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A Comprehensive Review on Green Synthesis of Nanoparticles from *Eichhornia crassipes* as a Potential Management Strategy to Negate the Adverse Effects of the Noxious Aquatic Weed

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Eichhornia crassipes, commonly known as water hyacinth, is an invasive aquatic weed native to Brazil and the Amazon basin, currently widespread in both tropical and subtropical regions globally. Due to the rapid growth and adaptability, it poses serious ecological and economic challenges to humans and the aquatic environment. Water hyacinth forms dense mats on water surfaces, which gradually obstruct water transportation, fishing, and irrigation systems. These dense mats also reduce the level of oxygen in water, causing the death of aquatic organisms. Traditional management strategies of water hyacinth include chemical, physical, and biological methods, which have limitations in controlling its growth and spread. Chemical control can often lead to the contamination of water bodies, physical control methods are labour-intensive, and biological control agents show very slow results and have unpredictable outcomes. The recent advancements have revealed the potential of the *E. crassipes* plant in nanoparticle synthesis, utilizing its phytochemical composition. This comprehensive review explores the synthesis of various metal nanoparticles using *E. crassipes* extracts, emphasizing their advantages as being eco-friendly, economic, and sustainable. The phytochemicals present in plant parts can act as reducing and capping agents in nanoparticle synthesis, as it is cost-effective, simple, and free from toxic chemicals, and these *E. crassipes*-mediated nanoparticles also have a wide range of applications. Overall, this review aims to highlight the dual benefit of managing *E. crassipes* proliferation while advancing green synthesis.

Keywords: Water hyacinth (*Eichhornia crassipes)*; nanoparticle; weed management; green synthesis.

1. Introduction

Eichhornia crassipes (EC*)*, more commonly known as water hyacinth, is a species of floating aquatic plant that belongs to the *Pontederiaceae* family [1]. Originally native to Brazil and the Amazon basin, this plant has successfully spread to various tropical and subtropical areas around the world, including multiple regions across Brazil, Argentina, Paraguay, Venezuela, and Chile [1], El Salvador, Panama, Costa Rica, Mexico, Portugal, Spain, Israel, Italy, Japan, India, and Indonesia, the United States of America and Virgin Islands, Egypt, Sudan, Kenya, Ethiopia, Nigeria, Zimbabwe, Zambia, and South Africa [2].

E. crassipes, characterized by its ability to float freely on the surface of water bodies, has broad, thick, glossy, ovate leaves that may rise as much as 1 meter above the water surface [3]. These leaves are supported by spongy, bulbous stalks. The plant also possesses striking lavender-blue flowers, each with six petals, which make it quite recognizable and aesthetically appealing despite its reputation as an invasive species [3].

The resilience of water hyacinth is remarkable, as it can thrive in a wide range of pH levels, temperatures, and nutrient concentrations [4]. This adaptability makes it difficult to control once it has established itself in a new environment. Due to these characteristics, the International Union for Conservation of Nature (IUCN) recognizes water hyacinth as one of the most aggressive invasive species globally lists it among the top ten worst aquatic weeds. This classification underscores the global concern regarding its management and the ongoing efforts required to control its spread and mitigate its impacts on ecosystems and human activities [2].

Water hyacinth is particularly known for its explosive growth rate. Under optimal conditions, it can reproduce both sexually and asexually, allowing it to cover large areas of water surfaces quickly [5]. This rapid proliferation often leads to significant ecological and economic problems. It blocks waterways, limits boat traffic, affects aquatic life by depleting oxygen levels in water, hinders access to irrigation and hydroelectric power sources, and directly and indirectly affects public health [5].

It grows rapidly, forming dense mats that hinder water flow, block sunlight, and deplete oxygen levels, which can devastate aquatic ecosystems. To manage and control this invasive species, various mechanical, chemical, and biological treatment methods have been employed: mechanical control, chemical control, and biological treatment, which will be discussed in detail in the coming sessions. The control of *E. crassipes* requires a well-coordinated approach that considers the ecological, economic, and social implications. While each method has its strengths and weaknesses, an integrated management strategy that employs mechanical, chemical, and biological treatments tailored to local conditions tends to be the most effective and sustainable way to minimize the impact of this invasive species on aquatic environments [6].

2. Negative impact of *E. crassipes*

Water hyacinths create serious problems for both mankind and aquatic ecosystems. Native to the amazon basin, this species has expanded it's range across many tropical and subtropical regions, and causes ecological disturbances.

2.1. Environmental impact.

Water hyacinth has several detrimental effects on ecosystems. It can cause the displacement of native species. The thick mats of water hyacinth spread across the water surfaces, significantly reducing light penetration and causing a decline in native aquatic vegetation [7]. A few such cases are discussed here.

Basuala *et al* indicated that the lakes within the Lake cluster of Pokra Valley serve as essential freshwater reserves and play a key role in supporting diverse fish populations in central Nepal [4]. However, the invasive water hyacinth plant facilitated the proliferation of non-native fish species such as *O. niloticus*, the fast-spreading *C. nama*, and the introduced *C. idella,* while adversely affecting the populations of indigenous fish. Additionally, there was a clear correlation between elevated carbon dioxide levels and extensive water hyacinth growth. Conversely, water clarity, pH levels, and dissolved oxygen were found to decrease with increased water hyacinth coverage, pointing to a deterioration in water quality [4].

