



REVIEW ARTICLE

Exploring the resource potential of water hyacinth and salvinia: A review

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Abstract

Invasive aquatic plants such as *Eichhornia crassipes* Mart. (water hyacinth) and *Salvinia molesta* D. Mitch. pose severe threats to water bodies in Kerala, ranging from small streams to large lakes. These species disrupt natural ecosystems, degrade water quality and impose significant economic costs. By forming dense surface mats, they block sunlight from reaching native aquatic vegetation, thereby inhibiting its growth. This leads to reduced biodiversity, declining water quality and serious imbalances in aquatic ecosystems, adversely affecting fish, invertebrates and other wildlife that depend on native plants for food and habitat. Furthermore, these invasive weeds interfere with recreational activities such as swimming, boating and fishing, reducing the ecological, economic and social value of water resources. Mechanical control methods are commonly employed to manage these weeds; however, they often prove ineffective due to high costs, labour intensity, environmental disturbance and rapid regrowth from plant fragments. This highlights the need for more sustainable and efficient management strategies. One promising alternative is bio-utilisation, which involves converting invasive aquatic weeds into valuable resources. Bio-utilisation not only helps control the spread of invasive species but also supports ecological restoration and economic development. Potential applications include energy production, such as biogas and biofuels; agricultural inputs, including compost, organic manure, animal feed and substrates for mushroom cultivation; phytoremediation for environmental cleanup; and the production of health-related products, such as phytochemical extracts and medicinal compounds. Integrating bio-utilisation into aquatic weed management thus offers a dual benefit: effective control of invasive species and the promotion of ecological sustainability and economic resilience.

Keywords: aquatic weeds; bio-utilisation; *Eichhornia crassipes*; *Salvinia molesta*

Introduction

Aquatic weeds are plants that grow in lakes, ponds, rivers, canals and reservoirs. They may be floating, submerged or emergent. While many aquatic plants contribute to oxygen production, water filtration and habitat provision, those that proliferate excessively or appear in unsuitable places are regarded as weeds. Their overgrowth can upset ecological balance, block water flow, reduce sunlight penetration, lower oxygen levels and interfere with human activities such as irrigation, fishing, navigation and recreation.

Invasive alien weeds are especially problematic. They are introduced through trade, aquaculture, aquarium releases or boat movement and in the absence of natural predators they spread rapidly. Invasive aquatic weeds have rendered approximately 40 % of India's 800000 acres of freshwater unsuitable for fish farming (1). Dense mats formed by these weeds degrade water quality, increase flood risk and generate high costs for control, maintenance and ecological restoration.

In India, approximately 160 species of aquatic weeds have been recorded, of which 10 are considered of primary concern: *Eichhornia crassipes* Mart. (water hyacinth), *Salvinia molesta* D. Mitch. (giant salvinia), *Nymphaea stellata* Willd., *Nelumbo nucifera* Gaertn., *Hydrilla verticillata* (L.f.) Royle, *Vallisneria spiralis* L., *Typha angustata* J. C. Wendl., *Chara* spp., *Nitella* spp. and *Ipomoea* spp. (2). Among these, *E. crassipes* and *S. molesta* have become particularly widespread and problematic in the aquatic ecosystems of Kerala.

Eichhornia crassipes was introduced to India in 1786 when the East India Company established the Botanical Garden in Calcutta (Plate 1). It is a free-floating tetraploid (2n=32) that reproduces both sexually and vegetatively. Under favourable conditions its population can double in 5–15 days and optimal growth occurs in nutrient rich water at temperatures of 28–30°C, pH 6.5– 8.5, salinity below 2 % and nutrient levels of 20 mg L⁻¹ nitrogen (N), 3 mg L⁻¹ phosphorous (P) and 53 mg L⁻¹ potassium (K) (3).



Plate 1. Water hyacinth (*Eichhornia crassipes*).

Salvinia molesta (Plate 2), locally known as African Payal, is the second most harmful weed in Kerala's aquatic ecosystems. It was first recorded in Veli Lake in the 1950s and became a major problem by 1964 (4). It belongs to the family Salviniaceae, is a sterile pentaploid ($2n = 45$) and reproduces via spores and by budding from broken stems or attached nodes. Its optimal growth range is 20°C – 30°C , pH 4–9 and it tolerates relatively high salinity (5).

High temperatures, eutrophic conditions and other environmental factors contribute to the rapid spread of these plants in regions where they have been introduced. Physical control methods have proven largely ineffective. While biological control has shown success in managing *S. molesta*, it has not been effective against *Eichhornia*. Due to their presence in aquatic environments, the use of herbicides is limited and poses environmental concerns. A more sustainable and effective approach to managing these invasive weeds is to explore and utilise their potential benefits for human use.

The review aims to evaluate the ecological and economic impacts of *E. crassipes* and *S. molesta* in Kerala, assess current management practices and explore their bioutilisation potential. By highlighting how these invasive weeds can be turned into valuable resources, it seeks to promote sustainable utilisation as a pathway to reduce their spread and support long-term control efforts.

Bioutilisation

Invasive weeds possess several characteristics that make them highly competitive and difficult to control. The current approach to managing invasive alien weeds increasingly emphasises eradication



Plate 2. Salvinia (*Salvinia molesta*).

through utilisation. This concept involves the economic exploitation of noxious species to harness their potential for meeting human needs while simultaneously reducing their spread and promoting their eventual eradication (6).

This approach can be implemented through various sustainable applications, broadly categorised into bioremediation, agricultural use, bioenergy production and industrial and medicinal applications (Fig. 1). *Eichhornia crassipes* effectively remove heavy metals and pollutants from contaminated soils and water bodies through phytoremediation. In agriculture, certain weeds improve soil health; leguminous species like clover fix atmospheric nitrogen, enhancing soil fertility and reducing reliance on chemical fertilisers. Weeds also serve as nutritious fodder resources offering a valuable dietary supplement, particularly in areas with limited access to conventional feed resources. Several noxious weeds possess medicinal properties and are used in traditional medicine systems. Notably, *S. molesta* and *E. crassipes* are utilised in various ethnomedicinal practices for their potential health benefits. Furthermore, the high biomass production and rapid growth enable continuous feedstock availability for bioenergy production, contributing to the development of sustainable fuel alternatives. Harnessing these attributes transforms invasive weeds from ecological threats into valuable resources. While numerous invasive aquatic weeds are present in Kerala, this paper critically reviews the bio-utilisation potential of two prominent aquatic weeds of Kerala viz., *E. crassipes* and *S. molesta*. The bioutilisation pathways of *E. crassipes* and *S. molesta* are presented in Table 1.

