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Green synthesis and phytomedicinal potential of *Eichhornia crassipes* (Mart.) Solms: A comprehensive review

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Abstract

Eichhornia crassipes (Mart.) Solms, commonly known as water hyacinth, is one of the world's most pervasive invasive aquatic macrophytes, causing enormous ecological disruption in tropical and subtropical freshwater ecosystems. Despite its notorious status as a noxious weed, mounting scientific evidence over the last decade has repositioned this plant as a valuable reservoir of bioactive phytochemicals and a versatile platform for green nanotechnology. This comprehensive review consolidates current knowledge on the phytochemical composition of *E. crassipes*, encompassing primary metabolites (proteins, lipids, and carbohydrates) and a diverse array of secondary metabolites, including phenolics, flavonoids, alkaloids, tannins, and saponins. The review critically examines plant-mediated (green) synthesis of silver (AgNPs), gold (AuNPs), and zinc oxide nanoparticles (ZnONPs) using aqueous extracts of *E. crassipes*, detailing the role of phytochemicals as natural reducing and stabilizing agents and the characterization of these nanoparticles using UV-Vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and electron microscopy (SEM/TEM). The biological and pharmacological activities of the plant, including antioxidant, antimicrobial, anti-inflammatory, and anticancer potential, are systematically reviewed. Furthermore, the environmental and economic applications of *E. crassipes* in wastewater phytoremediation, bioenergy production, and agricultural valorization are assessed within the framework of the circular bioeconomy. Challenges related to standardization, phytochemical variability, safety, and ecological risk are discussed, and future research directions towards sustainable utilisation of this invasive species are proposed. This review underscores the dual identity of *E. crassipes*: A formidable ecological threat and an untapped phytomedicinal and nanotechnological resource.

1. Introduction

The biological invasions are one of the key factors in the worldwide loss of biodiversity, posing a threat to the structural integrity and ecological processes of the natural ecosystems across the globe (Simberloff *et al.,* 2013). Specifically, invasive aquatic macrophytes cause disproportionate effects on the freshwater bodies, such as outcompeting indigenous flora, depleting dissolved oxygen, hindering water movement, and destabilising aquatic food webs (Villamagna and Murphy, 2010). One of the most ecologically destructive of these invaders is *Eichhornia crassipes* (Mart.). Solms (family Pontederiaceae), commonly known as water hyacinth, is a perennial, free-floating, Amazonian plant (Patel, 2012).

E. crassipes, whether released purposefully or accidentally into tropical and subtropical environments in Africa, Asia, Australia, and North America throughout the nineteenth and twentieth centuries, has been able to spread at an incredible pace into lakes, rivers, reservoirs, and irrigation canals (Téllez *et al.,* 2008). Its remarkable reproductive ability, both vegetative and sexual, allows doubling of the population in as little as a dozen days under the favourable circumstances, forming thick monospecific mats that suffocate the water surfaces (Malik, 2007). The socioeconomic impacts are disruption of fisheries, sea blockages, hydroelectric power generation interruption and loss of drinkable water with annual management costs worldwide estimated in billions of dollars (Gichuki *et al.,* 2012).

Ironically, the decades of control-based research have gradually provided more evidence that reinforces the reinstatement of *E. crassipes* as a multi-purpose biological resource. The astonishing capacity of the plant to take up the heavy metal in contaminated waters, the abundance of phytochemicals in plants and the large biomass that the plant yields have led to the study of phytoremediation, bioenergy, nutraceuticals, as well as pharmacology (Coetzee *et al.,* 2011; Rezania *et al.,* 2019). At the same time, the paradigm shift in synthetic to sustainable chemistry occurring worldwide has stimulated intense interest in the use of plants to synthesise metallic nanoparticles, where *E. crassipes* has shown significant potential (Ahmed *et al.,* 2016; Singh *et al.,* 2018).

The green synthesis, the production of nanoparticles by relying on biological reducing and capping agents, *i.e.,* plant extracts, microorganisms, biomolecules, *etc*., has definitive benefits over traditional physicochemical synthesis methods, which include reduced energy usage, elimination of toxic compounds, increased biocompatibility of the resulting nanoparticle, and compliance with

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the ideals of green chemistry. *E. crassipes* extracts, which contain a good number of polyphenols and flavonoids with strong electron-donating capacity, have been studied as an effective bio-reductant in the synthesis of silver, gold, and zinc oxide nanoparticles with proven antimicrobial and catalytic properties (Murugan *et al.,* 2015; Aswini *et al.,* 2021).

