinc hydroxide intermediates, and conversion into ZnO nanoparticles through calcination. Phytochemicals present in plant extracts interact with zinc precursors such as zinc acetate, zinc nitrate, or zinc chloride through hydroxyl, carbonyl, and carboxyl functional groups. These interactions facilitate metal ion complexation and regulate nucleation processes.

A commonly proposed mechanism involves the formation of $Zn(OH)_2$ intermediates through hydrolysis, followed by thermal conversion into crystalline ZnO nanoparticles. During this process, flavonoids, polyphenols, and other phytochemicals function as reducing, stabilizing, and capping agents. The resulting nanoparticles often exhibit improved dispersion and reduced aggregation compared with conventionally synthesized materials.

Several factors influence nanoparticle formation, including pH, reaction temperature, precursor concentration, extract concentration, and calcination temperature. Variations in these parameters significantly affect particle size, morphology, crystallinity, and photocatalytic performance. Studies have shown that alkaline conditions generally favor ZnO formation and that increasing calcination temperature often increases crystallinity while reducing specific surface area.

III. PLANT AND AGRICULTURAL WASTE RESOURCES FOR ZNO SYNTHESIS

Plant extracts and agricultural wastes serve as sustainable resources for ZnO nanoparticle production. These materials contain diverse phytochemicals that facilitate nanoparticle formation and stabilization.

IV. FRUIT AND VEGETABLE WASTES

Fruit wastes such as banana peel, citrus peel, pomegranate peel, and mangosteen leaves have been successfully employed for ZnO synthesis. These materials are rich in polyphenols, flavonoids, sugars, and organic acids that support nanoparticle formation. Fruit waste mediated ZnO nanoparticles have demonstrated promising photocatalytic and antimicrobial activities.

V. MEDICINAL PLANT EXTRACTS

Medicinal plants constitute one of the largest groups investigated for green ZnO synthesis. Plants such as Cassia fistula, Melia azedarach, Aloe vera, Solanum nigrum, and Euphorbia hirta have been widely reported. These plants contain bioactive compounds capable of controlling nanoparticle growth and morphology. Notably, ZnO nanoparticles synthesized using Cassia fistula and Melia azedarach extracts exhibited significant antibacterial activity in experimental studies.

VI. AGRICULTURAL RESIDUES

Agricultural wastes including rice husk, sugarcane bagasse, tea waste, coffee waste, coconut residues, and other agroindustrial byproducts have attracted increasing attention. Their abundance, low cost, and renewable nature make them attractive feedstocks for sustainable nanotechnology. Utilization of these wastes contributes to waste valorization while reducing environmental burden. The growing interest in agricultural waste mediated synthesis reflects broader efforts toward circular bioeconomy strategies and environmentally responsible nanomaterial production.

VII. CHARACTERIZATION OF GREEN SYNTHESIZED ZNO NANOPARTICLES

The successful synthesis of ZnO nanoparticles is generally confirmed through a combination of structural, optical, morphological, and elemental characterization techniques. These techniques provide essential information regarding crystal structure, particle size, morphology, chemical composition, and surface properties.

VIII. X RAY DIFFRACTION ANALYSIS

X ray diffraction (XRD) is the most widely used technique for confirming ZnO nanoparticle formation. Green synthesized ZnO nanoparticles typically exhibit diffraction peaks corresponding to the hexagonal wurtzite crystal structure. The absence of impurity peaks indicates phase purity, while peak broadening provides information regarding crystallite size. Crystallite size is commonly estimated using the Scherrer equation. Reported crystallite sizes for green synthesized ZnO nanoparticles generally range between 10 and 80 nm depending on synthesis conditions and plant sources.

IX. FOURIER TRANSFORM INFRARED SPECTROSCOPY

Fourier transform infrared spectroscopy (FTIR) is employed to identify functional groups involved in nanoparticle synthesis. The spectra commonly reveal hydroxyl, carbonyl, carboxyl, and amine groups originating from plant phytochemicals. These functional groups are believed to participate in reduction and stabilization processes. The appearance of Zn–O stretching vibrations confirms successful ZnO formation.

X. UV VISIBLE SPECTROSCOPY

UV Visible spectroscopy is used to investigate optical properties and determine the band gap of ZnO nanoparticles. Green synthesized ZnO nanoparticles generally exhibit strong absorption in the ultraviolet region due to electronic transitions between the valence and conduction bands. Variations in band gap values may arise from particle size effects, defect concentrations, and synthesis conditions.

