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(Review Article)

Sustainable solutions for water hyacinth invasion: Characteristics, impacts, control, and utilization

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Abstract

Water hyacinth *(Eichhornia crassipes)* is an invasive aquatic plant that has become a global issue due to its significant ecological and socio-economic impacts. This paper discusses the characteristics and impacts of water hyacinth invasion, emphasizing the urgency of effective management strategies. Various methods for harvesting and controlling water hyacinth, including physical, biological, and chemical approaches, are elucidated. Additionally, the paper highlights the potential utilization of water hyacinth for pollutant absorption and sequestration of heavy metals, organic contaminants, and excess nutrients. Furthermore, the opportunities to convert water hyacinth biomass into bioenergy sources such as biogas and bioethanol have been identified. The paper also presents the technical feasibility of using water hyacinth to produce biochar, high-quality bio-fertilizer, animal feed, and several other valuable products.

Keywords: Water Hyacinth; *Eichhornia crassipes*; Harvesting; Control; Bioproducts

1. Introduction

Water hyacinth *(Eichhornia crassipes)* is a free-floating and perennial aquatic plant, which originated from the Amazon River basin in South America and has spread throughout the world [1]. This neotropical plant, belonging to the Pontederiaceae family, has exhibited remarkable growth rates and has become a major concern globally. Beyond its native range in South America, water hyacinth can rapidly proliferate, reaching densities exceeding 60 kg/m^2 and causing the complete clogging of water bodies [2].

Water hyacinth's expansion beyond its natural habitat has been facilitated by human interventions, leading to its presence in various regions, including Africa, Asia, and North America. In fact, by 2010, it was estimated to be present in at least 62 countries. This invasive plant has been identified as one of the top 10 weeds worldwide, posing severe ecological, economic, and social challenges for the countries between 40 degrees north and 45 degrees south [3]. The uncontrolled growth and coverage of waterways by water hyacinth have resulted in the destruction of delicate ecosystems, creating a cascade of negative consequences. Furthermore, water hyacinth poses significant problems for agriculture, fisheries, transportation systems, irrigation systems [1].

Due to the extensive and detrimental consequences of water hyacinth infestations, it is crucial to implement effective management strategies. Developing a deep understanding of the invasive species' characteristics and behavior is essential in order to devise sustainable solutions that can effectively alleviate its impacts. This article explores various management strategies, the utilization of water hyacinth as a resource, and the potential economic benefits associated

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with its sustainable management to tackle the ecological, economic, and social challenges presented by water hyacinth. Overall, it covers the key aspects of addressing water hyacinth pollution while promoting sustainability and turning it into a positive outcome.

2. Characteristics of water hyacinth

2.1. Biology of Water Hyacinth

Water hyacinth, scientifically known as *Eichhornia crassipes* (Martius) Solms-Laubach, is a perennial herbaceous aquatic plant belonging to the family Pontederiaceae. Water hyacinth exhibits a range of plant heights, ranging from a few centimeters to 1m [4]. Its leaves are circular to kidney-shaped leaves with a smooth and glossy texture and can reach lengths of up to 20 cm and widths of 15 cm [5]. The leaves are attached to thick petioles filled with spongy tissue called aerenchyma, which enables the plant to float on water. Unlike other members of its family, water hyacinth remains afloat while being rooted in water bodies. The plant reproduces through stolons, which grow horizontally from the base of mature plants and give rise to daughter plants or ramets. Water hyacinth produces bisexual flowers that are purplish with a yellow center, arranged in single spikes up to 60 cm long. These flowers have the ability to self-fertilize. Water hyacinth exhibits prolific seed production, with each capsule containing up to 300 seeds that can remain viable for 5-20 years. Water hyacinth can propagate through both seed production and vegetative reproduction, with daughter plants separating from the mother plant and dispersing through various means like water currents and wind. Its rapid growth and reproductive capabilities contribute to its invasive nature [6].