2. Botanical description and distribution

Eichhornia crassipes (Mart.) Solms is a member of the family Pontederiaceae. The taxonomic sequence is given below: Kingdom: Plantae; Phylum: Tracheophyta; Class: Liliopsida; Order: Commelinales; Family: Pontederiaceae; Genus: *Eichhornia*; Species: *E. crassipes* (Mart.) Solms, 1883. The species name epithet *crassipes* (Latin: epithet *crassipes*) refers to the inflated aerenchymatous petioles, which help support the species in buoyancy (Cook and Gut, 1971).

E. crassipes is a rosulate free-floating herb with a height of 30-100 cm. Their roots are dark, feathery, fibrous, and unbranched and form thick masses that may reach 50 cm below the water surface; roots can take up large quantities of dissolved nutrients and heavy metals (Jayaweera and Kasturiarachchi, 2004). The leaves are broadly ovate to orbicular, glossy and covered with a waxy surface and have a characteristic venation pattern; the petiole is spongy, inflated when the plant is freely floating, giving the typical bulbous look. Floral structures are flaunting, short-lived (one day), zygomorphic, carried on straight terminal racemes of 8-15 flowers; the perianth is violet-blue with a yellow-blotched upper tepal, and a spathe subtends it. Fruits are trilocular capsules that contain many seeds, which can survive in sediments up to fifteen years (Holm *et al.,* 1977).

The *E. crassipes* is native to the Brazilian Amazon and has naturalised in all continents except Antarctica. It was introduced to Asia (India, Bangladesh, China, Southeast Asia) as an ornamental and fodder plant in the late nineteenth century (Charudattan, 2001). The species has now become widespread in water bodies in Kerala, West Bengal, Assam, Tamil Nadu, Andhra Pradesh and Karnataka, where it infests lakes, tanks, irrigation canals and in the lower portions of large rivers (Table 1). It is listed on the Global Invasive Species Database as one of the 100 worst invasive species worldwide (Lowe *et al.,* 2000) and on the IUCN list. It grows well in a water temperature of 25-30°C, a pH of 6.0-8.0 and in high levels of nutrients (particularly nitrogen and phosphorus), hence its booming growth in eutrophic water bodies (Shanab *et al.,* 2010).

Table 1: Global distribution and habitat characteristics of *E. crassipes*

S. No.	Region	Distribution status	Habitat type	Environmental conditions
1.	South America	Native	Rivers, lakes and wetlands	Tropical climate
2.	Asia (India)	Invasive	Ponds, reservoirs and irrigation canals	Warm temperature
3.	Africa	Highly invasive	Freshwater bodies	High nutrient load
4.	North America	Introduced	Lakes and slow-moving waters	Mild to warm climate
5.	Southeast Asia	Widely spread	Paddy fields and wetlands	Humid tropical conditions

3. Phytochemical composition

The phytochemical wealth of *E. crassipes* constitutes the scientific basis for its medicinal, nanotechnological, and environmental applications. Its metabolite profile varies significantly across plant organs (root, stem, leaf, flower), seasons, and growth habitats, necessitating systematic organand condition-specific analyses (Mokhtar *et al.,* 2019).

3.1 Primary metabolites

The proximate composition of *E. crassipes* biomass has been characterised on a dry-weight basis. Total carbohydrates range between 30.1% and 46.8%, including structural polysaccharides (cellulose, hemicellulose, pectin) and soluble sugars. Crude protein content is notable at 15.0-25.3% dry weight, with an amino acid profile encompassing essential amino acids such as leucine, lysine, and methionine, suggesting nutritional potential as animal feed after detoxification (Aboul-Enein *et al.,* 2014). Crude lipid content is relatively low (1.5-3.0%), with fatty acid profiling revealing linolenic acid (C18:3, omega-3) as a significant component. Crude fibre is abundant (15-22%), contributing to the lignocellulosic biomass amenable to bioenergy conversion. Ash content (mineral fraction) ranges from 16-22%, reflecting the plant's capacity to bioaccumulate potassium, calcium, phosphorus, magnesium, iron, and trace heavy metals from the aquatic environment (Shukla *et al.,* 2012).

