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REVIEW ARTICLE

From Waste to Nano: Unlocking Vegetable Residues for Sustainable Nanotechnology

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Abstract

Conventional nanoparticle synthesis has significantly advanced nanotechnology but often relies on hazardous chemicals, toxic solvents, and energy-intensive processes, raising environmental and health concerns. Consequently, green synthesis has emerged as a sustainable alternative that utilizes renewable biological resources as natural reducing and stabilizing agents. Among these resources, vegetable-processing residues are increasingly recognized as valuable feedstocks owing to their abundance and rich phytochemical composition. Peels, stems, seeds, pomace and other residues contain phenolics, flavonoids, proteins, polysaccharides, reducing sugars, and related metabolites that mediate nanoparticle reduction, nucleation, capping, and stabilization. These phytochemical constituents have enabled the eco-friendly synthesis of Ag, Au, Fe/iron-oxide, zinc oxide, copper oxide and other nanomaterials while simultaneously promoting waste valorization within a circular bioeconomy. Importantly, variations in feedstock chemistry influence nanoparticle size, morphology, stability, and functional performance, establishing a direct feedstock-process-property relationship. Waste-derived nanoparticles have demonstrated promising antimicrobial, catalytic, photocatalytic, sensing, and pollutant-remediation capabilities, with growing applications in food, agriculture, and biomedicine. This review critically examines vegetable residues as functional nano-feedstocks, highlighting their biochemical drivers, synthesis mechanisms, process determinants, characterization strategies, major nanoparticle classes, and emerging applications. It also discusses challenges associated with feedstock heterogeneity, reproducibility, biosafety, sustainability, and industrial scale-up, emphasizing that standardized feedstocks, mechanism-guided synthesis, and application-specific validation are essential for translating vegetable-waste nanotechnology into reliable and scalable sustainable technologies.

Key words: Circular bioeconomy, green synthesis, nanoparticles, vegetable waste, waste valorization

INTRODUCTION

The increasing generation of vegetable-processing residues has intensified interest in converting organic waste into value-added products. Peels, seeds, stems, leaves, pomace and rejected biomass are particularly attractive because they remain rich in bioactive compounds that can support resource recovery and circular-economy strategies.[1,2] Nanotechnology provides a promising route for this valorization by transforming low-value residues into functional materials with antimicrobial, catalytic, optical, sensing, and environmental applications.[3,4]

Conventional nanoparticle synthesis often relies on hazardous reagents, specialized equipment, and energy-intensive processes. Green synthesis seeks to reduce

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these limitations by employing biological resources as reaction media and reducing or stabilizing agents.[5,6] Among biological approaches, plant-mediated synthesis is particularly attractive because it avoids microbial culture maintenance and exploits naturally occurring metabolites capable of directing nanoparticle formation.

Vegetable residues are especially relevant because their phenolics, flavonoids, proteins, polysaccharides, reducing sugars, terpenoids, and related metabolites can participate in metal-ion reduction, nucleation, growth, capping, and stabilization.[5,7] Consequently, these wastes function not merely as inexpensive substitutes for chemical reductants but as chemically active feedstocks whose composition can influence nanoparticle size, morphology, stability and functionality. This feedstock-dependent behavior is central to understanding both the potential and variability of waste-mediated synthesis.

A wide range of nanomaterials has been produced using plant and food-processing residues, with silver nanoparticles (AgNPs) representing the most extensively investigated class, followed by Au, Fe/iron oxides, zinc oxide (ZnO), copper oxide (CuO) and other emerging systems.[2,7] Their reported functions extend from antimicrobial and catalytic activity to photocatalytic pollutant degradation, sensing, agriculture, food-related applications, and biomedical research. However, differences in waste composition, extraction procedures, and reaction conditions frequently produce inconsistent nanoparticle characteristics.

Moreover, biological origin alone does not guarantee environmental sustainability. Feedstock variability, incomplete mechanistic understanding, purification requirements, toxicity, storage stability, reproducibility, and industrial scale-up remain important barriers.[6,8] A rigorous assessment must therefore connect feedstock chemistry with synthesis mechanism, nanoparticle properties, functional performance, and process sustainability.