2.2. Chemistry of Water Hyacinth

Freshwater hyacinth contains approximately 95.5% moisture, 0.04% nitrogen (N), 1.0% ash, 0.06% phosphorus pentoxide (P_2O_5), 0.20% potassium oxide (K_2O), and 3.5% organic matter. On a zero-moisture basis, it consists of 75.8% organic matter, 1.5% nitrogen, and 24.2% ash. The ash component of water hyacinth contains 28.7% potassium oxide (K_2O), 1.8% sodium oxide (Na_2O), 12.8% calcium oxide (CaO), 21.0% chlorine (Cl), and 7.0% phosphorus pentoxide (P_2O_5). The crude protein content, determined using the Kjeldahl method and calculated as nitrogen amount multiplied by 6.25, includes 0.72g of methionine, 4.72g of phenylalanine, 4.32g of threonine, 5.34g of lysine, 4.32g of isoleucine, 0.27g of valine, and 7.2g of leucine per 100g of water hyacinth. Furthermore, water hyacinth possesses the natural capacity to absorb pollutants, encompassing toxic substances such as lead, mercury, and strontium 90, in addition to specific organic compounds suspected to have carcinogenic properties [5, 7].

2.3. Habitat

The water hyacinth is a highly adaptable aquatic plant that can thrive in a variety of habitats. It exhibits aggressive growth patterns, particularly in response to increased temperature, higher solar radiation, and extended sunshine duration, which may be further stimulated by global warming [3]. The plant's optimal growth occurs in eutrophic, still, or slow-moving fresh water with a pH range of 7, temperatures between 28 °C and 30 °C, and an abundance of nitrogen, phosphorus, and potassium [6].However, it is tolerant of a wide range of growth conditions and can survive climatic extremes. It is able to thrive in a broad temperature range spanning from 10 °C to 40 °C. Low air humidity (15% to 40%) and high salinity can limit its undisturbed growth [2]. Similarly, it demonstrates adaptability to a wide pH range of 4-10, the reason for which it can be utilized for the treatment of wastewater. The plant can withstand drought by surviving in moist sediments for several months [8]. The plant can persist in low-nutrient waterways, endure low-moisture substrates, and tolerate acidic waters. It cannot, however, survive in salt or brackish water [9].

3. Impacts of Water Hyacinth

3.1. Environmental Impacts

Water hyacinth is recognized as one of the most prolific plant species globally and is widely regarded as one of the most troublesome aquatic plants. Its growth rate is astounding, as it can double its size even within five days. A medium-sized water hyacinth mat can comprise an astonishing two million plants per hectare, with a combined weight ranging from 270 to 400 metric tons [10]. These dense mats on the water's surface block sunlight from reaching submerged plants and phytoplankton. This leads to reduced oxygen levels in the water, affecting aquatic organisms and causing fish kills. The dense mats also hinder the natural flow of water, disrupting hydrological processes and altering the habitat structure. It also outcompetes native aquatic plants for nutrients, light, and space, leading to the loss of native flora and fauna species and disrupting the balance of the ecosystem. Further, upon the demise of the water hyacinth, its submergence and subsequent decomposition are attributed to the significant release of nutrients into the surrounding environment, resulting in increased eutrophication of the water [11].

Additional impacts on water quality encompass increased sedimentation rates within the intricate root system of the plant and elevated evapotranspiration rates from water hyacinth leaves in contrast to evaporation rates from open water [12].

3.2. Socio-Economic Impacts

Water hyacinth imposes significant socioeconomic impacts on affected regions. The presence of this invasive plant hampers access and utilization of water resources for humans and animals. It obstructs water supply intakes, hydroelectric facilities, and industrial requirements. Navigation and irrigation systems become blocked, limiting fishing activities and hindering agricultural productivity. The hydrological balance of ecosystems is disrupted as water hyacinth rapidly loses water through its leaves, resulting in increased operational costs for water supply schemes and threatening viability in arid regions [13].

During floods, the plant accumulates against structures, obstructing water flow and exacerbating flood damage. It causes blockages in irrigation channels, impacting water distribution to fields and impeding agricultural activities. It outcompetes other species, reducing biodiversity and destroying the aesthetic appeal of the affected areas. Additionally, the plant accelerates evaporation and depletes nutrients, leading to less fertile ecosystems and negatively impacting marginal farmers, exacerbating poverty in less developed regions. Water hyacinth also creates breeding grounds for disease-carrying vectors, contributing to the spread of illnesses such as malaria, encephalitis, and filariasis. The hyacinth mats attract venomous snakes, posing additional risks [14, 15]. Further, Tourism and recreational industries suffer as the presence of water hyacinth detracts from the aesthetic appeal of water bodies, limiting activities such as boating, swimming, and fishing.

