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Chapter

Invasive Water Hyacinth Challenges, Opportunities, Mitigation, and Policy Implications: The Case of the Nile Basin

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Abstract

Many lakes and rivers all over the globe are experiencing environmental, human health, and socio-economic development issues due to the spread of invasive water hyacinth (WH) weed. WH is regarded as one of the world's most destructive weeds and is nearly impossible to control and eliminate due to its rapid expansion and ability to double its coverage area in 13 days or fewer. However, most people in developing countries appear to be hoping for a miraculous cure; there are none and never will be. In this regard, this chapter aims to give an insight to raise awareness, research its biology and challenges, management options, and potential prospects on integrated control-valorization and its policy implications. WH biomass has demonstrated potential as a biorefinery feedstock for bioenergy and biofertilizer production, heavy metal phytoremediation, handicraft and furniture making, animal feed, and other applications. As a result, large-scale integrated control and valorization is an economically viable strategy for preventing further infestation through incentivizing WH control: providing a sustainable environment, increasing energy mix, increasing fertilizer mix, increasing food security, reducing GHG emissions, boosting socio-economic development, and creating new green jobs for local and riparian communities. Therefore, it is a leap forward in addressing global sustainable development goals (SDGs) through the water-energy-food-ecosystem (WEFE) nexus.

Keywords: water hyacinth, integrated control, valorization, economic feasibility, WEFE nexus, policy implications

1. Introduction

Invasive aquatic weeds such as water hyacinth (WH, *Eichhornia crassipes*, 'Emboch' in Ethiopia) pose a severe threat to the environment, human health, socio-economic development, and access to clean water around the world [1]. WH is found in the tropical and subtropical regions (see **Figure 1**). The first appearance of this

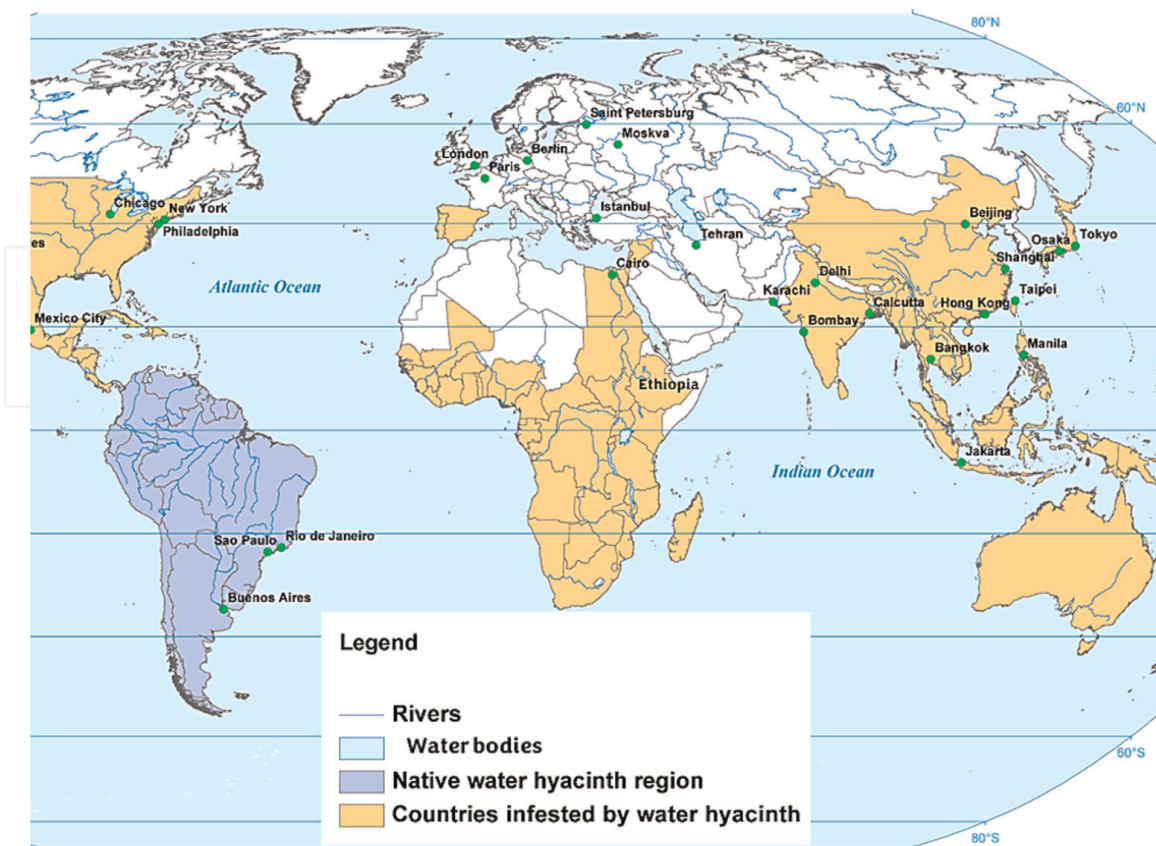


Figure 1. Worldwide spread of WH; current and future potential spreads (adapted from [2]).

species comes from the Amazon basin in Brazil and dates back to 1816. Subsequently, it was introduced as an ornamental plant to North America at the end of the 1800s [3]. It first appeared in Africa in the early 1900s and in Europe in the 1930s [4]. Known for its rapid spreading rate and noxiousness, WH has been reported to be able to double its coverage in an average of 13 days, allowing plants to cover a wide range of water surfaces in a short period of time [5, 6]. The term “noxiousness” indicates that WH has severely damaged the water bodies due to its biology and function in aquatic ecosystems.

The magnitude of the invasive WH weed problem has increased exponentially nowadays over the different water bodies in East Africa [1, 7]. Most water bodies in Ethiopia such as the Abay River Basin (Lake Tana and the Blue Nile), the Awash River Basin (Koka Lake and Koka Dam), the Baro-Akobo River Basin (Sorbate, Baro, Gillo, and Pibor rivers), the Rift Valley Basin (Lake Ellen, Lake Elltoke, and Lake Abaya), and many other parts of East Africa have been attacked by this noxious weed [8]. These water bodies are located in the Nile Basin, and contribute 90% of the Nile’s water [6, 9, 10]. However, WH is creating severe adverse impacts on these water bodies’ ecosystems and causing problems in navigation, which strongly affects the daily life of the local population and riparian communities [7]; interrupts hydro-power generation systems, causes high water losses through evapotranspiration, and blocks turbines [11]. There are also other health issues, such as the incidence of breeding habitat for the malaria-causing *Anopheles* mosquito and other disease vectors [6, 12]. Fishermen, especially related to women fish sellers, have seen a considerable drop in their earnings [6, 13]. Another issue is irrigation system blockage, farmers

that rely on irrigation water must spend a significant amount of time cleaning their water canals [11]. The previous attempts to biologically remove WHs or use chemicals to destroy them have been either economically infeasible or environmentally destructive [8, 13]. The alternative is to seek technology that encourages the valorization of this invasive plant, so its eradication will result in some cashback and, as a result, environmental benefits, incentivizing WH control by generating sustainable income [14–16].

