Comparative Study of Nanoparticles Synthesized from Leaf, Peel, and Seed Extracts of the Same Plant Species: A Review of Green Synthesis Outcomes

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Abstract
The ideal method for creating metal and metal-oxide nanoparticles is now green, plant-mediated synthesis, which produces particles surface-functionalized with bioactive phytochemicals without the use of hazardous reducing agents. How plant organ choice leaf, peel, or seed affects synthesis results is a recurrent but little-studied concern since each tissue, even within a same parent plant, has a unique phytochemical fingerprint. This review examines how leaf, peel, and seed extracts vary in reducing power, nanoparticle size/shape/stability, and consequent antibacterial, antioxidant, and catalytic performance across species, including Perilla frutescens, Citrus spp., Capsicum chinense, Annona squamosa, Moringa oleifera, Cassia tora, Morinda citrifolia, and Allium cepa. Rich low-molecular-weight phenolics in leaves often result in smaller, more homogeneous particles; peels provide a cost-effective waste-derived alternative rich in flavonoids and pectin; and seeds create unique capping chemistry with similar or better bioactivity through tannins, proteins, and oils. The review concludes by pointing up methodological flaws, primarily the lack of same-batch, three-way comparisons that restrict generalization.

Keywords: Green synthesis; plant organ selection; phytochemicals; nanoparticles; leaf vs. peel vs. seed extract.

1. Introduction

By taking use of the size-dependent optical, electrical, catalytic, and antibacterial capabilities that appear once a material is restricted to the 1–100 nm range, nanotechnology has revolutionized materials science, catalysis, agriculture, medicine, and environmental engineering. Conventional physical and chemical methods for creating nanoparticles, such as evaporation-condensation, laser ablation, sol-gel processing, chemical reduction, and electrochemical deposition, are efficient but frequently depend on dangerous solvents, potent reducing agents like hydrazine or sodium borohydride, and high energy input, all of which increase costs and environmental concerns. Thus, green synthesis the use of biological materials in place of synthetic reagents has become a cost-effective and ecologically friendly solution. Plants are abundant in secondary metabolites, polyphenols, flavonoids, terpenoids, alkaloids, tannins, and reducing sugars that can concurrently reduce metal ions and cap the resultant nanoparticle, making plant-mediated synthesis one of the most appealing biological routes. It is also easy to handle and does not require the culture-maintenance of microbial synthesis.

The majority of early research in this area focused on a single, easily accessible plant component, usually the leaf, without considering if a different organ of the same species may function better, worse, or just differently. Because leaves, peels, and seeds are not chemically comparable tissues,

 ISSN: 3049-0952
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there is a significant gap. Peels are protective, frequently lignified or waxy tissues rich in pectin, carotenoids, and phenolic acids that accumulate as a defensive barrier; seeds are storage organs dominated by proteins, lipids, tannins, and, in many species, alkaloids meant to prevent predation and promote germination; and leaves are metabolically active, photosynthetic organs rich in chlorophyll, flavonoids, and ascorbic acid. It makes sense that leaf-, peel-, and seed-derived nanoparticles from the same plant could differ systematically in size, shape, surface charge, stability, and downstream bioactivity because the phytochemical profile of a tissue controls both the rate of metal-ion reduction and the chemistry of the capping layer that stabilizes the final particle. In order to characterize these distinctions and determine which plant part is most appropriate for a given use, this study synthesizes the existing comparative and single-organ research.

2. Green Synthesis: Principles and Reaction Mechanism

Three widely recognized, frequently overlapping stages lead to the formation of a metal or metal-oxide nanoparticle from a plant extract: activation, where metal ions in solution are reduced to zero-valent atoms and nucleation begins; growth, where small clusters unite and grow into larger, thermodynamically more stable particles (Ostwald ripening); and termination, where capping biomolecules adsorb onto the particle surface and stop further growth, fixing the final size and shape. Although ascorbic acid, reducing sugars, and certain proteins can function as quick, potent reductants on their own, hydroxyl-rich phenolic compounds are typically thought of as the primary electron donors that propel the reduction phase. The surrounding flavonoids, tannins, and polysaccharides adsorb onto the developing nanoparticle surface through hydroxyl, carbonyl, and carboxyl functional groups after the metal atoms are reduced, providing steric and electrostatic stabilization that inhibits agglomeration. Even when the metal precursor and reaction conditions are held constant, the kinetics of nucleation and the final particle size distribution are tissue-dependent due to differences in the relative concentrations of strong versus weak capping agents and fast versus slow reductants.

