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REVIEW
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A Comprehensive Evaluation of the Existing Approaches for Controlling and Managing the Proliferation of Water Hyacinth (*Eichhornia crassipes*): Review

Fadoua Karouach[1], Widad Ben Bakrim[1], Amine Ezzariai[1], Mansour Sobeh[2], Mulugeta Kibret[1,3], Abdelaziz Yasri[2,4], Mohamed Hafidi[2,5]* and Lamfeddal Kouisni[1]

[1]African Sustainable Agriculture Research Institute (ASARI), Mohammed VI Polytechnic University (UM6P), Laâyoune-Morocco, Morocco, [2]AgroBioSciences Department, Mohammed VI Polytechnic University (UM6P), Ben Guerir, Morocco, [3]Department of Biology, Bahir Dar University, Bahir Dar, Ethiopia, [4]Institut National de la Recherche Agronomique (INRA), Rabat, Morocco, [5]Laboratory of Microbial Biotechnologies Agrosciences and Environment (BioMAgE), Labelled Research Unit CNRST, Faculty of Sciences Semlalia, Cadi Ayyad University (UCA), Marrakech, Morocco

The proliferation of the invasive Water hyacinth (WH) plant leads to ecological, economic, public health, and agricultural problems. Several efforts have been deployed to control its spread, but no concreate results have been obtained. Only few studies dealing with systematic approaches for the WH control have been conducted. To establish a road map for the best control methods to be adopted, this review highlights the control programs that have been tested worldwide and describes, through a deep literature analysis and comparison, the most effective and sustainable control programs for managing the proliferation of this aquatic weed. Through a critical analysis, this review evaluates the advantages and drawbacks of the main proposed control methods including biological, chemical and physical methods. The obtained results suggested that short and medium term physical control promptly manages the plant's proliferation and thus could complement the effect of the biological control. Moreover, to be economically viable, the harvested WH through physical means must be valorized to generate high value-added products. Furthermore, run-off nutrients control could reduce the end-of-catchment loads and would help the resilience of freshwater bodies and promote plant removal. Descriptive results analysis confirmed that an integrated control approach combining "biological and physical'' is the most sustainable and cost-effective approach. The adaptation of these methods based on the socio-economic context of each country, could promote ecosystem restoration, self-generation, and conservation for a sustainable development.

Keywords: Water hyacinth, Control, Valorization, Costs, Benefits, Sustainibility

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****Correspondence:***
Mohamed Hafidi
hafidi@uca.ac.ma

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HIGHLIGHTS

- Biological and physical mono-controls of WH were the most used methods worldwide.
- Mono-control approach of WH is not effective.
- Integrated Physical-Biological control (IPB) is the most used and cost-effective program worldwide.
- Integrated "Control-Valorization" approach is strongly recommended.

INTRODUCTION

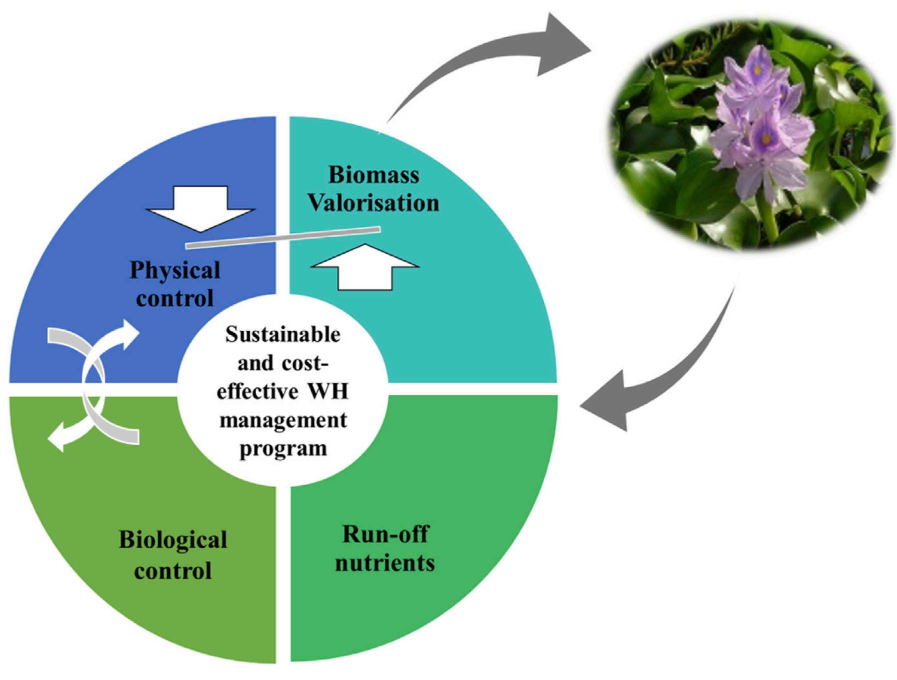
Water hyacinth (*Eichhornia crassipes*) (**Figure 1**) is commonly considered the most harmful aquatic weed in the world. The first appearance of the species dates back to 1816 in Brazil. Subsequently, it was introduced as an ornamental plant to America at the end of the 1800s (Brown et al., 2020). Its appearance in Africa was in the early 1900s, and in Europe in the 1930s (Yan et al., 2016). In Africa, WH has substantially invaded Lake Tana (Ethiopia), the largest freshwater body in the country with 3,074 km^2 surface area, thereby, negatively affecting the aquatic ecosystem. A study conducted by Dersseh et al. (2019), predicted the maximum invasion area of 30,728 ha in 2020, representing about 10% of the total surface of the Lake.