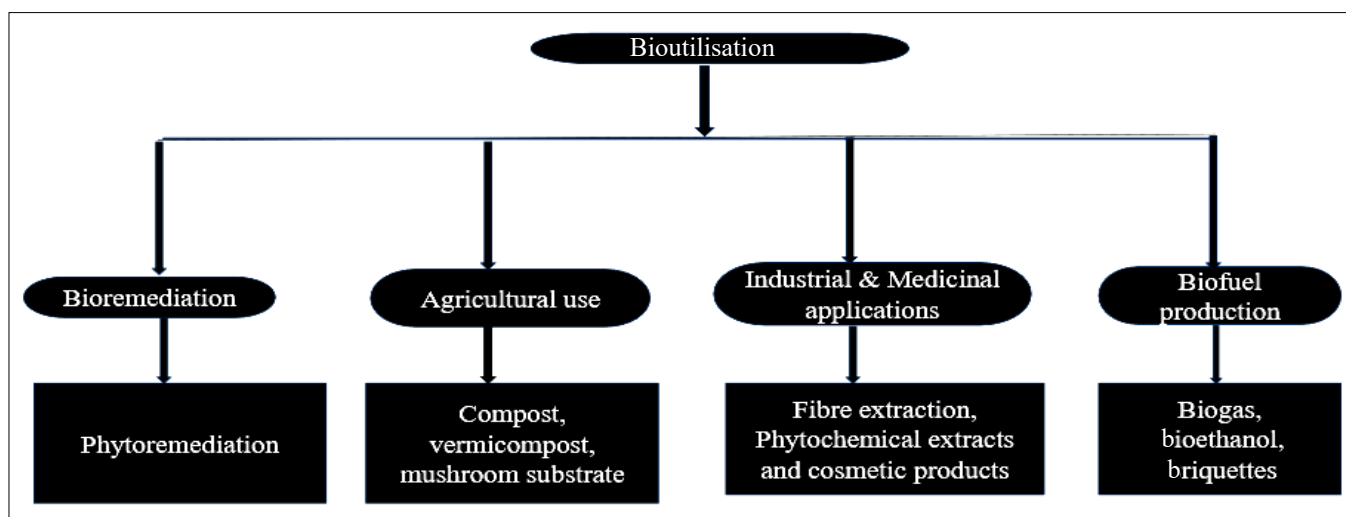


Fig. 1. Schematic diagram showing the bio utilisation of aquatic weeds.

Table 1. Major bio utilisation pathways of *Eichhornia crassipes* and *Salvinia molesta*

Utilization category	<i>Eichhornia crassipes</i> – Key applications	<i>Salvinia molesta</i> – Key applications	References
Bioenergy	Briquettes, biogas, bioethanol and biodiesel production	Biogas production	34–36, 41–45, 93–95, 38–40, 46
Soil amendments	Biochar	-	10–12
Wastewater treatment	Phytoremediation	Phytoremediation	17–21, 83–87
Animal feed	As silage	Feed supplement or ingredient as flour	25–27, 88–92
Mushroom substrate	Low-cost substrate for oyster mushrooms	-	47–49
Industrial uses	Fibres for ropes, mats, furniture, paper, fibreboards and handicrafts	-	50–56
Medicinal/phytochemicals	Bioactive active identified has antioxidant, anti-inflammatory, antimicrobial and anticancer potential and applications in cosmetic industry	Diverse bioactive compounds identified has antioxidant, antimicrobial, antidiabetic and anticancer properties	57–65, 79–82
Agricultural innovations	Floating vegetable gardens for flood-prone areas, vermicompost production	Vermicompost production and as organic manure	28–31, 66–69, 76–78, 97–100

Bioutilisation of water hyacinth

Water hyacinth (*E. crassipes*) has diverse applications, ranging from traditional medicine and biogas production to its use as bedding material for mushroom cultivation. It also plays a significant role in the production of carbon blocks, ropes, fibre boards and serves as animal fodder and fish feed. It is a valuable resource for green manure, compost, biochar and ornamental purposes (7–9).

Biochar production : Biochar is a carbon-rich material obtained through the pyrolysis of biomass under the absence of oxygen. Biochar production from *Eichhornia* is a cost-effective and environmentally friendly technology. Higher temperatures and longer durations reduce biochar yield but enhance carbon stability. Application of *Eichhornia* biochar at 20 g kg⁻¹ markedly improved maize performance and soil biological health, increasing seedling vigour index from 1.0 (control) to 1.61. The treatment significantly enhanced soil enzyme activities like acid phosphatase (+32 %), alkaline phosphatase (+22.8 %) and fluorescein hydrolase (+50 %) and stimulated soil biological activity, with a threefold increase in microbial biomass and a 1.9-fold rise in soil respiration (10). *Eichhornia crassipes* derived biochar produced under limited airflow showed a high yield (44.6 %) and favourable chemical properties. The biochar was alkaline, nutrient-rich, with substantial organic carbon and a balanced C:N ratio and supplied essential macro- and secondary nutrients such as N, P, Ca, Mg and K. Importantly, heavy metal concentrations remained within permissible limits, indicating its suitability and safety for agricultural application.

Application of water hyacinth biochar (WHBC) at a rate of 2500 kg ha⁻¹ produced Teff crop yields that were comparable to those achieved with chemical fertilisers and combined treatments. Characterisation using Fourier Transform Infrared (FTIR) spectroscopy and scanning electron microscopy (SEM) revealed significant structural modifications in WHBC, including enhanced porosity and surface features. These findings highlight WHBC's promise as an effective soil amendment for enhancing soil fertility and promoting sustainable agriculture (11).

Nano biochar from water hyacinth using *in situ* pyrolysis at temperatures between 250–550 °C, yielding the highest adsorption capacity at 450 °C (12). Some studies incorporated pretreatment steps such as carbonisation and preheating to optimise the feedstock before ball-milling, improving particle size and preventing re-aggregation.