4. Harvesting and Control of Water Hyacinth

Harvesting is necessary to control the spread of water hyacinth (WH), prevent its negative impacts on water resources, and restore the health of affected ecosystems. The uncontrolled growth of water hyacinth can lead to several ecological and socio-economic impacts as discussed in earlier section. Further, if the plants are not harvested within a certain time-period, they will undergo decomposition after death, depleting dissolved oxygen inside the water and leading to the release of nutrients back into the water. Therefore, harvesting should be done at regular intervals to interrupt this nutrient recycling process and maintain the ecological balance of the water system [16].

Harvesting promotes the utilization of WH biomass for sustainable purposes such as wastewater treatment, animal fodder, bio-fertilizer, biogas production, ethanol production, biochar production, and so on. Therefore, effective and timely harvesting of water hyacinth is crucial for ecological balance, water management, and resource utilization, ensuring the sustainable functioning of freshwater ecosystems. However, for a better phytoremediation effect, it is necessary to consider the appropriate harvesting period depending upon specific conditions [17].

Initially, the management strategy for water hyacinth beyond its native range was primarily aimed at eradicating the plant. The inherent challenges associated with this approach shifted the focus towards reducing the density of the plant to levels that mitigate both economic and ecological impacts. The most sustainable solution to effectively control water hyacinth beyond its native range would involve implementing large-scale plans to reduce nutrient levels. However, this approach necessitates comprehensive management and regulation of land use across catchment areas, which is inherently challenging and costly [12]

Several techniques (physical, biological, or chemical) are employed to control and manage water hyacinth depending on the scale of infestation, available resources, and specific environmental conditions [10]. However, physical methods (manual and mechanical harvesting) promote further sustainable utilization of water hyacinth, removal of nutrients, and prevent damage to the ecosystem [18].

4.1. Physical Harvesting and Control:

Physical methods of water hyacinth harvesting and control include several methods such as manual removal, mechanical harvesting, dredging, floating booms and barriers, and so on.

Manual collection is preferable for small-scale harvesting, whereas mechanical collection is more suitable for large-scale harvesting [17]. Manual harvesting involves the labor-intensive process of manually removing water hyacinth from the water surface. This method is often employed in rural areas where mechanical equipment is unavailable or unsuitable. Trained personnel use rakes, nets, or other tools to hand-pull or gather the plants, which are then manually loaded onto boats or carried to collection points.

Mechanical harvesting involves the use of specialized equipment designed to cut, collect, and remove water hyacinth from water bodies. These machines can be operated from boats and typically have rotating cutting blades or conveyor systems that scoop up the plants. Mechanical harvesting is often used for large-scale removal and can be more efficient than manual methods. Several mechanical harvesters had been designed for efficient and large scale removal of water hyacinth, including a conveyor-chopper harvester using a pusher boat, a single conveyor harvester using a pusher boat, an enlarged clamshell bucket operated by a dragline, a widescreen cleaner with moving rakes, and others [18, 19]. However, Mechanical water hyacinth (WH) harvesting involves significant expenses, and high energy consumption, and requires a fleet of water and land vehicles to transport the harvested mats.

Floating barriers or booms can be deployed in water bodies to contain and concentrate water hyacinth. These barriers create a confined area where the plants can be easily collected and removed using manual or mechanical methods. These devices consist of long, buoyant structures that are placed strategically on the water's surface to contain and concentrate water hyacinth growth. By creating physical barriers, they prevent the spread of water hyacinth to other areas and facilitate its removal. Harvesting or control efforts can be more efficient and targeted when using floating barriers or booms, leading to better management of water hyacinth infestations.

Dredging involves the use of specialized equipment to remove water hyacinth along with sediment from the bottom of water bodies. This method is suitable for situations where the plant has extensive root systems and is deeply rooted in the sediment.

Drainage of the water body and then removal of the water hyacinth is also a technique for water hyacinth control. However, the seeds will re-germinate after the re-introduction of water and the method is not technically viable for large-scale applications.

