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MANGROVE-DERIVED NANOMATERIALS: GREEN SYNTHESIS, CHARACTERIZATION, AND APPLICATIONS

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ABSTRACT
Nanomaterials have attracted significant attention due to their unique physicochemical properties, which differ substantially from their bulk materials counterparts and enable diverse applications in biomedical, environmental, and industrial fields. However, conventional nanoparticle synthesis methods often involve hazardous chemicals, high energy consumption, and environmentally harmful byproducts. Green synthesis has emerged as a sustainable alternative by utilizing biological resources as natural reducing and stabilizing agents. Among these resources, mangrove ecosystems represent a promising source of biomass because of their abundance, rich phytochemical composition, and ecological significance. This review highlights the potential of mangrove-derived materials for green synthesis of nanomaterials and discusses their ecological importance, phytochemical constituents, and roles in nanoparticle formations. Various mangrove species contain bioactive compounds, including phenolics, flavonoids, tannins, alkaloids, and terpenoids, which facilitate the synthesis and stabilization of nanoparticles while enhancing their functional properties. Recent studies have demonstrated that mangrove-mediated nanomaterials exhibit promising antimicrobial, antioxidant, catalytic, and environmental remediation activities. Furthermore, the utilization of mangrove biomass and its residues contribute to sustainable resource management and support circular bioeconomy principles. Despite these advantages, challenges related to synthesis standardization, mechanistic understanding, toxicity evaluation, and large-scale production remain to be addressed. Future research focusing on process optimization and practical implementation is essential to advance the development of mangrove-based nanomaterial. Overall, mangrove ecosystems offer a sustainable and environmentally friendly platform for green nanotechnology, providing opportunities for innovative applications while promoting environmental conservation.

Keywords: Mangrove, Green Synthesis, Nanomaterial, Environmental Applications

INTRODUCTION
Nanomaterials are materials with at least one dimension in the nanometer scale (1-100 nm), where matter exhibits unique physical, chemical, and biological properties that differ significantly from their bulk counterparts[1]. At this scale, materials demonstrate enhanced surface area to volume ratio, improved reactivity, distinctive optical characteristic and remarkable antimicrobial activity, making them highly valuable for biomedical, environmental and industrial applications. These unique properties arise from quantum effects and increased surface energy that dominate at the nanoscale, enabling applications in drug delivery, catalysis, sensing, water purification and advanced coatings. Traditional synthesis methods often involve toxic chemical reducing agents, high energy consumption, and environmental hazardous byproducts, which have driven the development of green synthesis approaches. Green synthesis utilizes biological materials such as plant extracts, microorganisms, and marine biomass to produce nanoparticles through eco-friendly, low cost, and sustainable processes that align with green chemistry principles. Among these biological sources, mangrove ecosystems have emerged as promising candidates for nanoparticle synthesis due to their abundant coastal biomass, rich bioactive compounds (phenolics, flavonoids, tannins), and economic viability, offering a sustainable alternative to conventional chemical synthesis while supporting environmental conservation and economic development in coastal communities.

Mangroves are a group of territorial plants that group in tropical and subtropical coastal region. Globally, mangrove ecosystems are estimated to cover approximately 17 million hectares. Indonesia hosts the largest extent of mangrove forests, accounting for about 4.2 million hectares, which represents nearly 23% the global mangrove area[2,3]. Mangrove contain various genera such as *Rhizophora, Avicennia, Sonneratia, Bruguiera, Ceriops, Lumnitzera* and others, which can grow in coastal areas [4]. Among these, species such as *Rhizophora apiculata*, *Avicennia marina*, and *Sonneratia caseolaris*, have been extensively investigated for their bioactive potential.

Mangrove species have been widely utilized for their antimicrobial, anti-inflammatory, antioxidant, and even anticancer activities[5]. These biological activities are primarily attributed to the presence of secondary metabolites such as alkaloids, flavonoids, steroids, tannins, and triterpenoids[6]. Importantly, this phytochemical also functions as effective reducing and stabilizing agents in the green synthesis of nanoparticles.

In addition, the high availability of mangrove biomass, encompassing leaves, stems, bark, roots, and fruits, together with the potential utilization of its natural residues, positions mangrove plants as promising and sustainable precursors for the development of nanomaterials via green synthesis approaches.

