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Appraising the Control and Benefits of Water Hyacinth (*Eichhornia crassipes* [Mart.] Solms)

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Abstract: In this review, the available management technologies for the water hyacinth (WH) menace were first appraised. In this case, the mechanical (physical), chemical, and biological options were investigated regarding their respective merits and demerits. Although the chemical option is effective, it was observed that it is not as benign as the biological option, which is considered the green technology for WH control. Further, the numerous benefits of WH were evaluated. These include agricultural, biochemical, chemical, industrial, and environmental benefits. WH's energy and water purification potentials (regarding extraction of biogas, bioethanol, and biodiesel) have surpassed other research areas into the use of the macrophyte due to the ongoing demand to satisfy global energy and water needs. Overall, the once-considered blatant environmental hindrance is now being cultured and managed to provide many benefits for human and animal survival.

Keywords: water hyacinth; control; phytoremediation; economic benefits; aquatic macrophytes.

1. Introduction

The water hyacinth (Eichhornia crassipes, referred to WH hereafter) is a perennial, herbaceous and invasive aquatic plant species of the family Pontederiaceae [1]. It originated from the Amazon basin in Brazil. Due to its rapid growth rate, propagation, and invasive characteristics, the plant spreads rapidly across Africa, Asia, Australia, and North America, facilitated by human activities from ballast water exchange during shipping [2]. However, it is a plant of great ornamental value used in gardening because of its beautiful flowers, smooth and glossy leaves. Despite these merits, the World Health Organization (WHO) listed it among the 100 International Union for Conservation of Nature (IUCN) most dangerous species due to its socio-economic aftermath [3].

The major problems caused by WH result from its rapid growth rate, ease of propagation, and its ability to compete with other aquatic plants successfully. These features initiate rapid multiplication of its biomass on the surface of various aquatic habitat with low salinity content, often interfering with water resource use and management. The primary problems associated with WH include interference with waterway transportation, natural water flow, recreation, and severe damages to hydroelectric systems [3]. The highly dense monoculture WH forms lower dissolved oxygen levels in waters, thereby reducing the productivity of the aquatic ecosystem [4]. It is also responsible for increasing the spread of diseases, such as malaria, in developing countries. During the peak infestation period, WH hosts crocodiles and snakes [5], making the waterways less secure for humans.

Aquatic macrophytes, such as WH, water lettuce, and duckweed, play an essential role in maintaining the aquatic ecosystem [6]. Emerging cost-effective and eco-friendly technologies for purifying wastewater before discharge into various water bodies are now a global interest theme. Specifically, there is growing interest in the potential use of some aquatic plants for wastewater purification and the use of resulting biomass to produce energy, fish feed, fiber, and other products [6,7].

Recently, Mohd Nizam *et al.* (2020) carried out a comparative study on the efficiency of five water plants (*Centella asiatica*, *Ipomoea aquatica*, *Salvinia molesta*, *Pistia stratiotes*, and *Eichhornia crassipes*) to phytoremediation three water contaminants viz. total suspended solids (TSS), ammonia nitrogen (NH_3^-N), and phosphate (PO_4^{3-}) [8]. The schematic diagram that depicts their experimental setup is shown in Figure 1, where a, b, c, d, e, and f represent *C. asiatica*, *I. aquatica*, *S. molesta*, *P. Stratiotes*, *E. crassipes*, and an experimental control prototype, respectively.