Biochar from *E. crassipes* improves soil organic carbon, microbial activity and crop performance. Key constraints include high ash content, potential heavy metal concentration and need for decentralised pyrolysis units.

Use in concrete : The feasibility of using water hyacinth fibres (WHF) as a partial substitute for fine aggregates in concrete has been explored. Compressive strength tests on concrete cubes and cylinders over 28 days revealed that 0.5 % water hyacinth fibres substitution produced the highest compressive strength. It was also observed that inclusion of water hyacinth fibres into concrete exhibited reduced water absorption, increased durability and improved performance under elevated temperatures (13). It was also reported that concrete incorporating up to 3 % water hyacinth demonstrated higher compressive strength compared to conventional ordinary Portland cement concrete, while the content of water hyacinth exceeds 3 %, compressive strength of concrete decreases (14). Pulverised water hyacinth can serve a dual role as a concrete admixture. Firstly, it can influence the setting time of concrete, depending on the quantity incorporated. Secondly, it consistently enhances the compressive strength, regardless of the amount used. These findings suggest that using pulverised water hyacinth as an admixture has strong potential to improve cement quality (15). In another study it was observed that the incorporation of superplasticisers along with the optimal dosage of water hyacinth ash significantly enhances the workability, compressive strength and durability of concrete (16). Performance of concrete with water hyacinth fibres is influenced by variability in fibre quality, particle size and processing methods. Potential biodegradation of untreated fibres, moisture sensitivity and water absorption issues may affect long-term durability. Additionally, scalability, standardisation and consistency of raw material supply remain practical challenges. Since the experiments are going on research and laboratory testing phase, the use of water hyacinth in concrete is at the early stages of technological readiness (equivalent to TRL 3–4). It has not reached commercial scale production.

Effluent treatment: Water hyacinth is highly effective in bioremediation and bio-absorption of heavy metals and organic pollutants (17). It can also tolerate substantial amounts of harmful chemicals such as formaldehyde, acetic acid, oxalic acid and phenol, even at high concentrations (18). The roots system facilitates the removal of particulate matter, N and K from nutrient-rich wetlands.

Water hyacinth accumulates higher concentrations of heavy metals (Fe, Zn, Cu, Mn, Al and Cr) (19). It was reported that higher concentrations of Fe, Zn, Cu and Mn were observed in water hyacinth compared to field water, soil and sediment (20). Water hyacinth is an effective, low-cost option for sewage treatment at effluent concentrations of 750–850 mg L⁻¹, particularly in tropical wet and dry climates. It requires minimal space, can be configured in series or parallel for high wastewater flows and operates without external energy, making it suitable for areas with limited or expensive power supply (21). These findings highlight the effectiveness of water hyacinth in remediating industrial effluents having Fe, Zn, Cu, Mn and organic pollutants. Effective application requires regular harvesting of water hyacinth biomass to sustain treatment efficiency, strict management to prevent its reintroduction or spread into natural waterways and safe disposal or beneficial use of contaminated biomass to avoid secondary pollution.

Animal feed : Due to its high protein and mineral content, processed water hyacinth can be used as feed for various livestock, including pigs (22), ducks (23), cattle and goats (24).

Palatable silage can be made from wilted hyacinth. For silage preparation, freshwater hyacinth is drained, chopped into small pieces, shade-wilted, mixed with additives such as molasses or cassava flour, compacted into airtight polythene bags and fermented for about 45 days. Optimum formulations include the wilted water hyacinth with molasses (5 %) or cassava flour (10 %) and wilted water hyacinth with cassava powder (10 %) plus rice straw (10 %) or guinea grass (10 %) (25). Addition of additives improve the quality of silage. Without additives, the silage had a pH of 7.33, which is relatively high and indicative of poor fermentation quality. When 15 % maize bran was added, the silage pH dropped to 4.1 and with 15 % molasses, it dropped to 4.2. These lower pH levels indicate successful fermentation and better preservation. Both types of treated silage were readily accepted by goats and young steers, suggesting that the additives improved not only the fermentation quality but also palatability and feed intake (26). A mixture of water hyacinth, molasses and pig manure in the ratio of 85:10:5 (percentage wet weight) was identified as optimal for silage production. The silage making process lasted for 28 days. The resulting silage had a protein content of 16 % and a dry matter content of 18 %, making it suitable for use as animal feed (27). Water hyacinth can be a substitute part of conventional feed for livestock and its nutritional value depends on processing.

Water hyacinth, despite its nutritive potential, contains several anti-nutritional factors such as tannins, phenols, oxalates and heavy metals, which can impair digestibility and adversely affect health. Therefore, proper fermentation during silage preparation is essential to reduce these compounds and ensure safe utilisation.

Vermicompost production : Water hyacinth efficiently absorbs N, P and K from water which makes it as a good compost material. Fresh biomass was thoroughly washed, chopped into small pieces and heaped under shaded conditions. The heap was then inoculated with a decomposing bacterial culture (*Bacillus* sp., MTTC No.: 297) and maintained at approximately 60 % moisture through regular water spraying. To facilitate faster decomposition, the biomass heap was turned every 7 days. After 30 days of pre-composting, the partially decomposed biomass was collected for vermicomposting. The pre-composted material was mixed with 30-day-old cow dung at 4:1 ratio (biomass to cow dung) and filled into pots, maintaining a uniform mixture weight in each pot. The moisture content was

adjusted to 60 %. Fifty adult earthworms (*Eudrilus eugeniae* Kinberg.) were introduced into each pot, which were then covered with jute gunny sacks and maintained under complete shade. Vermicast production commenced within one week of earthworm introduction (28).

Vermicomposting of pre-decomposed water hyacinth using the earthworm *Perionyx excavatus* Perrier. resulted in the production of compost within 25 days. The resulting vermicompost contained 47 % more N, 60 % more P and 40 % more K compared to compost produced through conventional composting methods (29).