3.2 Secondary metabolites

Secondary metabolites of *E. crassipes* underpin its pharmacological and nanotechnological relevance. Qualitative phytochemical screening across multiple studies consistently confirms the presence of phenolics, flavonoids, alkaloids, tannins, saponins, terpenoids, steroids, and glycosides, with quantitative content varying by plant part and extraction solvent (Bhattacharya *et al.,* 2020; Priya *et al.,* 2019) Figure 1.

Total phenolic content (TPC) in *E. crassipes* extracts, expressed as gallic acid equivalents (GAE), ranges from 8.5 to 64.7 mg GAE/g dry weight depending on solvent polarity (methanol > ethanol > aqueous > hexane). Identified phenolic acids include gallic acid, protocatechuic acid, caffeic acid, ferulic acid, *p*-coumaric acid, and chlorogenic acid, all recognised as potent free-radical scavengers (Priya *et al.,* 2019; Harborne, 1998) Table 2.

Flavonoid content spans 4.2-38.6 mg quercetin equivalents (QE)/g dry weight. HPLC-based identification has revealed quercetin, kaempferol, luteolin, apigenin, naringenin, and their glycosidic conjugates. Flavonoids function as primary phytochemical reductants in nanoparticle synthesis by donating hydrogen atoms or electrons to metal ions (Jain and Kachhwaha, 2018).

Spectrophotometric and chromatographic analyses have detected alkaloids in all plant organs (0.25-1.8% DW). Specific alkaloids tentatively identified include lycorine-type amaryllidaceae alkaloids and isoquinoline derivatives, though definitive structural characterisation is still limited in the literature and warrants further investigation (Kumar *et al.,* 2018).

Both hydrolysable and condensed tannins are present, with a total tannin content of 1.2-6.8% DW Figure 2. Tannins contribute astringent, antimicrobial, and antioxidant properties and also serve as capping agents in nanoparticle synthesis, preventing aggregation (Ayoola *et al.,* 2008).

Saponin content (0.8-3.2% DW) is detected in the root, leaf, and stem. The amphiphilic structure of saponins enables membrane disruption in microbial cells, contributing to antimicrobial efficacy (Rajkuberan *et al.,* 2017).

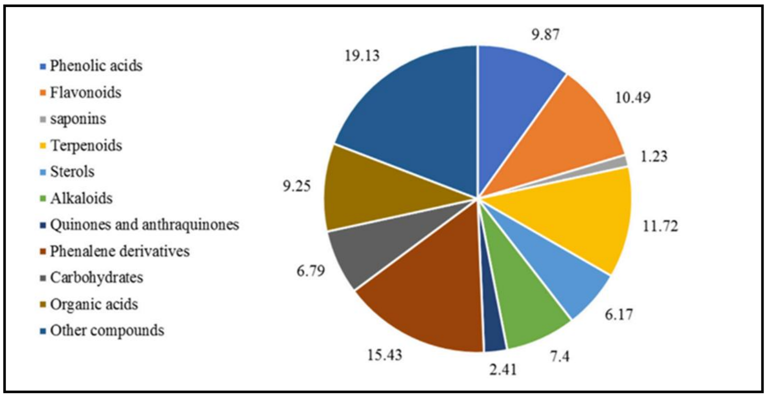

Figure 1: Major components found in *E. crassipes* (Ben Bakrim *et al.,* 2022).

Table 2: Major phytochemical constituents of *E. crassipes*

S. No.	Phytochemical class	Compounds reported	Plant part
1.	Phenolic compounds	Gallic acid, caffeic acid, ferulic acid	Leaves, roots
2.	Flavonoids	Quercetin, kaempferol	Leaves
3.	Alkaloids	Various nitrogenous compounds	Roots, whole plant
4.	Tannins	Hydrolysable and condensed tannins	Leaves, stems
5.	Saponins	Glycosidic saponins	Roots
6.	Terpenoids	Monoterpenes, diterpenes	Whole plant
7.	Steroids	Phytosterols	Leaves
8.	Glycosides	Cardiac glycosides	Whole plant