1. Ecology and ecosystem function of mangroves

Mangrove ecosystem played a crucial role in coastal protection by acting as natural barriers against shoreline erosion, wave action, and extreme weather event such as storms and tidal surges [7]. Their complex root systems, characteristic of genera such as *Rhizophora*, and *Avicennia*, effectively dissipate wave energy and stabilize sediments there by reducing coastal vulnerability [8].

In addition, their protective function, mangrove forests are recognized as significant carbon sinks, often referred to as “blue carbon” ecosystems, due to their extraordinary capacity to adsorb and store carbon on both biomass and sediment [9]. This function contributes significantly to global climate change mitigation effort. Mangrove ecosystems also support rich biodiversity by providing essential habitats, nursery grounds, and feeding zone for countless organisms such as fish, crustaceans, mollusks, and numerous bird species [10]. This ecological importance highlights their vital function in sustaining coastal food webs and underpinning the livelihoods of local communities.

Furthermore, the harsh environmental conditions in which mangroves thrive, characterized by high salinity tidal fluctuations, and low oxygen availability induce the production of diverse secondary metabolites such as polyphenols, flavonoids, and tannins. These bioactive compounds are not only essential for plant adaptation but also hold significant potential in nanotechnology, particularly as natural reducing and stabilizing agents in the green synthesis of nanoparticles.

2. Mangrove as a source of bio-reducing agents

2.1 Polyphenol

Polyphenols are one of the most abundant bioactive compounds present in mangrove plant, found ubiquitously across species such as *Rhizophora mucronata, Avicennia marina*, and *Excoecaria agallocha.* These compounds possess strong antioxidant activity due to the presence of multiple hydroxyl groups capable of donating electrons during redox reaction, as demonstrated by DPPH inhibition reaching 93,40% in *RHIZHOPHORA mucronata* mature leaves. In nanoparticle synthesis, polyphenol contributed to the reduction of metal ions such as $Ag^+ \rightarrow Ag^0$ and Au^{3+} to Au^0 into their corresponding metallic nanoparticles [11]. Furthermore, polyphenols enhance nanoparticle stability by performing protective layers on the particle surface.

2.2 Tannins

Tannins are high molecular weight polyphenolic compounds abundant in mangrove bark and leaves (*Rhizophora* spp.). Due to their strong metal binding ability, tannins accelerate metal ion reduction (Ag^+, Au^{3+}) and control nanoparticle growth during biosynthesis [12]. They also enhance nanoparticle stability and antimicrobial bioactivity through antioxidant properties.

2.3 Alkaloid

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Alkaloids are nitrogen containing secondary metabolites known for their diverse pharmacological activities, including antibacterial, antioxidant, and cytotoxic effects. Mangrove species such as *Avicennioa marina*, *Rhizophora apiculata*, *Rhizophora murconata*, and *Sonneratia alba* contain alkaloid compounds that contribute significantly to biological activities [13]. In mangrove mediated nanoparticle synthesis, alkaloids participate in the reduction process through interactions between nitrogen functional groups and metal ions. Phytochemical screening indicates that mangrove extracts have high concentrations of alkaloid compounds, as demonstrates in *Sonneratia alba* root extract which showed antibacterial activity against *S. aureus* and *E. coli* [14]. The presence of alkaloids, along with other secondary metabolites, has been confirmed in mangrove species including *Ceriops tagal* and *Bruguiera cylindruica* [15]. There compounds may also improve the biological activity of nanoparticles, including antibacterial and antioxidant properties. For instance, alkaloids from *Avicennia marina* and *Rhizophopa* species have demonstrated antimicrobial and cytotoxic activities in therapeutic applications.

2.4 Saponin

Saponins are amphiphilic glycosides characterized by their surfactant-like properties, found in mangrove species such as *Bruguiera gymnorrhiza*, *Rhizophora murconata*, *Rizophora apiculata*, and *Cerriops tagal*[16,17,18,19]. In nanoparticles synthesis, saponins contribute to particle stabilization by reducing surface tension and preventing agglomeration. Comparative analyses of saponin content in mangrove plants *Rhizophora mucronata* and *Rhizophora apiculata* confirm their presence as major bioactive phytochemical components. Saponins, together with flavonoids, tannin, and alkaloids, are consistently detected in mangrove leaf extract and contributes to the formation of stable nanoparticles. Their ability to interact with both hydrophilic and hydrophobic components make them beneficial for their maintaining nanoparticle dispersion and colloidal stability. Saponin stabilized nano-emulsions demonstrate stability up to 30 days, with saponin acting as both emulsifier and stabilizer [20]. Additionally, saponins from mangrove leavers (*Sonneratia* sp.) have shown potential antioxidant properties when incorporates into herbal formulations [21].