Research conducted at the Horticultural Research Station, Udthagamandalam, has demonstrated that water hyacinth can be effectively utilised for the production of high-quality vermicompost. In this process, water hyacinth biomass is mixed with cow dung in a 1:3 ratio and allowed to decompose for approximately 50 days. The partially decomposed material is then transferred to vermicomposting units, where African earthworms (*E. eugeniae*) are introduced at a rate of 1500 worms per tonne of weed biomass. Vermicomposting is continued for an additional 50 days, during which a substantial increase in the earthworm population is observed. In water hyacinth-based compost, the number of adult earthworms increases to 4590, representing more than a threefold rise from the initial population. In contrast, compost derived from agricultural waste supports a comparatively lower increase, reaching 2610 adult worms, which is less than double the initial population (30).

Water hyacinth can be effectively composted using the earthworm *P. excavatus*. To begin the process, the water hyacinth is cut into small pieces, sun-dried and then mixed with cow dung in a 5:1 ratio. This mixture is allowed to pre-decompose for 15 days. After the pre-decomposition period, earthworms are introduced into the medium. During the composting process, the moisture content should be maintained at 65–70 % to ensure optimal conditions for the earthworms. The compost is ready in approximately 105 days. The final vermicompost is significantly richer in both macro- and micronutrients compared to the original water hyacinth and cow dung mixture (31).

Vermicompost from *E. crassipes* enhances nitrogen, phosphorous and potassium (NPK) content, earthworm reproduction and decomposition rates. It also improves the availability of micronutrients and overall compost maturity compared to conventional compost. These benefits highlight its potential as a high-quality organic amendment for sustainable soil fertility management.

Effective utilisation requires pre-composting to reduce excess moisture and heat, ensuring earthworm survival and efficient decomposition. Additionally, biomass sourced from polluted or wastewater bodies may contain heavy metals or contaminants, necessitating careful source selection and quality monitoring before compost application.

Biofuel : Bioenergy is gaining traction as a cost-effective and eco-friendly alternative energy source. Water hyacinth biomass is ideal for biofuel production due to its high N and low lignin content (32). The biomass can undergo anaerobic fermentation to produce biogas which can be serve as a renewable energy source. This process not only turns waste into an economical resource but also benefits the environment (33).

Dried water hyacinth was carbonised at temperatures

between 350 °C and 500 °C and subsequently mixed with an 80 % (w/w) molasses solution in varying ratios (40:60, 30:70 and 20:80) to produce briquettes. The results indicated that variations in the molasses-to-charcoal ratio significantly influenced briquette quality. Increased binder content led to higher volatile combustible matter and fixed carbon, along with reduced ash content. Among the formulations, the 30:70 ratio exhibited the highest calorific value (16.6 MJ kg⁻¹) and compressive strength (19.1 kg cm⁻²), demonstrating the potential of water hyacinth as an alternative solid fuel (34). A study conducted in Kerala evaluated water hyacinth as a primary biomass for briquette production in comparison with conventional materials. The briquettes showed the lowest moisture content (2.95 %) and high impact and shatter resistance, confirming water hyacinth as a viable and sustainable feedstock for commercial briquette manufacturing (35). Higher moisture and ash content affects the combustion efficiency and thereby reduce the calorific value. Another study reported that water hyacinth briquettes had 7.8 % moisture, 12.4 % ash, 65.7 % volatile matter, 21.9 % fixed carbon and a calorific value of 14.44 MJ kg⁻¹. The fixed carbon content was comparable to other woody and herbaceous biomass, confirming the suitability of water hyacinth briquettes as an effective energy source (36).

Biomass residues with high cellulosic content are more suitable and cost-effective for the bioethanol production. Biomass of *E. crassipes* is rich in cellulose and hemicellulose (58.6 %) with a reduced lignin level (37).

Bioethanol production from water hyacinth involves hydrolysis, fermentation and distillation (Fig. 2). One kilogram of *E. crassipes* cellulose can yield ~0.56 kg of ethanol (38). Saccharification with 1 % (v/v) sulfuric acid at 121 °C for 1 hr, followed by fermentation with yeast strain 484 (*Candida intermedia* (Cif. & Ashford) Langeron & Guerra), produced 22.4 mL ethanol per kg of dried biomass (39). Among pretreatment methods, combined microbial and dilute acid treatment was most effective, yielding the highest cellulose content (39.4±2.8 %), reducing sugar (430.66 mg g⁻¹) and bioethanol concentration (1.40 g L⁻¹) without external cellulase (40). However, pretreatment and fermentation remain major cost drivers due to increased capital and operating expenses.

Biogas is produced through the anaerobic digestion of organic wastes, involving stages such as hydrolysis, acidogenesis, acetogenesis and methanogenesis (41). *Eichhornia crassipes* is an

ideal feedstock for biogas production due to its high carbon-to-nitrogen ratio (42). Additionally, its low lignin content (10 %) and high cellulose (25 %) and hemicellulose (35 %) composition make it a promising biofuel source (43). Low lignin content of water hyacinth enhances biodegradability, shortens digestion time and improves methane yield. Co-digestion of water hyacinth with cow dung enhances biogas yield, while the resulting slurry, rich in N and K, serves as a valuable fertiliser. The preliminary rotting of the biomass for about 20 days further improves gas production (44).

Anaerobic digestion was initiated using a cow dung-water (1:1) slurry, in which biogas formation begins within a week. After adding crushed water hyacinth, methane concentration gradually increased and combustible biogas with a blue flame was obtained after about 32 days of digestion (45). In a biogas plant, dried water hyacinth is anaerobically fermented in a sealed kiln reactor, initiating gas production within 24 hr. The raw biogas is purified to obtain methane for cooking and lighting, with reports suggesting that up to 10 kg of methane can be produced from 1 kg of plant waste (43).

Water hyacinth is also a promising feedstock for biodiesel production and is well accepted for its stability (38, 46). The property of biodiesel was analysed by blending it with petroleum diesel in various proportions and observed that the blend of 20 % biodiesel and 80 % diesel fuel was comparable to fossil fuels in terms of emissions and thermal efficiency (46).

The processes and constraints involved in bioenergy production from water hyacinth are summarised in Table 2.