This review critically examines vegetable waste as a functional feedstock for green nanotechnology, focusing on biochemical drivers of nanoparticle formation, metal and metal-oxide synthesis pathways, major waste-nanomaterial systems, synthesis determinants, characterization and functional applications. Particular emphasis is placed on reproducibility, biosafety, sustainability, and scale-up requirements needed to advance vegetable-waste-derived nanomaterials toward practical circular-bioeconomy technologies.

VEGETABLE WASTE AS A FUNCTIONAL NANO-FEEDSTOCK

Vegetable-processing residues-including peels, seeds, stems, leaves, pomace, trimmings, and rejected biomass-are increasingly regarded as renewable feedstocks for green nanotechnology. Their abundance, low cost, biodegradability, and retention of bioactive compounds make them attractive substrates for converting low-value biomass into functional nanomaterials.[2,7] Although a wide variety of vegetable residues can support nanoparticle synthesis, certain feedstocks exhibit superior performance due to their distinctive phytochemical composition. Potato peels are rich in starch, phenolic compounds, and carbohydrates that facilitate reduction and stabilization of metallic nanoparticles. Onion peels contain abundant quercetin, flavonoids, and sulfur-containing compounds that enhance reducing capacity and antioxidant activity, making them particularly effective for noble-metal nanoparticle synthesis. Tomato pomace provides lycopene, phenolics and organic acids, whereas capsicum residues supply polyphenols and reducing sugars that actively participate in nanoparticle formation. Likewise, moringa and orange peels contain high concentrations of polyphenols, flavonoids, and ascorbic acid that promote efficient reduction and stabilization while contributing additional antimicrobial and antioxidant functionality. These compositional differences indicate that feedstock selection should be based not only on waste availability but also on phytochemical suitability for the desired nanomaterial and application [Figure 1].



Figure 1: Representative vegetable-processing residues highlighting representative phytochemical-rich vegetable residues used as feedstocks for green synthesis of metallic and metal-oxide nanoparticles

The value of these residues extends beyond their availability. Vegetable wastes contain phenolics, flavonoids, proteins, polysaccharides, terpenoids, tannins, vitamins, and reducing sugars that participate in metal-ion reduction, complexation, nucleation, capping, and stabilization.[5,7,9] Their composition therefore establishes a feedstock-process-property relationship, in which waste chemistry influences reaction pathways and ultimately determines nanoparticle size, morphology, stability and functionality.[4,8]

This biochemical diversity is also a major source of variability. Waste composition differs with species, plant fraction, maturity, cultivation conditions, processing and storage; consequently, different residues cannot be considered chemically interchangeable. Variations in phytochemical concentration can alter reduction kinetics, particle growth, surface stabilization, yield, and biological activity.[8,10,11] Characterizing the starting feedstock is therefore essential for improving reproducibility and rationally selecting wastes for specific nanomaterials.

Vegetable residues have supported the synthesis of Ag, Au, ZnO, CuO, iron oxides, TiO_2, Pd, Se and other nanomaterials, although the strength of vegetable-specific evidence differs considerably among these classes.[2,3,7] Rather than treating all wastes as universal reductants, a more useful approach is to identify which feedstock chemistry is best suited to a particular nanomaterial and function.

From a circular-bioeconomy perspective, greater value may be achieved through cascading valorization, where high-value compounds such as polyphenols and carotenoids are first recovered, and the remaining biomass is subsequently directed toward nanomaterial production.[12] Such sequential utilization can improve resource efficiency and reduce waste generation. However, biological feedstocks alone do not guarantee sustainability; extraction, heating, purification, recovery, and end-of-life management must also be considered when evaluating the environmental benefits of waste-derived nanotechnology.[1,3,6]

Thus, vegetable waste should be viewed as a chemically functional and renewable nano-feedstock, rather than simply an inexpensive replacement for conventional reagents. Linking feedstock composition with synthesis behavior and nanoparticle performance is fundamental to developing reproducible, efficient, and genuinely sustainable waste-to-nano systems.