Various studies have been conducted in this regard, and various scholars have evaluated the potential use and economic benefits of converting WH weed biomass into value-added materials via physical control (both manual and mechanical harvesting) mechanism and valorization. These include natural fertilizer substitutes [17], industrial raw materials for composite and biopolymer production [18], handicrafts and furniture production [19], non-conventional protein sources for animal feed [20], phytoremediation capacity to deal with toxins and heavy metals [21, 22], and biorefinery feedstock for bioenergy (fuel briquette, biogas, and bioethanol) production and others [6, 15, 16, 23–31]. Nonetheless, in the local context, there are some challenges confronting the control of WH weed infestation through valorization techniques such as lack of community awareness, lack of a constituted body to enforce control programs and integrated valorization projects, the absence of a comprehensive and suitable policy framework, and high amounts of effluents released in the water bodies leading to eutrophication [6, 9, 16].

This chapter intended to review and highlight the potential applications of the invasive WH plant to recover valuable resources and assist the aquatic ecosystem's sustainability by rewarding long-term WH control through the cash generated from its valorization. It also gives an overview of WH biology, its control measures, and associated risks, as well as its socio-economic and environmental risks, prospects on various valorization options, and techno-economic benefits, to raise awareness among local and riparian communities in the Nile Basin. It also recommends policy implications and research for future legal frameworks. Therefore, through integrated control-valorization within the Energy-Water-Food-Ecology (WEFE) nexus, this assessment will build resilience on more sustainable solutions to address the harmful ecological effects of WHs, clean water issues, increased energy mix, and long-term food security. It ultimately helps to achieve the universally initiated global sustainable development goals (SDGs). As a result, Ethiopia's policymakers, the water, agriculture, and energy sectors have the potential to be driven toward the valuable resource recovery technologies from integrated control-valorization prospects.

2. Biology of water hyacinth

The WH, a large, free-floating aquatic weed found either on the surface of fresh waters or anchored in mud, is a tropical aquatic plant with attractive purple flowers, 10–15 cm wide and bright, shiny green leaves on long petioles. The mature WH consists of roots, stolons, petiole, leaves, leaf isthmus, peduncle of the flower spike, inflorescence, adventitious roots, daughter plants, and fruit clusters (see **Figure 2**) [32, 33]. The root morphology is highly plastic and fibrous, having one single main root with many laterals, forming a huge root system. Because each lateral root has a root tip, WH may exploit nutrients in a low-nutrient water body, which makes the lateral roots longer and denser at low phosphorus concentrations [33]. It can replicate both sexually by seeds and asexually by vegetative implying budding and stolen

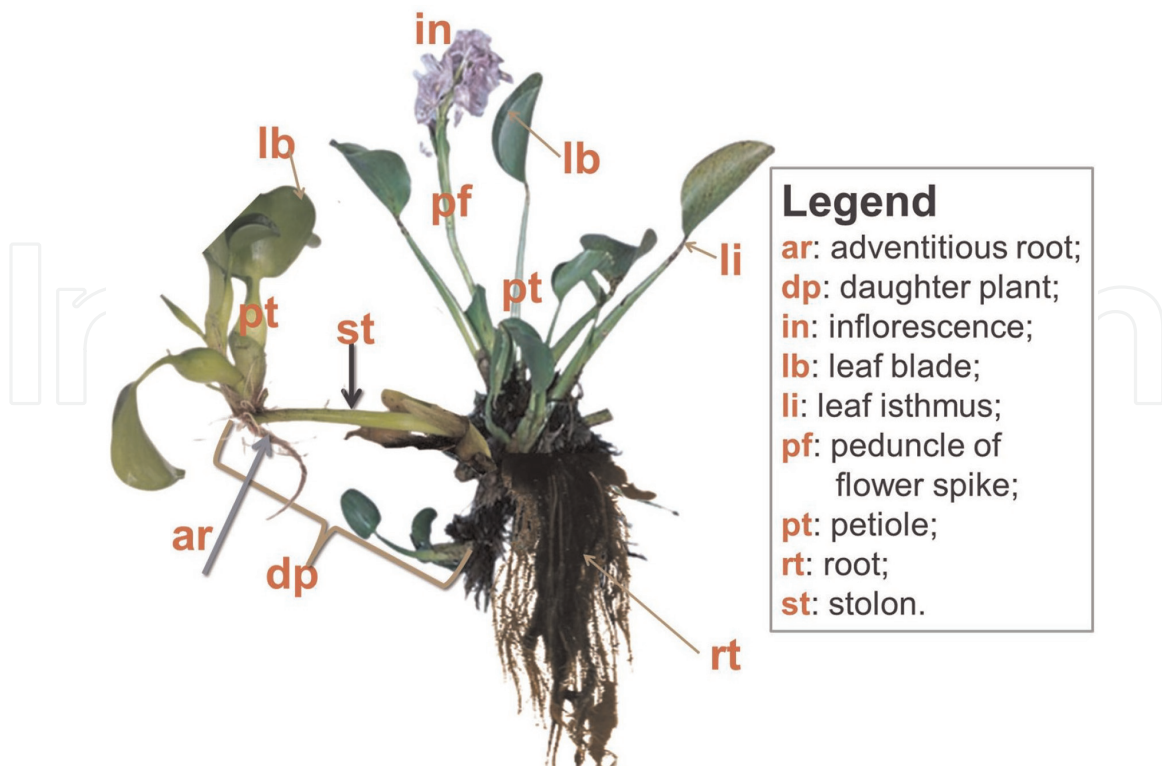


Figure 2.
Morphology of WH plants with stolons.

generation [32]. Both reproduction systems have a large production potential, within a very short period of time. The uniparental reproduction system happens through vegetative reproduction. In vegetative reproduction, 3.42 million plants can be produced in about 200 days and 43 daughter clusters of leaves in 50 days [32]. Three-parent plants can deliver up to 3000 new growing plants in 50 days, and two-parent plants can provide up to 30 offspring after 23 days. The sexual reproduction of the weed is through the production of seeds from its flowers by the agents of insects. Single WH plant can give flower in 26 days. The seed spread can be through a number of mechanisms including humans and the legs of birds [33]. Propagation by seeds may contribute to the spread of WH and can be a potent source of reinfestation [32].