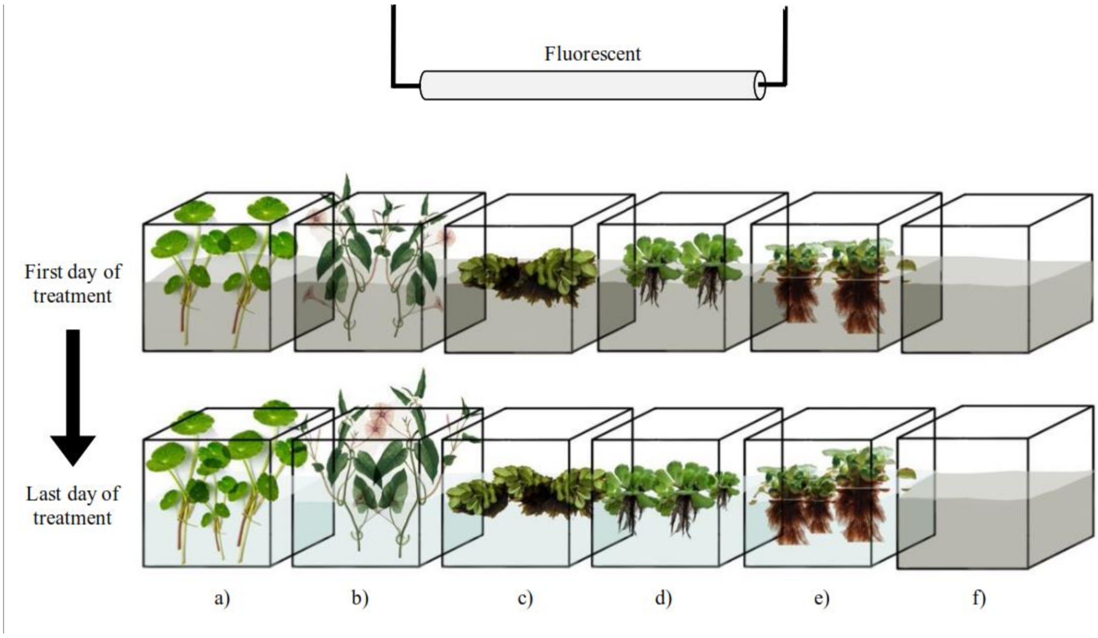

Figure 1. A schematic diagram of a study showing the phytoremediation potential of five water plants to treat TSS, NH_3^-N, and PO_4^{3-} [8].

The observed removal efficiencies (%) are listed in Table 1. Based on the target contaminants, *E. crassipes* and *P. Stratiotes* appeared to be the most efficient macrophytes amongst the group.

Table 1. Summarized performance of five water plants during a phytoremediation study [8].

Contaminant	*C. asiatica*	*I. aquatica*	*S. molesta*	*P. Stratiotes*	*E. crassipes*
TSS	90	73	96	98	89
NH_3^-N	98	73	74	78	64
PO_4^{3-}	64	50	98	89	89

The focus on WH in wastewater purification via phytoremediation is investigated because of the macrophyte's rapid growth and propagation in contaminated water. The plant's propensity to strive is driven basically by photosynthesis [9]. This technology functions based on the tendency of the water plant to assimilate the constituents in the contaminated water into its biomass. However, the contaminants could become highly toxic to the plant at excess levels [10].

Similar to land plants, aquatic plants generally require both macronutrients (such as nitrate, phosphate, and potassium) and micronutrients (such as Cu^{2+}, Zn^{2+}, and Fe^{2+}) for their metabolism [11]. Mainly, WH flourishes where these nutrients are abundant, even at excessive pollution levels. Recently, the various removal efficiencies of WH to remove excess nutrients, such as inorganic nitrogen [nitrate (NO_3^-N), ammonium (NH_4^-N), and total N)], phosphorus (PO_4^-P and total P), and metal ion from polluted waters, have been documented [12-14].

Other studies have also shown that WH biomass is extremely useful in energy production (as biogas or biofuel), livestock feed production for animals, and could be consumed as a vegetable because of its nutritional and medicinal benefits. Because the WH fiber is characteristic of high tensile strength upon air-drying, it has become a major source of economic sustenance for some countries (such as Thailand, China, Nigeria), wherein the fibers are used to produce baskets, bags and sacks, mechanical structures, furniture, kitchenware, etc. Figure 2 provides an overview of WH's control measure and socio-economic benefits.