4.2. Biological Control

Biological control of water hyacinth involves the use of natural enemies, such as arthropods, to manage the weed [20]. Careful selection of control agents is crucial to ensure that they only target the weeds and closely related plants and they don't become the pests themselves. Several natural enemies have been released in different countries, with the weevils Neochetina species being the most successful. However, the establishment and spread of control agents can be slow, and complete eradication of water hyacinth is often not achieved. Biological control offers an environmentally friendly and sustainable alternative to mechanical and chemical control methods. Nonetheless, it is important to consider potential impacts on water quality and non-target species when implementing biological control measures [21]. Further research is needed to fully understand the long-term effects of biological control on water hyacinth and its associated ecosystems.

4.3. Chemical Control

Chemical control of water hyacinth involves using herbicides such as Glyphosate, Diquat, amitrole, and 2,4-D amine to reduce its population. Achieving effective and long-term control of water hyacinth through chemical means necessitates skilled operators, strict spray schedules, constant monitoring, and frequent reapplication. However, the overall cost of chemical control, including expenses related to chemicals, equipment, labor, and environmental impact, is often considered prohibitively high. Further, herbicides are non-selective and can harm non-target algae and other aquatic plants, leading to ecological impacts and deoxygenation of water. Water use restrictions may be required following spraying, impacting socio-economic aspects. Careful consideration and adherence to regulations are essential for effective and responsible chemical control of water hyacinth [12, 22].

5. Wastewater Treatment using Water Hyacinth

Water hyacinth has garnered significant attention due to its ability to thrive in heavily polluted water and its capacity to accumulate metal ions. The versatility of water hyacinth makes it a valuable plant for phytoremediation purposes. Phytoremediation of wastewater using water hyacinth can be accomplished using various methods, including phytoextraction, rhizofiltration, phytostabilization, and phytotransformation/ phytodegradation [16].

Wetland systems naturally colonized by water hyacinth can function as "nature's kidneys," aiding in the proper treatment of effluents and preserving the Earth's precious water resources by preventing pollution. This plant has been successfully utilized for the decontamination of inorganic nutrients, toxic metals, and persistent organic pollutants, further highlighting its potential in wastewater treatment [10].

5.1. Removal of BOD, COD, and Nutrients

Water hyacinth has been widely studied and utilized for the treatment of parameters such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and total nitrogen and total phosphorus.

In India, water hyacinth-based wastewater treatment systems (both pilot-scale and full-scale) have shown successful reduction of BOD, COD, and total nitrogen. The study conducted by Khare and Lal [23] over a two-year period, demonstrated the capability of water hyacinth in treating sewage water. The results from the study concluded that *Eichhornia crassipes*, exhibited high efficiency in purifying sewage water, removing 61.85% BOD, 79.61% COD, 31.72% NO_3-N, 55.5% P, and 24.5% K.

At Coral Ridge, Florida, a Water Hyacinth system has been implemented to extract nutrients from the effluent of an activated sludge plant. Preliminary results presented that water hyacinths effectively decrease the levels of suspended solids and BOD_5 below the specified average of 5 mg/l, and also lower the nitrogen levels below the required threshold of 3 mg/l [24].

Another investigation carried out at Lihong Poultry Ltd. (egg-duck farm) in Deqing County, Zhejiang Province, China, yielded 64.4% removal of COD, 23.02% removal of TP and 21.78% removal of TN. The study found that utilizing a water hyacinth system proved to be successful in treating wastewater from the duck farm, especially during the water hyacinth growing season. Additionally, the study concluded that after harvesting, the water hyacinth served as a feed option for ducks [25].

In a study conducted at a small-scale dairy in Miraj, India, the potential of water hyacinth for treating wastewater was evaluated to ensure it meets the standards for disposal into public sewers. The study was conducted with varied COD concentrations (507 mg/L to 4,672 mg/L) and HRT up to 8 days. The study found that the growth of water hyacinth is affected by the organic strength of the wastewater, with COD values higher than 2,380 mg/L significantly impacting its growth. The water hyacinth system showed the best efficiency of 70-80% for low-strength dairy wastewater (COD= 1,672 mg/L, HRT= 6 days), but its efficiency decreased for high-strength wastewater. The reaction rate parameter varied with initial COD values, increasing up to 886 mg/L and then decreasing beyond that threshold [26].