Some authors report weight gains of 4.8% per day and the number of WH plants doubled on average every 13 days in a field observation [6]. It can grow most rapidly in water temperatures from 28 to 36°C [16] and at a pH from 4 to 8 [5]. They cease to grow when the water temperature is above 40°C or below 10°C, and the pH range for growth is between 4 and 10. The height of the plant can reach up to 1 m above the water surface, but its common height is 20–30 cm. The stalks are long, spongy, and bulbous. The roots are freely hanging on elongated treads with purple-black color and 2.54 cm underneath the water surface. The leaves of the weed have purple and yellow spots. Under favorable conditions, its biomass can reach up to 25 kg/m² or 300–442 tons/ha, 500,000 plants/ha, each flower can produce up to 400 seeds and a plant up to 5000 seeds [32]. In the tropics, it has been found a duplication of the population every 7 days and annual productivity of between 930 and 2900 tons/ha [34]. The seeds can live up to 15–20 years in water, silt, and mud [32, 35]. With these characteristics, the WH has become a major ecological and economic problem in this century in the tropics and subtropics [5, 16].

3. Chemistry of water hyacinth

Even though the chemical composition and characteristics of WH plants vary depending on the collecting locations and the environmental circumstances of growth sites, a WH plant can have a wide range of chemical compositions. Several studies confirmed that fresh WH plant has 95% moisture content, 0.04% nitrogen, 1.0% ash, 0.20% K₂O, 0.06% P₂O₅, and 3.5% organic matter. On a dry-weight basis, it has 75.8% organic matter, 1.5% nitrogen, and 24.2% ash. The ash also contains 28.7% K₂O, 1.8% Na₂O, 12.8% CaO, 21.0% Cl, and 7.0% P₂O₅. Through the analysis of the Kjeldahl technique, the WH plant yields: 0.72 g methionine, 4.72 g phenylalanine, 4.32 g threonine, 5.34 g lysine, 4.32 g isoleucine, 0.27 g valine, and 7.2 g leucine per 100 g crude protein (crude protein = quantity of nitrogen × 6.25) [36–39]. Furthermore, Lara et al. [40] presented the proximate analysis of the dried biomass of WH in **Table 1**.

Dry mass composition	Plant parts		
	Root	Stems	Leaves
Ash (wt %)	14.6–26.0	14.4–26.8	12.4–19.9
Alkali solubility (wt %)	54.4–55.9	48.9–52.4	51.2–51.8
Total extractives (wt %)	30.4–35.9	31.9–58.0	29.5–47.5
Runkel lignin (wt %)	8.8–13.4	5.9–4.5	11.5–14.3
Holocellulose (wt %)	23.7–43.4	11.4–40.0	17.1–36.8
Cellulose (wt %)	15.9–16.0	8.4–14.2	8.7–12.8
Hemicellulose* (wt %)	7.7–27.5	3.0–25.8	8.4–24.0
Elemental composition of WH from different plant parts (Atomic %)			
Sodium	0.67–5.80	2.01–4.43	0.68–1.51
Magnesium	0.46–16.37	5.33–6.00	3.76–7.39
Aluminum	0.25–8.84	0.27–0.82	0.03–0.21
Silicon	1.61–62.80	1.97–8.06	2.21–2.23
Phosphorus	1.81–5.99	4.64–5.12	5.87–8.61
Sulfur	1.07–5.91	0.37–2.44	0.44–2.76
Chlorine	0.71–12.20	19.43–21.47	15.93–17.44
Potassium	10.92–21.79	38.36–41.49	42.11–47.29
Calcium	5.30–28.92	15.05–20.27	16.11–23.98
Manganese	1.16–1.96	0.70–1.31	0.28–1.16
Iron	0.21–5.45	0.20–0.26	nd
Isolated primary metabolite (%) contents (mg/gdw) from different plant parts			
Carbohydrate	38.16 ± 0.102	56.33 ± 0.094	57.26 ± 0.065
Lipid/fat	2.79 ± 0.131	2.35 ± 0.187	5.22 ± 0.110
Protein	8.48 ± 0.200	5.53 ± 0.214	15.08 ± 0.084
Amino acid	1.14 ± 0.126	1.53 ± 0.082	1.67 ± 0.122

Table 1.
Analysis of dried WH biomass [39–41].

WH biomass also comprises chemical elements, such as Na, Mg, Al, Si, P, S, Cl, K, Ca, Mn, and Fe, with carbon and oxygen having the highest amounts see **Table 1** [39]. Ogamba et al. [41] also reported the composition of metabolites in WH biomass, shown in **Table 1**.

4. Environmental and socio-economic risks

Nowadays, WH weed causes major socio-economic and environmental concerns for millions of people in riparian communities and is, therefore, an added constraint on sustainable development [16, 42]. The common risks associated with WH weed are described under the following subsections and summarized in **Table 2**.

4.1 Environmental risks

WH weed distribution affects the ecological balance and changes natural diversity. These changes threaten the survival of many plants and sea-going creatures since weeds compete with the natives for food, sunlight, and space [6, 16]. This causes an imbalance in the aquatic micro-ecosystem and often means that a range of fauna that relies on a diversity of plant life for its existence will become extinct. Besides suppressing the growth of native plants and birds and negatively affecting microbes,

Problems posed by WH weed	Ent ^a	Eco ^b (%)	Soc ^c
Interference with irrigation and drainage system		x	x
Increase in disease outbreaks (malaria, cholera, etc.)			x
Less access to water points (domestic and livestock use)		x	x
Lack of clean water			x
Increase in incidence of snake and crocodile bite		x	x
Disappearance of the esthetic value of water bodies			x
Less access to harbors and docking	x	x	
Reduced fish catches	x	x	x
Difficulties in electricity generation	x	x	
Difficulties in water transportation		x	x
Difficulties in water extraction and purification	x	x	
Decline in diversity and abundance of aquatic life	x	x	
Effects on tourism	x	x	x
Decline in water quality	x	x	x
Increased water loss	x	x	
Increased siltation	x		
Increased potential for flooding	x		x

^aEnvironmental risks posed by spread of WH.

^bEconomic risks posed by spread of WH.

^cSocial risks posed by spread of WH.

Table 2. Summary of social, economical, and environmental risks of WH infestation.

WH prevents the growth and abundance of phytoplankton under large mats, ultimately affecting fisheries [16, 43]. For example, in Madagascar, many parts of the Alaotra Lake, a site of biological importance, have been reported as covered with carpets of WH that are detrimental to a number of animal species, such as the duck, *Thalassornis leuconotus*. A recent study in Lake Naivasha showed a massive reduction in the fish population due to reduced oxygen levels, which was attributed to the resurgence of WH [44]. The blockage of waterways by WH increases siltation and hinders activities like swimming, fishing, and sand extraction [1].