Mironga *et al* analyzed the impact of water hyacinth proliferation on Lake Naivasha's zooplankton communities in Kenya [8]. Since its introduction to the lake in 1986, water hyacinth has been influencing zooplankton diversity. Using the Shannon-Weiner Diversity Index (H') and the Simpson Diversity Index (D), they evaluated zooplankton diversity across 10 sampling sites from October 2003 to November 2004. The Shannon-Weiner Diversity Index (H') is a widely used method for measuring how diverse a community is by considering both the number of different species (species richness) and how evenly individuals are spread among those species (evenness). The Simpson Diversity Index (D) measures the likelihood that two randomly chosen individuals from a sample belong to the same species. It highlights which species dominate in a community, with lower values indicating higher diversity. Results indicated a significantly lower Simpson Diversity Index (D=0.50) in areas covered by water hyacinth compared to areas without (D=0.79), with a significance level of $p<0.005$ and H' is lower in water hyacinth infested areas (H'= 0.65) when compare to shoreline without water hyacinth infestation (H'=0.74) The findings suggest that water hyacinth is negatively affecting zooplankton diversity and abundance in the lake [8].

A comparative study conducted by Mengitsu *et al* in Lake Abaya examined the impact of water hyacinth infestation on macrophyte communities [9]. The research, comprised of four sites—two infested and two non-infested, each with 15 plots revealed the significant negative effects on macrophyte composition, abundance, and diversity due to the presence of water hyacinth which significantly affects macrophyte communities, often altering and reducing native plant diversity within Ethiopian aquatic ecosystems, highlighting the pressing need for effective management strategies to mitigate its ecological repercussions [9].

2.2. Economic impact.

The presence of water hyacinth significantly affects economic activities; a few cases are discussed herewith.

The impact of *Eichhornia crassipes* on fishing activities in the northeastern part of Tana lake was reported by Asmare *et al*, in a study conducted from June 2015 to October 2016 [10]. Water hyacinth in these areas affected fishing by entangling nets and jamming boat propellers, resulting in decreased fish catches. This reduction in fish harvests adversely affected the livelihoods of local communities and hampered the sustainable development in the area, resulting in a call for immediate action [10].

Honlah *et al* studied the water hyacinth invasion on communities along the River Tano and Abby-Tano Lagoon in Ghana [11]. They reported that the weed impeded navigation during dry seasons, leading to increased mosquito populations and malaria transmission, thereby affecting the community's health. Additionally, it obstructed the water transportation of students, and it will negatively affect their education [11].

Apr *et al.*'s case study on Warrenton Weir in the Vaalharts Irrigation Scheme observed that the water hyacinth directly threatened water resources by producing high rates of evapotranspiration, which led to large water losses [12]. This study evaluated the financial advantages of managing water hyacinth using the Warrenton Weir on the Vaalharts Irrigation Scheme. By estimating water losses under varying invasion levels, the study found that controlling this invasive plant could yield annual benefits ranging from R54 million to R1.18

billion, emphasizing the need for policies prioritizing the management of invasive species to protect water resources and economic productivity [12].

The proliferation of water hyacinth has affected the livelihoods of communities. Not only does it degrade water quality, rendering it unfit for consumption and domestic use, but it also fosters the breeding of disease-carrying mosquitoes, exacerbating the spread of malaria and other ailments. The expansion of *E. crassipes* leads to a decline in phytoplankton populations, depriving fish of their primary food source, thus causing a significant reduction in fish populations. This decline in fish stocks not only disrupts the local ecosystem but also adversely impacts the employment opportunities reliant on fisheries [13]. Additionally, the spread of water hyacinth contributes to oxygen depletion in water bodies, leading to the suffocation and death of aquatic life, further exacerbating the ecological and socio-economic ramifications of this invasive species [14].

2.3. Challenges faced in India.

Rapid proliferation of water hyacinth has also caused severe environmental and socio-economic impacts across India. The primary issues associated with *E. crassipes* in India include obstruction of water flow, degradation of aquatic ecosystems, reduction in fish productivity, and interference with hydroelectric and irrigation infrastructure [15, 16], and have also affected the fishing community severely. Certain studies have tried to utilize the water hyacinth and put it to beneficial purposes like converting biomass from these plants to biofuel, compost, polymer composites, organic fertilizers, animal feed, thermal insulation materials, etc [16-19].

3. Management approaches and challenges faced

Exploring the potential of water hyacinth to be converted into something useful is crucial due to the significant challenges it causes to the environment. All three methods widely used for the control of the spread of *E. crassipes* have multifaceted challenges.

Physical and Mechanical methods of removal are labor-intensive and costly, with the added challenge of managing the biomass [7]. Manual removal and mechanical harvesting are effective methods, but are labor-intensive, costly, and can lead to the destruction of aquatic ecosystems and biodiversity [7]. This can be an effective short-term solution in small areas or where rapid results are needed. The most used method is manual removal, which involves physically pulling the plants out of the water. This is intensive and often impractical if infestations are large. Utilizing machines to cut or collect water hyacinth is termed mechanical harvesting and is effective at reducing biomass but demands repeated operations [7].

Chemical control involves the use of herbicides to inhibit the growth of *E. crassipes.* This method is often used for widespread infestations but should be used carefully to avoid environmental damage. The efficacy of herbicides such as diquat, glyphosate, sulfosate, imazapyr, 2,4-D, metsulfuron-methyl, sulfentrazone, and imazapic in controlling water hyacinth was analyzed by Neves *et al*. However, controlled usage is inevitable for the protection of the non-target species and water quality [20]. Garlich *et al* studied the effectiveness of using imazamox to control *E. crassipes* [21]. The experimental results of Kurniadie *et al* suggested that Florpyrauxifen-benzyl can be an effective herbicide for controlling water hyacinth in Cangkuang Lake, and that its use did not have a negative impact on water quality [22].

Biological control methods for managing *E. crassipes* have been extensively studied and implemented worldwide. Various insects and other arthropods have been considered as promising biological control agents against water hyacinth, with some species demonstrating promising results in limiting its growth and spread [23]. An example is the water hyacinth moth *Niphograpta albiguttalis* [24], which has been successfully used to control water hyacinth. These insects feed on the plant, stunting its growth and reproductive capabilities. These studies collectively underscore the complex challenges associated with physical and chemical control methods and highlight the importance of implementing integrated and environmentally sustainable approaches to manage water hyacinth infestations in aquatic environments.