3. Green synthesis and characterization of nanoparticles using mangrove

Green nanotechnology has emerged as a sustainable and environmentally friendly approach for nanoparticle synthesis. Compared with conventional physical and chemical methods, plant mediated synthesis offers several advantages, including simpler procedures, lower cost, reduced energy consumption, and minimal use of toxic chemical. In recent years, mangrove plants have gained increasing attention as promising biological resources for green nanoparticle synthesis due to their rich phytochemical composition and adaptability to extreme coastal environments.

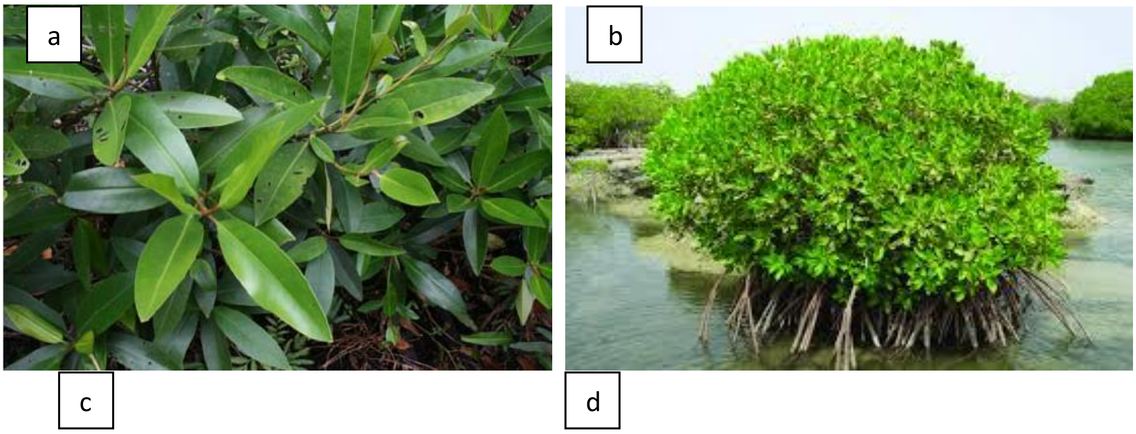

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Fig 1. (a)*Rhizophora apiculata, (b)Rhizophora mucronata, (c)Rhizhophora stylosa,* and *(d)Avicennia marina*

Several mangrove species, including *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizhophora stylosa,* and *Avicennia marina,* as shown to Figure 1, contain diverse secondary metabolites such as flavonoids, polyphenol, tannins, alkaloids, and saponins that can function as natural reducing and stabilizing agents during nanoparticle morphologies, have been reported in numerous studies. Among the numerous mangrove species reported in the literature, *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*, and *Avicennia marina* have been extensively studied for green nanoparticle synthesis. Their morphological characteristics are presented in Figure 2, while previous studies employing these species for nanoparticle production are summarized in Table 1.