Large WH mats prevent the transfer of oxygen from the air to the water surface or decrease oxygen production by other plants and algae [16]. The oxygen solubility levels can reach harmfully minimum concentration for fish that are touchy to such changes. Besides, low dissolved oxygen situations initiate the release of phosphorus from the silt, which then quickens eutrophication and can prompt a resulting increment in algal or WH blooms [1]. Death and decay of WH vegetation in large masses deteriorate water quality and the quantity of potable water and increase treatment costs for drinking water [45]. People often complain of localized water quality deterioration [43]. This is of considerable concern when people come to collect water, swim, and wash.

In addition, Amare [46] pointed out that the rate of loss of water due to evapotranspiration can be 1.8 times the same rate of respiration from the water surface, but it is plant-free. This already has major impacts on the area where water is scarce. For instance, it is evaluated that the flow of water in the Nile could be decreased by up to one-tenth because of expanded misfortunes in Lake Victoria from the WH invasion [47]. Thick WH tangles also block canals, waterways, and rivers leading to hazardous flooding. This effect is more aggravated on riparian residents with little capacity to protect themselves from the flood as well as flood-associated risks [48].

4.2 Economic risks

WH infestation can exhibit numerous impacts on the fishing activities; access to destinations ends up troublesome when weed invasion is available, loss of fishing equipment frequently results when nets or lines become tangled in the root frameworks of the weed and the consequence of these issues is, as a rule, a decrease in catch and consequent loss of livelihood [44]. WH floating mats may also limit access to the breeding, nursery, and feeding grounds for some economically important fish species [16]. For instance, In lake Tana, Ethiopia, it is reported that fishermen have reduced their income, reduced fish catch, increased unemployment and reduced resource availability, increased poverty, and reduced efficiency of fishing activity [46]. It is additionally detailed, as in Lake Victoria, fish get rates to reach the Kenyan segment diminished by 45% in light of the fact that WH mats blocked access to fishing grounds, deferred access to business sectors, and increased costs of materials and effort [11]. Similarly, in Lake Naivasha, the WH infestation has been observed to have a negative impact on the economic status of the fishery community [44].

Many large hydropower schemes are also suffering the effects of WH weed infestation [49], WH causes high water losses through evapotranspiration and blocking turbines. For instance, it is estimated that the flow of water in the Nile could be reduced by up to one-tenth due to increased losses from evapotranspiration by WH in Lake Victoria [47]. Furthermore, the Tana Beles hydropower scheme on Lake Tana has suffered the impact of the weed, hence plenty of time and money has been invested to clear and prevent the weed from entering the turbines, which may cause

damage and power interruptions [11]. On the Tana Beles hydropower scheme, the WH caused damage to water coolers and generators, prompting the power utility company to switch off generators for maintenance, and about 15 megawatts of electricity were lost causing a power cut in an urban area of Ethiopia [50].

4.3 Social risks

Water issues determine life and social sustainability. Both in Africa and worldwide, WH weed infestation is interfering with agriculture by closing irrigation and drainage systems and increasing water wastage [7, 11]. WH Floating mats have a significant impact on human life by supporting living creatures that are harmful to human health. For example, in Lake Victoria, the WH free-floating roots and semi-submerged leaves and stems reduce water currents and provide more breeding habitat for the malaria-causing *Anopheles* mosquito [6, 12]. The tangled weed mat is home to snails that serve as vectors for the *Bilharzia* parasite and *Mansonioides* mosquitoes, harmful to human health. WH has additionally been implicated in possession of an agent that causes the cholera virus [1, 6, 11]. For instance, from 1994 to 2008, the state of Nyanza in Kenya suffered from cholera on the border with Lake Victoria. The annual coverage of WH on Lake Kenya has also been directly linked to the number of cholera cases reported in the state [51].

At the local level increased incidences of crocodile attacks have been attributed to the heavy infestation of the weed, which provides cover to the reptiles and poisonous snakes [45, 47]. These impacts pose, especially in the least developed countries, an additional burden on the limited health services and facilities available to the rural communities. In Ethiopia, Senayit et al. [52] reported an increase in malaria incidence and lack of drinking water, whereas during peak infestation periods, the floating weed serves as a host for snakes and crocodiles. Moreover, when the water level decreases, the unpleasant smell from decomposed WH residues disturbs the villagers. WH also impedes the recreational use of rivers and lakes. Decreased recreational and esthetic value are also among the major societal problems caused by invasive WH plants [7].

5. Existing control mechanisms and challenges

Biological, chemical, and physical (manual and mechanical removal) control, and/or an integrated approach (the use of two or three control mechanisms together) are used to eradicate WH. However, no single method seems ideal for all infested areas as suitable, and each method has its limitations and challenges [5, 53]. One of the significant components in deciding on a control approach is the uniqueness of the infested area (infestation chronology, water body uses, size, spatial arrangement, and weather) [16].

5.1 Biological control

Biological control is also one of the processes employed to remove or stop the growth of WH plants. In this mechanism, several insects, moths, fungi, pathogenic bacteria, and weevils among others have been distinguished as control agents for WH proliferation [53]. It should be noted that because of the fast proliferation rate, the major obstacle can be a long time to start such projects because it can take many years to reach a sufficiently large population to cope with pests [1].

5.2 Chemical control

Chemical control is an immediate and short time solution to remove WH using chemical herbicides. However, it greatly affects the sustainability of the water systems since it utilizes herbicides and other poisonous synthetic compounds that impact and affect sea-going life [54]. Furthermore, chemical processes for WH control are wasteful when there is generous rain [55].

5.3 Physical control

Physical methods consist of two kinds of control (both manual and mechanical removal), the most widely utilized technique for WH management. Manual removal is done by human effort, to remove the WH plants from the water bodies [5], while the mechanical removal method is carried out by machines. Mechanical removal of WH consists of using weed cutters, harvesters, chaining, shredder boats, and a dredging process. Mowing, netting, and barriers are also used as ways of mechanical removal. Physical control remains the only method through which WH can be transformed into value-added products [16]. However, the significant disadvantage of this mechanism is that it expends a great deal of energy and needs a high investment cost [56].

6. Opportunities: valorization and value-added resource recovery

Although it has a significant negative impact on aquatic ecosystems, the valorization of WH offers a variety of potential economic benefits. The plant is known for many potential industrial applications reviewed in the following sections. The summary of the selected articles on valuable material recovery from WH is presented in **Tables 3** and **4**.

6.1 Animal fodder: nonconventional source of protein

The need for food security without exerting pressure on the global land use for agricultural purposes has necessitated the search for cost-effective, accessible, and healthy supplements. Studies have shown that WH is a decent source of creature feed because of its proven protein and mineral substance accessible to ruminants [63, 64]. WH leaf protein concentrate was shown to contain valuable amounts of nutrients including 56.38% crude protein, 33% carbohydrates, and 17 amino acids [63]. Researchers have promoted the use of WH as animal feed as it has high water and mineral content, which suggests that the nutritional value may be appropriate for certain animals, it can be used to supplement protein feed and roughage [65, 66]. Its utilization for creature feed is urged in developing countries to help tackle a portion of the dietary issues [67]. Fresh WH cooked with rice grain and fish feast and blended with vegetable waste, rice bran, copra cake, and salt and copra meal is utilized as feed for pigs, ducks, and lake fish in nations like Thailand, Malaysia, China, and the Philippines [57]. Other researchers also showed the utilization of WH as dairy cattle feed [56]. Akinwande et al. [68] also, with their study conducted on three water bodies in Nigeria, demonstrated that biomass yield, synthetic arrangement, and nutritive capability of WH to be used as feed for creatures, particularly ruminants.