Water hyacinth is recognized by its fast-spreading rate, it was reported that 2 plants can multiply to 1,200 plants in 120 days, which allows the plant to cover large water surfaces in a short period of time (Ajithram et al., 2020). The spread of WH and its colonization of other areas, can also increase by strong winds or high waves. WH grows rapidly in highly acidic and alkaline water, but its growth is slightly observed in neutral water as well. One of the main causes of its huge proliferation is water enrichment through nutrient runoff from agricultural and human wastes (Villamagna and Murphy, 2010). It consumes high amounts of nitrogen and phosphorus under optimum growing conditions (Krisnawati et al., 2020). Nutrient concentrations and temperature (of air and water) are considered the strongest determinants for WH growth and reproduction (Wilson et al., 2005).

Water hyacinth is considered as an invasive plant species and represents various ecological and economic negative impacts (**Figure 2**). It causes deleterious damage to biodiversity, freshwater ecosystems, and native species (Tewabe and Asmare, 2020). The plant forms dense mats that prevent the penetration of light into the water, thereby, decreasing its temperature, which and inhibiting plant photosynthesis (Wilson et al., 2005). The fast distribution of WH results in the occurrence of sedimentation and causes a siltation phenomenon in water bodies (Ratnani et al., 2020). If its growth is not controlled properly, WH could have severe environmental problems.

Therefore, these plant nuisances have led to the implementation of several control programs in all fields (physical, chemical, biological). Physical control (PC) consists of directly removing the plant by hand or with appropriate equipment, while the chemical control (CC) involves the use of herbicides, and biological control (BC) means the intentional use of natural enemies of the target invasive species. These methods can be used solely or in combined (George and Goldman, 2007).

Neochetina spp. weevils have been successfully used as biocontrol agents in several countries around the world (Julien, 2001). The most limiting factor for using this type of



GRAPHICAL ABSTRACT |

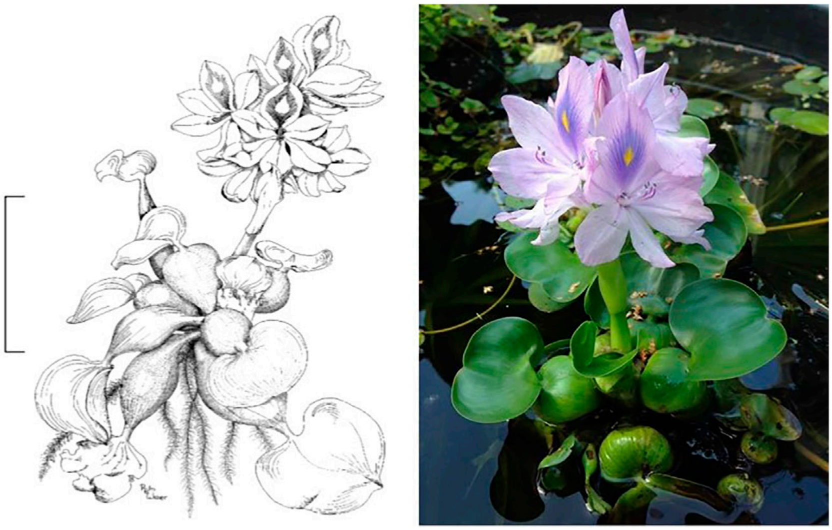


FIGURE 1 | Water hyacinth, *Eichhornia crassipes (*Martius) Solms-Laubach (Drawn by Rita Weber, SANBI). Scale bar = 10 cm.

controls is the need for a long time to achieve high performance (Abtew and Dessu, 2019). Chemical control using herbicides is very efficient to control WH (Villamagna and Murphy, 2010), but, it is unfortunately, harmful for the environment. The development of pesticide-resistant weeds may reduce its effectiveness (Kyser et al., 2021). Physical control, however, is the most ecofriendly method to remove WH from water bodies, but requires high investment (Malik, 2007). To overcome the high cost of the physical control, it is strongly recommended to valorize the recovered biomass (Mathew et al., 2015; Hernández-Shek et al., 2016; Priya et al., 2018).

