

GREEN SYNTHESIS OF NANOPARTICLES FROM PLANT PARTS AND WASTE FRUIT PEELS - A MINI REVIEW

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Abstract: In the recent past, there has been a massive demand for environmentally friendly and sustainable nanotechnology, which in turn has led to the development of novel green approaches for the synthesis of nanoparticles. The utilisation of waste fruit peels as bio-reductants and stabilizers has proven to be a promising, cost-effective, and environmentally benign technique. Often, fruit peels are discarded as waste, which are rich in bioactive components like polyphenols, flavonoids, and organic acids; these, in turn, facilitate the reduction and stabilisation of metal nanoparticles. This green method, apart from minimizing the use of hazardous chemicals, also contributes to waste valorisation and circular economy initiatives. In addition, fruit waste-based NP has shown better biological activities in comparison to plant/food extract alone. The collaboration of nanotechnology with sustainable waste management paves the way for greener solutions in pharmaceuticals, diagnostics, and environmental remediation. They have shown their effectiveness and reusability by being used catalytically in environmental remediation processes that include the breakdown of organic contaminants and decrease of harmful metal ions. Through this review (2020-2026), the aim is to provide valuable insights into the prospects of utilizing fruit waste and plant parts for nanomaterial synthesis by taking advantage of waste reduction and high-value nanomaterial synthesis.

IndexTerms - Fruit peels, bioactive compounds, Nanoparticles, biomedical application, environmental remediation, environmentally benign.

I. INTRODUCTION

Nanotechnology has emerged as an upcoming field in the past few decades. Nanotechnology is nothing but the modification of matter with at least one dimension sized from 1 to 100 nanometres (nm)^{1,2}. The resulting particles are commonly referred to as nanoparticles³. The nanoparticles displayed exceptional chemical, physical, and photothermal characteristics in comparison to their bulk counterparts, which include size control, morphology, mobility, energy absorption, and chemical reactivity⁴⁻⁶. Nanoparticles are potent candidates in fields like waste water treatment⁷, food industry⁸, medicine⁹, environmental remediation, sensors, electronics, cosmetics, cancer therapy, antioxidants, antimicrobial¹⁰⁻¹² etc. Nanomaterials demonstrated unique properties due to increased surface area-to-volume ratios and quantum effects. By adjusting the reaction conditions and chemicals used, the physical properties of nanoparticles, such as morphology and diameter, can be regulated¹³. Conventional methods of nanoparticles synthesis involve physical and chemical methods, but these methods of synthesis are associated with various disadvantages, which include costly equipment, release of toxic chemicals, instability, and high energy consumption for synthesis¹⁴. Leaves of *Rubus discolor*¹⁴ is rich in total phenolics, Flavonoids, Anthocyanins, Gallic acid and ferulic acid.

All over the world, fruit and vegetables are the most utilized agricultural products. They are rich in bioactive compounds, namely vitamins, minerals, tannins, antioxidants, flavonoids, polyphenols, and dietary fibres, all of which are beneficial for our health¹⁵. Fruits and vegetables are beneficial for human health by preventing several diseases, including strokes, heart diseases, cancer, and diabetes, as these compounds possess anti-inflammatory, antimicrobial, antioxidant, and anticarcinogenic properties. But at the time of processing, fruit and vegetables produce a considerable amount of waste, including peels, seeds, rind, etc¹⁶. So, from fruit and vegetable waste using the green synthesis method¹⁷⁻²⁵ nanoparticles can be conveniently synthesized. Peas are rich in dietary fiber, minerals (e.g., calcium, iron, and zinc) and vitamins (e.g., carotenoids and folic acid), also has a large content of polyphenolics, especially flavonoids, which exhibit various biological activities. Many metals like Ag, Au, Cu, Pd, Pt, and Fe are used for the synthesis of nanoparticles using green synthesis²⁶. Green synthetic methods are highly beneficial; they are cost-effective, require no external energy, are easy to handle, generate no waste, are eco-friendly, and are safe for humans and the environment²⁷. Green synthesis makes use of vegetable and plant waste, plant extracts, enzymes, and microbes for the synthesis of nanoparticles²⁸⁻³⁰. Synthesizing nanoparticles from bio-based waste will not only make the process cost-effective and eco-friendly, but it may also assist in the management of solid waste.