Valorization	Aim	Investigations	Ref.
Animal feed	Analogizing the effects of replacing Tifton-85 silage with WH silage in sheep's diets.	The protein content of WH biomass silage was 159 g CP/kg DM, compared to 63.9 g CP/kg DM in Tifton-85. Tifton-85 silage can be substituted with WH and is not toxic to sheep.	[20]
	Tilapia fish in their early stages can be fed WH leaves as an alternative protein source.	In the diet of tilapia, WH leaves effectively replaced 20% of the high-cost protein source from fishmeal and soybean meals.	[57]
Phytoremediation	Citric acid cross-linked with WH root powder was used to bioremediate total inorganic arsenic and turbidity from polluted water.	Cross-linking improved stability while decreasing turbidity. The highest adsorption capacity was discovered to be 28 g arsenic/g.	[58]
	Treatment of zinc and chromium with WH biomass from electroplating wastewater. Powdered WH leaves, petioles, and roots hold a great deal of promise.	The dry roots removed the most zinc, with 98.9%, and the dry stem removed the most chromium, with 96.4%.	[22]
Insulation fiberboard	The possible application of WH petiole in the manufacture of thermal insulation particleboard.	Because of the low lignin content of WH weed and its internal porous structure, self-supporting binder-free WH panels can be manufactured.	[19]
Biopolymers	Use of WH biomass for producing Polyhydroxybutyrate (PHB)	WH is a cost-effective option for producing sustainable biopolymer as the PHB produced was of good standard	[18]
	A report on the phytochemistry and pharmacological purposes of WH	WH Extracts have pharmacological effects. The ethyl acetate and aqueous extracts have a suitable wound healing potential on an incision wound.	[59]
Biosorbent	Use of effective microorganisms-based WH compost as biosorbent for removing basic dyes	The efficacy of effective microorganisms based WH compost to remove basic dyes were obtained as methylene blue (98.9%), malachite green (98.4%), and basic blue41 (89.1%).	[60]
	WH use as a biosorbent for removal of Cr (III)	WH removed 76.9 mg/g of Cr (III)	[21]

Table 3.

Summary of selected literature reviewed on animal feed, phytoremediation, biosorbent, insulation board, and biopolymers recovery technologies of WH.

Protein digestibility is a significant factor to evaluate the dietary quality of food; a high digestibility rate signifies high nutrients use. However, histology assessment revealed that the kidneys of the fish had degeneration of renal tubules, necrotic damage in tubular epithelial cells, and tubular lysis. There was no report of toxicity in the study of de Vasconcelos et al. [20], which was aimed at substituting Tifton-85 hay used in sheep diet with WH as the globulin concentrations were suitable. It is evident that WH is used as animal feed, however, it calls for suitable precautions procedures such as pretreatment before use to reduce its toxicity and seed viability.

Valorization	Aim	Investigations	Ref.
Briquette	Evaluating the fuel features of briquettes produced from the mixture of WH and empty fruit bunch (EFB)	The combination of WH and EFB showed a high perspective as the combustion properties: moisture content, ash content, fixed carbon content, and average calorific value is within a suitable range	[24]
	Development and characterization of charcoal briquettes from WH-molasses blend	The highest calorific value (16.6 MJ/kg) and compressive strength (19.1 kg/cm ²) with 30:70 charcoal/molasses ratio briquet was produced. Charcoal briquettes were tested for their flammable characteristics through their burning rates and ignition time	[23]
Bioethanol	Enhancing bioethanol yield from WH by integrated pretreatment method	1.40 g/L of bioethanol produced from the pretreatment of WH with microbial + dilute acid pretreatment. This was achieved without any additional cellulase.	[24]
	Evaluating the best method and the optimal conditions for fermentable sugar production from WH; these sugars were then fermented to bioethanol.	14 g/l bioethanol produced from <i>C. tropical</i> is Y-26 in the fermentation of fungal- and acid-treated hydrolysate was higher than the 6 g/l bioethanol produced from the fermentation of acid-only-treated hydrolysate.	[26]
Biogas	The potential bioenergy recovery from anaerobic digestion of WH and its co-digestion with fruit and vegetable waste (FVW)	The biogas potential of WH-FVW (0.141 m ³ /kg VS) co-digestion was 23% higher than that of WH alone (0.114 m ³ /kg VS).	[29]
	Investigation of the effects of chemical pretreatment (H ₂ SO ₄) on biogas production from WH	Cellulose was degraded during pretreatment. The optimum biogas yield of 424.30 mL resulted from the 5% v/v H ₂ SO ₄ pretreatment at a residence time of 60 min	[30]
	Comparative investigation on biogas yield and quality from anaerobic digestion of WH and <i>Salvinia</i>	Biogas production from WH (552 L/kg VS) was considerably greater (p < 0.05) than <i>Salvinia</i> (221 L/kg VS). The biogas yield is estimated to generate 1.18 kWh and 0.47 kWh energy from WH and <i>Salvinia</i> (per kg VS), respectively.	[61]
Bio-fertilizer	Investigation of the viability of utilizing WH composted with pig manure and without pig manure as a peat substitute.	For tomato seedling germination, substrates 1–3 performed well (92.0–95.3%), while Figure substrate 4 was poor (76.0%). However, substrate1 (72.5%) performed better than others in cabbage growth, with substrate4 being the lowest.	[62]
	WH as green manure for organic farming.	WH can be used as a biofertilizer when incorporated into soil increasing the performance of the wheat plant. It is revealed that both physical and chemical parameters of the wheat plant treated with WH compost had higher values as compared to control.	[17]

Table 4. Summary of selected literature review on renewable energy, biofuel, biogas, and agricultural fertilizer recovery technologies of WH.

6.2 Phytoremediation: scavenging toxic elements and heavy metals

Despite the negative impacts of the expansion of water bodies, WH can adsorb pollutants due to its polyfunctional meta-binding sites and chemical functional groups. In the use of WH for the adsorption of dye, most studies investigated the effects on cationic dyes [21, 60] with limited studies on anionic dyes [69]. In this respect, WH is an excellent choice for remediating contaminated sites because of its propensity to absorb heavy metals from wastewater [70]. WH was able to absorb and transport Ag, Cd, Cu, Pb, Sb, Sn, and Zn from an effluent waste recycling plant, demonstrating its ability to remove heavy metals from water. Nash et al. [71] tested the efficiency of WH in remediating sago mill effluent for a month at different concentrations of 20%, 15%, and 10%. Ammonia, phosphorus, and chemical oxygen demand (COD) concentrations were lowered approximately by 91–97%, 80–97%, and 86–97%, respectively. Other studies proved WH can be used to remediate heavy metals [22, 58, 71].