The success of biological control programs depends on understanding the growth patterns and population dynamics of *E. crassipes* [25] and is dependent on the influence of environmental factors, such as water levels and plant density, on the efficacy of biological agents like weevils. In South Africa, for example, coordinated biological control programs have been established by government agencies to manage water hyacinth infestations, highlighting the successful integration of biological control agents into comprehensive management strategies [26]. However, as mentioned, the effectiveness of biological control agents can differ, depending on factors such as environmental conditions and the availability of suitable host plants [27]. Study such as [28], underscored the complexities involved in selecting and deploying effective biological control agents while mitigating potential ecological impacts. Despite these challenges, research efforts are going on still to explore new biological control agents and improve existing methods for the sustainable management of water hyacinth. Overall, biological control remains a promising approach for mitigating the impact of water hyacinth on aquatic ecosystems, offering environmentally friendly and cost-effective solutions.

The need for continuous management due to the rapid regrowth of water hyacinth imposes significant financial burdens. These challenges underscore the importance of considering the ecological and socio-economic impacts of physical control measures while developing comprehensive management plans for water hyacinth infestations.

The invasion of *E. crassipes* has significant negative ecological and economic impacts. Effective management is complex and resource-intensive, often requiring a combination of physical, chemical, and biological methods. Sustainable approaches are essential to mitigate these impacts, potentially including the conversion of water hyacinth into economically beneficial products, for example, bioenergy, biofuel, or biochar, as suggested by recent studies exploring its valuation [29]. *E. crassipes* processed through pyrolysis yield bio-oil and biochar. The bio-oil produced could serve as a viable candidate for refined chemical products, further enhancing the potential of utilizing this invasive species for beneficial applications [30]. The high carbon content and structural properties of water hyacinth make it suitable for engineering applications. Characterization studies reveal its potential in engineering applications, including additives and microchips, promoting sustainability while reducing reliance on non-renewable materials and mitigating fossil fuel pollution [31]. The highly abundant lignocellulosic material in water hyacinth makes it an ideal substrate for the production of bioethanol. Fermentation processes yielded a higher bioethanol output compared to previous reports using other substrates like potato peels, cassava peels, and millet husks, thereby providing an economical solution for managing this invasive species while contributing to renewable energy production [32].

Another effective approach is utilizing the water hyacinth for nanoparticle synthesis. *E. crassipes* has been studied for its phytochemical properties and thereby explored for its potential use in the synthesis of nanoparticles. The leaf extract of *E. crassipes* contains various bioactive compounds, such as flavonoids, tannins, saponins, alkaloids, and phenolics. These phytochemicals can play a crucial role in the bioreduction of metal ions to metal nanoparticles. The process of synthesizing nanoparticles using plant extracts, including that of *E. crassipes*, is considered green and eco-friendly because it typically does not require harmful chemicals or high energy inputs [33]. Hublikar *et al* have demonstrated that the use of *E. crassipes* in nanoparticle synthesis can be particularly effective due to its high biomass production and the richness of relevant phytochemicals [33]. Thus, utilizing this invasive plant in productive ways could also help in managing its spread in natural water bodies, where it often causes significant ecological disruption.

Table 1. This study compares various management strategies adopted for the control of water hyacinth.

Management method	Pros	Cons
Mechanical control	Fast Removal: Mechanical harvesting can rapidly reduce the biomass of water hyacinth, improving water flow and light penetration for native aquatic plants [34].	High Operational Costs: Mechanical removal can be expensive due to equipment maintenance and labor costs [35].
	Free from chemicals: This method avoids the introduction of noxious chemicals into the environment, which can have adverse effects on aquatic ecosystems [36].	Regrowth Potential: Without ongoing management, water hyacinth can quickly regrow after initial removal, necessitating repeated interventions [37].
Chemical control	Rapid Effectiveness: Herbicides can quickly reduce water hyacinth populations, allowing for immediate restoration of water bodies [36].	Environmental Risks: The use of chemicals can lead to water contamination, affecting aquatic life and potentially harming human health [34].
	Convenience of application: Chemicals can be applied over large areas without the need for extensive labor or equipment [37].	Resistance Development: Over time, water hyacinth may develop resistance to certain herbicides, reducing the effectiveness of chemical control [35].
Biological Control	Sustainable Solution: Biological agents (such as specific insects or pathogens) can provide long-term control by targeting the plant specifically, leading to reduced need for continuous intervention [38].	Potential for Non-target Effects: Introduced biological agents may affect non-target species, disrupting local ecosystems [39].
	Environmental Compatibility: Biological control methods generally have a lower environmental impact compared to chemical treatments [40].	Slow Impact: Biological control methods may take longer to achieve visible results compared to mechanical or chemical methods [41].
Integrated management approaches	Holistic Solution: Combining mechanical, biological, and chemical methods can maximize effectiveness while minimizing negative impacts [39].	Complexity in Implementation: Coordinating multiple methods can be logistically challenging and may require significant planning and resources [40].
	Adaptability: Integrated approaches can be tailored to specific local conditions and stakeholder needs, leading to more successful management outcomes [38].	Need for Monitoring: Continuous assessment is necessary to adapt management strategies effectively, which can strain resources and require expert involvement [41].

4. Utilizing *E. crassipes* for nanoparticle synthesis

4.1. Nanoparticles.

Nanomaterials, which are materials engineered at a scale of 1 to 100 nm, exhibit novel properties due to their nano-sized dimensions. These materials possess characteristics such as a high surface area relative to their volume, increased chemical reactivity, and improved mechanical strength, making them highly valuable across various fields [42]. Nanoparticles, which are more complex than simple molecules, consist of three distinct layers: a surface layer that can be functionalized with small molecules, metal ions, surfactants, or polymers; then a shell layer made of a chemically different material from the core; and the core, which is the central part of the nanoparticle typically referred to as the nanoparticle itself [43, 44]. Metallic nanoparticles are particularly significant in research, especially in biomedical sciences and engineering, due to their ability to be modified with various chemical functional groups. This modification facilitates their conjugation with antibodies, ligands, and drugs, enhancing their application in fields such as antimicrobial activity and drug delivery. Commonly utilized metallic nanoparticles include silver (AgNPs), copper (CuNPs), and iron sulfide (FeS) [45].