In a recent publication, researchers reported a reduction of NPs with beet juice, and they found that by decreasing the amount of beet juice, they were able to synthesise larger-sized Ag NPs, which further showed much greater catalytic activity and stability than those synthesized using NaBH₄ for the conversion of 4-nitrophenol to 4-aminophenol³¹. Another group of researchers showed that that on using green tea extracts, bimetallic NPs of Fe/Pd were obtained since extracts of green tea can act as both reductive as well as capping agent³². Greener nanoparticles have been extensively used in environmental remediation, like for water and soil purification, as antimicrobial agents, and for control of air pollution.³³⁻³⁹

Sundarraaj et al.^{34a} reported jackfruit peel contains cellulose (27.75%), pectin ($7.52 \pm 0.12\%$), protein ($6.27 \pm 0.03\%$) and starch (4%). Jackfruit peel serves as a potential source of valuable biomolecules for application in the design and synthesis of valuable products, thereby providing a sustainable approach towards waste management. These nanoparticles serve as transporters for therapeutic compounds, transporting them directly to patients to cure a variety of disorders. Nanomaterials that are generated from vegetable/fruit waste provide several benefits that are not available with standard processes. These benefits include improved biocompatibility, stability, and reactivity qualities⁴⁰.

Guha et al., in their study, showed that seed pre-treatment with G-nZVI can help increase crop vigour and yield effectively. Nano-scale zero-valent iron (G-nZVI) was synthesized using fruit peel waste of *Punica granatum* L and they were further characterized using XRD and optical spectroscopic techniques. The seed pre-treatment with G-nZVI required very low doses, which will impose a negligible threat to the soil microbiome and help to cut down the fertilizer usage to some extent. The synthesis of G-nZVI is cost-effective and eco-friendly, since it involves the recycling of food waste⁴¹. The seeds were primed with G-nZVI at six different concentrations (0, 10, 20, 40, 80, and 160 mg L⁻¹) to determine the dose which is optimum for increasing germination percentage and seedling vigour of rice (*Oryza sativa* L. cv. Gobindobhog). Upon priming seeds with 40–80 mg L⁻¹ G-nZVI highest growth rate was found. A field experiment was also carried out by the researchers where nanoprimered seeds and traditional hydroprimered control seeds were sown in plots and it was found that crop yield was higher in nanoprimered seeds. Compared to control hydroprimered sets, a 1.53-fold higher crop yield was observed upon seed priming with 80 mg L⁻¹ G-nZVI.

Priya et al. in their review⁴² come up with various sources of biogenic NPs, including their synthesis utilizing fruit/vegetable waste, their types, extraction processes, the pharmacological functionality of NPs, and industrial importance.

Zayed et al. carried out⁴³ an eco-friendly process to impart multifunctional properties to cotton fabric using Citrus Sinensis peel (orange peel) extract. Water and ethanol were used as the solvents to carry out the synthesis of silver and zinc oxide nanoparticles. The cotton fabric was treated with orange peel extract, silver nanoparticles, and zinc oxide nanoparticles, which were loaded with chitosan. The treated cotton samples were further characterized by scanning electron microscopy. Antimicrobial activity studies, mosquito repellent effect, and self-cleaning properties were also reported.

Selenium nanoparticles (Se-NPs) were synthesized by Ahmed et al. by adopting⁴⁴ an environment-friendly green synthetic method by utilizing waste biomaterial obtained from the apple peel extract. The produced NPs were further characterized by UV–Visible spectroscopy, atomic force microscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, field emission-scanning electron microscopy, and transmission electron microscopy. The absorption peak at λ_{max} 295 nm confirmed the formation of Se-NPs. The minimum inhibitory concentration at 500 $\mu\text{g mL}^{-1}$ against *C. albicans*, *C. guilliermondii*, and *C. ciferrii*, confirmed their antifungal activity in control and minor statistical difference ($p < 0.05$) in the mean zones of inhibition for the Se-NPs treatment against these fungi. The Se-NPs exhibited their antifungal effect against the multidrug-resistant microbes.

Rajput et al. have employed⁴⁵ fruit extracts (*Punica granatum* and *Artocarpus heterophyllus*) for efficient, inexpensive and eco-friendly green synthesis of silver nanoparticles at room temperature, which have unique optical, antibacterial and catalytic properties. Reducing properties of phytochemicals present in fruit waste caused the reduction of metal precursors into their respective nanoparticles. The size, shape, and crystallinity of the synthesized silver nanoparticles were studied using transmission electron microscopy and selected area electron diffraction. The produced nanoparticles were shown to be highly stable over months, as evidenced by Dynamic light scattering (DLS) and zeta potential, and were then tested for antibacterial efficacy. Antibacterial sensitivity against *E. coli* of the formed silver nanoparticles was also determined by the researchers.