Because the interaction of numerous metals has yet to be defined, there have been significant differences in the degree of adsorption of heavy metals by WH; it is hypothesized that WH contains lignocellulose, which can result in the tethering of metal ions [21]. The use of WH as a biological agent for phytoremediation has been challenged because the plant has the potential to evade the chosen site and become a disturbance [69]. Along with phytoremediation, a sustainable mechanism to transform WH biomass into value-added products is required. For example, Sayago [72] designed a sustainability system in which WH is used to treat chromium-infested water, then its biomass was used to produce bioethanol. Therefore, when WH is used for phytoremediation, adequate precautions need to be accompanied as it has a terrible effect on the environment.

6.3 Handicraft materials: insulation boards, paper, rope, and furniture production

Nowadays, in the wake of global warming, bio-based building materials are becoming increasingly popular to reduce energy consumption in the construction industry. WH biomass can be professionally transformed into durable, esthetic furniture and handicrafts [67]. According to Salsa-Ruiz et al. [19] investigations, insulation boards made of WH have demonstrated their effectiveness in the construction sectors. Fiberboards (see **Figure 3**) made of WH fiber are also adequately useful for indoor partitions and low-cast roofing material due to their proven physical properties [47, 67, 73].

WH also provides a highly appealing mash that may be utilized to make a range of paper and sheets (see **Figure 3**) that are easy to produce [74]. Various studies have confirmed this; for instance, small-scale industry paper-making ventures have been fruitful in different countries, including the Philippines, Indonesia, and India [47, 67, 73, 74]. Paper made from WH stem is used for making envelopes and boxes. However, to increase the quality of WH paper, the fiber can be mixed with waste paper or jute [74].

The fiber from the WH plant's stems can also be used to produce rope; the rope-making process is like that of jute rope, used to make furniture (see **Figure 3**). However, because of the greater material quality interest and the difficulty of production procedures, using WH rope for furniture manufacturing is still challenging. In this case, the finished WH stem rope is treated with sodium metabisulfite $\text{Na}_2\text{S}_2\text{O}_5$ to prevent the product from rotting [67]. The rope, obviously, can be utilized



Figure 3.
Handcrafts: rope, furniture, fiberboard, paper, basket, and trash bin made from WH biomass.

accordingly, yet countless items, similar to those referenced above and bins/basket making (see **Figure 3**), can likewise be fabricated from it [53, 73].

6.4 Biopolymers

Several renewable resources are now being investigated for biopolymer synthesis; Because of its high cellulose content and rapid growth rate, WH has attracted interest as a potential source for cement composites and bioplastics. Salas-Ruiz et al. [19] discovered that WH root ash might be used to remediate pollutants in cement matrices as a substitute for pozzolans. These new biopolymers are highly compatible, readily available, cost-effective, and encourage waste and pollution recycling and eradication. They include polysaccharides, polypeptides, and polynucleotides [56]. WH could be used with other agricultural wastes to create bioplastic with a high biodegradability rate and replace synthetic plastics. Food packaging, hydrogels, medicine delivery, and pharmaceuticals are just a few of the applications for these biopolymers [18].

Thermochemical and alkaline-peroxide treatments were employed to obtain high-quality cellulose nanoparticles from WH stem cellulose [75]. The leaves of the WH plant are used to make silver nanoparticles. Also, environmentally friendly manufacture of platinum nanoparticles employing WH plant aqueous extracts as effective reducing and stabilizing agents has been suggested [76]. The synthesis of silver nanoparticles using cellulose extracted from WH was also achieved [77]. Nanomaterials produced from WH have been applied in wound dressings [59], biodegradable packaging films [18], and hydrogel [78]. However, more research on the WH plant's wound-healing abilities is required.

6.5 Biorefinery feedstock: bioenergy and biofertilizer production

Sustainable energy sources and organic fertilizers are essential to meet human energy consumption and agricultural needs, as hydrocarbon sources are depleting at an alarming rate [24]. WH can be explored for the production of bioenergy and bio-fertilizer due to its high hemicellulose and cellulose content, rapid growth on the water surface, accessibility to various tropical and sub-tropical areas, and quick proliferation after being gathered. WH offers many benefits as it can flourish on the water without competing for crops and vegetables [28]. Some techniques for valorizing WH biomass as bioenergy and organic fertilizer resource feedstock incorporate fuel briquette by biomass densification through mechanical conversion, biogas through anaerobic digestion; biohydrogen and bioethanol through hydrolysis and fermentation; syn-gas, biochar, and bio-oil through thermochemical conversion via pyrolysis, gasification, and hydrothermal liquefaction (HTL); and organic fertilizer creation by composting [14]. However, fresh WH biomass may contain up to 95% water, which may complicate harvesting and processing [6]. The biofuel yields from thermal processes such as combustion, gasification, and pyrolysis generally suffer from wet biomass resources, which necessitates pretreatment and dewatering [16]. As such, the scope of this chapter is limited to the biochemical and mechanical conversion of WH biomass via fuel briquette, bioethanol, and biogas production. This is based on the intention of this chapter to focus on economical benefits for rural communities, which require that approaches are less technologically complex yet economically feasible, as well as being based on local socio-economic capacity and the existing energy situation in Ethiopia.

6.5.1 Fuel briquette production

Briquetting is the densification of biomass to enhance the properties with more added values by increasing the energy density of different biomass residues [31]. The possibility of WH transformation to the briquettes has been evaluated for two decades, which was reviewed recently [73]. In terms of combustion characteristics, WH briquette showed a higher calorific value in comparison to the mangrove and firewood [79]. Carnaje [23] produced and tested the highest calorific value (16.6 MJ/kg) with 30:70 charcoal/molasses ratio WH briquette. Charcoal briquetting from WH weed is practiced by Kenyan researchers based on Lake Victoria WH biomass source and they proposed that development as a suitable technology for the briquetting of charcoal dust from the pyrolysis of WH [24]. It is suggested that a small-scale WH charcoal briquetting industry could have several beneficial aspects for the lakeside communities; for instance, providing an alternative income, source of biomass, improvement of the lake shore environment through the removal of WH, improved access to the lake and less risk to maritime transport, and reduced health risk associated with the presence of WH. It also serves as a potential alternative to firewood and charcoal, alleviation of pressure on other biomass fuel sources, such as wood, thereby reducing deforestation and associated soil erosion.