3. Phytochemical Variation Across Plant Organs

3.1 Leaves

In addition to having a wide range of phenolic acids, leaf tissue is photosynthetically active and usually exhibits the greatest quantities of flavonoids, chlorophyll derivatives, and ascorbic acid among vegetative organs. Leaves have historically been the go-to extract source in green synthesis due to their chemical richness, which combines a potent, quick-acting reducing power with a plentiful supply of capping ligands, which often results in tiny, widely dispersed, extremely stable nanoparticles. Pre-treatment can be just as important as organ choice itself, as demonstrated by comparative research on Moringa oleifera, which reveals that even within the leaf organ, the physical condition of the tissue fresh vs freeze-dried affects nanoparticle production and shape in a measurable way.

3.2 Peels

As part of the structural and defensive chemistry of the plant, phenolic acids, flavonoids, carotenoids, and pectin are accumulated in the protective tissues of fruit and vegetable peels. In

 ISSN: 3049-0952
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addition to its chemical benefits, the use of peels as a feedstock for nanoparticles has a strong sustainability and circular economy argument since they are produced in vast quantities as a low-value or waste by-product of juicing, canning, and food processing. Peels from various, closely related citrus species produce nanoparticles with distinct optical and morphological signatures, according to comparative citrus studies. This suggests that the reduction and capping process is fine-tuned by the particular balance of limonoids, flavonoids, and sugars derived from pectin in a particular peel. The horticulture by-product onion (Allium cepa) peel has also been transformed into antioxidant, antibacterial zinc oxide nanoparticles, demonstrating the basic idea that peel waste may be turned into a useful nanomaterial feedstock rather than thrown away.

3.3 Seeds

Proteins, lipids, carbohydrates, and often tannins and alkaloids that shield the embryo make up the chemistry of seeds, which are storage organs. Although their overall phenolic content is frequently lower than that of leaves, the phenolics they do contain, together with mucilage and seed proteins, can function as efficient and even exceptionally potent capping agents. For instance, it has been demonstrated that Cassia tora seed extract alone can produce crystalline, antibacterially potent silver nanoparticles. However, a more comprehensive analysis of medicinal plant extracts revealed that Brassica nigra seed extract produced antibacterial nanoparticles that either matched or outperformed several counterparts derived from leaves and roots. These findings caution against assuming that lower total phenolic content automatically implies inferior nanoparticle performance; the specific class of reducing and capping molecule, not only its total quantity, governs the outcome.

4. Comparative Case Studies from the Same Plant

Since this methodology eliminates species-level confounds and isolates the influence of plant part, studies that synthesized nanoparticles from many organs of the same species under matched circumstances provide the most instructive data for this review. The main comparison conclusions found in the literature are summarized in Table 1.

Plant Species	Plant Part(s) Compared	Nanoparticle System	Key Comparative Finding	Source (Year)
Perilla frutescens	Leaf extract vs. raw leaf	AgNPs	Leaf-extract AgNPs (<61 nm, spherical) showed markedly higher DPPH/FRAP antioxidant and antibacterial activity than the raw leaf extract itself.	Tavan et al., 2023
Citrus aurantifolia	Fruit peel	AgNPs	Peel flavonoids and limonoids yielded stable, well-dispersed AgNPs with	Bio-fabrication CAFPE