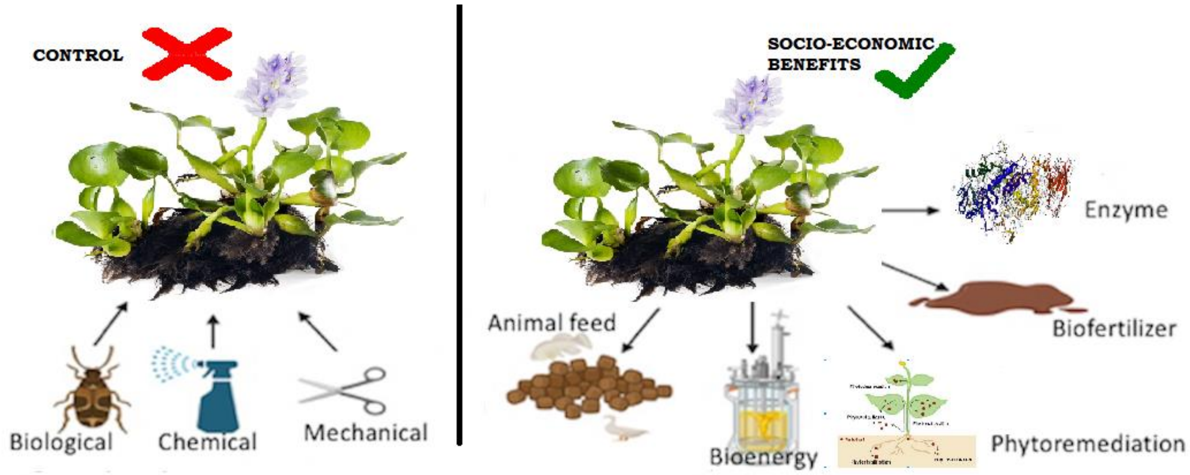

Figure 2. An overview of the control measure and socio-economic benefits of Water Hyacinth.

This current review appraises how WH can be optimally utilized environmentally, chemically, mechanically, and agriculturally in a waste-wealth approach to enhance a greener and sustainable environment. This review also considers the distribution and negative impacts of the water plant on the environment.

2. Overview

2.1. Ecological tolerance.

The growth rate and survival of WH in water are dependent on five major factors, viz. salinity, temperature, nutrients, disturbance, and natural enemies (including pathogens and allelopathy) [4,15]. The ideal growth of WH occurs in still or slow-moving fresh water under high relative humidity, long sun exposure, a water temperature of 28-30°C, and abundant availability of nitrogen, phosphorous, and potassium [16].

The plant thrives excellently in water with low salinity; It is intolerant to salinity >2 ppt [17]. In South America, WH's growth in salinities ranges from 1.3 – 1.9 ppt [18]. However, it tolerates a wide range of growth and extreme weather conditions, such as frost, although prolonged exposure to cold weather may terminate the plant while the seeds remain viable [19].

2.2. Impacts of water hyacinth.

The presence of WH on the waterways poses a severe threat to humans and hinders various economic activities. The major impacts are socio-economic and environmental. For instance, WH contains 90% water, making it highly dense for mechanical excavation [20].

Uncontrollable growth of WH on the waterways affects agricultural practices during irrigation and navigation of ships and boats during transportation and fishing. This, in turn, affects the economy of the region. For instance, in Nigeria, the Nigerian Ports Authority spends millions of naira yearly to cart WH away from her waterway to enhance smooth navigation of vessels at the ports. Similarly, millions of dollars are spent annually to spread WH under control in Florida.

Moreover, one of the environmental impacts of WH is flooding. Excessive WH growth on the waterways often gets into sewers and drainage, clogging them, leading to watercourse blockage [21]. Such scenarios could endanger human lives and property. For example, during peak infestation periods in Ethiopia, WH mat serves as a hideout for snakes and crocodiles and as a host for mosquitoes, leading to an increase in diseases such as malaria in the region [5].