Physical synthesis of nanoparticles generates particles with a uniform size distribution and high purity. This method does not involve harmful chemicals, but it poses significant challenges in preventing particle agglomeration due to the lack of stabilizers or capping agents. Techniques in physical synthesis include mechanical and vapor-based methods, utilizing diverse forms of energy. Notably, the ball milling process employs mechanical energy to pulverize bulk metal using high-speed collisions with hard balls made of materials like ceramics or stainless steel, creating high local pressure [46]. The electrical arc discharge method produces nanoparticles by utilizing a direct DC-powered arc-discharge device [47]. Laser ablation, an effective method for synthesizing nanoparticles, involves generating metal colloids without chemical reagents, although stabilizers such as polyvinyl pyrrolidone (PVP) are used to ensure colloid stability [48]. Additionally, physical vapor deposition encompasses sputtering and evaporation techniques, where sputtering involves bombarding a target material with a high-energy charge, and evaporation involves heating the material to its boiling point under vacuum to deposit material on substrates [49].

On the other hand, chemical synthesis uses chemical reducing agents such as ascorbic acid, sodium borohydride, and others, in aqueous or non-aqueous environments to reduce ions [50]. While chemical methods can achieve homogeneous particles with high precision, they often involve toxic and carcinogenic chemicals. Furthermore, physical methods are typically energy-intensive and costly with lower yields, whereas chemical methods, despite not requiring significant energy, are also economically and environmentally less favorable [51].

Hence, the most sustainable alternative for synthesizing nanoparticles is biological methods. It utilizes microorganisms or plant parts like leaves, bark, or seeds, which act as natural reducing and capping agents, making this approach more eco-friendly and economically viable [52]. Biological methods of synthesizing nanoparticles using microorganisms face significant challenges, including the need for sterile conditions and the high costs associated with microbial isolation. Consequently, plant-based sources have emerged as preferable alternatives for the production of nanoparticles. Plants are advantageous because they serve as natural sources of both reducing and capping agents, essential for nanoparticle synthesis. Various plants and their extracts, rich in secondary metabolites, have been effectively utilized in the formation of NPs. These metabolites are crucial as they undertake dual roles of reducing and stabilizing the nanoparticles during synthesis [53].

Green synthesis, a concept within the overlapping fields of biotechnology and nanotechnology, refers to the eco-friendly production of nanoparticles using plants or their components [54]. This method is favored because it is sustainable, cost-effective, and minimizes waste. Various plant elements like carbohydrates, fats, enzymes, and various phytochemicals such as flavonoids, polyphenols, and alkaloids serve as natural reducing agents in this process [55]. Common plant parts used include leaves [56], bark [57], seeds [58], and roots [59], highlighting the versatility and environmental benefits of this approach.

4.2. Green synthesis using E. crassipes.

The most common method of green synthesis of nanoparticles using *E. crassipes* starts with the preparation of an extract by mostly using leaves of the plant, although other plant parts like flowers are also employed in certain cases. Usually, the leaves or the desired plant parts are collected, cleaned, dried, and subjected to extraction procedures, typically using water, ethanol [60], or methanol as solvents through processes like boiling [61]. The prepared extract is mixed with a solution of a metal precursor, silver nitrate, for nanoparticle synthesis [33]. Various parameters, including pH, temperature, and concentration of both the extract and metal precursor, influence the size, shape, and stability of the nanoparticles. Increasing the pH typically leads to smaller nanoparticles, as higher pH values facilitate the availability of more reducing agents in the extract [62].

The synthesized nanoparticles can be characterized to study their physicochemical characteristics using various techniques, as discussed below, and are depicted in Figure 1.

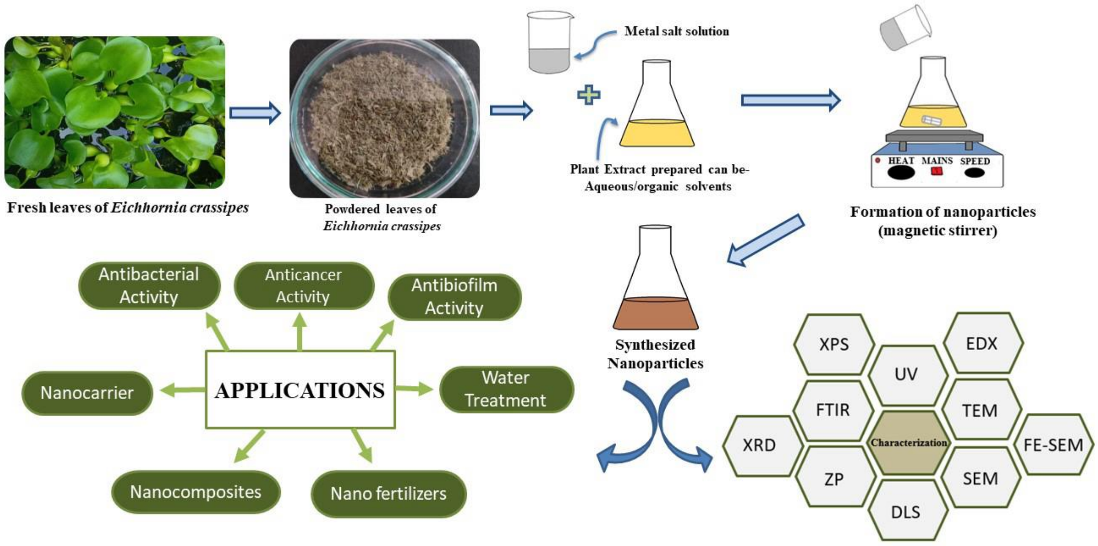

Figure 1. Shows the method of green synthesis of nanoparticles from *E. crassipes* extract, their characterization, and various applications.