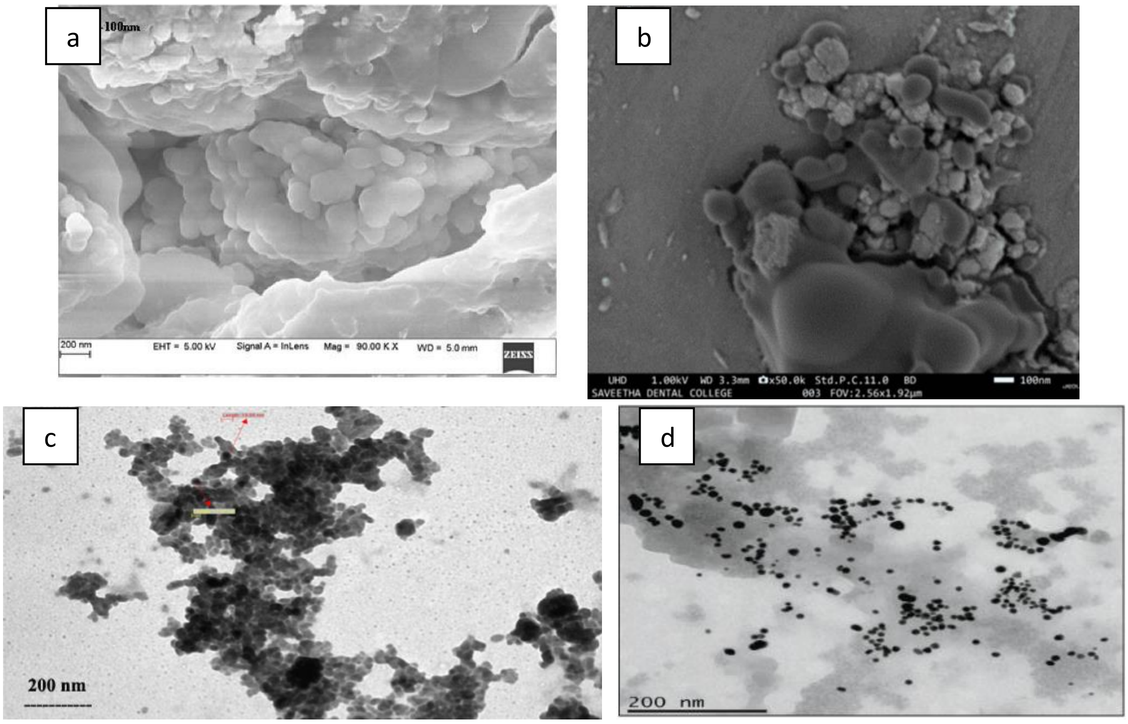

Fig 2. (a)SEM of *Rhizophora apiculata*, (b)SEM of *Avicennia marina*, (c)HRTEM of *Rhizhophora stylosa*, and (d)TEM of *Rhizophora mucronata*

Table 1. Overview of nanoparticle synthesis using mangrove extracts and their resulting physicochemical and biological properties.

Type (Species)	Part	Nanoparticle	Characterization	Size Range	Properties	Reference
Rhizophora apiculata	Leaf extract	AgNPs	UV-Vis, SEM-EDX, XRD, FTIR, PSA, Zetasizer	30-50 nm	Cytotoxicity MG-63 (IC_{50}: 45.6 µg/mL) high antioxidant, tannin rich	22
Rhizophora apiculata	Leaf extract	AgNPs	UV-Vis, FTIR, PSA, SEM-EDS, XRD, Zetasizer	35-100 nm	Antioxidant, anti-inflamation (76.65% inhibition), recovery scars (82.79%), anticancer (A375/31.84%, A549/56.09%, KB-3-1/22.59%)	23
Rhizophora apiculata	Leaf extract	AgNPs	UV-Vis, SEM, XRD, and FTIR	20-80 nm	Strong antimicrobial, antioxidant, anticancer (Cytotoxic to cancer cell)	24
Rhizophora apiculata	Leaf extract + Glucose	AgNPs	UV-Vis, FTIR, TEM	13-40 nm	Stronger antibacterial than glucose alone, comparative evaluation	33
Rhizophora apiculata	Leaf	ZnO	UV-Vis, FTIR, XRD, SEM-EDX	28,4 nm	Antibacterial (E. coli, S. aureus), green synthesis	34
Rhizophora apiculata	Stem bark	AgNPs	UV-Vis, FTIR, PSA, Zeta potensial	80-150 nm	Antibacterial activity for *S. aureus & E. coli*, antioxidant (IC_{50}: 12.6 µg/mL)	25
Avicennia marina	Leaf extract	AgNPs	UV-Vis, FTIR, SEM-EDS	10-20 nm	Oral Antibacterial: *S. aureus, S. mutans, Klebsiella* sp.; SPR peak @420 nm	26
Avicennia marina	Leaf extract	AgNPs & AuNPs	UV-Vis, SEM, XRD, DLS, and FTIR	AgNPs: 70-80 nm	Larvacidal to *Culex pipiens* (AgNPs > AuNPs),	27