Mushroom cultivation : Water hyacinth (*E. crassipes*) stems and leaves have been shown to be an effective, low-cost substrate for mushroom cultivation. When used alone, they support oyster-mushroom growth with a biological efficiency comparable to more expensive materials such as wheat or teff straw (47) and they can be further enhanced by blending with sawdust (yield ~ 202.6 g bag⁻¹ vs. 94.2 g bag⁻¹ for hyacinth alone) (48) or with rice straw in a 1:1 ratio (49). After mushroom harvest, the spent substrate can be processed into vermicompost, adding an economical, sustainable waste-management step. Together, these findings demonstrate that *E. crassipes* is a viable, inexpensive substrate for mushroom production, offering both economic and environmental benefits.

Although water-hyacinth can take up trace heavy metals such as lead, cadmium or arsenic from the environment, studies show these metals do not accumulate in the fruiting bodies beyond

Table 2. Bioenergy production from water hyacinth – summary of processes and constraints

Bioenergy pathway	Energy outputs	Pretreatment requirements	Optimal conditions / Key findings	Constraints / limitations
Briquette production	Solid fuel, calorific value: 14.4–16.6 MJ kg ⁻¹	Drying, carbonisation (350–500 °C), mixing with binder (molasses)	Molasses: charcoal ratio of 30:70 showed highest calorific value (16.6 MJ kg ⁻¹) and compressive strength	Requires drying and carbonisation, binder availability, ash content varies
Bioethanol production	Liquid fuel; ~22.4 mL ethanol per kg dried biomass	Size reduction, acid pretreatment (dilute H ₂ SO ₄), hydrolysis, fermentation	1 % (v/v) H ₂ SO ₄ at 121 °C for 1 hr; yeast <i>Candida intermedia</i> showed high ethanol yield	Acid handling, inhibitor formation, relatively low ethanol yield per kg
Biogas production	Methane-rich biogas for cooking and lighting	Chopping/crushing, slurry preparation, optional pre-rotting	Anaerobic digestion period ~30–32 days; co-digestion with cow dung enhances yield	Long retention time, initial CO ₂ dominance, seasonal biomass availability
Biodiesel production	Biodiesel suitable for blending (B20 blend optimal)	Oil extraction, transesterification	B20 (20 % biodiesel + 80 % diesel) showed comparable emissions and efficiency to fossil diesel	Low lipid content, additional processing cost

the safety limits set by expert committees, provided the substrate is sourced from unpolluted sites and regular monitoring is performed (49). Consequently, the main contamination risk lies in using contaminated biomass, which can be mitigated by proper site selection and pretreatment of the substrate.

Fibre : Water hyacinth stalks are used in the production of medium-quality paper, fibreboards and fibrous pulp (50). The marketability of water-hyacinth crafts is robust and growing, especially in today's eco-conscious climate. Water hyacinth is a valuable raw material for various industries producing ornamental items, furniture and paper. It has been used widely to make ropes, bags, mats and other handicraft items, as well as furniture (51). Scalability is a key strength because the plant raw material is abundant and rapidly renewable across tropical and subtropical water bodies, providing a virtually unlimited supply without depleting natural resources.

Water hyacinth stems are harvested, cut into 12 cm pieces and boiled to produce a black pulp, which is washed. To enhance paper strength, water hyacinth pulp is combined with waste paper pulp. The mixture is then dyed using appropriate dyes, with the required amount determined through practical experience. The process concludes with the final steps of lifting, drying and peeling of paper (52). Handmade paper was made from water hyacinth stalks. After removing leaves and roots, the cleaned stalks were air-dried, cut into short pieces and pulped under alkaline conditions. The resulting pulp was washed, disintegrated and bleached before being formed into hand sheets with a standard sheet former (53).

The process of fibre extraction begins with selecting and separating mature water hyacinth stems of 50 cm long, as younger stems produce brittle or soft fibres. The selected stems are split lengthwise and air-dried, then sorted by length and thickness. The dried strips are treated, twisted into ropes of varying diameters and supplied to artisans who craft handbags, flower vases, mats, matting and furniture. In Kerala, the Kottappuram Integrated Development Society, an NGO located in Thrissur, has facilitated small women's groups in extracting fibre from water hyacinth and producing various handicrafts (54).

In Kerala, water-hyacinth stems are first decorticated and anaerobically retted for 5–7 days, after which the fibres can be pulled out by hand. The fibres then undergo a brief alkali (NaOH) treatment, followed by neutralisation with acetic acid and a cold-water rinse. This retting step enhances overall fibre strength, while the alkali treatment markedly improves tensile strength (55). Another study revealed that grating the outer layer of water hyacinth stems using a semi-automatic fibre extraction machine, followed by chemical treatment, produced fibres with a smoother surface texture and the highest degree of extraction efficiency (55). Fibres extracted from water hyacinth and treated with NaOH for 3 hr exhibited significantly improved absorbency, retaining approximately 5–11 times their own weight in water (56). Water hyacinth fibres are both renewable and biodegradable, which makes them a greener substitute for man-made synthetic fibres.

Medicinal and cosmetic applications : Water hyacinth has been widely utilised in medicinal and cosmetic products due to its beneficial properties. Results of the research studies indicated that the plant enhances skin health, promoting radiance and smoothness, making it a valuable ingredient in skin and hair care products. Its anti-inflammatory properties make it effective in the

treatment of eczema, sore throat and toothache (57). Water hyacinth is known to possess several antioxidants, including glutathione and ascorbic acid. In a study evaluating the anti-ageing potential of its ethyl acetate extract, two skin cream formulations were tested using DNA damage inhibition and DPPH radical scavenging assays. The results showed a concentration-dependent increase in both DNA protection and free radical scavenging activity across the tested range (1–20 mg) for both formulations. These findings highlight the potential of *E. crassipes* as a promising candidate for cosmeceutical applications (58). Water hyacinth leaves have been traditionally used to treat snakebites and the plant's antibacterial properties make it effective against sexually transmitted infections (57). The seeds of water hyacinth are used for cholesterol regulation whereas its flowers have been used to regulate menstrual cycles (59). *Eichhornia crassipes* is rich in bioactive secondary metabolites such as sterols, alkaloids, phenolics, flavonoids, tannins and saponins and its extracts exhibit diverse pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, anticancer, neuroprotective, hepatoprotective and skin-whitening effects (60). Certain fractions of the crude extract exhibited selective anticancer activity against liver cancer cell lines, while others showed strong cytotoxic effects against hormone-dependent cancers, such as cervical and breast tumours (61). Studies on multiple cancer cell lines (MCF-7, HeLa, HepG2 and EACC) showed that crude extracts of *E. crassipes* exhibited the strongest cytotoxic and antioxidant activity, while isolated compounds displayed cell line-specific effects, highlighting the plant's anticancer potential (62). The results showed that the aqueous extract exhibited the highest antibacterial activity against *Escherichia coli*, whereas the hydro-methanolic extract was most effective against *Pseudomonas aeruginosa* (63).