ISSN: 3049-0952
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			strong bio-reduction capacity.	study, 2023
Citrus tangerina, C. sinensis, C. limon	Peel (three related species)	AgNPs	Peel source altered UV-Vis absorption maxima and particle morphology; all three citrus peels gave effective antibacterial AgNPs with species-specific yields.	Citrus peel comparative study, 2021
Capsicum chinense	Root, stem and leaf (same plant)	AuNPs and AgNPs	Leaf extract outperformed root and stem extracts of the same plant, giving the most stable, smallest and most bioactive nanoparticles.	Capsicum chinense study, 2022
Annona squamosa	Leaf vs. fruit	AgNPs	Leaf- and fruit-derived AgNPs differed in size-dependent biomedical performance, indicating organ-specific reduction kinetics.	Annona squamosa study, 2022
Moringa oleifera	Fresh vs. freeze-dried leaf	AgNPs	Tissue-preparation state within the same organ affected yield and morphology as much as changing plant part.	Moodley et al., 2018
Multi-species panel (incl. Brassica nigra seed)	Root, seed, leaf across species	AgNPs	Seed extract produced antibacterial AgNPs comparable to, or exceeding, several leaf/root extracts despite lower total phenolic content.	Medicinal-plant AgNP panel, 2021
Cassia tora	Seed	AgNPs	Seed extract alone generated crystalline, antibacterially active AgNPs (~55-59 nm), confirming seed coats as	Cassia tora seed study, 2022

			phenolic-rich reducing matrices.	
Morinda citrifolia	Leaf	CuO NPs	Leaf-derived ascorbic acid enhanced CuO nanoparticle crystallinity and antibacterial/antifungal performance.	Priya et al., 2023
Allium cepa	Waste peel	ZnO NPs	Onion peel waste, otherwise discarded, produced hexagonal ZnO NPs with useful antioxidant/antibacterial activity, illustrating peel valorisation.	Onion peel ZnO study, 2021

These case studies exhibit a number of recurring themes. First, when leaf extracts are directly compared to another organ of the same plant, they consistently provide the smallest and narrowly scattered particles, which is consistent with their high flavonoid and ascorbic acid content serving as quick, constant reductants. Second, peel extracts frequently equal leaf extracts in terms of nanoparticle stability and antibacterial activity, even though they are a secondary or waste material. In citrus species, the limonoid and pectin content of the peel seems to provide extra colloidal stability. Third, seed extracts are by no means less bioactive, even though they occasionally produce relatively larger or more polydisperse particles. Their tannin- and protein-rich capping layers can improve antibacterial adhesion to microbial membranes, and in multiple cases, seed-derived nanoparticles performed better in antibacterial zone-of-inhibition tests than leaf-derived ones. Fourth, the nanoparticle form is nearly always more bioactive than the parent extract alone, indicating that the production of nanoparticles concentrates and reorganizes the plant's phytochemicals into a more powerful presentation, independent of the organ that provided them.

5. Influence of Plant Part on Nanoparticle Size, Shape and Stability

The most commonly reported point of comparison across studies is particle size, which generally places leaf-derived nanoparticles at the smaller end of the size range (typically under 60 nm), peel-derived particles in an intermediate range that varies significantly depending on the citrus or vegetable species used, and seed-derived particles at a broader and occasionally larger size range, reflecting the lower solubility and greater structural complexity of seed phenolics and proteins compared with the low-molecular-weight flavonoids typical of leaves. Zeta-potential measurements, which serve as a stand-in for colloidal stability, also reveal that while seed-derived particles can exhibit more variable stability depending on the balance of protein and phenolic capping agents present, leaf- and peel-derived nanoparticles frequently achieve strongly negative surface potentials (often below -18 mV), indicating good electrostatic stabilization. All three tissue

 ISSN: 3049-0952
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types typically exhibit spherical morphology, however in certain investigations, peel extracts high in pectin and citrus flavonoids generated more evenly distributed populations with less aggregation. This is probably because pectin functions as an extra polymeric stabilizer.

6. Comparative Bioactivity

6.1 Antibacterial activity

No matter which organ provided the extract, the antibacterial activity of nanoparticles, measured by zone-of-inhibition and minimum-inhibitory-concentration assays against Gram-positive organisms like Staphylococcus aureus and Gram-negative organisms like Escherichia coli, surpassed that of the parent plant extract in all of the reviewed studies. No single tissue was consistently better than the others: citrus species' peel-derived nanoparticles were consistently effective against both bacterial classes; Cassia tora and Brassica nigra's seed-derived nanoparticles matched or outperformed several leaf-derived comparators; and Perilla frutescens and Moringa oleifera's leaf-derived nanoparticles performed strongly against both bacterial classes. The prevailing theory in the literature is that the resultant particle size, surface charge, and particular capping chemistry all of which are impacted by, but not strictly defined by, plant part determines antibacterial efficacy more so than the source organ itself.