				AuNPs: 95-100 nm	cytotoxicity splenic cells, hepatoxicity.	
Avicennia marina	Leaf extract	ZnO NPs	UV-Vis	~20-50 nm	Oral Antibacterial: (*S. aureus* 9.5 mm, *S. mutans* 7.5 mm, Klebsiella sp. 9.5 mm) @ 100 µg/mL	28
Avicennia marina	Leaf extract	AgNPs	UV-Vis, SEM, EDS, XRD, FTIR	10-30 nm	Potential antibacterial, larvicidal Ae. aegypti & An. stephensi (LC_{50}: 4.374 and 7.406 mg/L ; LC_{90}: 4.928 and 9.865 mg/L)	29
Rhizophora mucronata	Bark extract	AgNPs	UV-Vis, XRD, HRTEM, EDX, and DLS	10-100 nm (Spherical, polydisperse)	Antibacterial potential, antimicrobial function	30
Rhizophora mucronata	Bark extract	AgNPs	UV-Vis, Zeta potential, AFM	~78-99nm (spherical, 3D smooth surface)	Marine animal immunostimulant, 2 months stability, Zeta: −20.3 mV antioxidant (IC_{50}: 65.59 µg/mL)	31
Rhizophora mucronata	Leaf extract	AgNPs	UV-Vis, XRD, FTIR, AFM	60-95 nm	Larvicidal LC_{50}: 0.585 mg/L (Ae. aegypti), 0.891 mg/L (Cx. quinquefasciatus) ; LC_{90}: 2.615 mg/L, 6.291 mg/L	35
Rhizophora stylosa	Fruit extract	AgNPs	UV-Vis, FTIR, XRD, TEM	TEM 10-60 nm, XRD 38-77 nm	-	32

The successful synthesis of mangrove-mediated nanoparticles has been confirmed using various characterization techniques, including UV-Vis spectroscopy, XRD, PSA or DLS, zeta potentioal measurements, and electron microscopy.

3.1 UV-Vis spectroscopy

UV-Vis spectroscopy is commonly employed as the initial characterization technique to confirm nanoparticle formation. Silver nanoparticles synthesized using *Rhizophora apiculata, Rhizophora mucronata, and Avicennia marina* generally exhibit surface plasmon resonance (SPR) successful reducing Ag^+ ions into metallic silver nanoparticles. Meanwhile, ZnO nanoparticles synthesized using *Rhizophora apiculata and Avicennia marina* exhibit characteristic absorption band in the ultraviolet region, confirming the formation of ZnO nanostructures.

3.2 XRD

XRD analysis further confirms the crystalline structure of synthesized nanoparticles. Silver nanoparticles generally exhibit diffraction peaks corresponding to the face-centered cubic (FCC) crystal structure of metallic silver, particularly the (111), (200) and (220) planes at approximately $2\theta = 38.1^\circ, 44.3^\circ$, and 64.4°, of the sample to the JCPDS 652871 [44]. For example, AgNPs synthesized using *Rizophora mucronata* exhibited these characteristic FCC reflections, confirming the formation of crystalline metallic silver. Similarly, AgNPs prepared from Avicennia marina showed reflections at approximately 30.04˚, 37.02˚, 40.13˚, 48.33˚, and 78.01˚, which were indexed to the (120), (200), (230), (240), (301), and (410) plane of FCC silver. This pattern sorrelated with JCPD no (04-0783) [45].

3.3 PSA and DLS

Particle size measurements obtained using PSA and DLS reveal that mangrove-derived nanoparticles generally possess hydrodynamic diameters ranging from tens to hundreds of nanometers depending on the mangrove species, precursor concentration, and synthesis parameters. For example, *Rhizophora stylosa* mediated AgNPs exhibited primary particle size of approximately 5-87 nm based on TEM, whereas their hydrodynamic diameters measured by DLS ranged from 98 to 125 nm[42]. Differences between DLS and TEM particle sizes are frequently observed because DLS measures the hydrate particle diameter in suspension whereas TEM determines the actual particle core size

3.4 Zeta potential

Zeta potential values reported in several studies indicate that mangrove-mediated nanoparticles exhibit good colloidal stability. For example, silver nanoparticles synthesized using *Rhizoma stylosa* leaf extract exhibited zeta potential values ranging from -24.9 to -277.7mV and remained stable for more than one month. Similarly, AgNPs synthesized using *Rhizophora mucronata* bark extract showed a zeta potential of -20.3 mV and maintained stability for up to two months. The negative surface charges are generally attributed to the adsorption of negatively charged phytochemicals on the nanoparticle surface, reducing particle aggregation through electrostatic repulsion [42,43].