BIOCHEMICAL AND MECHANISTIC BASIS OF NANOPARTICLE FORMATION

Biochemical drivers

Vegetable-waste extracts function as multicomponent reaction systems in which phenolics, flavonoids, proteins, polysaccharides, reducing sugars, terpenoids and related metabolites collectively mediate nanoparticle formation. Polyphenols and flavonoids are particularly important because their electron- and hydrogen-donating groups facilitate metal-ion reduction and may subsequently contribute to surface capping.[8,13,14] Experimental decreases in phenolic and flavonoid contents following nanoparticle synthesis further support their direct participation in these reactions.[13]

Proteins and carbohydrates provide complementary functions. Proteins can interact with nanoparticle surfaces through amino, carboxyl, and hydroxyl groups, whereas reducing sugars participate in electron transfer and polysaccharides provide steric stabilization or influence particle growth.[8,11,15] Changes in polyphenols, reducing sugars and amino acids during waste-mediated synthesis indicate that nanoparticle formation generally results from synergistic metabolite action rather than a single phytochemical.[16]

Reduction, nucleation, growth and stabilization

For metallic nanoparticles, synthesis generally follows a bottom-up sequence involving precursor interaction, reduction, nucleation, growth, and stabilization. Phytochemicals initially chelate dissolved metal ions and can donate electrons to generate zero-valent atoms. Once a critical concentration is reached, these atoms form nuclei that subsequently grow through atom deposition, aggregation, or ripening.[4,17,18]

Reduction kinetics strongly influence final particle characteristics. Rapid reduction generally increases nucleation density and can favor smaller particles, whereas slower reduction allows more extensive growth. Adsorbed biomolecules subsequently restrict coalescence and stabilize particle surfaces, thereby influencing size, morphology, and dispersion [Figure 2].[17-19] Thus, the same waste extract may provide both reducing and stabilizing functions without requiring additional synthetic surfactants.

Mechanistic interpretation should nevertheless remain cautious. Fourier transform infrared (FTIR) can identify functional groups associated with nanoparticle surfaces, but it cannot independently establish the complete electron-transfer pathway. Stronger mechanistic evidence requires integration of extract composition, changes in metabolites during synthesis, reaction kinetics, and nanoparticle surface characterization.[3,4]

Metal versus metal-oxide pathways

The biochemical mechanism varies substantially with nanomaterial class. Ag and Au nanoparticles predominantly form through reduction of ionic precursors to elemental Ag^0 or Au^0, followed by nucleation, growth, and phytochemical-mediated capping.[7,9,13] This reduction-driven mechanism is particularly well established for AgNPs.