Abdella et al used red dragon fruit (*Hylocereus polyrhizus*) mucilage for the synthesis of selenium nanoparticles (SeNPs)⁴⁶ and its integration into chitosan (Cts) nanoparticles to form antimicrobial nanocomposites (Cts/DrF/SeNPs). The materials were characterised using spectroscopy, electron microscopy, and physicochemical analysis (FTIR and DLS). Cts, DrF/SeNPs, and Cts/DrF/SeNPs, were tested for antibacterial and antifungal activities against *S. aureus* and *C. albicans*. MIC were (50.0, 47.5, and 27.5 $\mu\text{g/mL}$) against *S. aureus* for Cts, DrF/SeNPs, and Cts/DrF/SeNPs, respectively. MIC were (47.5, 55.0 and 32.5 $\mu\text{g/mL}$) against *C. albicans* for Cts, DrF/SeNPs, and Cts/DrF/SeNPs, respectively. The Cts/DrF/SeNPs-treated fabrics showed the maximum antimicrobial effects in comparison to those treated with DrF or DrF/SeNPs alone against both *S. aureus* and *C. albicans*. Cts/DrF/SeNPs can be used as green antimicrobial agents in the treatment of resistant skin infections.

Due to the recent advancements in the use of nanoparticles, a new scope has arisen to control microbial resistance⁴⁷ and to overcome microbial defence mechanisms⁴⁸. Selenium nanoparticles (SeNPs) have emerged as a potential candidate due to their biological efficacy, biocompatibility, and in being less toxic⁴⁹. SeNPs disrupt bacterial membranes and interfere with metabolic processes, leading to a broad-spectrum antimicrobial effect. Also, SeNPs control microbial signalling and inhibit efflux pumps, causing antibiotic resistance. Their selective cytotoxicity toward cancer cells, with minimal harm to normal cells, highlights their use as a safer alternative to conventional chemotherapies.

Alam et al in their study⁵⁰ used selenium nanoparticles (SeNPs) and colistin-conjugated selenium nanoparticles (Col-SeNPs) against multidrug-resistant *Pseudomonas aeruginosa*, antifungal-drug-resistant *Candida* spp., and human breast carcinoma (MCF-7) cells. AgNPs are synthesized from ash gourd and cucumber peel extracts by mixing vegetable peel extract with silver nitrate solution⁵¹. The peel extracts of ash gourd and cucumber contain polyphenols, flavonoids, glycosides, proteins, vitamins, minerals, carbohydrates, beta-carotene, magnesium, potassium, manganese, calcium, iron, potassium and iodine^{51a-c}. The phytochemicals and nutrients that are present in the peel extracts are responsible for producing the AgNPs.

Silver nanoparticles were subjected to various characterization techniques to investigate their morphology, stability, shape, size, and crystallinity. The bioactive molecules present in the peel extracts not only reduced the Ag⁺ ions to AgNPs but also further

stabilized the synthesised AgNPs. XRD analysis determined the nature and particle size of the synthesised AgNPs. The surface morphology was further analyzed by SEM. The synthesised AgNPs exhibited antimicrobial activity on selected microorganisms. It was reported by the researchers that synthesised AgNPs directly interacted with the outer membrane of the microorganism, causing the membrane to rupture and killing the microorganism.

Some of the recent work in the application of nanoparticles synthesized from plant and fruit peels has been reported by researchers all over the world⁵²⁻⁶⁵.

CATALYTIC APPLICATIONS OF NANOPARTICLES

The metal oxide nanoparticles that are commonly used in industries include TiO₂, ZnO, Fe₃O₄, CeO₂, CuO, Al₂O₃, SiO₂, SnO₂, WO₃, NiO, Co₃O₄. With high surface–volume ratio, metal oxide nanoparticles have a number of active sites for catalytic reactions, making it a highly effective heterogeneous catalyst⁶⁶.

Titanium dioxide (TiO₂) nanoparticles have been widely applied as photocatalysts to decompose organic pollutants, in self-cleaning surfaces, and in systems for environmental purification. TiO₂ generates reactive oxygen species under UV and visible-light irradiation which can oxidize organic compounds to harmless products. ZnO nanoparticles have also demonstrated outstanding photocatalytic activity and are of great interest for environmental and industrial catalytic applications.

The nanoparticles of cerium oxide (CeO₂) are important catalysts because they can store and release oxygen via reversible Ce³⁺/Ce⁴⁺ redox transitions. CeO₂ is a common component of automobile catalytic converters, where it is used for the oxidation of carbon monoxide and hydrocarbons and the reduction of nitrogen oxides. Likewise, iron oxide nanoparticles are used in Fenton-like catalytic systems, hydrogenation reactions, and wastewater-treatment processes⁶⁷.