4. Applications of Mangrove-Derived Nanoparticles

4.1 Biomedical

Mangrove-derived nanoparticles have emerged as promising candidates for various biomedical applications due to their unique properties, biocompatibility, and bioactive compounds from green synthesis. Silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), and zinc oxide nanoparticles (ZnO NPs) synthesized from mangrove extracts exhibit remarkable antibacterial, anticancer, antioxidant, and wound healing properties.

4.1.1 Antibacterial Activity (Gram + & Gram -)

Mangrove-derived AgNPs demonstrated significant antibacterial against both Gram-positive (*S. aureus*) and Gram-negative (*E. coli, S. mutans, Klebsiella* sp.) bacteria. Rhizophora apiculate AgNPs (30-100 nm) and Avicennia marina AgNPs (10-20 nm) shoe effective inhibition at 100 μg/mL. The tannin and flavonoid content in mangrove extracts acts as reducing and capping agents. This makes mangrove AgNPs ideal for antimicrobial coating in medical devices and wound dressing [22,23,26,28].

4.1.2 Anticancer and Cytotoxicity

Mangrove AgNPs exhibit cytotoxicity against various cancer cell lines. *Rhizophora apiculata* AgNPs showed IC_{50} of 45.6 μg/mL against $MG^{-6}3$ (osteosarcoma), 31.84% against skin cancer, 56.09% against lung cancer, and 22.59% against oral cancer. *Rhizophora apiculata* fruits AgNPs demonstrated IC_{50} of 578.5 μg/mL against MCF^{-7} (breast cancer). These finding support potential for targets cancer therapy and drug delivery applications [22,23, 31].

4.1.3 Wound Healing and Anti-inflammatory

Rhizophora apiculata AgNPs achieved 82.79% wound closure and demonstrated 71.65% anti-inflammatory activity. The high antioxidant content (DPPH 17.5-51.8 %) reduce oxidative stress at the wound site. These properties make mangrove nanoparticles ideal for tropical wound dressing that promote accelerates tissue regeneration [23,36].

4.1.4 Antioxidant activity

Mangrove AgNPs show strong antioxidant activity. *Rhizophora apiculata* leaf AgNPs demonstrated DPPH scavenging of 17.5 – 51.8% and make nitric oxide scavenging of 19.5%. *Rhizophora mucronata* bark showed IC_{50} of 65.59 μg/mL. This makes them suitable for antioxidant rich biomedical formulation [30, 36].

4.1.5 Larvicidal activity

Mangrove AgNPs effectively control disease transmitting mosquitoes. *Rhizophora mucronata* and *Avicennia marina* AgNPs showed LC_{50} of 0.585 – 20.33 μg/mL against *Ae. Aegypti, An. Stephensi*, and *Cx. Quinquefasciatus*. This offered an eco-friendly alternative to chemical larvicides for malaria and dengue control [34,35].

4.1.6 Drug delivery (Potential Future Application)

Mangrove AgNPs show promising potential for drug delivery due to their biocompatibility, nanomaterial size (5-100 nm), and high zeta potential (-20.3 to -60.7 mV) indicating excellent colloidal stability. The spherical morphology and 2-month stability make them suitable for targeted cancer therapy and sustained release formulations [23, 30, 31].

4.2 Environmental Applications

The growing environmental crisis caused by metal contamination, organic pollutants, and waterborne pathogen has driven intensive research into sustainable nanomaterial for environmental remediation. Mangrove derives nanoparticles offered a green, eco-friendly solution for addressing these critical environmental challenges. Their unique surface chemistry, high adsorption capacity, antimicrobial properties, and photocatalytic activity make them highly effective for heavy metal removal, pollutant degradation, water purification, and environmental monitoring.

4.2.1 Heavy Metal Adsorption

Mangrove biochar effectively adsorbs heavy metals. Charcoal from bark mangrove demonstrated Pb (II) adsorption capacity. The high surface area and functional groups (phenolic, carboxyl) enable metal ion binding through complexation. This makes mangrove adsorbents valuable for industrial wastewater treatment [37].

4.2.2 Water Filtration

Mangrove soil derived AgNPs (10-100 nm) showed antimicrobial activity (MIC: 2.5 – 20 μg/mL), suitable for water filtration membrane. The natural humic/fulvic acid coating provides stability and biocompatibility. Mangrove nanocomposites can effectively remove both microbial contaminants and heavy metal from water [12].

