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From Botanical Extracts to Functional Nanocatalysts: A Critical Review of Green Synthesis and Photocatalytic Performance

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Abstract. Plant extract mediated production of environmentally benign nanomaterial is growing demand and an emerging branch of green nanotechnology. Utilization of natural phytochemicals as reducing, stabilizing, and capping agents provides an eco-friendly route for nanoparticle synthesis. These secondary metabolites reduces chemical hazards while producing stable nanostructures which are suitable for catalytic and other functional applications This paper provides a comprehensive overview of recent advances in the biosynthesis of various nanomaterials such as metal, metal oxide, and composite, hetero-junction nanomaterials using diverse plant extracts, emphasizing the phytochemical mechanisms governing nucleation, growth, morphology control, and functionalization. Phyto-synthesized nanomaterials are further employed in environmental remediation processes, including the degradation of organic pollutants, removal of heavy metals and dyes from water *via* photocatalysis and soil, and antimicrobial treatments, owing to their enhanced reactivity, high surface area with great stability and eco-friendly synthesis route. The review concludes with emerging trends and future research directions aimed at enhancing reproducibility, exploring underutilized plant resources, integrating hybrid green synthesis strategies, and advancing the practical deployment of phytogenic nanomaterials in photocatalytic technologies.

1. Introduction

The world is currently increasingly relies on the field of nanotechnology as it is play a wide role in the development of advance scientific, industrial and technological fields. Especially, nanomaterials show good chemical and physical properties compared with bulk materials due to its size ranging from 1 to 100 nm. Furthermore, nanomaterials have found

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extensive applications across diverse domains including industry, agriculture, medicine, and remediation of environment [1, 2]. Green synthesis of nanomaterials gaining the more interest due to its non-toxic, cost friendly and safe to the environment. Moreover, green synthesis is free from the usage of chemical reducing or capping agents which are harmful to environment in the formation of naomaterials.

1.1. Green synthesis of nanocatalyst using plant parts

Nowadays, the synthesis of nanomaterials using different plant extracts has increasing significant role due to non-toxic, cost free, easily availability and environment friendliness [3]. Especially, botanical extracts contain numerous phytochemicals including alkaloids, flavonoids, phenolic acids, tannins, glycosides, saponins, etc . Phytochemicals act as efficient natural reducing, capping, and stabilizing agents during nanoparticle formation [4]. Phytochemicals available in plant extracts avoid toxic chemical reducing agents in the formation of nanomaterials [5]. Hence, green synthesis is considered as eco-friendly, cost-effective, and sustainable compare with conventional physical or chemical methods [6]. Numerous research reports have been stated that green synthesized NPs used for the controlled oxidative stress, genotoxicity and apoptosis related changes respectively. Moreover, due to the tremendous properties of green synthesized NPs, they have been utilized in medicinal applications like antibacterial, antifungal, anticancer, antidiabetic, antiviral agents, used food industries and cosmetics [7]. Also, these NPs were act as catalytic agents in the organic transformations, water treatment, photocatalytic degradation of industrial effluents [8]. Benefits of green nanocatalyst are given in figure 1.

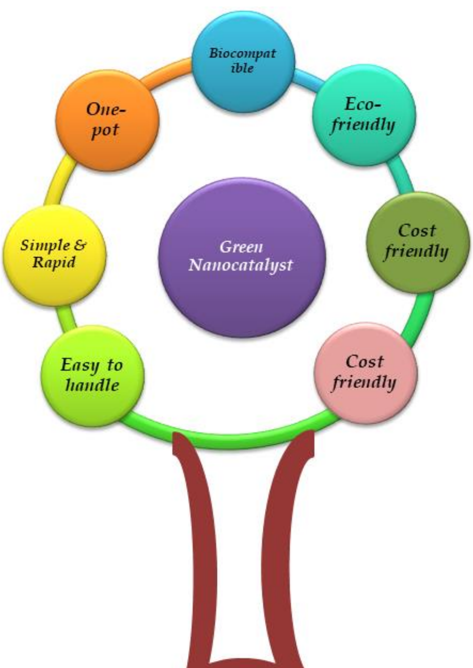

Fig. 1. Benefits of green nanocatalyst.