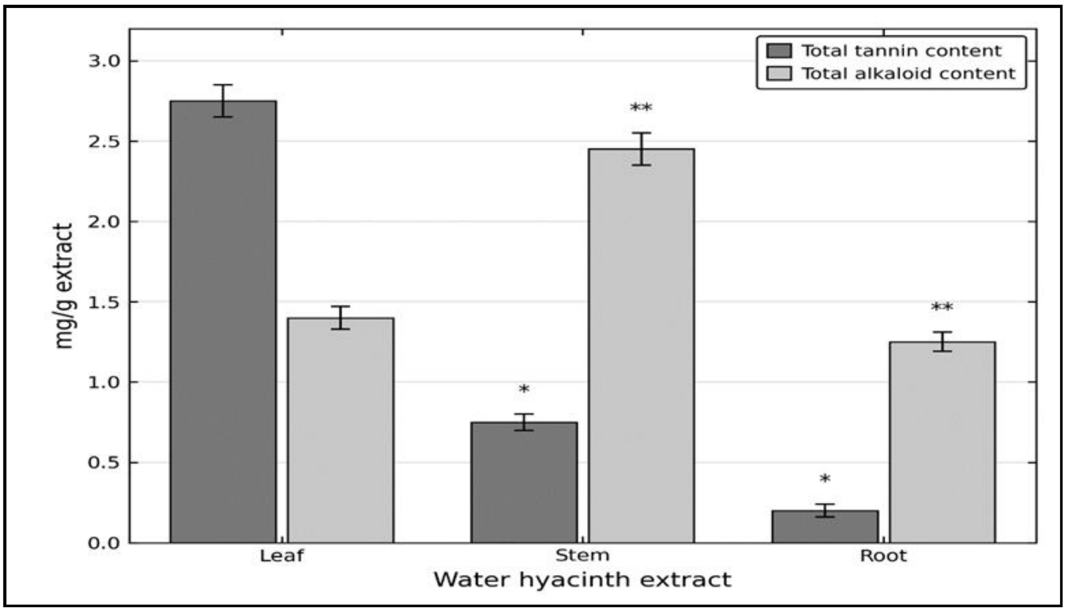

Figure 2: Secondary metabolites of *E. crassipes extract* (mg/g extract) (Eden *et al.,* 2023).

4. *E. crassipes* green synthesis

Green synthesis is the fabrication of nanomaterials under environmentally benign conditions by using biological systems as functional alternatives to the detrimental chemical reagents, such as plants, bacteria, fungi, algae and their extract (Iravani, 2011). The strategy is in line with the twelve principles of green chemistry: waste prevention, atom economy, less hazardous synthesis, designing safer chemicals, safer solvents, energy efficiency, use of renewable feedstocks, reduction of derivatives, catalysis, degradability, real-time analysis, and inherently safer chemistry (Anastasand Warner, 1998; Anastas and Eghbali, 2010). Specifically, plant-mediated synthesis has the advantage of scalability, simplicity, cost-effectiveness, and biological compatibility of the capping phytochemicals attached to surfaces of the nanoparticle (Kharissova *et al.,* 2013).

Green synthesis is much more energy-saving than conventional physical (laser ablation, ball milling, sputtering) and chemical (Turkevich method, sodium borohydride reduction) synthesis routes, does not require inert atmospheres, and generates nanoparticles with phytochemical coatings that provide further biological functionality (Mittal *et al.,* 2013).

4.1 Nanoparticle formation

The nanoparticle synthesis mechanism involving plant extracts has been conceptualised to occur in a series of three steps: activation (reduction of metal ions), growth and termination (Jeevanandam *et al.,* 2018) Figure 3. *E. crassipes* extract contains polyphenols and flavonoids, which are primary reductants because they give electrons or hydrogen atoms to metal ions (*e.g.,* $Ag^+ \rightarrow Ag^0$, $Au^{3+} \rightarrow Au^0$), starting), starting the nucleation. The functional groups of proteins, tannins and saponins-carbonyl, hydroxyl and amine functional groups-adsorb onto the nascent nanoparticle surfaces as stabilising and capping groups to prevent agglomeration caused by steric and electrostatic repulsion. Extract concentration, metal ion concentration, pH, temperature, and reaction time control the final size, shape, and dispersity of nanoparticles (Kuppusamy *et al.,* 2016).

