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Green Synthesis of Nanoparticles: Advantages and Applications in Agriculture

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Nanotechnology and Agriculture

Nanotechnology applications in agriculture have grown in recent years. Nanotechnology holds promise for enhancing agricultural productivity and supporting future food security (Seleiman *et al.*, 2023). Nanotechnology involves the use of materials with particle sizes ranging from 1 to 100 nanometres, which exhibit unique physical, chemical and biological properties compared to larger-scale materials. Nanoparticles (NPs) demonstrate improved uptake by plants compared to equivalent bulk chemicals. Foliar application of NPs gives faster and more effective results than soil application of fertilizers (El-Zohri *et al.*, 2021). The high surface-to-volume ratio of nanoparticles enhances their reactivity, allowing them to efficiently adsorb essential compounds and nutrients crucial for plant growth and metabolism. Increased reactivity and penetration ability of NPs facilitate the availability of essential nutrients within plant cells, thereby boosting plant metabolism and defense mechanisms. Nanoparticles are being explored as nano-fertilizers, nano-pesticides and carriers for various plant growth regulators. They have attracted significant attention from agricultural scientists due to their high efficacy, cost-effectiveness and environmentally friendly characteristics (Seleiman *et al.*, 2023).

Synthesis of Nanoparticles

Two fundamental synthesis approaches are commonly used to synthesise nano-particles. They are top-down and bottom-up methods. Top-down methods involve the reduction of bulk materials to nanoscale dimensions through techniques such as lithography, ball milling, etching and sputtering. In contrast, bottom-up methods involve the assembly of nanoparticles from simpler precursor molecules. This approach encompasses several techniques including chemical vapor deposition, sol–gel processes, spray pyrolysis, laser pyrolysis and

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atomic/molecular condensation (Singh *et al*., 2018). Various techniques have been explored for the synthesis of metal nanoparticles, including chemical reduction, photochemical reduction, gamma-ray irradiation, microwave irradiation, micro-emulsion, laser ablation and electrochemical reduction. However, traditional methods often present significant drawbacks. These include the use of flammable organic solvents and harmful chemicals, substantial waste generation, high toxicity, the need for expensive equipment, energy inefficiency and challenges in purification. Consequently, there is a growing need for novel synthesis methods that are energy-efficient, environmentally friendly and non-toxic. In this context, the use of biological materials from the Plantae kingdom offers a promising alternative. These methods, known as biogenic or green synthesis, provide an eco-friendly, simple, rapid, stable and cost-effective approach to nanoparticles synthesis, aligning with the principles of green chemistry (Ghotekar *et al.,* 2020; Das *et al.,* 2021).

Green synthesis of Nano-Particles

Green synthesis aims to prevent the formation of harmful by-products by employing reliable, sustainable and environmentally friendly synthesis methods. Achieving this goal requires the use of ideal solvent systems and natural resources, such as organic systems (Singh et al., 2018). Green synthesis uses biological entities, including bacteria, fungi, algae and plants for the biosynthesis of metallic nanoparticles.