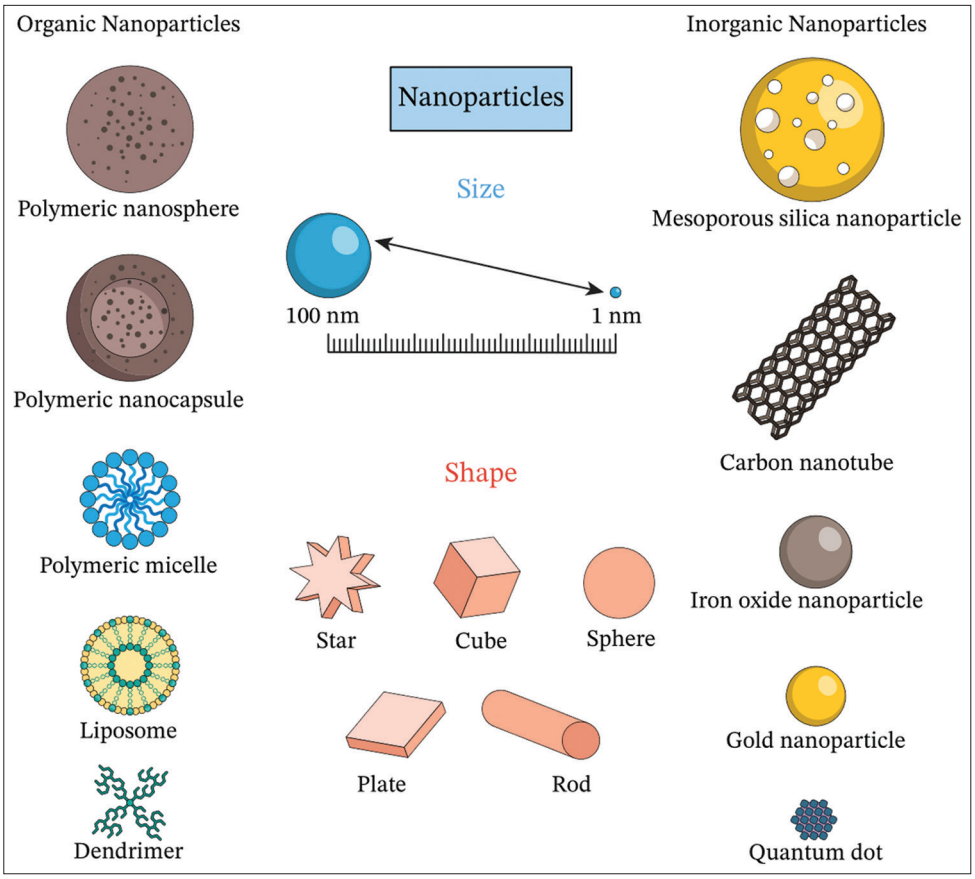


Figure 2: Influence of nanoparticle size, morphology, and structural diversity on physicochemical properties and functional applications

Metal oxides follow more complex pathways and should not be interpreted as simple reduction to the elemental state. In iron-based systems, phytochemicals may chelate Fe^{2+}/Fe^{3+} ions and participate in reduction and stabilization, while the final products can contain different oxide phases and oxidation states.[6,7] ZnO and CuO synthesis commonly involves metal-phytochemical complexation, hydrolysis or intermediate precipitation, followed by oxidation and/or thermal conversion into crystalline oxides.[3,20,21]

Overall, vegetable-waste-mediated nanoparticle formation is best described as a biomolecule-controlled, material-specific process. Noble metals are primarily governed by reduction and nucleation, whereas metal oxides involve additional coordination, hydrolysis, precipitation, oxidation, and thermal transformations. Understanding these distinctions is essential for moving waste-mediated synthesis from empirical experimentation toward mechanism-guided nanoparticle design [Table 1].

Table 1: Proposed biochemical pathways governing vegetable-waste-mediated synthesis of metallic and metal-oxide nanoparticles

Nanomaterial	Predominant pathway	Representative support
Ag, Au	Ionic reduction → M^0 → nucleation → growth → capping	[4,18,19]
Fe-based	Chelation/reduction → phase formation → stabilization	[6,7]
ZnO, CuO	Complexation → intermediate formation → oxide conversion	[3,21]

ZnO: Zinc oxide, CuO: Copper oxide

VEGETABLE WASTES AND NANOMATERIALS PRODUCED

Building on the biochemical characteristics discussed above, different vegetable residues exhibit distinct capacities for synthesizing specific classes of nanoparticles because their phytochemical profiles govern reduction kinetics, stabilization efficiency, and nanoparticle functionality. Vegetable-processing residues have been used to produce diverse metallic and metal-oxide nanoparticles, although the evidence is uneven among material classes. AgNPs are the most extensively investigated, followed by gold nanoparticles (AuNPs), ZnO, CuO and iron-based nanoparticles, while Se, Pd, TiO_2, carbon-based and hybrid systems remain comparatively less established for vegetable-specific wastes [Table 2].[2,7,22,23]

Table 2: Representative vegetable and agro-food wastes used for nanoparticle synthesis