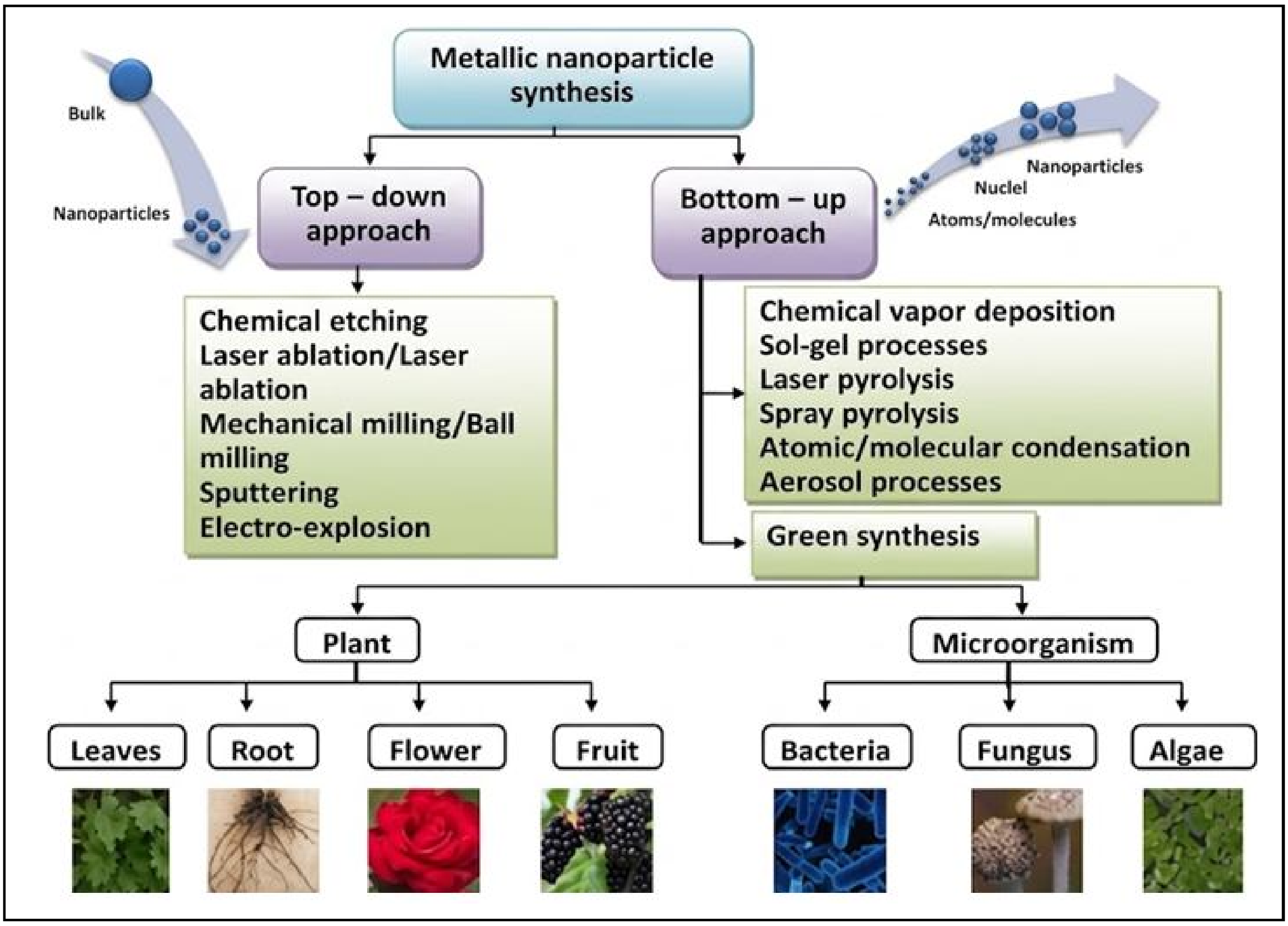

Figure 3: Various synthesis approaches for metal nanoparticles (Singh *et al.,* 2018).