1.2. Caractérisation of green nanocatalysts

Synthesized plant mediated green nanocatalysts size, morphology, functional groups present on the surface and optical properties are characterized by various techniques. The crystallinity and size of nanoctalysts characterized by X-ray diffraction analysis. Several functional groups which are derived from plant extracts on the surface of nanocatalysts such as hydroxyl and carbonyl moieties, indicating effective bio-capping and stabilization revealed by FTIR spectroscopy [9]. Visible light absorption with reduced band gap and phytochemical interactions are demonstrated by UV-Visible spectroscopy. Complete morphology analysis such as surface shape, size, agglomeration and crystallinity through distinct lattice fringes are confirmed by SEM and HR-TEM analysis. Elemental purity, compositions and oxidation states of the metal and presence of surface hydroxyl species determined by EDX and XPS analysis respectively. The absorption and catalytic activity favored surface of nanocatalysts analyzed by BET [10].

1.3. Photocatalytsis

Photocatalysis is an efficient catalytic technique for purification of water by degrading various effluents and producing hydrogen by splitting water molecule in the presence of light. Light energy activates the nanocatalyst to generate electron-hole pairs. These charges produce hydroxyl radicals (•OH) and superoxide (O_2^{-}•) which play a significant role in the break down pollutants present in the water [11]. Plant mediated nanocatalysts show excellent photocatalytic activity due to its surface functional groups. Green nanocatalysts generate electrons and holes when exposed to light.

$$Nanocatalyst + h\upsilon = e_{CB} + h_{VB}$$

Where,

$h\upsilon$ = light energy

e_{CB} = Excited electrons in conduction band

h_{VB} = holes in valance band

Mainly, one of the major limitations is generated electron-hole recombination. Green synthesized nanocatalysts increase charge separation by biomolecule surface capping, formation of defect site and oxygen vacancies and enhanced surface hydroxyl groups respectively [12]. The plausible mechanism of photocatalytic activity by green nanocatalyst is given below.

a) Formation of superoxide radicals

$$e_{CB} + O_2 \rightarrow \cdot O_2^{-}$$

b) Formation of hydroxyl radicals

$$h_{VB} + H_2O \rightarrow \cdot OH + H^{+}$$

Or

$$h_{VB} + OH \rightarrow \cdot OH$$

Where,

$\cdot OH$ = Hydroxyl radical

$\cdot O_2^{-}$ = Superoxide radical

c) Degradation of pollutants from water

$$\cdot OH / \cdot O_2^- + \text{Pollutants} \rightarrow \text{Intermediate compounds}$$

$$\text{Intermediates} \rightarrow CO_2 + H_2O + \text{inorganic ions}$$

2. Photocatalytic performances of green nanocatalysts

Recently Berhe A. et al., in 2025 synthesized phytochemicals mediated NiO green nanocatalysts using leaf extract of *Calpurnia aurea* [13]. The surface bound phytochemicals on NiO nanoparticles play an important role in absorption of light, charge separation and surface absorption of malachite green (MG) dye. NiO nanomaterials absorbs photons as greter than the band gap in the presence of visible light. This process generates electron-hole pair by the excitation of electrons from conduction band (CB) to valance band (VB). Bio capping agents on surface of NiO nanomaterials achieved from plant extract acts as electron traps and stabilizers and supress the rapid recombination of photo generated charge carriers. Mainly, superoxide radicals generated by the excited electrons in CB, while hydroxyl radicals generated by holes in VB. These generated ROS ($\cdot OH / \cdot O_2^-$) attack on the chromophoric structure of MG dye and leads to degradation. In figure 2 show the synthesis of NiO nanomaterials using plant extract and Photocatalytic degradation of MG dye.