Phytochemical test results from various experiments indicated the presence of alkaloids, flavonoids, phenols, sterols, terpenoids, anthraquinones, quinones, anthocyanins, saponins and tannins in water hyacinth. The detection of such a wide range of phytochemical constituents suggests that the plant possesses diverse bioactive compounds. This diversity implies the plant may have multiple therapeutic and medicinal applications, potentially offering significant benefits to the population (64). The results of the phytochemical analysis of the hyacinth flower extract showed positive results for phenolic compounds, tannins, flavonoids and saponins. The antioxidant activity, evaluated using the DPPH method, was interpreted based on IC₅₀ values. The IC₅₀ values for the hyacinth flower extract were 1085.31 ppm for n-hexane, 950.71 ppm for ethyl acetate and 35.83 ppm for methanol. A lower IC₅₀ value indicates stronger antioxidant activity, demonstrating that the methanol extract exhibited the highest antioxidant potential among the 3 solvent extracts (65). The toxicity and safety profiles of water hyacinth extracts remain poorly characterised, as most data come from *in vitro* studies. Comprehensive *in vivo* evaluations, chronic toxicity testing and allergenicity assessments are necessary before clinical or cosmetic application. Standardisation also presents a major challenge, since phytochemical composition varies with plant parts, growth conditions, season and extraction solvent, resulting in inconsistent bioactivity and difficulty establishing reproducible doses or quality benchmarks. Additionally, extraction scalability is limited, as bioactive-rich extracts often rely on organic solvents (e.g., methanol or hydro-methanol) that are costly, environmentally burdensome, or require extensive purification for large-scale production. Addressing these issues through validated safety

studies, standardised protocols and cost-effective green extraction technologies is essential to translate laboratory findings into safe, market-ready products.

Floating vegetable gardens : Floating gardens made from water hyacinth are a traditional, innovative farming system used in flood-prone wetlands, particularly the Haor regions of Bangladesh. Known locally as baira, dhap, gatoni and other names, these floating beds enable vegetable and spice cultivation during prolonged monsoon flooding. Practiced by nearly 60–90 % of local communities, the system supports year-round, biodiverse crop production while integrating open-water fishing. Recognised by FAO in 2015 as a Globally Important Agricultural Heritage System (GIAHS), this approach offers a sustainable, eco-friendly solution that enhances agro-biodiversity, livelihoods and efficient wetland resource use (66).

Floating garden construction begins with collecting water hyacinth and forming a raft, typically ~8 m long, 1.5–2 m wide and <1 m high. Bamboo poles are temporarily used to shape and stabilise the raft, then removed once the structure sets. After 7–10 days, more water hyacinth is added, followed by ~25 cm layer of compost to create the planting bed.

Seasonal vegetables are sown in the compost layer, cucurbits during the monsoon and crops like beans, tomatoes, cabbage and root vegetables in winter. The raft is fenced to protect crops and anchored so it rises with floodwater and prevents submergence. Harvesting occurs 2–3 times per week and after one season the raft is composted and reused as fertiliser, ensuring a sustainable cultivation cycle (67).

Floating gardening using water hyacinth provides a sustainable way to manage this invasive weed while enhancing food security, livelihoods and environmental sustainability by enabling vegetable cultivation on water bodies and improving dietary diversity beyond fish-based diets (68). Floating vegetable cultivation requires very less capital. It was reported from Bangladesh that the total cost required for the floating garden constructed using water hyacinth of size 45 x 3 ft was only ₹5600 and the income generated during the monsoon period was ₹21000 (69).

Successful implementation of floating gardening, despite its simplicity, requires pilot studies tailored to specific countries and ecosystems. These should evaluate suitable materials for raft construction, measures to protect platforms and crops from physical and biological stressors, strategies for marketing produce and the agronomic performance and long-term sustainability of the system. Floating gardens provide a low-cost wetland farming approach that enhances food security and livelihoods in flood-prone areas; however, challenges such as raft durability, nutrient depletion, labour intensity and ecosystem specificity necessitate location-specific optimisation for sustainable adoption.

Bioutilisation of *Salvinia*

Although *Salvinia* can be controlled to some extent during preparatory cultivation in rice fields, it has been reported recently as a problem in paddy fields in many districts. There, it interferes with farming practices and reduces rice yields by competing for nutrients. *Salvinia* can be utilised for human benefits as follows.

As vermicompost : Vermicomposting offers an effective strategy for transforming *S. molesta*, an invasive aquatic weed, into nutrient-rich organic fertiliser. This process degrades the plant's lignin content and allelopathic compounds, producing compost with a fertilising

potential comparable to that of animal manure. Leaves of *Salvinia* contains 0.4–0.7 % polyphenols (70) and lignin content of 13.7 % (71, 72) which was higher than those present in water hyacinth and lantana (73, 74). Vermicomposting of *Salvinia* resulted in a near-complete elimination of polyphenol content, a significant reduction in lignin content and a marked decrease in the C:N ratio from 53.9–9.35. Additionally, the humification index was substantially lowered from 8.79–1.49, indicating enhanced stabilisation and maturation of the compost (75).

The conventional vermicomposting method involves mixing *Salvinia* biomass with animal manure in a 70:30 ratio and allowing it to pre-decompose for 20–25 days, during which initial microbial breakdown occurs. Earthworms (*Eudrilus eugeniae*) are then introduced and complete conversion to mature compost typically takes 2–4 months (76). In contrast, a rapid vermicomposting technique has been developed that eliminates the need for animal manure. Fresh *Salvinia* is washed and placed in lined containers with water-soaked jute cloth inoculated with earthworms and processed using pseudo discretised continuous reactor operation. This approach produces vermicompost in just 15–20 days, is more economical and increases production efficiency 3–4-fold compared to conventional methods (77).