5. Phytomedicinal and biological activities

The therapeutic potential of *E. crassipes* is supported by the increasing amount of *in vitro*, *ex vivo*, and *in vivo* research. It has a wide range of secondary metabolites that underlie a range of pharmacological activities, as discussed below Table 3.

5.1 Antioxidant activity

The best-investigated bioactivity of *E. crassipes* is antioxidant capacity, which is a biochemical analog of its phenolic and flavonoid richness (Figure 4). Several *in vitro* tests have always shown high radical-scavenging activity: DPPH (2,2-diphenyl-1-picrylhydrazyl)

IC_{50} values of 18.4-72.6 µg/ml and ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid) assays. The maximum antioxidant potential of the methanolic leaf extract is uniform, indicating the highest concentration of phenolics. These results justify the use of *E. crassipes* ethnomedicinally as an anti-aging and hepatoprotective agent (Saleem *et al.,* 2019).

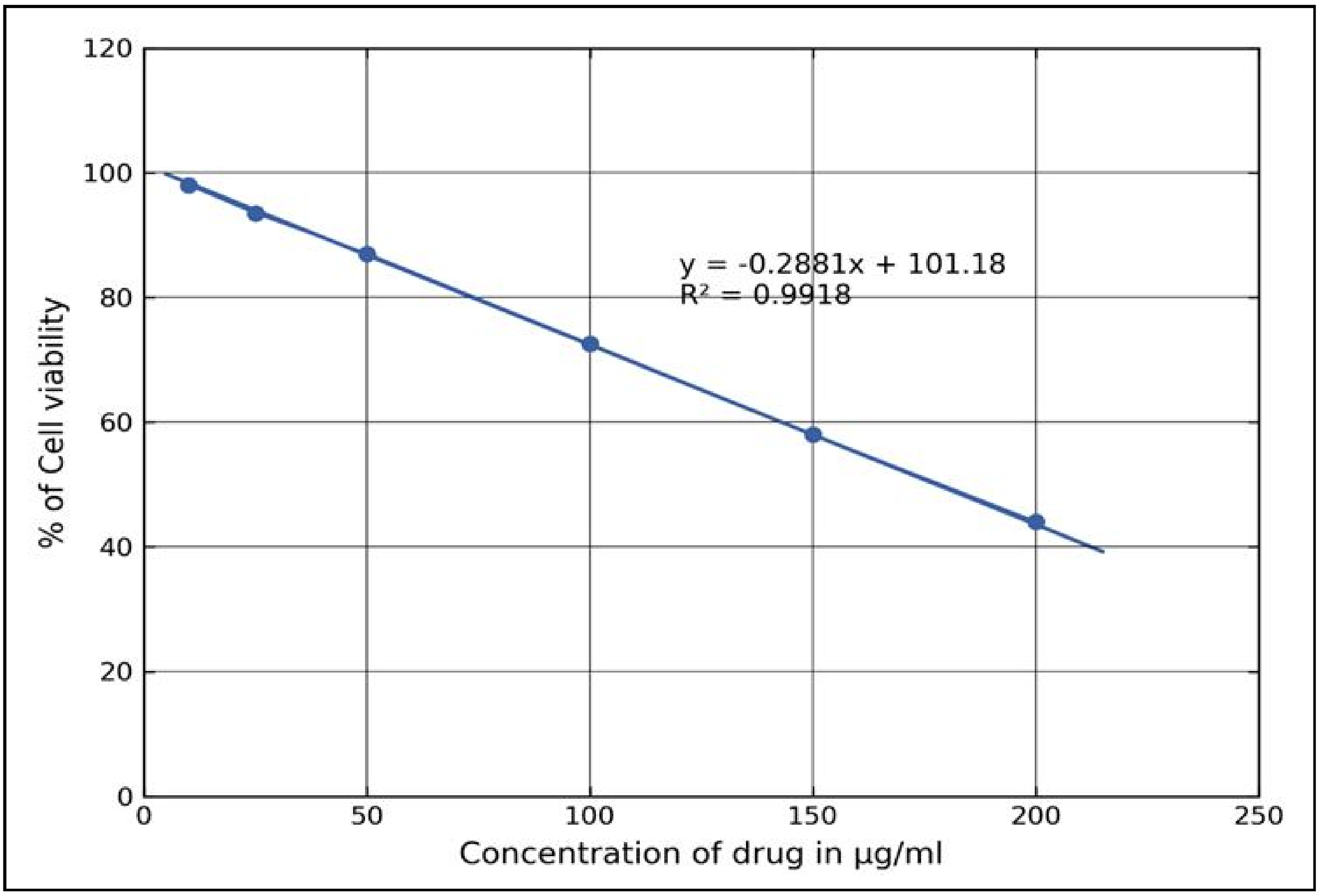

Figure 4: Dose-response relationship of the methanolic extract of *E. crassipes* petioles against MG-63 cell lines.