UV-Visible Spectroscopy: This technique is used to confirm the formation of nanoparticles. The surface plasmon resonance (SPR) peak for silver nanoparticles typically appears in the range of 420-450 nm, depending on the size and morphology of the nanoparticles [63].

Fourier-transform infrared spectroscopy (FTIR): FTIR analysis is carried out to identify the functional groups present in the extract that are responsible for the reduction and stabilization of nanoparticles. Peaks corresponding to O-H, C=O, and N-H stretching indicate the presence of alcohols, ketones, and amines, respectively, which play a pivotal role in the synthesis [64].

X-ray Diffraction (XRD): XRD is used to study the crystalline nature of the nanoparticles. The presence of sharp diffraction peaks at specific angles confirms the formation of crystalline silver nanoparticles. The average crystallite size can be calculated using the Debye-Scherrer equation [33].

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM): SEM and TEM provide detailed insights into the morphology and size distribution of the synthesized nanoparticles. SEM images reveal the surface morphology, while TEM is used for precise measurement of particle size, showing nanoparticles in the range of 5-50 nm with varying shapes (spherical, hexagonal, etc.) [65].

Zeta Potential Analysis: The stability of the synthesized nanoparticles is assessed using zeta potential analysis. A zeta potential value above ±30 mV indicates high stability due to repulsion between the particles, minimizing the chances of aggregation [66].

Nanoparticles exhibit unique physicochemical properties, and they significantly influence the potential applications of the same across diverse domains. Surface area, biological interactions, particle size, and size distribution are significant properties of nanoparticles. Smaller nanoparticles with a greater surface-to-volume ratio show improved reactivity [67] because nanoparticles can assume a variety of shapes and sizes, they can exhibit unique capabilities, which in turn determine their ability to adsorb substances and interact with biological systems [68]. Surface chemistry, including functional groups and coatings, further influences nanoparticle interactions with their environment, with functionalization enhancing targeting, reducing toxicity, and improving dispersion [69]. Additionally, the stability and aggregation behavior of nanoparticles in colloidal solutions are significantly influenced by their surface charge, which is quantified as zeta potential. Higher absolute values of surface charge indicate better stability via electrostatic repulsion [70]. The optical, electrical, and catalytic properties of nanoparticles are influenced by their phase composition and crystallinity since different crystalline structures can result in different levels of mechanical stability and reactivity [71]. Moreover, optical characteristics of metallic nanoparticles are influenced by size, shape, and composition, thereby giving rise to special phenomena like SPR, which increases the particles' usefulness for biosensing and imaging [72]. Lastly, the catalytic properties of nanoparticles are determined by their high surface area-to-volume ratio and active sites, allowing for enhanced catalytic activity compared to bulk materials, particularly in processes involving metal nanoparticles like platinum and palladium [73].

4.3. Phytochemicals present in E. crassipes.

The production of nanoparticles through biological means involves a bottom-up approach, utilizing reducing and stabilizing agents. The extracts from *E. crassipes* leaves contain different plant components, which are identified through phytochemical analysis [74,75], and throw light on the presence of various secondary metabolites which act as capping and reducing agents in nanoparticle synthesis.

The study by Baehaki *et al* aimed to investigate the phytochemical compounds and the antioxidant capabilities of water hyacinth flower extracts, assessing their potential as natural antioxidants [76]. The research process involved multiple steps: sampling, preparation, extraction, and determining the extract yield, followed by analyses of phytochemicals such as phenols, tannins, alkaloids, flavonoids, and saponins. Antioxidant activity was tested using the DPPH method and assessing reducing power. The findings indicated that the extract yields varied with solvents: n-hexane yielded 4.95%, ethyl acetate yielded 1.69%, and methanol produced the highest yield at 26.06%. Phytochemical analysis confirmed the presence of phenols, tannins, flavonoids, and saponins. The antioxidant activity, measured by IC_{50} values, showed that methanol extracts had significantly higher antioxidant properties with an IC_{50} of 35.83 ppm, compared to 1085.31 ppm for n-hexane and 950.71 ppm for ethyl acetate extracts, indicating that lower IC_{50} values correspond to stronger antioxidant activity [76].

Research has been conducted by Rorong *et al.* to analyse the phenolic, flavonoid, and tannin contents in the leaves of water hyacinth [77]. The process involved several steps, including sample preparation, maceration extraction, and evaporation. The findings indicated that the highest phenolic content in the leaves was 2.72 mg gallic acid per kg of sample using

60% methanol, while the lowest was 1.07 mg gallic acid per kg with distilled water. For flavonoids, the highest content was 3.29 mg quercetin per kg using 80% methanol, with the lowest at 1.65 mg quercetin per kg in distilled water. The greatest number of condensed tannins was found to be 0.7 mg catechin per kg with 80% methanol. [77].

The study of Elvira *et al*, reported the isolation of flavonoids from water hyacinth and tested their antioxidant activity using the DPPH method [78]. The process began with maceration in ethanol, followed by hydrolysis with HCl, and purification via column and preparative thin-layer chromatography. Analysis using UV-vis and FTIR spectrophotometry suggested the isolates were like quercetin 7-methyl ether, based on observed functional groups. The antioxidant testing revealed an IC_{50} value of 254.66 mg/L, indicating the potency of the isolated flavonoids [78].

4.4. Synthesis of metal nanoparticles using E. crassipes.

E. crassipes is now widely used for the green synthesis of nanoparticles, especially metal nanoparticles like silver nanoparticles, iron nanoparticles, gold nanoparticles, copper nanoparticles, etc. These nanoparticles synthesized in such a green route possess various biological properties.