XI. ELECTRON MICROSCOPY TECHNIQUES

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are commonly employed to examine morphology and particle size. Green synthesized ZnO nanoparticles have been reported in various morphologies including spherical particles, nanorods, nanoflowers, nanosheets, and hierarchical structures. TEM analysis provides high resolution images that enable direct observation of particle size and crystallinity.

XII. ENERGY DISPERSIVE X RAY SPECTROSCOPY

Energy dispersive X ray spectroscopy (EDX) is used to determine elemental composition. The presence of zinc and oxygen peaks confirms ZnO formation, while the absence of additional elemental signals indicates good purity. Overall, the combined use of XRD, FTIR, UV Visible spectroscopy, SEM, TEM, and EDX provides comprehensive information regarding the structural and functional properties of green synthesized ZnO nanoparticles.

XIII. APPLICATIONS OF GREEN SYNTHESIZED ZNO NANOPARTICLES

Green synthesized ZnO nanoparticles have demonstrated significant potential in environmental, biomedical, agricultural, and energy related applications. Their high surface area, photocatalytic activity, antimicrobial properties, and semiconducting behavior contribute to their multifunctional performance.

XIV. PHOTOCATALYTIC DEGRADATION OF ORGANIC POLLUTANTS

Photocatalytic degradation is one of the most extensively investigated applications of ZnO nanoparticles. Under ultraviolet irradiation, ZnO generates electron hole pairs that react with water and oxygen molecules to produce reactive oxygen species. These species degrade organic pollutants into simpler and less harmful compounds.

Green synthesized ZnO nanoparticles have been successfully applied for the degradation of methylene blue, methyl orange, rhodamine B, Congo red, and other industrial dyes. Their photocatalytic efficiency is influenced by particle size, crystallinity, morphology, and defect concentration.

XV. ANTIMICROBIAL ACTIVITY

ZnO nanoparticles exhibit broad spectrum antimicrobial activity against bacteria, fungi, and certain viruses. The antimicrobial mechanism is generally attributed to the generation of reactive oxygen species, disruption of cell membranes, release of zinc ions, and induction of oxidative stress. Several studies have reported strong antibacterial activity against Gram positive and Gram negative bacterial species. The presence of residual phytochemicals from plant extracts may further enhance biological activity.

XVI. WASTEWATER TREATMENT

ZnO nanoparticles have attracted attention for wastewater treatment because of their combined photocatalytic and adsorption capabilities. Their high surface area facilitates pollutant adsorption, while photocatalytic activity enables degradation of organic contaminants. These properties make ZnO nanoparticles promising materials for sustainable water purification technologies.

XVII. AGRICULTURAL APPLICATIONS

Recent studies have explored the use of ZnO nanoparticles in agriculture as nano fertilizers, plant growth promoters, and antimicrobial agents. Zinc is an essential micronutrient for plants, and ZnO nanoparticles may enhance nutrient availability under certain conditions. However, further research is required to understand their long term environmental effects.

XVIII. ENERGY RELATED APPLICATIONS

ZnO nanoparticles have been investigated for supercapacitors, lithium ion batteries, photocatalytic hydrogen production, and solar energy conversion systems. Their high surface area and semiconducting properties contribute to improved electrochemical and photocatalytic performance. Although energy applications remain less explored than environmental applications, they represent a rapidly expanding area of research. Overall, the multifunctional nature of green synthesized ZnO nanoparticles has established them as promising materials for sustainable environmental and technological applications.

XIX. CONCLUSION

Green synthesis has emerged as a sustainable and environmentally friendly approach for the production of zinc oxide nanoparticles. Unlike conventional chemical and physical methods, plant mediated synthesis utilizes naturally occurring phytochemicals as reducing, stabilizing, and capping agents, thereby minimizing the use of hazardous chemicals and reducing environmental impact.

Plant extracts and agricultural wastes such as banana peels, citrus peels, rice husk, sugarcane bagasse, tea waste, coffee waste, coconut residues, and medicinal plants have been successfully employed for ZnO nanoparticle synthesis. These biological resources are abundant, renewable, inexpensive, and rich in phytochemicals that facilitate nanoparticle formation and stabilization.

The synthesized ZnO nanoparticles have been characterized using various analytical techniques including X ray diffraction, Fourier transform infrared spectroscopy, UV Visible spectroscopy, scanning electron microscopy, transmission electron microscopy, and energy dispersive X ray spectroscopy. These studies have confirmed the successful production of crystalline ZnO nanoparticles with diverse morphologies and functional properties.

Green synthesized ZnO nanoparticles have demonstrated considerable potential in photocatalytic degradation of organic pollutants, antimicrobial activity, wastewater treatment, agriculture, and emerging energy applications. Their high surface area, photocatalytic efficiency, and multifunctional characteristics make them promising materials for sustainable environmental and technological solutions.

