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TRANSFORMING BIOWASTE INTO FUNCTIONAL NANOPARTICLES: A REVIEW

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ABSTRACT
The rapid expansion of fruit processing industries worldwide has resulted in the generation of substantial quantities of biowaste, including peels, seeds, rinds, and pomace. These residues are often discarded without value recovery, leading to environmental contamination and inefficient utilization of natural resources. Simultaneously, the growing demand for nanoparticles across biomedical, environmental, and industrial sectors has intensified concerns regarding conventional synthesis approaches, which typically involve toxic chemicals, high energy inputs, and environmentally harmful reaction conditions. A renewable and environmentally friendly solution that is in line with the ideas of green chemistry and the circular economy is the conversion of fruit-derived biowaste into functional nanoparticles using green synthesis. Polyphenols, flavonoids, tannins, organic acids, sugars, proteins, and other bioactive ingredients are abundant in fruit wastes and can serve as natural reducing, stabilizing, and capping agents during the creation of nanoparticles. This study highlights the underlying reaction processes and the function of phytochemicals in nanoparticle stabilization while offering a thorough overview of current developments in the synthesis of metal and metal oxide nanoparticles utilizing fruit waste extracts. Additionally included are important characterization methods used to assess surface characteristics, crystallinity, morphology, and particle size. The review also outlines the possible uses of nanoparticles obtained from biowaste in fields like food packaging, biomedical treatments, environmental cleanup, and catalytic processes. Fruit waste-mediated nanoparticle synthesis is a potential approach for creating sustainable nanomaterials with a variety of uses through promoting trash valorization while decreasing environmental impact.

Keywords: *Biowaste valorization, green synthesis, Fruit waste, Functional nanoparticles, Sustainable nanotechnology*

INTRODUCTION
By providing nanoscale materials with special physicochemical characteristics like high surface-to-volume ratio, quantum size effects, tunable optical behavior, and increased catalytic efficiency, nanotechnology has transformed materials science and made them essential for use in biomedical, environmental, sensor, and catalytic applications (1,2). Metal and metal oxide nanoparticles (such as silver, zinc oxide, and gold) have drawn special interest among different nanomaterials due to their strong antibacterial and catalytic properties (3, 4). However, harmful reducing agents, toxic solvents, and high energy inputs are frequently used in the conventional physicochemical synthesis of nanoparticles, which not only increases production costs but also poses serious dangers to the environment and human health (1,5).

Green synthesis methods, which use biological resources including microorganisms, plants, and agricultural waste as natural reductants and stabilizing agents, have surfaced as sustainable alternatives in recent years (6, 7). In accordance with the twelve principles of green chemistry, this bio-mediated approach avoids hazardous substances and unfavorable environments while providing scalable, economical, and environmentally friendly synthesis pathways (1,6).

Fruit wastes, such as peels, seeds, pomace, and rinds, are particularly promising biological resources as precursors for the synthesis of nanoparticles because they are widely available and contain high concentrations of bioactive phytochemicals, such as flavonoids, polyphenols, tannins, organic acids, and vitamins, which can function as both reducing and capping agents (8,9). Millions of tons of this type of organic waste are produced globally each year by the fruit processing industries, creating environmental problems with disposal, greenhouse gas emissions, and pollution of soil and water (10). In line with the concepts of the circular economy, turning this trash into nanomaterials adds economic value while simultaneously reducing environmental impacts (11).

Numerous nanoparticles have been successfully created from fruit waste. Citrus fruit peels, for instance, have been used to create silver nanoparticles (AgNPs) with potent antibacterial and antioxidant properties (12).

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Similarly, extracts from banana and orange peels have produced biogenic AgNPs that are effective against plant and human diseases (13). Zinc oxide nanoparticles (ZnO-NPs) generated from orange peel extract also exhibit improved antibacterial activity against Escherichia coli and Staphylococcus aureus; their shape is affected by synthesis variables such as pH and temperature (4, 14). Furthermore, ZnO-NPs with spherical and hexagonal morphologies for biological applications have been created using pomegranate peel extract (8), while ZnO-NPs with significant antioxidant and photocatalytic activity have been synthesized using papaya peel extract (15). In addition to Ag and ZnO, pineapple and passion fruit peels have been used to create gold nanoparticles (AuNPs), which produce biocompatible nanosystems appropriate for use in biomedical applications (9).

In addition to mediating the reduction of metal ions, the intrinsic bioactive phytochemicals found in fruit waste extracts also offer capping and stabilization, resulting in nanoparticles with better functional qualities and colloidal stability than those made using traditional chemical techniques (16, 12). Due to surface functionalization by biomolecules found in fruit waste extracts, these green-synthesized nanoparticles have shown encouraging antibacterial, antioxidant, photocatalytic, and potentially anticancer properties.