Some other results for the removal of BOD, COD, and nutrients by water hyacinth are provided in Table 1.

Table 1 Removal of BOD, COD, and nutrients by water hyacinth

S. No.	Treatment System	Pollutant removal	Reference
1.	Lab scale wetland with water hyacinth	80% BOD, 70% COD	[27]
2.	Magnetic biochar derived from water hyacinth	~96% P	[28]
3.	Constructed wetland (Subsurface flow) containing water hyacinth	87.7% ammonia, 81.4% phosphate	[29]
4.	Industrial wastewater treatment by Constructed wetland water hyacinth	83.7% COD, 67.5% nitrates, 71.6% ammonia, 90.2% phosphates	[30]
5.	Water hyacinth in cylindrical tanks of 400L capacity	82.45% COD and 84.91% BOD	[31]

5.2. Removal of Toxic Pollutants and Heavy Metals

Water hyacinth has appeared to be an efficient, cost-effective, and environmentally friendly phytoremediation technology for the sequestration and removal of heavy metals (Fe, Al, Cu, Zn, Cd, Cr, Ni, Co, As, etc.) and toxic pollutants from industrial wastewaters. Water hyacinth not only absorbs and accumulates heavy metals, but it can also tolerate their toxicity by converting them from chemically active and toxic states to inactive and non-toxic forms [7]. The roots stems and leaves of water hyacinth, all of them have the potential for the adsorption of heavy metals [11]. The water hyacinth possesses numerous polyfunctional sites that can bind to both cationic and anionic metal complexes. These sites include carboxyl, amine imidazole, phosphate, sulfate, sulfhydryl, hydroxyl, and various chemical functional groups found in cell proteins and sugars. Due to these properties, the water hyacinth has the ability to remove various heavy metals and other pollutants [32, 33].

Lu, Kruatrachue [34] examined the phyto-accumulation of cadmium (Cd) and zinc (Zn) by water hyacinth (E. crassipes). Water hyacinth treated with 4 mg/L of Cd showed the highest concentration both in the roots (i.e. 2044 mg/kg) and shoots (i.e. 13.2 mg/kg) after a period of 8 days. Similarly, those treated with 40 mg/L of Zn displayed the highest concentration in the roots (i.e. 9652.1 mg/kg) and shoots (i.e. 1926.7 mg/kg) after a period of 4 days. Lu, Kruatrachue [34] reported moderate metal accumulation capabilities of water hyacinth, as indicated by the bio-concentration factor (BCF) values of 622.3 for Cd and 788.9 for Zn. This suggests that water hyacinth has the potential to be employed in the treatment of water containing low concentrations of Cd and Zn.

In another study, samples contaminated with Hexavalent Chromium (Cr VI), collected from the quarry water storage area of Sukinda Chromite Minings (Orrissa, India), exhibited remarkable efficiency in removing 99.5% of Cr (VI) within a 15-day experimental timeframe upon treatment with water hyacinth systems [16].

Singh and Balomajumder [35] focused on the use of *Eichhornia crassipes* (water hyacinth) for the removal of phenol and cyanide from water. The plant showed successful removal rates of up to 96.42% for phenol (300 mg/L) and 92.66% for cyanide (30 mg/L) over a 13-day period at pH 8. The study also examined the effects of pH and initial concentration on the removal process. The plant exhibited a higher accumulation of phenol in the presence of cyanide, with effective pollutant transfer from the root to the stem. This research demonstrates the potential of water hyacinth for treating highly polluted wastewater.

Low, Lee [36] investigated the potential of dried biomass of water hyacinth roots as a biosorbent for basic dyes, specifically methylene blue and Victoria blue. The results showed that water hyacinth roots have a high sorption capacity for basic dyes, with maximum capacities of 128.9 mg/g for methylene blue and 145.4 mg/g for Victoria blue. As water hyacinth roots are abundant and readily available, they have the potential to serve as an inexpensive biosorbent for basic dyes.

