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Green Nanobiotechnology: Focusing on Plant-Mediated Synthesis of Nanoparticles as An Eco-Friendly Alternative to Traditional Chemical Methods



Sumaira Anjum¹

¹Department of Biotechnology, Kinnaird College for Women, Lahore, Pakistan
sumaira.anjum@kinnaird.edu.pk

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Nanoparticles (NPs) have revolutionized biomedicine, agriculture, environmental remediation, electronics, and materials science through precise control of size, shape, and surface chemistry [1, 2]. Yet the conventional method through chemical synthesis has proven environmentally unsustainable and biologically hazardous. Chemical synthesis often involves expensive reagents, which have a detrimental effect on the environment [3]. This editorial argues that plant-mediated green synthesis is the is a more effective, sustainable, and forward-looking approach. However, green synthesis is an eco-friendly, sustainable, cost-effective, and safe method for manufacturing nanoparticles [4]. By using plant extracts as natural reducing and capping agents, this approach delivers high-quality NPs under mild, aqueous conditions while eliminating toxic reagents, energy waste, and hazardous by-products [5].

Traditional chemical synthesis depends on harsh reducing agents such as sodium borohydride, the most widely used reductant, along with organic solvents and elevated temperatures or pressures [6]. These processes generate toxic waste, require expensive disposal protocols, and leave residual chemicals in the environment. This creates long-term environmental and health hazards [7]. Comparative studies repeatedly demonstrate that organic solvents have higher health risks, including behavioral, reproductive, and neurological effects, with longer environmental persistence [8]. Sometimes, the nanoparticles synthesized using the green method have enhanced quality and size compared to chemical synthesis. A recent study investigated the comparison of synthesizing Fe₃O₄ nanoparticles using chemical and green methods. The size of NPs using the chemical method was 87-400 nm, which is much larger than the size of 2-80 nm of nanoparticles synthesized via green synthesis [9].

Plant-mediated green synthesis offers a complete contrast. It offers no harsh chemicals, is non-toxic, cost-effective, environment-friendly, sustainable, and a safe option for the synthesis of NPs. Additionally, by employing green reducing and capping agents, the NPs show unique properties such as biocompatibility and enhanced stability [10]. Plant extracts are packed with diverse phytochemicals such as polyphenols, flavonoids, alkaloids, terpenoids, proteins, and enzymes that function as powerful capping agents, reducing agents, and stabilizers. As these compounds donate electrons to metal ions while preventing aggregation and enhancing stability [11].

Real-world examples from recent studies underscore why plants are the best raw material. Leaf extracts of *Alcea rosea* leaves produce highly stable, bioactive silver with superior antimicrobial, anticancer, and antioxidant activity [12]. Silver (Ag) and Gold (Au) NPs were also synthesized by using floral extracts from *P. domesticum* and *H. sabdariffa*, exhibiting good cytotoxic and antioxidant activity [13]. *Nigella sativa* seeds were also used for the synthesis of extremely small-sized 8-80 nm NPs [14]. Hence, NPs synthesized using the green method provide stable, biocompatible, and eco-friendly properties with enhanced antioxidant, anticancer, and antimicrobial properties [15].

However, producing nanoparticles using plant extracts faces several challenges. That includes: maintaining uniformity



during scale-up, ensuring long-term stability and proper storage, and removing impurities from extracts are major hurdles. Due to environmentally induced variations in plant phytochemical composition, achieving consistent and reproducible nanoparticle synthesis across different batches is challenging. Also, controlling nanoparticle size and shape is tricky, as factors like pH, temperature, salt content, and reaction time can change the outcome. Overcoming these issues requires careful adjustment of reaction conditions and collaborative optimization of methods [10, 11].

To sum up, the scientific community has made joint efforts that plant-mediated synthesis represents the gold standard in green nanobiotechnology. They produce greener, safer, more cost-effective products and possess natural multifunctionality that cannot be easily copied in chemical routes. Since the world is demanding sustainable nanomaterials in biomedicine, agriculture, and environmental applications, it is high time to adopt this plant-based synthesis. Moreover, we need more investment in methods that can be scaled up, better testing in living systems, and close collaboration between researchers, industry, and regulators to tackle the remaining challenges and make the full potential of these nanoparticles a reality.

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