2.3. Control measures.

Globally, immeasurable efforts have been made to completely eradicate WH from the waterways because of its negative socio-economic and environmental impacts on humans. Total eradication seems impossible because of its rapid growth rate and ease of propagation. Its voracious spread can only be managed but not wholly curtailed. Available techniques to control the WH bloom can be categorized into mechanical, chemical, and biological methods [22].

2.3.1. Mechanical method.

The mechanical method involves in situ cutting and carting out of WH from the waterway using hand or machinery [23]. It is the most efficient non-polluting method of controlling WH because the plant is retrieved from the waterway, unlike the chemical and biological method where chemical and biological agents are introduced. However, the process is more laborious than others, advantageous because of its beingness, and requires no specific expertise. Besides the financial implications for offsite disposal of cut WH, this practice results in a huge mass of decomposed bodies that deplete the dissolved oxygen (DO) in the water, thereby altering the livelihood of the aquatic species [20]. However, because WH thrives in the DO depleted environment, new WH's subsequent growth is catalyzed, especially because of the nutrient and carbon imbalance caused by the decomposed parts [24].

2.3.2. Chemical method.

This control option requires some expertise, and it is more laborious and cost-insensitive than the mechanical technique [20]. The use of fine chemicals and herbicides to control the WH biomass on the waterways has been practiced for many decades. However, they are often associated with aftermath secondary pollution [22].

Toxic, trace metals, such as Cd have been documented as efficient in truncating the lifespan of WH [25]. The plant treated dies and decomposes within two weeks [26,27]. The most widely used herbicides are chemicals such as glyphosate, diquat, and 2,4-D [(2,4-

dichlorophenoxy) acetic acid] have been the most widely used herbicides. Others include sulfentrazone, imazapyr, imazapic, metsulfuron-methyl, Imazamox, sulfosate [28,29]. They are considered effective for controlling WH. Despite the effectiveness of the various herbicides, they could cause secondary environmental problems if applied inappropriately [29]. Such scenarios could be more cataclysmic than the initial physical problems posed by WH. Besides, herbicides are less selective than the mechanical approach. Most herbicides terminate non-targ*et al*gae, disrupting the food web's foundation in the aquatic ecosystem [30].

2.3.3. Biological method.

Primary and secondary infection are two wide approaches experimented with for biological control. *Colletotrichum gloesporiodes* and *Alternaria alternata* are the two primary infection pathogens whose WH control efficiencies are driven by environmental conditions, especially dew and temperature [26]. As regards secondary infection, *A. alternata* requires 12 days to influence the spread of WH significantly. Whereas, *Helminthosporium* sp. It would take 36 days post-application to hinder the progressive population of most water plants, including WH [27]. The introduction of natural enemies to control WH is a green approach. In Africa, the popular natural enemies for WH are *Neochetina eihhorniae*, *Neochetina bruchi*, *Eccritotarsus catarinensis*, *Niphograpta albigutallis*, and *Othogalumna terebrantis*. The first two are the most widely distributed continent [28].

Because the chemical method is cost-ineffective and harmful to the environment, the biological approach is considered a more cost-effective and eco-friendly technique. Two South American weevils, *Neochetina Eichhornia* and *Neochetina bruchi*, have been widely used and efficient in Australia, Asia, and Africa [29]. The limitation of this method is the time it takes to achieve the desired control. For instance, it takes about 2 to 4 years to achieve control in the tropics, as it is influenced by climate, level of infestation, and water nutrient level. Elsewhere, some fungal pathogens bearing mycoherbicide capability (such as *Sclerotinia sclerotiorum* and *Cercospora rodmanii*) have been identified on the body of diseased WH [28]. These pathogens are the only commercially available mass application to control WH on our waters.