Findings from a study revealed that using sun-dried *Salvinia* as a feedstock under semi-continuous reactor conditions resulted in the highest vermicast yield (60.5 %) and earthworm biomass (75.2 %) (78).

Application of *Salvinia* vermicompost alone at 13.2 t ha⁻¹ or application of *Salvinia* compost at 3.3 t ha⁻¹ along with NPK dose of 45:13: 6.2 kg ha⁻¹ resulted in taller plants, a greater number of panicles per square metre, higher dry matter production, yield and B:C ratio in rice (76).

Vermicomposting of *S. molesta* efficiently transforms this invasive weed into nutrient-rich fertiliser, rapidly producing high-quality compost that enhances crop growth, increases yield, boosts economic returns and supports sustainable weed management.

Extraction of phytochemicals : Phytochemical analysis of *S. molesta* was performed by extracting plant material with appropriate solvents. The resulting extracts were then subjected to high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS), which confirmed the presence of a diverse array of bioactive compounds. The HPLC analysis of the butanol extract revealed the presence of 6'-O-(3,4-dihydroxybenzoyl)-β-D-glucopyranosyl ester, 4-O-β-D-glucopyranoside-3-hydroxymethyl benzoate, paeoniflorin and pikuroside. In contrast, the ethyl acetate extract was found to contain methyl benzoate, hypogallic acid and caffeic acid (79). While GC-MS analysis of the ethanol extract of *S. molesta* revealed the presence of several phytochemical constituents, including apiol, methyl palmitate, hexadecatrienoic acid methyl ester and methyl isostearate (80). In another study, analysis of the crude extracts from *S. molesta* revealed varying levels of metabolites depending on the solvent used. The chloroform extract contained the highest number of phyto-constituents (7/12), followed by ethanol (6/12), then acetone, benzene, aqueous and petroleum ether (5/12). Phenols and tannins were present in all extracts. Steroids were found in chloroform, ethanol, acetone and benzene extract. Coumarins were present in ethanol, acetone, aqueous and petroleum ether extracts. Saponins were detected in chloroform, benzene and petroleum ether extracts. The flavonoids were present in chloroform extracts.

Xanthoproteins were found in ethanol, acetone and aqueous extracts. Proteins were present in chloroform, benzene and petroleum ether extracts (81). The phytochemicals identified in *S. molesta* have various anti-oxidative, antidiabetic, anti-carcinogenic, anti-microbial, anti-allergic, anti-mutagenic and anti-inflammatory properties (79–82). The aqueous and ethanol extracts of *S. molesta* revealed the presence of phytochemicals like tannins, phenols, saponins, flavonoids and alkaloids. It was also revealed from the results that ethanol extract showed highest antibacterial activity against *E. coli*, whereas aqueous extract showed highest antibacterial activity against *P. aeruginosa* (82).

As most reported bioactivities are based on *in vitro* studies, *in vivo* validation, toxicity assessment and dose standardisation are essential before therapeutic or nutraceutical application.

Wastewater phytoremediation: *Salvinia molesta*, commonly known as giant salvinia, is an aquatic fern recognised for its rapid growth and dense floating mats. Its ability to absorb contaminants has made it a promising candidate for phytoremediation, particularly in wastewater treatment applications. The ability of *S. molesta* to treat palm oil mill effluent was tested in an outdoor raceway pond over a period of 16 days. The plant removed 95 % of phosphate from the wastewater reducing its concentration to 0.17 mg L⁻¹. By the end of the experiment nitrate levels were measured at 0.50 mg L⁻¹ while ammonia levels fluctuated with an average concentration of 2.62 mg L⁻¹. Water quality assessment showed that there was a decrease in the turbidity from 7.56 NTU to 0.94 NTU within 2 days (83).

Agricultural residues such as wheat and rice straw along with *S. molesta* biomass can be used as a green technology treatment for removing heavy metals from the waste water (84).

The municipal waste water samples were collected from four industrial locations across 2 districts in Kerala including a) Kaloor, Kadavanthra road (near PVS Memorial hospital), Ernakulam b) KSRTC Road, South Chalakudy, Thrissur c) Kadukutty, Kathikudam (Nitta Gelatin), Chalakudy, Thrissur and d) Kokkala, Thrissur. After 5 and 10 days of treatment with *S. molesta*, the concentration of heavy metals decreased revealing the plant's ability to absorb and accumulate contaminants through rhizofiltration. Results also revealed that *S. molesta* acts as a hyperaccumulator of iron in acidic conditions (pH 5.5–6.5) and can remove zinc in alkaline conditions (pH 7.7–8.8), though a longer treatment period was required (85). *Salvinia molesta* demonstrated greater efficiency in removing endosulfan from aqueous solutions compared to *Hydrilla verticillata* and *S. minima*. Within a period of 21 days, *S. molesta* was able to remove up to 97.94 % of endosulfan (86). A study evaluating the effectiveness of *S. molesta* in removing methyl orange dye from water showed that the plant achieved decolorization efficiencies of 42 %, 20 % and 15 % at dye concentrations of 5, 15 and 25 mg L⁻¹, respectively. In comparison, the control samples without the plant exhibited significantly lower decolorisation rates of 12 %, 7 % and 6 % for the same dye concentrations. These results highlight the important role of *S. molesta* in the removal of methyl orange from contaminated water (87).

Salvinia molesta demonstrates strong potential as a phytoremediation agent, effectively removing nutrients, heavy metals, pesticides and dyes from various wastewater sources. Its rapid growth, dense mats and ability to act as a hyperaccumulator under different pH conditions make it a versatile and eco-friendly

option for improving water quality in industrial and agricultural effluents, though treatment efficiency may vary with contaminant type, concentration and exposure time.