Although substantial progress has been made in the green synthesis of nanoparticles, existing studies remain scattered across diverse fruit waste sources and nanopaterial types. To date, there is a lack of a comprehensive and critically evaluated review dedicated specifically to nanoparticle synthesis mediated by fruit waste. This review aims to systematically consolidate and analyze recent research published between 2015 and 2025 that focuses on the environmentally benign and cost-effective production of nanoparticles using fruit waste materials. Emphasis is placed on comparing synthesis approaches, physicochemical properties of the resulting nanoparticles, and their potential applications. By integrating and critically assessing current findings, this review seeks to identify existing gaps and provide direction for future investigations toward scalable and sustainable nanomaterial production utilizing biowaste resources.

GREEN PRODUCTION OF NANOPARTICLES (NPS) FROM FRUIT WASTE

Green synthesis of nanoparticles (NPs) based on fruit waste has emerged as a practical and affordable alternative to conventional chemical and physical procedures. Many fruit peels and biowastes, including banana (Musa paradisiaca), citrus (orange, Kinnow, Citrus limetta), pomegranate (Punica granatum), papaya, Chrysophyllum albidum, and Wodyetia bifurcata, have been investigated extensively as bio-reductants and stabilizing agents for the synthesis of metal (Ag, Au) and metal oxide (ZnO, TiO_2) nanoparticles. These agro-industrial wastes are rich in polyphenols, flavonoids, tannins, terpenoids, and organic acids, which enhance stability and bioactivity by reducing metal ions and capping the nanoparticles (1, 12).

1 Silver Nanoparticles (AgNPs) from Fruit Peels

Fruit peels such as banana and orange are rich sources of bioactive compounds, including flavonoids and organic acids, which make them suitable reducing and stabilizing agents for the green synthesis of silver nanoparticles (AgNPs). Banana peel–mediated AgNPs have been reported to be predominantly spherical with particle sizes below 100 nm and exhibit significant antibacterial and antifungal activity against both Gram-positive and Gram-negative microorganisms (16). Similarly, AgNPs synthesized using orange peel extract showed strong inhibitory effects against major foodborne pathogens, including Listeria monocytogenes and Escherichia coli O157:H7, highlighting their potential application in food packaging and preservation systems (17). In addition, Chrysophyllum albidum peel has been identified as an effective eco-friendly precursor for AgNP synthesis, producing spherical nanoparticles in the size range of 15–60 nm with broad-spectrum antimicrobial activity against Candida albicans, E. coli, and Staphylococcus aureus (18). Overall, these findings emphasize the promising role of fruit peel waste as a sustainable resource for the synthesis of silver nanoparticles with valuable biomedical and food-related applications.

2 Zinc Oxide Nanoparticles (ZnO-NPs) from Fruit Wastes

Fruit processing residues have emerged as efficient bioresources for the green synthesis of zinc oxide nanoparticles. For instance, pomegranate peel extract has been employed to fabricate ZnO-NPs with particle sizes ranging between 20 and 40 nm and predominantly spherical to hexagonal morphologies. These nanoparticles demonstrated notable antibacterial, antioxidant, and biocompatible properties, highlighting their potential suitability for biomedical applications (8).

Similarly, ZnO-NPs synthesized using papaya peel extract exhibited multifunctional bioactivities, including effective antibacterial action against Salmonella typhi and Escherichia coli, significant antioxidant capacity, and photocatalytic efficiency in dye degradation. Such diverse functionalities indicate their promising applicability in both environmental remediation and biomedical fields (14).

In addition, ZnO-NPs with smaller particle sizes (11–25 nm) and pronounced antibacterial performance have been successfully prepared from less commonly utilized fruit wastes, such as Wodyetia bifurcata peels. This further demonstrates that a broad spectrum of fruit-derived wastes can serve as sustainable and effective green precursors for the synthesis of ZnO nanomaterials (19).

3 Titanium Dioxide (TiO_2) and Gold (Au) Nanoparticles

Fruit-derived waste materials have emerged as effective green resources for the synthesis of metal and metal oxide nanoparticles while preserving their inherent bioactive compounds. For instance, TiO_2 nanoparticles with an average size of approximately 58 nm have been successfully synthesized using kinnow peel extract. The resulting nanoparticles retained significant phytochemical activity, particularly antioxidant properties, highlighting the dual role of fruit waste as both a reducing and stabilizing agent (16).