Transition metal oxides like Co₃O₄, NiO, MnO₂ and CuO are very good catalysts for oxidation, reduction and electrochemical reactions. Copper oxide nanoparticles have been extensively used in carbon monoxide oxidation, methanol synthesis and organic transformations. Manganese oxide nanoparticles are excellent catalysts in oxidation reactions and energy-related catalytic processes⁶⁹.

Among them, magnetic metal oxide nanoparticles like Fe₃O₄ are particularly interesting as they can be easily separated and recycled by applying an external magnetic field, thus minimizing catalyst loss and operational expenses. Although tremendous advances have been made, catalyst deactivation, nanoparticle agglomeration, and long-term stability are challenges for industrial catalytic systems⁷⁰.

Metal oxide nanoparticles are commonly used in coatings and paints for mechanical durability, corrosion resistance, UV protection, antimicrobial properties, self-cleaning properties, and thermal stability. Problems with environmental degradation, microbial contamination, and ultraviolet radiation are common with conventional coatings. The use of MONPs greatly improves the coating performance and prolongs its service life⁷¹.

In the field of corrosion, cerium oxide nanoparticles are becoming a promising corrosion inhibitor in metal coatings, as they can generate protective oxide layers which can lessen the degradation of the metal. The use of copper oxide nanoparticles as a coating material is suitable for marine, medical, and industrial applications, in which it inhibits the growth and biofouling of microorganisms.

Metal oxide nanoparticles have gained significant importance in the textile and packaging industry due to their antimicrobial activity, UV protection, barrier activity, durability and self-cleaning abilities. Functional textiles are widely used, incorporating ZnO and TiO₂ nanoparticles for their antibacterial, antifungal and UV-blocking properties. ZnO nanoparticles can achieve antimicrobial effects on textile surfaces by generating reactive oxygen species and releasing zinc ions, which inhibit microbial growth and help prevent odours and infections. TiO₂ nanoparticles impart self-cleaning and stain-resistant properties to products through the photocatalytic degradation of organic contaminants under light exposure⁶⁸.

Metal oxide nanocomposites containing silver are increasingly being used in healthcare textiles, sportswear and protective clothing as a result of their improved antimicrobial properties. The addition of silica nanoparticles increases the strength of the fabric, its wrinkle resistance, and its water repellence; aluminium oxide nanoparticles increase the thermal qualities and abrasion resistance of the fabrics⁷².

The exceptional electrical, magnetic, optical, semiconducting and dielectric properties of metal oxide nanoparticles make them valuable for many modern applications in electronics and optoelectronics. They have nanoscale dimensions which allow their miniaturization, improvement in charge transport, and improvement in their performance in electronic systems⁷⁴.

Due to their wide band gap, high electron mobility and strong luminescence properties, ZnO nanoparticles are one of the most extensively studied semiconducting materials for optoelectronic applications. Light-emitting diodes, photodetectors, transistors, transparent conductive films and ultraviolet lasers make use of ZnO nanostructures. They are also used for nanogenerators and flexible electronic devices because of their piezoelectric properties⁶⁸.

With their high refractive index and excellent electron-transport capability, titanium dioxide particles are widely used in photovoltaic devices, photocatalytic systems and optical coatings. Tin oxide (SnO₂) nanoparticles are used in transparent conducting materials for displays, touch screens and solar cells. Other important transparent conductive nanoparticles are indium oxide and indium tin oxide nanoparticles, which are used for optoelectronic devices⁶⁸.

Many transition metal oxides, including NiO, Co₃O₄, and WO₃, have been studied for applications in memory devices, electrochromic windows, and smart electronic systems. Tungsten oxide nanoparticles can change colour when stimulated with an electric current, which can be helpful in display technologies and smart windows. The semiconductor use of CuO nanoparticles is gaining more and more attention due to the low cost of the material and the potential for use in flexible electronics⁶⁸. Although significant technological advances have been made, there are still important issues associated with large-scale fabrication, long-term stability, interfacial defects, and environmental safety that should be addressed in support of the future development of electronic and optoelectronic devices based on MONPs⁷³⁻⁷⁵.

II. RESULTS AND DISCUSSION

This review systematically analyzes the existing literature on the green synthesis of various types of NPs from vegetable and fruit peel waste, highlighting their extraction methods and their bioactive potential. By critically investigating the latest advancements, this paper aims to provide insights into the potential of green synthesis as a sustainable and eco-friendly approach for NPs production.

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