Waste feedstock	Nanomaterial	Representative outcome	References
Potato peel/waste	Ag, Au, ZnO, Fe-based	AgNPs approximately 3.91–27.07 nm; multiple nanoparticle systems reported	[24,25]
Onion peel	Au, Ag	Antibacterial, anticandidal and antioxidant potential	[24,26]
Mixed market vegetable waste	AgNPs	Approximately 10–90 nm; antibacterial activity	[27]
Mixed market vegetable waste	AuNPs	Approximately 10–70 nm; antibacterial activity	[27]
Capsicum waste	AgNPs, AuNPs	Multiple metabolites involved in nanoparticle formation	[16]
Moringa peel	ZnO	Approximately 94% crystal-violet degradation	[28]
Date-pulp waste	ZnO	Approximately 90% dye degradation	[20]
Orange peel	SeNPs	Antibacterial and antibiofilm activity	[29]

SeNPs: Selenium nanoparticles, ZnO: Zinc oxide, AgNPs: Silver nanoparticles, AuNPs: Gold nanoparticles

Potato and onion residues are among the better documented individual feedstocks. Potato waste has been explored for Ag, Au, ZnO, and iron-based systems, with potato-peel-derived AgNPs reported within approximately 3.91–27.07 nm.[24,25] Onion peel has similarly supported noble-metal synthesis, including AuNPs with antibacterial, anticandidal and antioxidant activities.[24,26]

Mixed vegetable residues further demonstrate that segregated high-value feedstocks are not always necessary. Market vegetable waste has generated AgNPs and AuNPs with reported particle-size ranges of 10–90 and 10–70 nm, respectively, together with antibacterial activity.[27] *Capsicum* residues have also produced AgNPs and AuNPs, with changes in polyphenols, reducing sugars, and amino acids indicating direct biochemical participation during synthesis.[16]

Metal oxides and other emerging systems broaden the functional potential of vegetable-waste nanotechnology. Waste-derived ZnO has demonstrated substantial photocatalytic activity, including approximately 94% crystal-violet degradation by *Moringa*-peel-derived ZnO and about 90% dye degradation by date-pulp-mediated ZnO.[20,28] Orange-peel-mediated selenium nanoparticles have additionally shown antibacterial and antibiofilm activity.[29]

The available evidence therefore indicates that feedstock selection should be function-driven rather than simply waste-driven. AgNPs currently provide the broadest vegetable-waste evidence base, whereas AuNPs and metal oxides offer more specialized optical, catalytic, antimicrobial, and remediation functions. Emerging systems such as Pd, silica, carbon-based materials and hybrids are promising, but much of their support currently comes from broader agro-waste rather than vegetable-specific literature.[2,4,30]

Rather than continually expanding the list of nanoparticles that can be synthesized, future studies should identify which waste fraction-nanomaterial combinations provide the most reproducible properties and strongest application-specific performance.

FACTORS GOVERNING WASTE-MEDIATED NANOPARTICLE SYNTHESIS

Nanoparticle formation is controlled by interactions among feedstock chemistry, extraction conditions, and reaction parameters. These factors regulate reduction and nucleation kinetics and ultimately determine particle size, morphology, yield, crystallinity, and stability.[4,8,31]

Feedstock and extraction

Waste source and plant fraction strongly influence synthesis because their phytochemical profiles differ in reducing, complexing, and stabilizing capacity. Extraction conditions further determine which metabolites enter the reaction medium. Solvent polarity, extraction temperature, solid-to-solvent ratio, and extract concentration can therefore substantially alter nanoparticle formation.[8,32,33]

Moderate extraction temperatures may improve phytochemical recovery, whereas excessive heating can degrade active biomolecules. Similarly, insufficient extract may limit reduction and surface coverage, while excessive concentrations can alter reaction kinetics and particle growth.[19,32] Standardizing both the feedstock and extraction procedure is therefore essential for batch-to-batch reproducibility.