5.2 Antimicrobial activity

Agar disc diffusion and broth microdilution antimicrobial bioassays indicate that *E. crassipes* extracts and nanoparticles have a broad spectrum of inhibitory activity. The zones of inhibition with bacteria range 10-24 mm depending on the pathogen and concentration; minimum inhibitory concentrations (MIC) of crude extracts are 100-500 µg/ml, and AgNPs reach MICs of 3.1-25 µg/ml - similar to conventional antibiotics - with activity against multidrug-resistant strains. It has been shown to be antifungal against pathogenic fungi (*Candida albicans*, *Aspergillus niger*, *Fusarium oxysporum*) with ZnONPssynthesised using *E. crassipes* extract exhibiting especially high activity (Thakur *et al.,* 2020). The synergistic effect of the phytochemical surface ligands (phenolics, saponins) and the nanoparticle core (physical membrane disruption, reactive oxygen species generation) helps to achieve the better performance of the biogenic nanoparticles compared to the same concentrations of bulk metals or crude extracts (Oves *et al.,* 2018).

5.3 Anti-inflammatory activity

E. crassipes extracts regulate inflammatory pathways in several ways. *In vitro* research using lipopolysaccharide-stimulated RAW 264.7 macrophages shows dose-dependent inhibition of nitric oxide (NO) generation and decreased inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2) expression (Kalaiselvan *et al.,* 2017). They also inhibit the production of pro-inflammatory cytokines (TNF-α, IL-1β, IL-6). The study of carrageenan-induced paw oedema in rodents *in vivo* validates that *E. crassipes* ethanol extract has a significant anti-oedematous effect with a dosage of 200-400 mg/kg body weight, which is similar to the effect of the reference drug diclofenac sodium (Borah *et al.,* 2020). The major anti-inflammatory constituents are phenolic acids and flavonoids (especially quercetin and luteolin), and they operate through inhibition of the NF-κB pathway (Yao *et al.,* 2019).

5.4 Anticancer potential

New data indicate that *E. crassipes* extracts and biogenic nanoparticles have great anticancer potential. MTT cytotoxicity assays show selective toxicity against human cancer cell lines, including HeLa (cervical), MCF-7 (breast), HepG2 (hepatocellular) and A549 (lung)-with IC_{50} of 32-145 µg/ml with crude extracts and 12-58 µg/ml with AgNPs. Induction of apoptosis (caspase-3/9 activation, mitochondrial membrane depolarisation, phosphatidyl-serine externalisation) and cell-cycle arrest at G2/M phase are demonstrated by mechanistic studies with flow cytometry and fluorescence microscopy (Khan *et al.,* 2019). The reported selectivity index (SI = IC_{50} normal / IC_{50} cancer > 2) of some extract-fraction combinations shows therapeutic potential that should be investigated further in preclinical studies. The binding affinity of *E. crassipes* flavonoids (quercetin, kaempferol) to EGFR and topoisomerase II has been predicted in studies of molecular docking, providing mechanistic information on the antiproliferative activity (Daina *et al.,* 2017).