Several researches and studies have been done to demonstrate the efficiency of water hyacinth to accumulate heavy metals and toxic pollutants. However, it is necessary to optimize the treatment process on a laboratory scale for influent concentration, pH, temperature, hydraulic retention time, and so on for better treatment results. The addition of certain microbial population and integrating the treatment process with other technology can further scale the efficiency of wastewater treatment.

Some other results for the removal of toxic pollutants and heavy metals by water hyacinth are provided in Table 2.

Table 2 Removal of toxic pollutants and heavy metals by water hyacinth

S.No.	Treatment System	Pollutant removal	Reference
1.	Magnetic porous biochar derived from water hyacinth	Cr (VI) adsorption capacity: 202.61mg/g; Tetracycline adsorption capacity: 202.62 mg/g	[37]
2.	Water hyacinth plant in 400 ml water containing Naphthalene coupled with rhizospheric bacteria	100% Naphthalene removal	[38]
3.	Constructed wetland (Subsurface flow) containing water hyacinth	74.7% Cu, 54.9% phenol	[29]
4.	Pot study with water hyacinth	Sulfadiazine antibiotic by 83.5%	[39]
5.	Industrial wastewater treatment by Constructed wetland water hyacinth	97.5% Cd, 95.1% Ni, 99.9% Hg and 83.4% Pb.	[30]
6.	Water hyacinth powder as biosorbent	66% Cd (II)	[40]

6. Bioproducts from Water Hyacinth

Water hyacinth is an aquatic plant notorious for its rapid proliferation in freshwater bodies. However, this invasive species also possesses immense potential for various sustainable applications. Water hyacinth can be harvested and transformed into valuable products such as biogas, biofuels, and organic fertilizers. Additionally, the fibrous nature of water hyacinth also makes it suitable for the production of handicrafts, paper, and textiles. By harnessing the potential of water hyacinth, we can mitigate its negative impacts and turn it into a valuable asset for sustainable development and resource management.

6.1. Biogas Production

Biogas production from water hyacinth has gained significant attention due to its potential as a renewable energy source and the environmental benefits associated with its utilization. Water hyacinth, an invasive aquatic plant abundant in many water bodies, can be utilized as a feedstock for biogas production through anaerobic digestion.

Water hyacinth has been found to have favorable characteristics for biogas production, such as high moisture content, soft organic matter, and a suitable carbon-to-nitrogen ratio ranging from 20:1 to 30:1. The C/N ratio of water hyacinth is well-suited for efficient microbial decomposition [17]. Water hyacinth offers the advantage of requiring less water compared to other biomass sources for biogas production [41]. Several studies have explored the feasibility of using water hyacinth for biogas production, demonstrating its potential as a sustainable energy resource.

Rathod, Bhale [41] experimented with anaerobic digestion of water hyacinth in a batch-type biogas plant. Water hyacinth was first chopped, crushed, and mixed with water before being introduced into the digester. Biogas production commenced four days after sealing the plant, and gas samples were analyzed using a thermal conductivity detector gas chromatograph. The analysis revealed that the biogas generated from water hyacinth contained approximately 58% methane (CH_4) and 45% carbon dioxide (CO_2). The daily measurement of biogas production indicated its potential use as a clean fuel for cooking, lighting, and water heating.

Tasnim, Iqbal [42] analyzed and compared biogas production from different biomass sources through anaerobic co-digestion. Experiments were conducted using cow manure, sewage sludge, kitchen waste, and water hyacinth as biomass sources for anaerobic co-digestion. Results showed that 1L batch of water hyacinth, cow manure, and sewage sludge produced a total of 812 ml of biogas with 65% methane content after 800 hours. Whereas, kitchen waste and cow manure yielded 335 ml of biogas with 60% methane content. The addition of water hyacinth and sewage sludge improved reaction rates, gas production, and methane content.

The Anaerobic co-digestion of water hyacinth with other organic materials, such as elephant grass and scrap by Okewale, Omoruwou [43] yielded higher biogas production, with a methane content of 62% observed in the best-performing reactor [44]. Furthermore, the digested slurry obtained from the anaerobic digestion process can serve as fertilizer for agricultural purposes.