Espinosa *et al* used fresh leaves of *E. crassipes* collected from Yuriria Lagoon in Mexico to extract bioactive compounds for the green synthesis of silver nanoparticles [61]. Initially, 20 grams of washed and chopped leaves were boiled with 100 mL of distilled water, and the extract was subsequently filtered and stored at 4°C. For nanoparticle synthesis, 10 mL of this leaf extract was mixed with 90 mL of a 1 mM silver nitrate solution and heated at varying temperatures (75, 80, 85, 90, and 95°C) over different time intervals (0, 30, 60, 120, and 180 minutes) to monitor the reduction of silver ions. The colour changes and UV-Vis spectroscopy detected the formation of AgNPs, which showed a maximal SPR peak between 350 and 450 nm. The results of TEM analysis revealed irregularly shaped particles with diameters between 20 and 40 nm at different reaction periods and temperatures. At 95°C and 120 minutes of reaction time, the EC-AgNPs solution had the greatest antibacterial activity against *E. coli*. These results point to possible uses for the produced AgNPs in antibacterial therapies that target gram-negative bacteria [61].

The production and analysis of amorphous iron nanoparticles (Ec-FeNPs) were synthesized from Fe (III) salts using aqueous extracts of *E. crassipes* and their subsequent characterization were reported by Wei *et al* [79]. The findings confirmed the successful creation of amorphous iron nanoparticles with sizes ranging between 20 and 80 nm, predominantly consisting of zero-valent iron nanoparticles stabilized by organic materials from the extracts. Batch tests demonstrated that the EC-FeNPs removed 89.9% of Cr (VI), significantly outperforming the extracts alone and Fe_3O_4 nanoparticles, which removed 20.4% and 47.3%, respectively. The removal process was predominantly through adsorption and reduction, followed by co-precipitation, as suggested by kinetic studies and XPS analysis [79].

Hublikar *et al* produced silver nanoparticles from EC leaf extract at room temperature [33]. A 1:4 ratio of precursor (0.1N $AgNO_3$) and plant extract at a pH of 9–11. After mixing and agitation, the reaction mixture was exposed to sunlight for approximately 15 minutes. The colour change from green to light brown to dark brown indicated the formation of silver nanoparticles. Various characterization techniques showed that the particle size was from 15 to 25 nm. The phytochemical analysis of leaf extract indicated the presence of flavonoids, particularly quercetin, which facilitated the reduction of silver ions to silver nanoparticles. It also exhibited antimicrobial activity against both gram-positive and gram-negative bacteria [33].

Hernández *et al* reported the biosynthesis of TiO_2 using *E. crassipes* gathered from the Valsequillo reservoir in Puebla, after cleansing and dehydration at 50°C for 36 hours, around 125 mg of the *E. crassipes* leaf was blended with 80% v/v ethanol [80]. The resulting mixture underwent filtration, and its filtrate was combined with 0.1 M TiO_2. Solutions of NaOH (0.1 M) and HNO_3 (0.1 M) were used to adjust the pH to 12, 7, and 4, respectively, to examine the pH effect. The nanoparticles showed a peak at 327 nm with a size of 20 to 50 nm. They exhibited photocatalytic efficiency as well as antibacterial activity [80].

Silica nanoparticles were created using the biological waste from *E. crassipes* collected from Dundigal and Pochampally lake in Hyderabad, Telangana, by Vakkanti *et al* [11]. The plant and the various parts of this plant were processed through two different synthesis techniques, one of which involved Tetraethyl orthosilicate (TEOS) as the silica source. In the first method, leaves from *E. crassipes* were dried at 60°C, powdered, and calcined at 750°C for four hours. The resultant ash was treated with HCl at 60°C to remove impurities, washed until neutral pH, and then processed to obtain sodium silicate by adding NaOH and stirring at 80°C. The resulting silica sol was acidified, centrifuged, washed, dried, and preserved as silica (SN1). The second method involved boiling freshly washed leaves for 30 minutes, filtering the extract at 60°C, and reacting it with TEOS for 10 minutes. After acidification and heating at 700°C for four hours, a white powder was stored in an airtight container. The third method mirrored the second but used thoroughly washed roots of the plant, following the same steps to produce and store the silica powder. The nanoparticles produced, labeled as SN1, SN2, and SN3, underwent characterization through several methods, including FTIR, X-ray Diffraction analysis, SEM, and ZP. The FTIR results for all types showed the presence of silanol groups, with absorption bands at 1094 cm^{-1}, 1063 cm^{-1}, and 1058 cm^{-1} indicating the Si-O-Si vibrations for SN1, SN2, and SN3 respectively. SN1 was specifically selected for further analysis because of its smooth surface texture and was confirmed to have a crystalline and spherical structure with a size ranging from 10-15 nm, and the zeta potential of -24.1 mV, indicating good stability [81].

Priya *et al* explored the biosynthesis of carbon nanoparticles using *E. crassipes* because carbon nanoparticles (CNPs) are known to possess various effects, including antimicrobial, catalysis, sensing, etc [82]. The leaves of *E. crassipes* were collected from the Palkani tank located in Pallavaram, Chennai, India. This method involved burning of the leaves to create biosoot, from which CNPs were derived. These particles were then characterized using techniques and analysis indicated that CNP possessed size ranging from less than 10 nm to about 990 nm, with FESEM showing sizes between 57 nm and 194 nm, FTIR analysis showing the presence of functional groups such as alcohol, carboxylic acids, alkyl halides, aryl halides, alkenes and alcohol [82].