Animal feed : *Salvinia molesta* has shown potential as a feed ingredient for various livestock and aquaculture species. It can be used as an alternative for traditional protein sources like soybean meal. *Salvinia molesta* can be utilised as a feed supplement or ingredient in tilapia diets (88). Feeding chicken with diets containing up to 18 % *Salvinia* increased the N retention, muscle protein mass and the body weight (89). Studies showed that a 6 % inclusion level in chicks resulted in a significant weight gain (28.22 g day⁻¹) whereas a higher inclusion level resulted in lower weight gains (22.30 g and 19.33 g respectively) (90). The inclusion of 15 % *S. molesta* in the local duck ration led to improvements in body weight and feed conversion ratio (FCR), as well as an increase in income over feed cost (IOFC) by approximately IDR 2468.65. This formulation proved to be the most efficient compared to the control and other experimental rations (91). *Salvinia molesta*, when processed into flour, can serve as an affordable alternative ingredient in duck feed (92).

Biogas production : Biogas production from *S. molesta* holds a significant potential for renewable energy. Potential production per kilogram of *S. molesta* was 58.16 L with methane concentration of 54 % indicating that *S. molesta* potentially can be used as a substrate for biogas raw material (93). Biogas formation using batch system recorded a yield of 221 L of biogas per kilogram of wet *S. molesta* biomass (94).

For biogas generation, *S. molesta*, was harvested from freshwater ecosystems and employed as the primary lignocellulosic substrate. The digestion process was initiated with a starter inoculum composed of cow dung mixed with twice its volume of water to enhance methanogenic microbial activity. The mixture was introduced into synthetic fibre biogas digesters, designed with a tank diameter of 60 cm, a dome diameter of 56 cm, a gas outlet tube diameter of 7 cm and a tube mouth diameter of 13 cm. Biogas production was sustained through the periodic addition of *S. molesta* and supplementary plant materials, ensuring adequate surface area and inclusion of root biomass to optimise microbial decomposition. This method enabled the efficient utilization of *S. molesta* as a sustainable and cost-effective substrate for biogas production. Experimental comparisons across different volatile matter (VM) loading rates—1.55, 3.10 and 4.65 g L⁻¹ day⁻¹—revealed that gas production per kg of volatile matter increased by 44 %, 34 % and 102 % respectively, during the hot season compared to the rainy season, when the ambient temperature was generally below 30 °C. These results underscore the significant influence of temperature on biogas yield, particularly at higher organic loading rates (95).

Salvinia molesta demonstrates strong potential as a renewable biogas substrate, yielding substantial methane and overall gas volumes, particularly under optimised loading rates and warm conditions. Seasonal temperature and organic loading significantly influence biogas production, highlighting the need for site- and season-specific management to maximise energy recovery from this invasive aquatic weed.

As organic manure : A study was carried out to evaluate the effectiveness of *S. molesta* as an organic fertiliser. The results showed that garden soil amended with powdered *S. molesta* had higher nutrient content compared to untreated garden soil. This suggests that *Salvinia*, typically considered a waste plant, can be efficiently

utilised as manure due to its rich composition of both macro- and micronutrients (96). *Salvinia molesta* contains 0.62–4 % N, 0.03–1.07 % P₂O₅ and 0.31–5.32 % K₂O, making it suitable as an organic manure (97). Incorporating *Salvinia* into soil increased water-soluble potassium by 2–4 kg ha⁻¹ and exchangeable potassium by 10–43.5 kg ha⁻¹ (98). Leachates collected on the 7th and 14th days of decomposition showed biological activity, indicating the release of auxin-like compounds from decomposing *S. molesta* (99). A study conducted at Birsā Agricultural University on soybean cultivation revealed that the application of 50 % of the recommended dose of fertilisers (RDF) combined with 4 t ha⁻¹ of *S. molesta* resulted in the highest grain yield. The results also indicated that the application of *S. molesta* at 1 t ha⁻¹ produced a yield equivalent to that obtained with 50 % RDF alone. These findings suggest that *S. molesta* holds significant potential as an organic manure and could serve as a sustainable alternative to chemical fertilisers in soybean production (100).

While *S. molesta* offers multiple bioeconomic and environmental benefits, its practical utilisation faces several constraints. The high polyphenol and lignin content of the biomass can inhibit microbial degradation, slow decomposition rates and reduce nutrient availability during composting or vermicomposting, thereby requiring longer processing times or pre-treatment. Its dense mats and rapid growth make harvesting labour-intensive and technically challenging, particularly in large water bodies, which limits scalability for applications such as biogas production, manure, or animal feed. Additionally, slow decomposition can restrict timely nutrient release when used as an organic fertiliser and the mechanical removal of biomass for multiple uses often demands significant effort, specialised equipment, or repeated interventions. These factors increase operational costs and may reduce overall economic feasibility. Addressing these limitations through optimised pre-treatment methods, mechanised harvesting and integrated management strategies could enhance the efficiency and sustainability of *S. molesta* utilisation.

Conclusion

The literature reviewed in this manuscript demonstrates that *Eichhornia crassipes* and *Salvinia molesta* possess substantial and underutilised resource potential that can complement conventional aquatic weed management strategies. Across studies, *E. crassipes* emerges as a versatile biomass resource with validated applications in biochar production, biogas generation, vermicomposting, phytoremediation, bioethanol and briquette production, mushroom cultivation, fibre extraction and selected medicinal and cosmetic formulations. The rapid spread of water hyacinth and salvinia in Kerala is not just an environmental issue but a challenge that touches every aspect of life, from agriculture to community well-being. Human activities have accelerated this problem, leading to a loss of biodiversity and weakening our ecosystems natural defences. Bioutilisation offers a practical, sustainable approach that not only addresses the weed problem but also contributes to community resilience. It transforms a significant challenge into an opportunity for innovation and growth, helping to support farmers, protect ecosystems and reduce the overall ecological footprint. The synthesis of evidence indicates that bio-utilisation can significantly contribute to weed suppression, resource recovery and rural

livelihood enhancement when implemented through science-based, region-specific strategies. Advancing this approach will require coordinated research, community engagement and policy support to convert invasive aquatic weeds from ecological burdens into sustainable bioresources.

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Authors' contributions

SKR conceptualised and designed the review topic. VDVS drafted the manuscript. Proper guidance was provided by SKR, JD and SPP. VDVS, AS, MRP, ARD, KGV, AM involved in the drafting, reference collection, editing, correction of the manuscript. All authors have read and approved the final manuscript.

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