4.2.3 Photodegradation of Pollutants

Iron oxide nanoparticles (Fe_3O_4) show potential for photodegradation of organic pollutants. Mangrove derived metal oxide nanoparticles could be enhanced by bioactive compounds acting as sensitizers, representing a potential research area for degrading dyes, pesticides, and pharmaceutical residues in wastewater [38].

5. Benefits of Using Mangrove-Derived Nanomaterials

5.1 Economics Benefit

Mangrove serve as naturally abundant biomass resources in coastal regions, offering significant economic advantages for nanoparticle production. The low-cost raw material availability reduces dependency on expensive chemical reagents used in conventional synthesis, making mangrove-derived nanoparticles economically viable for large-scale industrial applications [39]. The biosynthesis approach eliminates the need for high temperature, energy consumption, and high pressure, resulting in substantial cost savings compared to physical and chemical methods [34]. Mangrove derived nanoparticles can be developed into a valueable products such as antibacterial coating, water filters, wound dressing, and environmental sensors. The use of fallen leaves and waste biomass support circular economics principal by converting waste into a high-value nanomaterials.

5.2 Environmental Benefit

The green synthesis process using mangrove extracts is environmentally friendly, producing minimal toxic waste that uses toxic sodium borohydride and hydrazine, mangrove derived nanoparticle utilized natural bioactive compounds (phenolic, flavonoids, and tannins) as reducing and capping agents [34, 40].

The process supported circular economy concepts by utilizing biomass waste (fallen leaves). Mangrove ecosystems naturally harbor diverse biogeochemical pathways that enhance resilience against pollutants, making mangrove derived nanoparticles ecologically relevant [12]. This approach aligns with natural mangrove functions as blue carbon sinks (32 tons C/ha/year) and coastal ecosystem predator [41]. Thus, the utilization of mangrove biomass for nanomaterial synthesis not only provides functional materials but also aligns with sustainable environmental management.

6. Challenges and future perspectives

6.1 Limitations

Mangrove derived nanoparticles face significant challenges that limit their industrial application. The composition of mangrove extracts varies significantly due to seasonal changer, geographical location, and extraction methods, leading to inconsistent phenolic and flavonoid content. The complex mixture of alkaloids, tannins terpenoids, and saponin create synergistic effect that are difficult to characterize limiting optimization potential and scaling feasibility.

6.2 Future Directions

Future research must address these limitations through methods standardization developing fixed extraction protocols with standardized solvent ratios, temperature, time, and pH conditions, along with quality control for phytochemical quantification. Production scale up from laboratory to industrial scare requires continuous flow system, cost optimization through automation, and sustainable biomass supply on water treatment (heavy metal adsorption, filtration) which represent the most promising near-term opportunities due to proven efficacy and growing market demand. These efforts will enable mangrove derived nanoparticles to transition from laboratory research to commercial applications in water treatment, biomedical, and environmental sectors.

CONCLUSION

Mangrove-derived biomass has emerged as valuable and sustainable resource for the green synthesis of materials. The rich diversity of phytochemicals presents in mangrove species, including phenolics, flavonoids, tannins, alkaloids, and terpenoids, enables their effective use as a natural reducing, capping, and stabilizing agents during nanoparticle synthesis. This approach offers a greener alternative to conventional physicochemical methods by reducing the reliance on hazardous chemicals and energy, intensive processes.

In addition to their ecological significance as coastal protectors, biodiversity hotspot, and blue carbon reservoirs, mangrove ecosystems provide abundant renewable biomass that can be utilized for the production of functional nanomaterials with promising biomedical, environmental, and industrial applications. Recent studies have demonstrated that mangrove-mediated nanoparticles exhibit enhanced antimicrobial, antioxidant, catalytic, and sensing performances, highlighting their potential in addressing current technological and environmental challenges.

Despite the advantages, several limitations remain, including the lack of standardized synthesis protocols, incomplete understanding of the underlying synthesis mechanism, and limited large scale production studies. Future research should focus on process optimization, mechanistic investigation, toxicity assessments, and scalability to facilitate the practical implementation of mangrove-based nanomaterials. Overall, the integration of mangrove resources with green nanotechnology represents a promising strategy for advancing sustainable material development while supporting environmental conservation and circular bioeconomy initiatives.

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