Zinc oxide nanoparticles (ZnONPs) synthesis was reported by González *et al*, who utilized the approach of synthesis by precipitation of water hyacinth leaf extract in alkaline conditions [83]. The analysis of their properties showed distinct characteristics. The prominent peaks in the FTIR spectra indicated the presence of organic compounds. The size of the nanoparticles varied depending on the concentration of the extract, with measurements of 202 nm, 244 nm, and 313 nm for E100, E50, and E25 concentrations, respectively. Examination via scanning electron microscopy revealed triangular shapes of the ZnONPs, with some clustering observed, particularly in the E25 sample. Surprisingly, the antimicrobial effectiveness, as studied by minimum inhibitory concentration (MIC), remained consistent across different extract concentrations [83].

E. crassipes mediated Zinc oxide (ZnO) and cadmium oxide-zinc oxide (CdO-ZnO) nanoparticles were synthesized by Kalaivani *et al* [84]. Dried and powdered leaves of water hyacinth were boiled in distilled water, and the resulting extract was mixed with a zinc nitrate solution. This mixture was heated, and the plant extract was added until a colour change was observed, and the resultant ZnONP powder was annealed at 400°C for 2 hrs. The synthesized EC-CdO-ZnOnNPs were characterized using UV-Visible spectroscopy, which showed an absorption peak at 270 nm. The crystalline nature of the EC-CdO-ZnOnNPs was confirmed by XRD, and FTIR analysis detected the presence of aromatic compounds, primary amines, and alcohols. SEM-EDX revealed the cubic hexagonal shape of the EC-CdO-ZnOnNP nanoparticles. These biosynthesized nanoparticles were then applied as nanofertilizers for cassava cultivation in low-quality soils, which could enhance the macro and micro nutrients, photosynthesis rate, promote root growth, and increase plant yield [84].

Belay *et al* explored the ability of this plant extract to mediate the synthesis of bimetallic nanocomposites [85]. *E. crassipes* leaves were collected from Lake Tan, Bahir Dar, Ethiopia, washed, and dried before grinding into a uniform powder. Powder was mixed with water, stirred for 30 minutes, and shaken for 72 hours. The filtered solution was mixed with 0.25 M $CuSO_4 \cdot 5H_2O$ and $AgNO_3$, adjusting pH to 10.5. After adding leaf extract and heating, the compound formed was centrifuged, washed, dried, and calcined to obtain CuO/Ag_2O/Ext NCPs. The product was then calcinated in a muffle furnace at 550°C for 4 hours to obtain CuO/Ag_2O/Ext NCPs. The surface plasmon absorption band at 550 and 383 nm specifies the formation of the nanocomposite. SEM results showed a spherical morphology with a size of 13.38–13.56 nm, and XRD analysis indicated a crystalline structure. FTIR results revealed the presence of alcohols, phenols, carboxyl groups, alkenes, and metal-oxygen bonds. Additionally, TGA analysis provided insights into the thermal properties and potential applications of the synthesized compounds, highlighting the advantages of using plant leaf extract in the synthesis process the biosynthesized EC-CuO/Ag_2O/Ext NCNCPsshowed good antibacterial activity against four human pathogenic bacteria such as *E. coli*, *K. pneumonia*, *S. aureus*, and *S. epidermides* [85].

Perera *et al* successfully synthesized iron oxide nanoparticles using the aqueous extract of freeze-dried petiole parts of *E. crassipes* and $FeCl_3.6H_2O$ [86]. The resulting nanoparticles were coated with sulfated polysaccharides, exhibiting moderate stability and water solubility. Particle size analysis showed a mean diameter of 50-120 nm, with 61% of the particles below 100 nm. FTIR spectroscopy confirmed the functionalization of nanoparticles with negatively charged sulfated polysaccharides, supported by a negative zeta potential value (-23.7 mV). Powder X-ray diffraction analysis indicated the amorphous nature of the synthesized particles [86].

Hemalatha *et al* conducted a study to synthesize CuO nanoparticles utilizing *E. crassipes* from leaves harvested from Kurachi Lake in Coimbatore [87]. The leaves were dried, powdered, and extracted with 100 ml of water, followed by heating for an hour. Subsequently, a solution containing 1M copper sulfate and NaOH was added. The resulting black precipitate, identified as copper nanoparticles, was filtered, washed, and dried. Characterization of the nanoparticles was performed using UV-visible spectroscopy, which indicated absorption at 410nm. FTIR analysis revealed the presence of biomolecules responsible for capping and reducing the nanoparticles, while SEM analysis displayed their spherical morphology. Finally, the synthesized nanoparticles were evaluated for their antimicrobial effects against bacterial pathogens [87].

Zelekew *et al*. synthesized Cr_2O_3/ZnO composite nanoparticles using *E. crassipes* leaf extract collected from Lake Koka in Ethiopia [60]. These were effective in degrading methylene blue dye, with the most effective degradation shown by the 0.08 CrZn composite, i.e, degradation of 85% methylene blue with 90 minutes of exposure. Comparatively, the 0.1CrZn, 0.06CrZn, 0.04CrZn, 0.02CrZn, ZnO, and Cr_2O_3 catalysts degraded only 80%, 74%, 79%, 76%, 52%, and 74% of MB, respectively. The enhanced photocatalytic efficiency observed in the 0.08CrZn composite was attributed to the optimal chromium precursor concentration, which likely reduced electron-hole recombination and improved porosity due to the influence of the plant extract, thereby increasing the overall catalytic activity [60].

Moudgil *et al*. synthesized crystalline silver nanoparticles using *E. crassipes* extract and demonstrated its antibacterial, antibiofilm, and anticancerous properties as a nanomedicine [65]. The physicochemical characterization confirmed the spherical form, with a diameter of 12.48 ± 3.43 nm, and good stability with ZP −31.53 mV. The antioxidant capacity of the nanoparticles was measured at 100 µg/ml, and the results reveal an impressive activity (93.6%). Gram-negative bacteria showed MIC values of 7.8 µg/ml, while Gram-positive bacteria needed greater doses of 31.25 µg/ml and 250 µg/ml. 15 µg/ml of EC-AgNPs exhibited a significant decrease in biofilm formation (74.7%) and violacein synthesis (86.89%). Furthermore, HeLa, HCT 116, and L6 cell lines were used to assess the anticancer capability; the IC50 values were 13.32, 14.71, and 19.91 µg/ml, respectively. This is one of the first reports to report the anticancer property of EC-AgNPs, which emphasizes its scope as a biomedicine [65].