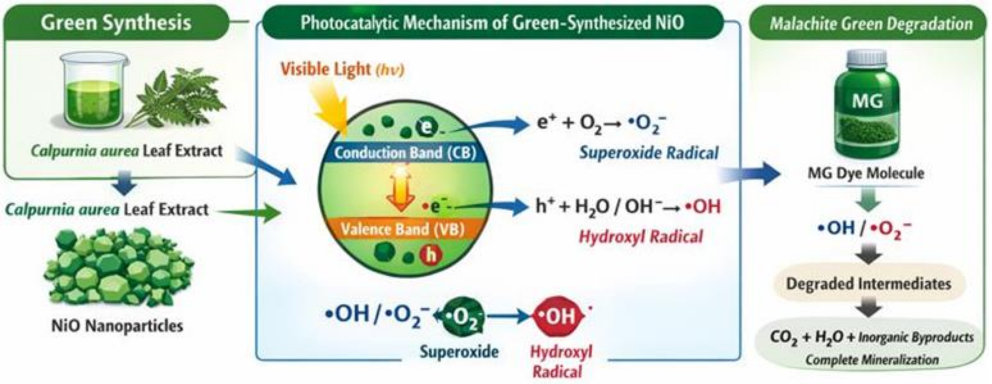

Fig. 2. NiO nanomaterials synthesis using *Calpurnia aurea* leaf extract and photo-catalytic degradation of MG dye under visible light. **Reprinted with permission from Elsevier (**Berhe et al., in 2025**).**

Also, in 2023, Mali D.G et al., used mulberry plant leaf extract for synthesising of TiO_2 and Ag/Cu doped TiO_2 nanoparticles. Further, TiO_2 and Ag/Cu doped TiO_2 nanocatalysts were examined for the photocatalytic activity. Nanocatalysts with different doping ratio such as 1 %, 2 %, and 3 % Ag/Cu doped TiO_2 and undoped TiO_2 utilized for the degradation of methylene blue (MB) dye in the presence of sunlight irradiation. High photoctalytic degradation of MB dye as 98.55 % within 90 min under sunlight irradiation was observed with the green-synthesized 3 % Ag-doped TiO_2 nanocatalyst. The reduced band gap, enhancing absorption and supressing electron-hole recombination enhances the photocatalytic efficiency of nanocatalysts. The schematic representation of the photocatalytic reaction depicted figure 3.

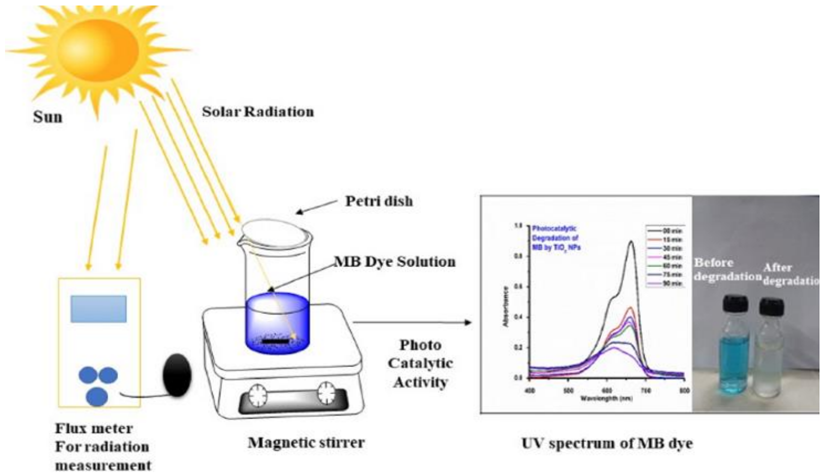

Fig. 3. Photocatalytic degradation of MB dye using Ag/Cu doped TiO_2 nanoparticles under sunlight **Reprinted with permission from Elsevier** (**Mali D.G. et al., in 2023**).

Barrios-Navarro et al., In 2025, demonstrated their research work on degradation of various dyes such as rhodamine B (RB), malachite green (MG), methyl orange (MO), methyl red (MR), amido black 10B (AB10B), methylene blue (MB) respectively by photocatalysis. Especially, ZnO nanoparticles were synthesized using green synthesis from *Mammea americana* extract as a reducing and stabilizing agent [15]. About 95 % of the dye degradation was observed for all dyes within 180 min using green synthesized nanoparticles under sunlight. The obtained results suggested that, synthesized ZnO nanoparticles are very efficient materials and sustainable catalyst for environmental remediation process. In another study, aqueous fruit extract of fresh *Muntingia calabura* was used for the synthesis of silver nanoparticles (Ag NPs) [16]. The green synthesized Ag NPs were further utilized for the evaluation of biological applications such as anticancer, cytotoxic, antioxidant, antibacterial and photocatalytic applications respectively. The direct sunlight was used for the degradation of Basic Fuschen (BF) dye in 30 min by green synthesized AG NPs. Furthermore, more than 90% dye was degraded within 30 min under sunlight. This rapid degradation is due to the interaction of photo excited electrons and generation of super oxide and hydroxide radicals followed by the suppression of electron-hole recombination. The UV-Visible spectroscopic analyses of BF dye degradation using Ag NPs under direct sunlight shown in figure 4.