6.5.2 Ethanol production

Bioethanol is made from the fermentation of biomass and is a promising alcoholic biofuel existing in the market today because of its clean combustion. WH, because of its low lignin content is an alluring source of biomass, as cellulose and hemicellulose

are all the more effectively changed over to fermentable sugar accordingly bringing about a lot of utilizable biomass for the biofuel business [28]. Production of bioethanol from WH demonstrates that in parallel with the physical control approach of gathering and landfill, it is financially viable to deliver bioethanol from the gathered biomass [28]. Nevertheless, some studies have reported high bioethanol yield in the absence of cellulase [24, 26]. The study conducted by Manivannan et al. [80] revealed that bioconversion of WH to bioethanol using two sequential steps of acid hydrolysis followed by fermentation with *Candida intermedia* NRRL Y-981 produced a maximum bioethanol yield of 0.21 g/g with a productivity of 0.01 g/l/h. The yield can be improved by integrating low-cost pretreatments followed by fermentation with improved bioethanol-producing microorganisms and will play a critical role in making the process economically viable [16, 24].

Several investigations proposed that pretreatment of WH biomass for ethanol generation is important and requires a moderately high temperature and strong acid/alkali pretreatments given that WH has low sugar and high lignocellulose substance; thus, energy cost is generally high, making it hard to accomplish a positive energy balance [6, 24, 26, 28]. Notwithstanding its commitment to energy enhancement, the creation of bioethanol utilizing WH as a feedstock can not just control the fast invasion of WH yet can likewise add to carbon discharge reduction and water quality improvement. While the production cost of bioethanol is high, ecological qualities assume a significant job in the financial support of the generation. The coupled utilization of WH as a phytoremediation plant and bioethanol feedstock is a potential reaction to green advancement techniques [28].

6.5.3 Biogas production

Many scientists have suggested that the valorization of invasive WH plants for biogas production plays a significant role in controlling weed infestation [24]. One of the options is anaerobic (AD) digestion, which takes place in a reactor or digester in the absence of oxygen, and the produced biogas can be used as a heat source for cooking, lighting, or heat energy to provide shaft power for generating electricity [6]. In addition to biogas, digestate from the AD process is utilized as a biofertilizer for soil conditioning and mushroom cultivation media [6, 81, 82]. WH biomass contains much water, rich in crude protein, and rich in nitrogen, cellulose, hemicellulose, and other natural substances with the C:N ratio (10-30:1) [4, 6]. Due to the reliance of the AD process on the activities of the microbial consortium, the maximum yield of biogas production depends on several parameters [30, 61]. Pretreatment [6], optimization of process parameters, suitable digester design, stimulation of microbial populations, and co-digestion with other organic wastes have all been used to increase the biogas generation yield of WH biomass [29, 83].

Furthermore, WH's energy potential is significant and encouraging. According to Castro and Agblevor, 2020 [84], one tonne of fresh biomass can produce 846.5 MJ of energy, with just 6.8 percent of the total energy required for mechanical harvesting. As a result, while power is necessary to collect the WH biomass from its infested water body, the total energy provided by the biomass is more than enough to keep operations running. Annually, 50 kg/m² ash-free WH biomass can be produced, with daily biomass productivity of 0.04–0.08 kg/m² [85]. The annual energy potential of one tonne of collected biomass is comparable to 13.3 m³ biogas or 18.35–18.75 kWh electricity. Up to 75%, higher methane levels can be obtained, increasing electricity production by 25 MJ/kg [86]. That is an incredible opportunity for communities that have

been severely affected by the WH invasion and are economically dependent on agriculture to manage weeds, generate income, and profit from self-sustaining energy resources.

6.5.4 Biofertilizer

The agricultural sector is in crisis because of the lack of cheap and accessible sources of organic nutrients to sustain the growing demand for food caused by overpopulation, especially in developing countries [6]. Biofertilizers are organic material of natural origin that provides one or more nutrients essential to plants for their growth. One of the most available strategies for soil fertility remediation is the valorization of WH weeds. The presence of phosphorus (P), potassium (K), and nitrogen in the WH biomass, and the C/N ratio make it a suitable substrate for composting as a biofertilizer [86, 87].

Composting is a high-temperature aerobic microbial disintegration process that is one of the most widely used ways of producing organic fertilizer from WH biomass [47]. WH Compost is an excellent natural supplement for sandy soils due to its hygroscopic nature and high moisture retention properties [64, 86]. A study by Vedy and Girish [17] shows that the WH plant can be used as a biofertilizer when mixed into the soil, boosting the performance of wheat plants. The study included control experiments that did not employ WH compost; physical and chemical properties were studied. Physical parameters such as root length, percentage germination, shoot length, and biomass content; shoot ratios were studied. The study also assessed chemical characteristics such as chlorophyll, reducing sugar, and protein content. According to the findings, both physical and chemical metrics exhibited greater values when compared to the control.

Therefore, composting WH biomass is a potentially feasible solution for WH biomass valorization on a large scale or in a commercial setting [88]. It is also a step toward overcoming the increasing food demand caused by overpopulation, particularly in developing countries, by utilizing the cost-free sustainable biofertilizer derived from WH biomass, increasing socio-economic benefits to rural communities while also assisting in the control of the WH invasion [86, 87].

7. Techno-economic analysis via valorization of WH

Ecological and economic assessments are influenced significantly by the feasibility analysis of environmental solutions for the valorization of WH at the industrial level. The objective of WH valorization into value-added products is to use an optimistic approach to addressing the threat of WH infestation while also meeting economic and environmental benefits. The techno-economic feasibility analysis of WH valorization for value-added material recovery practiced in different countries was appraised, as indicated in **Table 5**. The economic feasibility models used were more realistic and consistent with potential changes in future cash flow and discount rates because, unlike existing control approaches, costs and revenues of valorization technologies are intrinsic. In most cases, net present value (NPV) is used, which basically uses the current discount rate to identify the monetary value and support the sensitivity of future cash flow and exchange rate changes [27, 28, 90, 91]. Also, parameters that do not take into account the time value of money, such as life cycle analysis (LCA), return on assets (ROA), payback periods, profit margin, and internal rate of return

Valorization	Country	Model	Cost (\$)	Benefit (\$)	Lifetime (y)	Discount rate (%)	Investigations	Ref.
Bioethanol	USA	LCA	—	4×10^2	—	—	The cost of collecting WH as a biorefinery source does not exceed the cost of controlling the invader, making it a competitive biorefinery feedstock source.	[89]
	China	LCA	2.76×10^7	1.60×10^8	15	10	The study looked at the economic feasibility of producing bioethanol from WH and compared it to the ongoing status of landfill disposal. The results demonstrated that producing bioethanol from WH is cost-effective and that environmental advantages play an essential part in economic analysis.	[28]
Biogas	Mexico	LCA	6.4×10^7	—	15	5	The study looked at the viability of a constructed wetland and activated sludge plant as a wastewater treatment plant and anaerobic digestion of WH biomass for biogas generation. The results demonstrated that the biogas technology developed from WH biomass valorization is feasible since it reduces GHG emissions while addressing water pollution.	[25]
	Vietnam	NPV	4×10^2	1×10^3	15	3.5	The study looked at the cost-benefit analysis of co-digesting WH biomass and rice straw as feedstocks for biogas generation. It concluded that the technology is cost-effective considering the benefits to personnel and society.	[90]
	China	NPV	2×10^5	1.9×10^6	15	6	The study looked at an opportunity to generate biogas from WH biomass, and the results showed that biogas is a cost-effective option with a positive energy balance. WH valorization for biogas production increases water quality while lowering GHG emissions.	[91]

Table 5.
 Techno-economic feasibility of WH valorization into bioenergy (bioethanol and biogas).