3. Benefits of Water Hyacinth

The benefits are WH are enormous. Many researchers have carried out several laboratory experiments on every part and extract of the plant.

3.1. Environmental benefits.

Conventionally, physical, chemical, and biological methods have been used to reduce the concentration of contaminants in wastewaters to the environment tolerance range before discharge into the environment [31]. Phytoremediation is a biological method for mitigating pollutant concentrations in contaminated soils, water, or air using plants (such as phytoaccumulators and hyperaccumulators) to contain, degrade, or eliminate toxic metals pesticides, solvents, explosives, crude oil, and other water contaminants [32]. Phytoremediation is more environmentally friendly, accessible, and affordable than other methods. It is an effective and promising technology, applicable globally without sophisticated machinery or human expertise.

Some of the aquatic plants used in phytoremediation include WH, water lettuce, and duckweed [13]. WH is arguably the most promising phytoremediator of the aquatic plants due to its rapid growth rate, wide tolerance range, and extensive root system [33-35]. WH is useful for the remediation of water contaminated with heavy metals and radio-active elements via root uptake. For example, WH has effectively remove Fe, Mn, Cd, Al. Cu, Mo, and Zn from moderately contaminated water bodies. Its enormous biomass production rate, high tolerance to pollution, and high absorption capacities for toxic metals and nutrients qualify it for use in wastewater treatment ponds [33]. However, so far, there are yet any commercialized or large-scale applications of this phytoremediation.

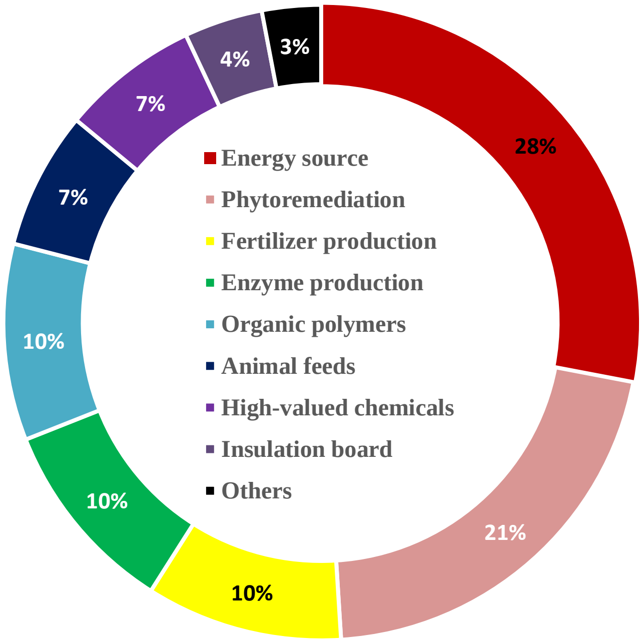

Figure 3. Percentage distribution of several uses of water hyacinth.

Studies have shown that WH can clean up various contaminated waters [36-38]. It can be used to treat wastewater from dairies, tanneries, sugar factories, pulp and paper industries, palm oil mills, distilleries, etc. [39]. The plant can phytoaccumulate trace metals in major concentrations from the water columns and flourish in waters laden with organics and nutrients [39-41]. In some lagoons in Nigeria (such as Ologe Lagoon), WH has been reported to absorb the toxic metals in the lagoon, even at trace levels [42]. In California, WH leaf tissue was found to have the same mercury concentration as the underlay sediment, suggesting that plant harvesting could help mediate mercury contamination [24]. While WH's capacity to absorb nutrients makes it a potential biological alternative for treating agro-industrial wastewater, properly disposing of the vast amount of plant materials, which may have to be considered toxic waste, remains a challenge for environmentalists.

The root structures of WH (and other aquatic plants) provide a suitable environment for aerobic bacteria to function [21]. Aerobic bacteria feed on nutrients to produce inorganic compounds, which nourish the plant. The flourishes can then be harvested to provide rich and valuable compost. WH has also been used to remove or reduce nutrients, trace metals, organic compounds, and pathogens from water [1].