Reaction conditions

Among reaction variables, pH, temperature, precursor concentration, extract-to-metal ratio, and reaction time are particularly influential. pH modifies metal speciation and biomolecule ionization, thereby affecting reduction and surface interactions. Temperature controls reaction kinetics: moderate heating can accelerate reduction and nucleation, whereas excessive temperatures may degrade phytochemicals or favor particle growth.[4,8,34]

Precursor and extract concentrations determine the balance between available metal ions and reducing or capping molecules, while reaction time governs continued nucleation, growth, and surface restructuring. Consequently, optimization of a single parameter in isolation may be misleading because these variables interact throughout nanoparticle formation.[33,35]

Reproducibility and process optimization

Synthesis conditions ultimately determine nanoparticle size, morphology, crystallinity, aggregation, and surface charge, which directly influence functional performance. Colloidal stability is commonly assessed using particle-size distribution and zeta potential, although both electrostatic and steric interactions contribute to stability.[8,33,34]

Reproducibility remains challenging because vegetable wastes vary with species, plant fraction, maturity, cultivation environment, storage, and processing history. Incomplete reporting of extraction and reaction conditions further limits comparison among studies and complicates scale-up.[6,8]

Future optimization should therefore move beyond one-factor-at-a-time experiments toward multivariable approaches capable of evaluating interactions among extract concentration, precursor level, pH, temperature, and reaction time. Combining standardized feedstock characterization with controlled extraction, complete process reporting, and statistical optimization will be essential for producing reproducible and scalable waste-derived nanoparticles.[33,36]

CHARACTERIZATION OF WASTE-DERIVED NANOPARTICLES

Reliable characterization of waste-derived nanoparticles requires complementary optical, structural, microscopic, elemental, and colloidal analyses, since no single technique can fully establish nanoparticle formation, composition, morphology, phase, and stability [Table 3].[23,37,38]

Ultraviolet-visible (UV-Vis) spectroscopy provides rapid preliminary evidence of nanoparticle formation, particularly for plasmonic Ag and Au systems, whereas FTIR identifies surface-associated functional groups involved in reduction and capping.[38-40] However, color change or UV-Vis absorption alone cannot confirm particle size or morphology, and FTIR cannot independently identify the exact metabolite responsible for electron transfer.

Structural and morphological characterization is primarily achieved through X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). XRD establishes crystallinity and phase identity, which is especially important for distinguishing metallic nanoparticles from ZnO, CuO, and different iron-oxide phases. SEM and TEM provide direct evidence of particle morphology, aggregation, and primary size, while energy-dispersive X-ray (EDX)/energy dispersive spectrometer confirms elemental composition.[37,38,41] X-ray photoelectron spectroscopy (XPS) can provide additional information on oxidation states and surface chemical composition.

For dispersed nanoparticles, dynamic light scattering (DLS) measures hydrodynamic size, while zeta potential provides information on surface charge and colloidal stability.[38,42] DLS-derived sizes may therefore differ from TEM measurements because the former includes hydration layers and surface-bound biomolecules. Raman spectroscopy and thermal methods such as thermogravimetric analysis (TGA)/differential scanning calorimetry can provide additional phase, surface and thermal information when required.[16,20,43]

An effective workflow should therefore combine UV-Vis and FTIR for formation and surface chemistry, XRD for crystalline phase, SEM/TEM for morphology and size, and EDX for elemental composition, supplemented by DLS, zeta potential, XPS, Raman, or thermal analysis where necessary.[23,38,44] Importantly, the original waste extract should also be characterized alongside the nanoparticles to establish meaningful relationships between feedstock chemistry, synthesis mechanism, and final nanoparticle properties.[16,38]

Table 3: Core characterization framework for waste-derived nanoparticles

Technique	Principal information	Key limitation
UV-Vis	Nanoparticle formation and optical response	Does not confirm morphology or size alone
FTIR	Surface functional groups and capping	Cannot identify the exact reductant
XRD	Crystallinity and phase identity	Limited for highly amorphous materials
SEM/TEM	Morphology and primary particle size	Requires complementary chemical analysis
EDX/EDS	Elemental composition	Limited information on oxidation state
DLS/Zeta potential	Hydrodynamic size and colloidal stability	Strongly influenced by dispersion conditions
XPS/Raman/TGA	Surface state, phase, and thermal behavior	Specialized analysis; application dependent