(IRR) are used [6, 25, 27, 92]. Various studies have used more than one feasibility model to compensate for the drawbacks of each model in quantifying and identifying costs and revenues from cost savings of valorization strategies [6, 25, 27, 28, 90–92].

The potential economic advantages of valorizing WH biomass are not intended to promote the spread of the invasive plant. Instead, they are meant to reduce the negative consequences and costs of controlling it. Bioenergy production such as bioethanol, biogas, and fuel briquettes has long been one of the most popular alternatives of WH valorization; experimentally justified and economically feasible options [6, 25]. In this regard, It is not the only sustainable solution for WH eradication; it also contributes to the energy mix, and fertilizer mix, increase food security, lowers greenhouse gas emissions, and improves water quality and livelihoods in riparian communities. Small and independent industries can utilize the new energy resources to cut their energy expenditure while utilizing the available waste streams means that no additional waste management costs are incurred. This allows communities to sustain their small industries, while local green jobs are created, eventually leading to wealth creation.

In addition, encouraging appropriate incentives for lowering feed costs, such as utilizing WH biomass, may benefit rural livelihoods that rely on livestock farming. Rural populations impacted by the WH invasion can be honored by using the plant for animal rearing, whether on a commercial or personal basis, because of the many options of employing the plant for animal feed. That could imply that controlling WH as feed could be done in a sustainable way to generate value, benefit society, and ensure long-term food security. [16, 65, 66].

Moreover, making handicrafts from WH biomass is becoming an appropriate technique to combine economic rewards and social empowerment while employing a plant that has traditionally been viewed simply as a problem [93]. The strategy can lower poverty levels associated with a lack of available jobs by creating new and green jobs for green development; to providing the community with the capacity to deal with environmental challenges. The opportunity to make biofertilizers from WH biomass should be appealing enough for affected riparian populations to use WH composting for soil amendment, which will help to ensure long-term food security [16]. As a result, WH waste can be adequately mitigated, and increased crop production will help improve the livelihoods of the local people.

8. Summary and policy implications

The rapid growth rate of WH weeds, the negative impact on the water ecosystem, and the high cost of eradication make the existing control mechanisms unattractive, so it calls for the adoption of alternative control strategies that exploit the unseen invasive WH potential valorization. WH weed could be considered a sustainable supply and biorefinery feedstock material for various value-added products rather than being perceived as an invasive noxious weed. WH weed biomass can be utilized for bioremediation and bioadsorption of different contaminants, animal feed, biopolymer, and composite material production, handicraft and furniture manufacturing, bioenergy generation, and organic fertilizer production, among other things. Techno-economic analyses have revealed that integrated valorization procedures with phytoremediation can be beneficial, particularly for more expensive valorization techniques such as bioethanol production. Therefore, the adoption of valorization techniques for widespread utilization of this noxious weed is an attractive and effective method of

addressing energy shortages, long-term food security, and economic benefits in order to incentivize the control costs by integrating with the relatively unsuccessful traditional WH weed management mechanisms. It is also a step forward to contribute to achieving global sustainable development goals (SDG) by addressing the water, energy, food, and ecosystem nexus. As a result, for practicability, sustainability, and economic feasibility of WH mitigation, the combined control-valorization techniques are more viable to be adopted locally.

For policymakers to make enlightened decisions, much more techno-economic information is required on the costs and benefits of ecosystem management programs through valorization. For instance, it is often stated that there are not enough resources to control WH. However, when the costs of improved water ecosystems are weighed against the costs of increased water-borne diseases, reduced fish catches, reduced tourism income, and increased hydropower generation interruption, the resources required for WH control are likely tolerable compared to potential losses from its proliferation. There are untapped potential opportunities for WH biomass valorization, which can subsequently cover the control costs and boost the local economy.

In addition, widespread WH valorization requires the commitment of local communities, stakeholders, and decision-makers to raise awareness among local people and riparian communities for sustainable mitigation of the WH weed impacts. Nutrient runoff from industries, sewage, municipal waste, and agricultural lands should all be monitored to ensure that they do not leak into water bodies, as they are a significant contributor to the rapid growth of WH weeds. Industries that discharge effluents into bodies of water must be required to take corrective action and pay for the harm they have induced. There should be inspection mechanisms to ensure that all industries in the country have sewage treatment plants. Also, there is a need to encourage these industries to set up new business units or incorporate the harvested WH into their existing conversion process and motivate them through combined appropriate policy and institutional plans, insurance subsidies, and tax credits.

Furthermore, since most of the affected water basins in East Africa are cross-border resources, WH infestation can be seen as a symptom of broader watershed management and pollution-related problems. It calls for a concise national and cross-border resources legal framework for control through valorization. Also, the countries sharing it should come together to draft regional legislation pertaining to WH invasive species. This will ensure that the countries come up with a unified approach to controlling these species through interagency cooperation and coordination. These countries must collaborate to boost the Nile Basin's water resources, as well as pursue a variety of multifaceted projects in which they might share resources equitably. Countries, for example, may get involved in the biorefinery sector for mass usage and transformation of WH weed into valuable resources and also rescue the Nile Basin's source from further WH weed infestation apart from subsidizing control costs.

Finally, to stimulate the implementation of valorization measures, this chapter contributes to policy and research directions on the fiscal understanding of the material recovery from WH weed biomass. It also stimulates scholars to develop new techniques for valuing the weed and research into policy frameworks.

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Conflict of interest

The authors declare no conflict of interest.

Nomenclature

AD	anaerobic digestion
CBD	convention on biological diversity
COD	chemical oxygen demand
DM	dry matter
GHG	green house gas
EEB	empty fruit bunch
FVW	fruit and vegetable waste
HTL	hydrothermal liquefaction
IRR	internal rate of return
LCA	life cycle analysis
NPV	net present value
ROA	return on assets
SDGs	sustainable development goals
WEFE	water-energy-food-ecosystem nexus

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