Table 3: Phytochemicals, green synthesis role, and therapeutic applications of *E. crassipes*

S. No.	Plant part	Major phytochemicals	Role in green synthesis	Synthesised nanoparticles	Therapeutic/ biological activities
1.	Leaves	Flavonoids, phenols, tannins	Reducing and stabilising agents	AgNPs, AuNPs	Antioxidant, antimicrobial
2.	Roots	Alkaloids, saponins, terpenoids	Metal ion reduction and capping	AgNPs, ZnO NPs	Antibacterial, anti-inflammatory
3.	Stems/petioles	Phenolics, lignin, carbohydrates	Surface functionalisation and stabilisation	AgNPs	Antioxidant
4.	Whole plant	Mixed secondary metabolites	Synergistic reduction and stabilisation	AgNPs, AuNPs, ZnO NPs	Broad-spectrum antimicrobial, anticancer potential

5.5 Antidiabetic activity

The antidiabetic potential of *E. crassipes* has been demonstrated at multiple mechanistic levels. Enzyme inhibition assays confirm concentrationdependent inhibition of pancreatic α-amylase (IC_{50} : 124-268 μg/ml) and intestinal α-glucosidase (IC_{50} : 86-214 μg/ml) by aqueous and ethanolic leaf extracts, reducing postprandial glucose absorption (Lalitha *et al*., 2012; Patel, 2012). Chlorogenic acid, the most abundant confirmed component, acts as a competitive inhibitor of α-glucosidase, binding the active site through hydrogen-bonding and hydrophobic interactions with catalytic residues Asp203 and Asp542. In STZ-induced diabetic rat models, 21-day oral administration of standardised extract (200-400 mg/kg) significantly reduced fasting blood glucose (FBG) by 28-35% and HbA1c-equivalent markers, restored serum insulin to nearnormal levels, and improved dyslipidaemia (total cholesterol ↓, LDL ↓, triglycerides ↓, HDL↓) (Lalitha *et al*., 2012). Pancreatic β-cell regeneration (histomorphometric quantification of islet area) and skeletal muscle GLUT4 transporter upregulation *via* PI3K/Akt/mTOR pathway activation are proposed as additional mechanisms contributing to improved insulin sensitivity *in vivo* models (Patel *et al., 2012*).

5.6 Hepatoprotective activity

Oral administration of standardised aqueous root extract of *E. crassipes* (200-400 mg/kg body weight, 14-day pre-treatment) provided significant hepatoprotection in CCl_2 -induced hepatotoxicity rat models (Rezai *et al.,* 2019). Treated animals showed significant reductions in serum hepatotoxicity markersALT (48%), AST (42%), ALP (38%)to levels approaching those of the silymarin reference standard. Hepatic lipid peroxidation marker malondialdehyde (MDA) was reduced by 54%, while antioxidant enzymes (SOD, CAT, GPx) and non-enzymatic antioxidant (GSH) were restored to 78-91% of normal values. Histopathological examination confirmed reversal of hepatocyte necrosis, vacuolar degeneration, and Kupffer cell infiltration in extract-treated groups. The mechanism involves attenuation of CCl_2 -derived trichloromethyl radical (•CCl_3) formation, scavenging of reactive oxygen species by gallic acid and quercetin, suppression of hepatic NF-κB and TNF-α expression, reducing inflammatory infiltration, and flavonoid-mediated stabilisation of hepatocellular membranes through lipid peroxide chain-breaking activity (Rezai *et al.,* 2019).

6. Conclusion

This overall analysis confirms *E. crassipes* as a highly damaging aquatic invasive species, in addition to carrying an incredible sizeable repertoire of bioactive phytochemicals, and being an effective biological factory in the production of green nanoparticles. The documented antioxidant, antimicrobial, anti-inflammatory and anticancer activities of the plant are based on the rich phenolics, flavonoids, alkaloids, tannins and saponin profile, as well as the phytochemical reducing and capping machinery of silver, gold and zinc oxide nanoparticles with enhanced biological properties. Its massive, fastproduced biomass has concrete possibilities in phytoremediation, bioenergy, and agricultural valorisation, which inherently belong to the concept of a circular bio economy.

Nevertheless, it requires interdisciplinary collaboration to convert this potential into safe, standardised, and sustainable applications. Prerequisites include systematic toxicological profiling, bioassaydirected isolation of active compounds, pharmacopoeial standardisation, and regulatory harmonisation. More importantly, any exploitation of *E. crassipes* should be preceded by sound invasive species management programmes to avoid unintended ecological damage. Through these protective measures, *E. crassipes* can be turned from an environmental liability into a scientifically demonstrated and economically viable resource a perfect demonstration of the principle of changing an environmental liability into a biochemical asset. Evidencebased pharmacology, sophisticated nanotechnology and sustainability science will be central in achieving this transformative potential in the future.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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