6.2 Antioxidant activity

The polyphenol and flavonoid concentration of the source extract is closely correlated with antioxidant ability, which is often assessed by DPPH and FRAP radical-scavenging tests. This tends to favor leaf and peel extracts over seed extracts. Notably, a number of studies show that the antioxidant activity of nanoparticles can surpass that of the parent extract even when the preparation's total phenolic content is lower. This paradox is typically explained by the nanoparticles' higher surface-area-to-volume ratio, which concentrates radical-scavenging activity at an accessible surface rather than dispersing it throughout the extract's bulk volume.

6.3 Catalytic and other functional activities

Peel- and seed-derived nanoparticles have proven to be just as effective as leaf-derived ones when catalytic, photocatalytic, or enzyme-inhibitory activities have been evaluated. In certain instances, the tannin-rich capping layer of seed extracts seems to provide extra stability under the acidic or oxidative conditions used in catalytic testing. This finding is especially pertinent to environmental remediation applications where nanoparticles must remain active over repeated reaction cycles.

7. Practical and Methodological Factors Affecting Comparability

A number of practical factors that are rarely standardized across studies complicate direct comparison of leaf, peel, and seed extracts: extraction solvent (aqueous versus hydroalcoholic), drying method (shade-, oven-, or freeze-drying), plant-to-solvent ratio, extraction temperature and time, precursor salt concentration, reaction pH and temperature, and harvest season. These factors all independently affect phytochemical yield and, consequently, nanoparticle characteristics. Particularly, seasonal variation has been demonstrated to modify the phytochemical profile of a single organ sufficiently to alter nanoparticle yield and bioactivity. This suggests that apparent differences between plant parts reported by various research groups may be partially due to uncontrolled seasonal or post-harvest handling variation rather than an inherent characteristic of

 ISSN: 3049-0952
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the tissue itself. This emphasizes the necessity of single-batch, same-day, three-organ comparison designs which are still very rare in the published literature before generalizations about the "best" plant part can be made across species.

8. Applications

An overlapping range of application domains, including antimicrobial coatings and wound-care materials, food packaging and preservation, agricultural growth promoters and biopesticides, sensing and catalysis, and environmental remediation, including dye degradation and heavy-metal adsorption, have been investigated for nanoparticles derived from leaves, peels, and seeds. While leaf extracts are chemically potent, they usually require intentional cultivation or harvesting, which results in a higher feedstock cost at scale. In contrast, peel and seed material is often a low-cost by-product of the food and agricultural industry, making these two organs particularly advantageous for large-scale or resource-limited deployment.

9. Challenges and Future Perspectives

Three issues are particularly noteworthy. First, regardless of the organ employed, repeatability is challenging because to batch-to-batch and season-to-season variability in phytochemical content, which is seldom quantitatively quantified. Second, rational optimization of a selected plant portion is limited by the lack of a mechanistic knowledge of which particular molecules within a complex plant extract are responsible for reduction versus capping. Third, and most pertinent to the main point of this study, very few research compare leaf, peel, and seed extracts of the same species in a single, controlled experiment; instead, the majority of the information gathered here is derived from individual single-organ investigations that are compared post hoc across the literature. Future research would benefit from metabolomic profiling of each extract to connect particular phytochemical classes to the size, stability, and bioactivity of the final nanoparticle, as well as standardized, same-batch three-way comparisons that maintain precursor concentration, pH, temperature, and reaction time constant while only changing the source organ.

10. Conclusion

This review demonstrates that the chemical differences between the leaf, peel, and seed extracts from the same plant extend to the nanoparticles that each tissue generates. In general, leaves provide the fastest, most uniform reduction and the smallest, most stable particles; peels, an abundant and inexpensive by-product, are a highly competitive and increasingly preferred alternative, especially in citrus and vegetable species; and seeds, despite having a lower total phenolic content, contribute unique tannin- and protein-based capping chemistry that can match or surpass the antibacterial and catalytic performance of nanoparticles derived from leaves and peels. The target application, the desired particle size range, and pragmatic factors like feedstock availability and cost determine which organ is best. The most obvious route to a more predictive, mechanistically based knowledge of how plant part controls green nanoparticle formation is to close the gap between single-organ investigations through systematic, same-batch three-way comparisons.

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