6.2. Bioethanol Production

Bioethanol is an eco-friendly and renewable energy source obtained through the fermentation of carbohydrates and serves as a viable substitute for petroleum. The production of bioethanol from renewable biomass has a positive impact on the environment. Currently, a significant portion of the global ethanol production is derived from the fermentation of sugars [45].

Bioethanol production from water hyacinth is an emerging area of research and development. The plant's high cellulose (approximately 35%) and hemicellulose content (approximately 20%) make it a promising feedstock for biofuel production [46]. The cellulose extracted from water hyacinth has shown better enzymatic hydrolysis performance and higher reducing sugar yields compared to cellulose from other plant materials [17]. The presence of lignin in plants serves to bind cellulose molecules together and protect them from chemical degradation. However, due to its low lignin content (<10%), water hyacinth offers the advantage of easier conversion of cellulose and hemicellulose into fermentable sugars. This characteristic of water hyacinth results in a significant amount of functional biomass, making it an ideal resource for the biofuel industry [47]. The production of bio-ethanol from biomass encompasses several sequential steps, i.e. preparation of water hyacinth, pretreatment, hydrolysis, lignin separation, saccharification, fermentation, and distillation [48].

Utilizing water hyacinth for bio-ethanol production poses challenges that need to be addressed. Improving sugar yields while retaining hemicellulose content, requires suitable pretreatment methods. Determining optimal hydrolysis conditions, such as cellulose and substrate concentrations, is crucial for efficient hydrolysis. Further research is needed to optimize fermentation conditions and enhance ethanol production. The pre-fermentation hydrolysis-simultaneous saccharification and fermentation (PH-SSF) mode of enzymatic hydrolysis and fermentation has shown promising results in increasing ethanol concentration and yield. Continued research and development are necessary to overcome these challenges and fully exploit the potential of water hyacinth as a feedstock for bioethanol production [48].

6.3. Biochar Production

Biochar production from water hyacinth involves the conversion of this invasive aquatic plant into a carbon-rich material through gasification. Solar drying is necessary before the gasification process to reduce the high moisture content in the water hyacinth feedstock to below 30%. Biochar derived from water hyacinth can be transformed into higher-value products, including fertilizer, activated carbon, catalysts, conductors, furniture, and geopolymer [49]. Studies have investigated the use of treated biochar in various applications, such as adsorbents, catalysts, conductors, and electrodes. Commercial applications of biochar are being developed in industries and agriculture, where it can serve as low-quality activated carbon and a soil amendment. Furthermore, biochar can be used in wastewater treatment processes to remove contaminants and improve water quality. It has been shown to effectively adsorb heavy metals, organic pollutants, and nutrients, reducing their concentration in the water. The biochar derived from hyacinth has exhibited elevated pH levels (~9) and possesses cation exchange capacity, enhancing its ability to effectively absorb and exchange ions. This suggests that hyacinth biochar could be utilized in soils contaminated with metals for remediation purposes and to enhance soil quality [11, 50]

6.4. Compost

Composting is a controlled process for the natural decomposition of biodegradable organic matter in aerobic conditions by microbes such as fungi and bacteria into a simple and uniform mixture of humified organic matter, known as compost. The water hyacinth can be utilized on land either as surface mulch or as compost. When used as mulch, it has been found to increase the production of crops such as lady's finger (67%), potato (14%), and tomato (90%) compared to not using mulch [51]. Compared to other crop plants, water hyacinth has a short composting time of only 30 days instead of 2-3 months [7].

After removing water hyacinth from the water, it is dried for a few days and then it is combined with soil, ash, and animal manure. Chopping freshwater hyacinths into 5-cm long pieces is crucial for effective composting, as it improves microbial access to the plant material and enhances bacterial decomposition [52]. Microbial decomposition breaks down the fats, lipids, proteins, sugars, and starches present in the mixture. The mixture can be piled up for composting, with the warm climate of tropical countries expediting the process and yielding pathogen-free compost that can be directly applied to the soil. In order to minimize evaporation and nitrogen losses, such as ammonia, it is possible to place a protective layer over the compost, such as straw, grass, or plastic. One benefit of utilizing straw is that microorganisms utilize it as an energy source, effectively capturing the ammonia that would otherwise escape and fulfilling their nitrogen requirements. This compost enhances soil fertility, crop yield, and overall soil quality. Particularly in developing countries where mineral fertilizer is expensive, this approach presents an effective solution to both water hyacinth proliferation and poor soil quality [18].