Jayasree *et al* synthesized silver nanoparticles from *E. crassipes* collected from Vembanad Lake in Kerala and studied their photocatalytic degradation properties [88]. Spherical-shaped nanoparticles were obtained with a size around 10-20 nm, and they exhibited excellent dye degrading properties on pollutants like methylene blue and methyl orange with 92.46% and 91.9%, respectively [88].

Thus, it has been studied that the synthesized nanoparticles from *E. crassipes* can possess biological activities like antimicrobial, antioxidant, and catalytic activities. Their bioactivity is largely influenced by their size, surface area, and functionalization by phytochemicals. Smaller nanoparticles exhibit higher surface area-to-volume ratios, making them more reactive and effective against a broad spectrum of pathogens [89]. In addition, functionalized nanoparticles exhibit enhanced interactions with microbial cell membranes, resulting in increased bactericidal efficiency [90].

Table 2. Applications of various metallic nanoparticles synthesized using different types of extracts of *E. crassipes*.

Nanoparticles	Type of Extract	Application	Size (in nm)	Structure	Reference
EC-AgNPs	Aqueous leaf extract	Antibacterial activity	20-40	Spherical	[61]
EC–AgNPs	Aqueous leaf extract	Antibacterial activity	16-65	Spherical	[33]
EC-TiO_2NPs	Ethanol leaf extract	Antibacterial activity	25-35	Tetragonal	[80]
EC-SiO_2NPs	Aqueous leaf extract	Nanomedicine	10-15	Spherical	[81]
EC-CNPs	Biosoot	Nanocarrier, Pharmaceutical, Cosmeceutical applications	57-194	Spherical	[82]

Nanoparticles	Type of Extract	Application	Size (in nm)	Structure	Reference
EC-CuONPs	Aqueous leaf extract	Antibacterial activity	20-22	Spherical	[87]
EC-FeNPs	Aqueous extract	Hexavalent chromium removal	20-80	Spherical	[79]
EC-CuONPs	Aqueous leaf extract	Antifungal activity	13.38-13.56	Spherical to irregular	[85]
EC-ZnONPs ZnOE 100 ZnOE 50 ZnOE 25	Aqueous leaf extract	Antibacterial activity	202 244 313	Triangular-like shape	[83]
EC-CdO-ZnO NPs	Aqueous leaf extract	Nanofertilizer	24-36	Cubical and hexagonal spherical shapes	[84]
EC-Cr_2O_3/ZnO	Aqueous whole plant extract	Photocatalytic degradation of methylene blue dyes	Size not mentioned	Flat sheet-like structure	[60]
EC-AgNPs	Aqueous whole plant extract	Antibacterial, antibiofilm, anticancer	12.48±3.45	Spherical	[65]
EC-AgNPs	Aqueous leaves and petioles extract	Noncatalyzed degradation of methyl orange and methylene blue dyes.	10-20	Spherical	[88]

5. Advantages of synthesizing nanoparticles with the *E. crassipes* extract

Using plant extracts for nanoparticle synthesis is a green and sustainable approach that reduces the reliance on chemical methods, minimizes environmental impact, and promotes eco-friendly practices. *E. crassipes*, or water hyacinth, is an invasive aquatic plant that proliferates in many water bodies worldwide. Utilizing this abundant and often problematic plant for nanoparticle synthesis not only provides a sustainable use for its biomass but also helps in waste management. Compared to conventional chemical methods, synthesizing nanoparticles with plant extracts can be more cost-effective, as it eliminates the need for expensive reagents and energy-intensive processes [54].

The synthesis process using plant extracts is often relatively simple and can be performed under mild reaction conditions, making it accessible to researchers with limited resources and equipment. The composition and properties of nanoparticles synthesized with plant extracts can be tailored by adjusting parameters such as pH, temperature, and reaction time, offering versatility in their applications [33]. Plant extract-mediated synthesis is environmentally friendly, cost-effective, and notably efficient in various applications, particularly in their bactericidal properties [91]. Nanoparticles synthesized using *E. crassipes* extract are likely to be biocompatible, making them suitable for various pharmaceutical applications [82], such as drug delivery, imaging, and tissue engineering.

The nanoparticles synthesized with *E. crassipes* extracts may possess inherent antimicrobial properties [61], which could be beneficial for various biomedical and environmental applications, such as water treatment. Thus, it can be summarized that synthesizing nanoparticles with the extract of *E. crassipes* provides a sustainable, cost-effective, and environmentally friendly approach with potential applications across various fields, including biomedicine, environmental remediation, and catalysis.

6. Conclusion

The management of *E. crassipes* demands a multifaceted approach that acknowledges the complexities of ecological systems and the potential consequences of control methods. The literature reviewed underscores the complexities and challenges inherent in relying solely on chemical, biological, or physical means to combat its spread. Instead, a holistic strategy integrating various methods tailored to local conditions and sustainability goals emerges as a necessity. Sustainable management not only mitigates ecological and economic impacts but also opens avenues for the utilization of water hyacinth in beneficial ways, such as bioenergy production or nanoparticle synthesis. Moving forward, rigorous ecological risk assessments, regulatory scrutiny, and innovative approaches are essential to effectively manage water hyacinth infestations while promoting environmental management and socio-economic well-being.

Author Contributions

Conceptualization, A.S.N. and A.S.; investigation, A.S.N. and A.S.; resources, A.S.N. and A.S.; writing—original draft preparation, A.S.N. and A.S.; writing—review and editing, R.R.P.; supervision, R.R.P.

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Conflicts of Interest

The authors declare no conflict of interest.

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