It is established that WH has an exceptional ability to absorb toxic metals. Elsewhere, Woldemichael *et al*. (2011) stated that WH can assimilate trace elements and metals, some of which were essential metals for the growth of the plant and aquatic weed [43]. Macronutrient-laden wastewater often enhances plants’ removal of toxic metals from a solution. Similarly, WH can phytoremediate essential metals such as K, Fe. Mg, and Ca [44,45]. Also, the plant could be used to treat domestic sewage by reducing the biological oxygen demand (BOD) and chemical oxygen demand (COD) by 89% and 71%, respectively.

3.2. Material benefits.

Although WH is seen in many countries as a weed and is responsible for many problems, many individuals, groups, and institutions have turned the problem around and found useful applications for the plant in several waste-to-wealth schemes.

The plant has fibrous tissue and a high energy and protein content, which can be used for various useful applications. Some plant uses have been developed, and others remain in their infancy or remain as ideas only [46]. WH is useful in producing paper. For instance, the Mennonite Central Committee of Bangladesh has been experimenting with paper production from the water plant for many years. Two huge projects for papermaking, using WH stems as stock material, have been established. The plants blend waste paper or jute with WH to improve the quality of the final product. Usually, the pulp is spiked (in stoichiometric quantities) with bleaching powder, $CaCO_3$, and Na_2CO_3 prior to the thermal treatment in the production [31].

Similarly, WH is used in the production of fiberboards for various end uses. Many researchers like the House and Building Research Institute in Dhaka have experimented on fiberboard production from its fiber and other indigenous materials. The plant was used to manufacture a local fibreboard for general-purpose use and manufacture a bituminized board for low-cost roofing material [42]. The physical properties of the board produced with WH are sufficiently good for use on indoor partition walls and ceilings.

The fiber from the WH plant stems can be used to make rope by allowing the shredded lengthways stalk to dry after several days, similar to making jute rope. Both materials are used for making local furniture, whose finishes are characteristically elegant and durable. In the Philippines, a properly dried stalk of the macrophyte is used to make baskets and matting for domestic use. The stalks are properly dried (zero moisture) to avoid quick rot.

3.3. Chemical and biochemical benefits.

Extracts obtained from WH tissue portray potential use. For instance, Adelodun *et al.* (2020) assessed the organic components of WH using the GC-MS analysis of the plant extract [11]. In conclusion, they found oleic acid (35.5%) as the most dominant organic component of the plant. This acid is an excipient in pharmaceuticals and an emulsifying or solubilizing agent in aerosol products. It has been opined that oleic is causative of olive oil's hypotensive (or blood pressure reducing) effects [47]. Elsewhere, the potential of WH as a valuable biomass source of levulinic acid, an essential building block used in the synthesis of several organic compounds, was carried out by another group of scientists [48]. In their research, they carried out acid-catalyzed hydrolysis of the macrophyte at varying temperatures (150 and 175 °C), sulphuric acid concentrations (between 0.1 and 1 M), and WH intakes (1 and 5 wt %). The highest yield of levulinic acid was 53% (mol/mol) based on the available C6-sugars of the fresh WH or 9 wt% based on the dried sample.