Vermicomposting is a more beneficial method for managing water hyacinth due to its unique advantages. When water hyacinth undergoes vermicomposting, it becomes even more valuable as the process eliminates its ability to reproduce vegetatively after passing through the gut of earthworms. The process of vermicomposting involves the use of earthworms to break down organic matter, including water hyacinth, into nutrient-rich compost. Meanwhile, utilizing vermicompost derived from water hyacinth does not negatively impact the growth and flowering of vegetable crops [53].

6.5. Animal feed

Utilizing water hyacinth as a feed option has the potential to alleviate nutritional challenges faced by developing nations. In Southeast Asian countries, water hyacinth has emerged as a viable animal feed source. Chinese pig farmers, for instance, incorporate boiled and chopped water hyacinth into a feed mixture containing vegetable waste, rice bran, copra cake, and salt. Similarly, in Malaysia, water hyacinth is cooked with rice bran and fishmeal, combined with copra meal, and used as feed for pigs, ducks, and pond fish. The inclusion of water hyacinth in the diet of ducks has exhibited an increase in egg weight, subsequently leading to an increase in eggshell weight. Channel catfish fingerlings' growth has been enhanced by incorporating dehydrated water hyacinth into their diet. When biomass is dried under the sun, it has been discovered to possess abundant protein, vitamins, and minerals, making it a valuable feed source for nonruminant animals, poultry, and fishery industries. With its high crude protein content (18%) and low acid detergent fiber (33%) content, water hyacinth holds promise as a potential roughage source for ruminant animals [5, 7].

It has been observed that 30% of the bean straw can be replaced with hay derived from dried water hyacinths for feeding sheep without any negative impact on growth rate. However, the presence of air-filled intercellular spaces in water hyacinth stalk tissues can lead to excessive water consumption by animals, reducing the nutritional value of their rumens. To overcome this issue, the hyacinth should be chopped, and the solid and soluble components should be separated by pressing and centrifuging and then washed with acid-soluble calcium oxalate before processing it into animal fodder [54].

6.6. Other Products

Water hyacinth offers versatile applications beyond its use as phytoremediation, biofuel, compost, and animal feed. The plant's stem fibers can be utilized to make ropes, baskets, and high-quality paper when combined with waste paper or jute. Small-scale papermaking projects have been successfully implemented in countries like the Philippines, Indonesia, and India. Additionally, the plant's potential as a pulp to produce greaseproof paper has been investigated successfully. Water hyacinth can also be employed in the production of fiberboards for roofing material and indoor partition walls. The technology of briquetting charcoal dust obtained from the pyrolysis of water hyacinth offers another avenue for its extensive utilization. Furthermore, water hyacinths can be transformed into furniture and handicrafts, as demonstrated in India, Thailand, China, and Indonesia. While challenges remain in terms of material quality and processing, there is potential for the development of durable and aesthetically pleasing furniture and domestic goods from water hyacinth [5].

7. Conclusion

Overall, the sustainable management and control of water hyacinth are essential to mitigate the significant ecological and socio-economic impacts resulting from its rapid proliferation. Various manual, mechanical, chemical, and biological methods can be employed to harvest and control this invasive species, each with its advantages and limitations. However, it is crucial to consider the most appropriate approach based on specific circumstances and environmental considerations.

Additionally, by harnessing the pollutant removal capabilities of water hyacinth, it can be effectively utilized in wastewater treatment systems, contributing to sustainable water management practices. Furthermore, the plant's rapid growth can be leveraged to generate renewable energy in the form of bio-gas and bio-fuel, reducing reliance on fossil fuels. Converting water hyacinth into compost and mulch can enhance agricultural yields, while utilizing it as animal feed can reduce feed costs and maintain nutritional value. Water hyacinth biomass can also be utilized for the production of paper, yarn ropes, and various handicraft materials.

By promoting the sustainable utilization and management of water hyacinth, we have the opportunity to transform this global menace into a valuable resource. Through effective control measures and exploring its potential applications, we can significantly reduce its negative impacts and pave the way for a more sustainable future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest for disclosure

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