UV-Vis: Ultraviolet-visible, FTIR: Fourier transform infrared, XRD: X-ray diffraction, EDX: Energy-dispersive X-ray, EDS: Energy dispersive spectrometer, XPS; X-ray photoelectron spectroscopy, DLS: Dynamic light scattering, SEM: Scanning electron microscopy, TEM: Transmission electron microscopy, TGA: thermogravimetric analysis

FUNCTIONAL APPLICATIONS

The functionality of waste-derived nanoparticles is governed by their composition, size, morphology, surface chemistry, dissolution behavior and biomolecular capping. Reported applications span antimicrobial systems, environmental remediation, food and agriculture, and biomedicine, although the maturity of evidence differs substantially among these areas.

Biological and biomedical potential

Antimicrobial activity represents the most consistently demonstrated biological function, particularly for AgNPs. Vegetable-peel-derived AgNPs have shown activity against *Escherichia coli*, *Staphylococcus aureus,* and other microorganisms, while Au-, Fe-based, ZnO, CuO, and Se nanoparticles have also demonstrated antimicrobial potential. Their activity is influenced by nanoparticle composition and physicochemical properties as well as the biochemical characteristics of the waste-derived capping layer.[29,45,46]

Antioxidant and cytotoxic activities have also been reported, but these findings remain predominantly *in vitro*. Radical-scavenging assays such as 2,2-diphenyl-1-picrylhydrazyl and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) indicate chemical antioxidant capacity rather than therapeutic efficacy, while cytotoxicity alone does not establish anticancer selectivity. Biomedical translation therefore requires dose-response analysis, normal-cell controls, hemocompatibility, genotoxicity, biodistribution, clearance, and *in vivo* safety assessment.[4,8,47]

Environmental remediation

Environmental remediation is among the strongest applications because it combines waste valorization with pollutant removal. Waste-derived Ag, ZnO, CuO, and Fe-based nanoparticles have been investigated for wastewater treatment, photocatalytic degradation, catalytic oxidation, and contaminant sensing. Potato-peel-derived AgNPs, for example, substantially reduced biochemical oxygen demand and chemical oxygen demand (COD) in wastewater, while vegetable-waste-derived CuO and ZnO systems have demonstrated high photocatalytic dye-degradation efficiencies. Cauliflower-waste-derived AgNPs have additionally been explored for dye degradation and Hg^{2+} sensing [Figure 3].

However, high dye-decolorization percentages alone do not establish environmental effectiveness. Practical validation should include mineralization or total organic carbon/COD reduction, degradation-product identification, catalyst recovery and reuse, metal leaching, ecotoxicity and performance in real wastewater matrices.[1,6,14]

Food and agricultural applications

Food and agricultural applications remain promising but comparatively less mature. AgNPs and ZnO nanoparticles are being explored for antimicrobial packaging, sensing, pathogen suppression, and treatment of contaminated water due to their antimicrobial and functional surface properties.[6]

For food-contact applications, antimicrobial efficacy alone is insufficient; nanoparticle migration, metal-ion release, food-matrix interactions, storage stability, and consumer exposure must also be considered. Similarly, agricultural use requires evaluation of persistence and effects on crops, soil microorganisms, beneficial microbes and other non-target organisms. Application-specific assessment should therefore integrate functional efficacy with exposure, environmental fate and biosafety before practical deployment.[6,8]

Overall, waste-derived nanoparticles show considerable multifunctionality, but the evidence is strongest for antimicrobial and environmental applications. Food, agricultural and biomedical uses remain promising areas where stronger safety and application-specific validation are required before translation.