3.4. Energy benefits.

Energy generation via biofuels (such as biogas, biodiesel, and bioethanol) has become a viable alternative measure to minimize greenhouse gas (GHG) emissions to mitigate climate change and address energy insecurity within the transport sector. Utilization of WH for bioethanol production has been a proposed alternative because of its potential to produce a lignocellulosic substrate with high hemicellulosic (44.68 ± 0.39%, w/w) [49,50]. To extract bioethanol from WH, the process of conversion follows the sequence: pretreatment, enzymatic hydrolysis or acid/alkali hydrolysis, fermentation and/or saccharification or simultaneous saccharification, and distillation [51]. Elsewhere, Das and co-workers evinced bioethanol production through WH bioconversion [52]. Their research attempted using various pre-hydrolysis treatment methods, using various dilute acids, alkali, thermal treatment, or combinations of two of the three methods. Also, varying fermentation time (h), fermentation pH, and Saccharomyces to Zymomonas (fermenting agents) ratio were considered. Enzymatic saccharification of pretreated WH was done at different levels of cellulase, ranging from 10 to 30 FPU/g. Also, the pH and temperature were varied from 4.0 to 8.0 and 40 to 55 °C, respectively, while the solutions were agitated on a rotary shaker at 100 rpm for 48 h. Their research findings showed that the sugars production was optimized at 50 °C, pH range of 5.0–5.5, and with 5 % substrate concentration and 30 FPU/g enzyme loading. Further, ethanol was produced via the response surface method. The ethanol production was optimized (13.6 mg/ml) at a fermentation time and pH of 37.7 h and 6.41, respectively, while keeping the ratio of Saccharomyces to Zymomonas as 1 [52].

A year later, another group of researchers evaluated biofuel (biodiesel and bioethanol) production and other biochemical compounds, including pigments and glycerol from non-edible WH [53]. They informed that WH showed variable lipid contents (6.79–10.45%), which by transesterification produced biodiesels (3.22–6.36%) and sediment (pigments+glycerol). To evaluate the efficiency of biodiesel produced from the plant, recent research exploited different biodiesel blends of WH (10%, 20%, 30%, 40%, and 100% on a volume basis) with neat diesel fuel on the performance, combustion, and emission characteristics of a diesel engine [54]. Their findings inferred that WH-derived biofuels and their blends possessed a lower level of hydrocarbon, CO, and smoke emissions, and 20% WH-based biodiesel and 80% diesel fuel blend can be used as a potential alternative feedstock for future diesel engine applications.

3.5. Agricultural benefits.

In agricultural practices, WH can be used as compost, bio-fertilizer, or feed for animals. The water plant has substantial agricultural benefits because it is rich in protein, vitamins, and minerals when fresh and sun-dried [55]. It is used as a high-quality feedstock for some non-ruminant animals, poultry, and fishery if not primarily used to remove trace metals or toxic substances from wastewaters [40]. Decomposed WH can also be used as green manure or as compost that improves poor quality soils [42].

In China, pig farmers boil chopped WH with vegetable waste, rice bran, copra cake, and salt to make a suitable feed. In Malaysia, fresh WH is cooked with rice bran and fishmeal and mixed with copra meal as feed for pigs, ducks, and pond fish. Similar practices are used in Indonesia, the Philippines, and Thailand. Because of its high water and mineral contents, its direct consumption by animals, especially ruminants, is mere [56]. However, when the fibrous content can be concentrated and made suitable for the animals (especially cattle), WH as animal feed could mitigate against the nutritional problems faced by the developing countries. Similarly, humans cannot directly consume the water plant because of its excessively high alkalinity (pH >9) [57].

4. Conclusions and future prospects

Water hyacinth (WH) is arguably the most researched floating water macrophyte. This could be attributed to ubiquitousness, high environmental tolerance, tough fibrous stem, chemical composition, among other intrinsic potentials and benefits. Recent research into the plant's benefits is revealing its enormous inherent potentials, thereby reorienting humans' outlook about it as a waterways menace. However, in some cases, its control is imperative. Biological control has sufficed as the most benign and green option in this case. Of its numerous benefits, it is opined that WH's wastewater purification and energy potentials (regarding extraction of biogas, bioethanol, and biodiesel) are presenting attracting more research and investment than other areas due to the imminent need to satisfy the ever-increasing global energy and water demands. Consequently, water hyacinth, the once considered environmental enemy of the coastal regions, is now cultivated to provide many benefits for human and animal survival.

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Conflicts of Interest

The author declares no conflict of interest whatsoever.

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