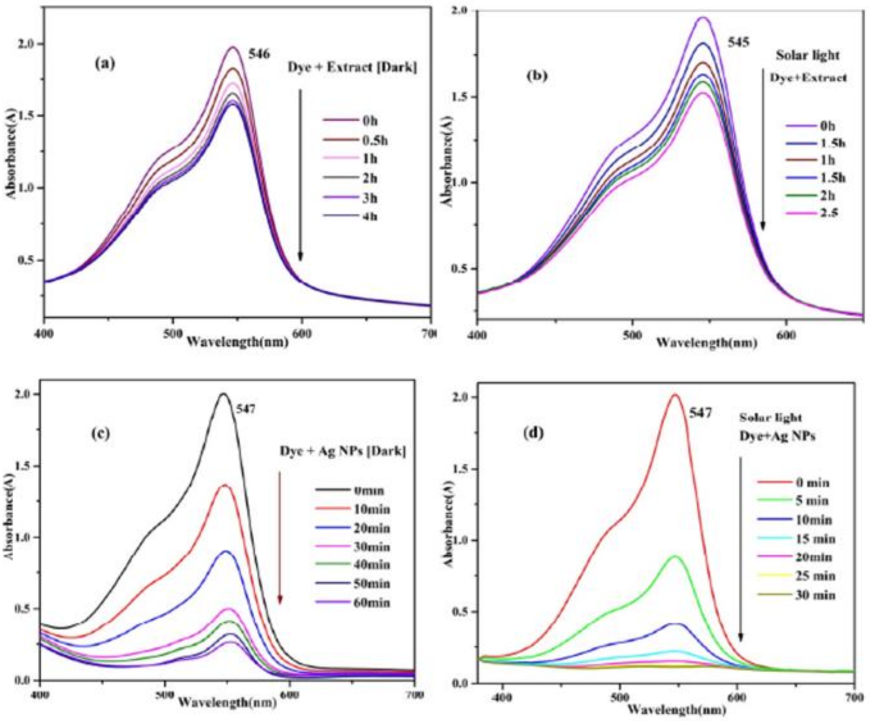

Fig. 4 UV-Visible spectroscopic analysis of BF dye using green synthesized Ag NPs under sunlight. **Reprinted with permission from Elsevier (S. Sivakami** et al., in 2025**).**

3. Discussion

The literature survey and review of various studies stated that green synthesis is versatile and sustainable route for the nanocatalysts synthesis using plant extracts. Biomolecules present in plant extracts play a significant role in formation of nanocatalysts as of both reducing and stabilizing agent. These biomolecules controls particle size, morphology, also introduce surface functional groups which are influences light absorption, surface charges, and catalytic activity respectively. The crystalline structure, bio capped surfaces, enhanced surface area, reduced band gaps which are favourable for formation of nanocatalyst and photoctalysis were determined by various analytic techniques such as XRD, FTIR, UV–Vis, SEM/TEM, XPS, BET.
The green synthesized nanocatalysts such as NiO, TiO_2, Ag/Cu doped TiO_2, ZnO and Ag NPs exhibit remarkable photocatalytic activity under irradiation of visible and sunlight. Plant derived capping agents on the surface of synthesized nanocatalysts acts as electron traps, inducing defect sites, oxygen vacancies and surface hydroxyl groups followed by reduces electron-hole recombination. Further, green nanocatalysts are capable to generate the ROS (•OH and O_2^{-}•) which are effectively participate in the degradation of various dyes including malachite green, methylene blue, methyl orange, rhodamine B, and others.

4. Conclusion

The present review highlights preparation of plant extracts and synthesized nanocatalysts using plant extracts as reducing and stabilizing agents. Further, green synthesized nanocatalysts used for the water treatment process by degrading various organic effluents from water. Plant extract mediated nanocatalysts exhibits various benefits like eco-friendliness, low cost, non-toxicity, and sustainability, while simultaneously providing excellent photocatalytic performance. The recent studies suggested that plant mediated metal and metal oxide nanocatalysts are excellent materials for the effective degradation of industrial effluents under visible and sunlight. This activity making them as promising candidates for large-scale environmental remediation materials. Overall, green nanocatalysis represents a viable and sustainable strategy for addressing water pollution challenges while aligning with the principles of green chemistry.

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