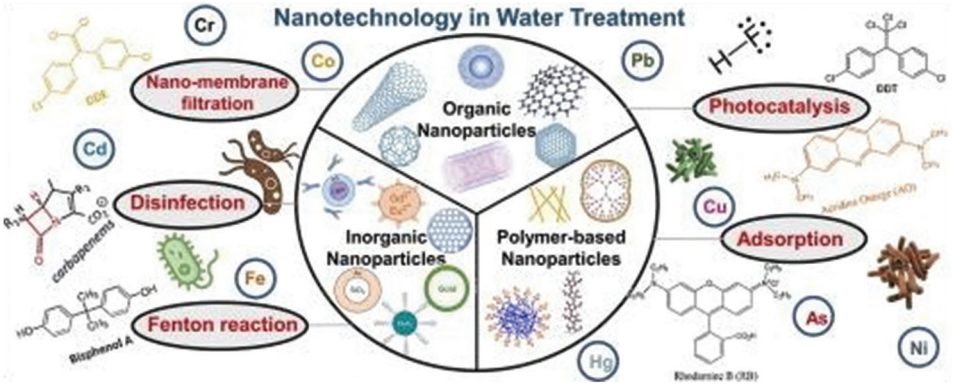


Figure 3: Major environmental applications of vegetable-waste-derived nanoparticles in water purification, wastewater treatment, catalytic degradation and contaminant sensing

FROM GREEN SYNTHESIS TO SUSTAINABLE TRANSLATION

Vegetable-waste-mediated nanoparticle synthesis supports circular-bioeconomy principles by converting renewable residues into functional materials while potentially reducing dependence on hazardous synthetic reagents.[2,48] However, biological origin alone does not guarantee sustainability. Extraction, heating, precursor use, purification, nanoparticle recovery, and waste disposal contribute to the overall environmental footprint and should be considered across the complete production chain.[6,22,47]

Biosafety is equally important because nanoscale materials may interact with biological systems differently from their bulk counterparts. Potential effects on humans, plants, microorganisms, aquatic organisms and ecosystems therefore require evaluation alongside functional performance.[6,8,42,49] Long-term toxicity, environmental persistence, nanoparticle release, recovery, reuse and end-of-life fate remain particularly important knowledge gaps.

Scale-up is further constrained by feedstock heterogeneity and process reproducibility. Vegetable wastes vary with species, cultivar, maturity, cultivation environment, storage and processing history, producing differences in phytochemical composition and synthesis behavior. Standardization should therefore begin with waste source, plant fraction, storage, extraction procedure, and phytochemical profile, followed by control of precursor concentration, extract-to-metal ratio, pH, temperature, reaction time, and purification.[8,50]

Future development should move beyond proof-of-concept synthesis toward mechanism-guided, application-specific and scalable processes. Comparative feedstock screening, multivariable optimization, life-cycle assessment, economic analysis and regulatory evaluation will be essential for identifying waste-nanomaterial combinations that provide reproducible performance with genuine environmental and economic advantages.[8,51]

Thus, successful translation depends not simply on whether vegetable waste can produce nanoparticles, but on whether the resulting process is reproducible, safe, scalable, economically viable and environmentally justified.

CONCLUSION

Vegetable residues represent a sustainable and chemically active resource for the green synthesis of functional nanomaterials, providing an effective strategy for converting agro-food waste into high-value products within a circular bioeconomy framework. Their diverse phytochemicals facilitate reduction, nucleation, capping, and stabilization, enabling the synthesis of a broad range of metallic and metal-oxide nanoparticles with promising antimicrobial, catalytic, environmental, and emerging agricultural applications. However, practical implementation depends on overcoming challenges related to feedstock heterogeneity, process reproducibility, nanoparticle safety, large-scale production, and regulatory acceptance. Future research should emphasize standardized feedstock characterization, mechanism-guided synthesis, multivariable process optimization, comprehensive biosafety assessment, and life-cycle analysis. Addressing these priorities will accelerate the translation of vegetable-waste-derived nanomaterials from laboratory research to reliable industrial and environmental applications, strengthening the role of green nanotechnology in sustainable resource utilization.

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