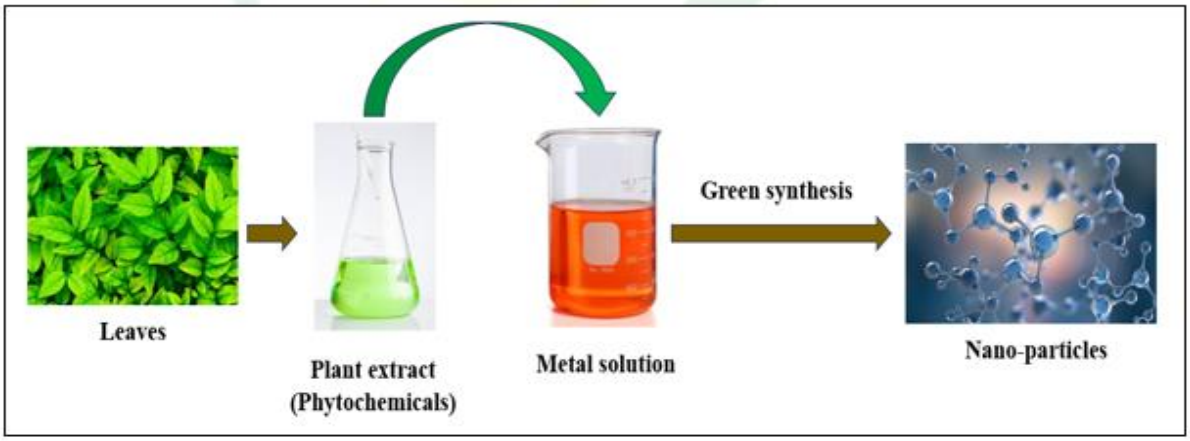

Figure: Green synthesis of Nano-particles by using plant extracts

Among the green synthesis methods for metal and metal oxide nanoparticles, the use of plant extracts is particularly advantageous due to its simplicity and scalability compared to bacterial or fungal-mediated synthesis. Plant-based methods are cost-effective, as they do not

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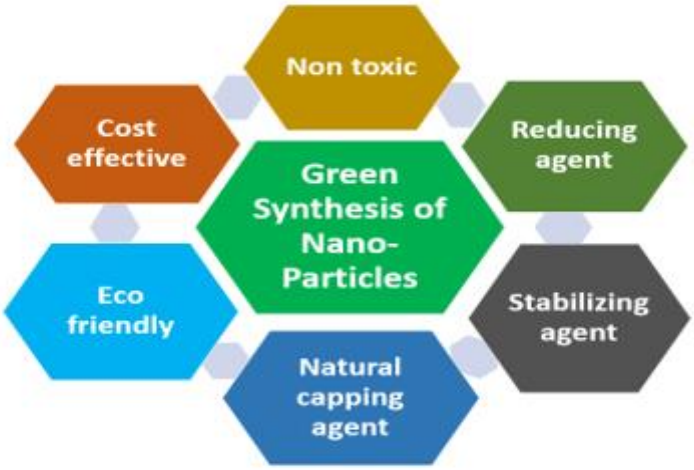
require high pressures, high energy, or toxic chemicals and they are readily adaptable for large-scale industrial production. Furthermore, plant diversity provides a rich source of various phytochemicals, including ketones, aldehydes, flavonoids, amides, terpenoids, carboxylic acids, phenols and ascorbic acids, which can effectively reduce metal salts to form metal nanoparticles (Das *et al*., 2021; Abbes *et al.*, 2022).

During synthesis of nanoparticles by using plant extracts, the plant extract is mixed with metal precursor solutions under various reaction conditions. The parameters influencing the reaction include the type and concentration of phytochemicals in the plant extract, the concentration of metal salts, pH and temperature. These factors control the rate of nanoparticle formation, as well as their yield and stability (Dwivedi et al., 2010). Phytochemicals in plant leaf extracts possess significant potential to reduce metal ions rapidly compared to microbial methods, which generally require longer incubation periods. Consequently, plant leaf extracts are considered an excellent and eco-friendly source for synthesizing metal oxide nanoparticles. In this process, plant leaf extracts serve a dual function: they act as both reducing and stabilizing agents, facilitating the synthesis of nanoparticles. The composition of the plant extract plays a crucial role in the synthesis process. Different plants contain varying concentrations of phytochemicals, which can influence the efficiency of nanoparticle synthesis. Key phytochemicals involved include flavonoids, terpenoids, sugars, ketones, aldehydes, carboxylic acids and amides, all of which are responsible for the bioreduction of metal ions in to metal nanoparticles (Singh et al., 2018; Li et al., 2011).

Advantages of Green synthesis of Nano-Particles by Using Plant Extracts



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