Despite significant progress, challenges related to reproducibility, standardization of synthesis protocols, mechanistic understanding, scalability, and long term environmental safety remain important areas for future investigation. Addressing these challenges will facilitate the translation of laboratory scale research into practical applications. The green synthesis of ZnO nanoparticles using plant and agricultural waste resources represents a promising strategy that combines nanotechnology, waste valorization, and sustainable development. Continued research in this field is expected to contribute significantly to environmental remediation, resource utilization, and advanced functional materials.

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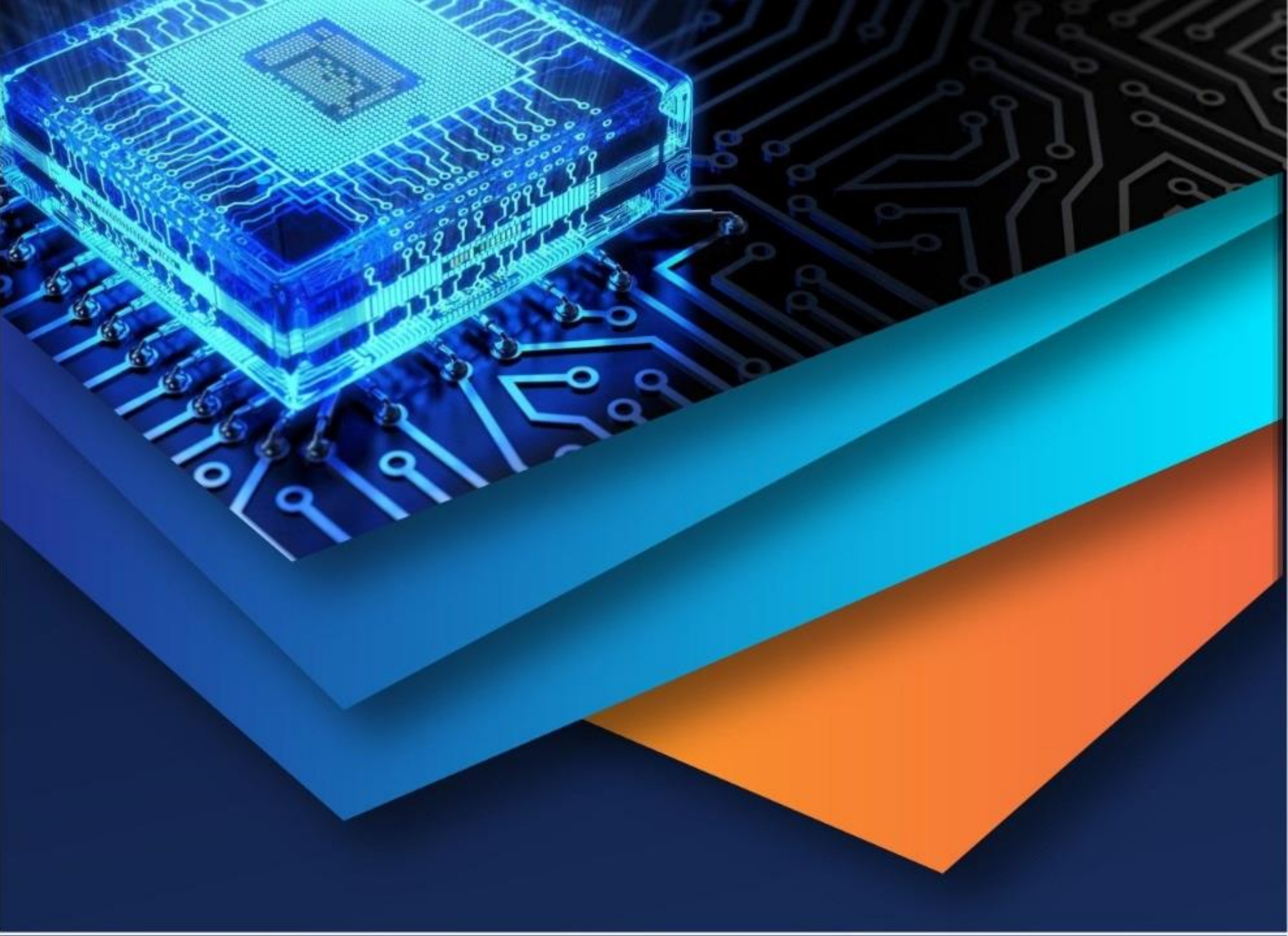

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