Similarly, papaya peel extract has been employed for the green synthesis of gold nanoparticles with sizes ranging between 44 and 50 nm. These biosynthesized AuNPs exhibit a broad spectrum of biological activities, including antibacterial, antidiabetic, anti-inflammatory, and antioxidant effects. In addition, their ability to catalyze dye degradation under light exposure underscores their applicability in environmental remediation as well as biomedical fields (9).

4 Mixed Fruit Waste and Circular Economy Approaches

The green synthesis of Ag/ZnO nanoparticles with sizes ranging from 20 to 60 nm using combined fruit peel extracts from citrus and pomegranate has demonstrated that nanoparticle characteristics can be effectively tuned by adjusting the composition of the plant extract and the metal precursor ratios. Such control enables the development of multifunctional nanomaterials suitable for diverse applications, including agriculture, catalysis, and antimicrobial activity (20). Furthermore, studies involving a wide range of fruit and vegetable residues highlight the potential of agro-industrial biowastes as valuable resources within a circular economy framework. These waste-derived extracts not only reduce environmental burden but also facilitate the production of eco-friendly nanomaterials with promising applications in environmental remediation and biomedical fields (21).

Nanoparticle	Fruit Waste Source	Size (nm)	Synthesis Conditions	Key Applications	Reference
AgNPs	Banana peel	10-23.7	Room temp, 1:4 extract	Antibacterial (E. coli, S. aureus)	(22)
AgNPs	Pomegranate peel	5-50	pH 8-12, 20-60°C	Antibacterial, anticancer	(23)
AgNPs	Orange peel	15-30	Stirring, phenolic	Antimicrobial, dye degradation	(24)
AgNPs	Dragon fruit peel	25-26	pH-dependent	Antibacterial	(25)
AgNPs	Papaya peel	16-20	Aqueous extract	Pathogen inhibition	(26)
AgNPs	Lemon peel	10-70	Dose: 20-100 µL	Strong vs. E. coli (20.2 mm zone)	(27)
AgNPs	Mandarin peel	10-50	Microwave-assisted	Dose-dependent	(28)
AuNPs	Pomegranate peel	10-50	Phenolic reduction	Anticancer	(29)
ZnO NPs	Banana peel	40-80	Microwave 450-800 W	Photocatalytic, antioxidant	(30)
CuO NPs	Citrus peels	5-10	Sol-gel, 20-60°C	Antifungal, nutrient delivery	(31)

CONCLUSION

The eco-friendly synthesis of nanoparticles using fruit waste represents a significant step toward sustainable nanotechnology, as it transforms readily available agricultural residues into valuable antibacterial and therapeutic nanomaterials with sizes typically ranging from 5 to 100 nm. Extracts derived from fruit wastes such as banana peels, pomegranate rinds, and citrus peels have been shown to successfully generate stable silver, gold, and metal oxide nanoparticles. These biologically synthesized nanoparticles demonstrate enhanced antibacterial activity against Escherichia coli and Staphylococcus aureus, while offering clear advantages over conventionally synthesized counterparts in terms of biocompatibility, economic viability, and environmental friendliness. Beyond antimicrobial applications, these nanomaterials exhibit promising potential in wastewater treatment, smart food-packaging systems for improved shelf life, and targeted drug-delivery platforms. Additionally, their production contributes to waste reduction and promotes value addition in fruit-producing regions. The presence of naturally occurring polyphenols and flavonoids in fruit waste plays a crucial role as both reducing and stabilizing agents, enabling the formation of uniformly dispersed nanoparticles, as confirmed through standard physicochemical characterization techniques.

FUTURE SCOPE

Future research should focus on scaling up laboratory successes to industrial-level production by adopting continuous-flow reactor systems and developing standardized protocols for the collection and processing of fruit-derived waste materials. The integration of nanoparticles with smart biopolymers, such as chitosan, opens new opportunities in controlled-release agricultural inputs and intelligent food packaging systems capable of responding to changes in pH and freshness. In the biomedical field, further in vivo investigations may enable the translation of these nanomaterials into advanced applications, including targeted drug delivery for cancer therapy and bioactive wound-healing dressings. Expanding the range of feedstocks—such as mango seeds, pineapple residues, and other underutilized fruit wastes—and exploring non-metal nanoparticles like selenium and iron can significantly broaden their functional applications. In addition, embedding these technologies within a circular economy framework through decentralized biorefineries, supported by carbon credit mechanisms and blockchain-based traceability, can enhance transparency and sustainability. Over the next five to ten years, such advancements are expected to position fruit-waste-derived nanoparticles as a vital pillar of sustainable nanotechnology.

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