Despite its high negative impact on the aquatic ecosystem, the WH presents diverse potential financial benefits (**Figure 2**). The plant is famous for many potential industrial applications. It could be used as a phytoremediation agent because of its ability to grow in wastewater and its capacity to accumulate metals, radionuclides, nanoparticles, and other pollutants (Lazim et al., 2020). Numerous studies on its capacity to purify domestic wastewater have been carried out. A study conducted by Rezania et al. (2016), proved that the plant could treat successfully domestic wastewater, and improve its purification efficiency to 96% of nutrient removal. The plant can also be used

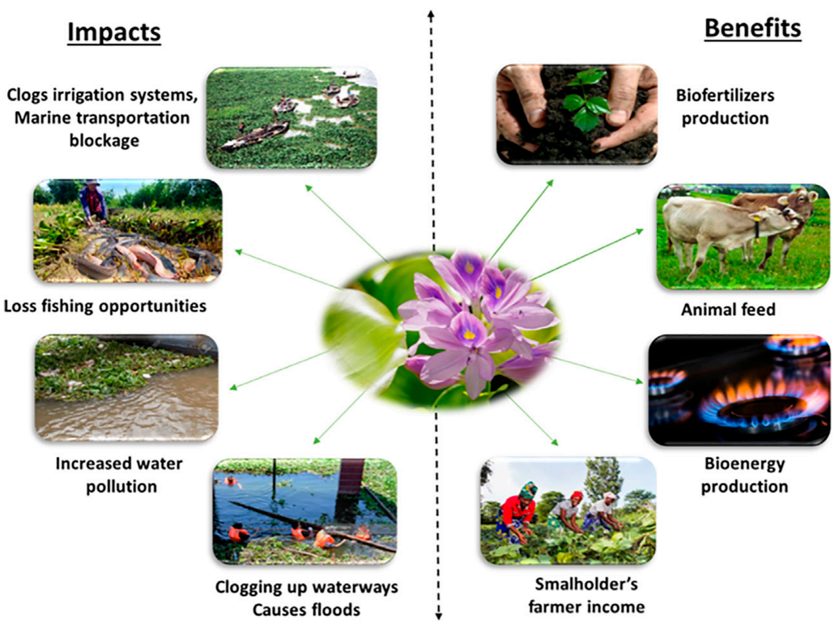


FIGURE 2 | Some of negative impacts and benefits of Water hyacinth.

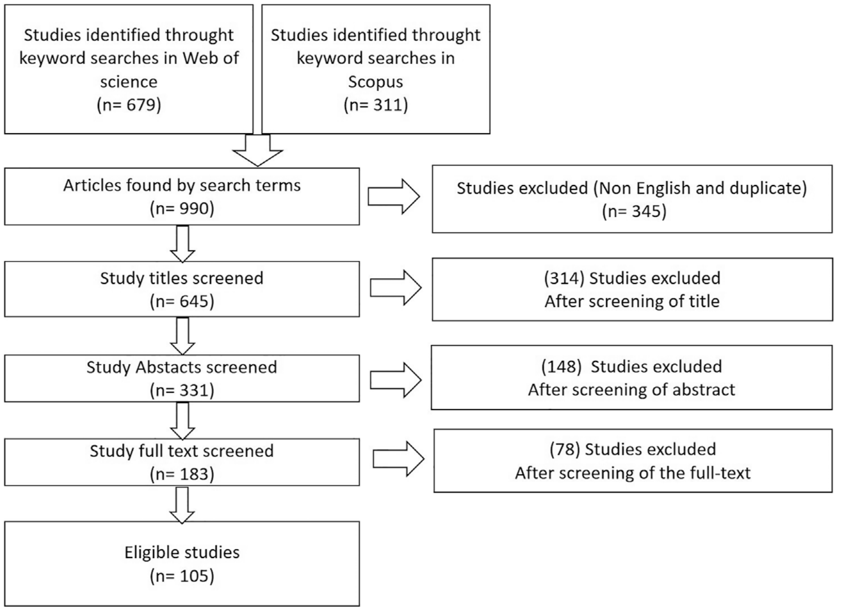


FIGURE 3 | Selection of studies for inclusion in the review [(n) the number of studies].

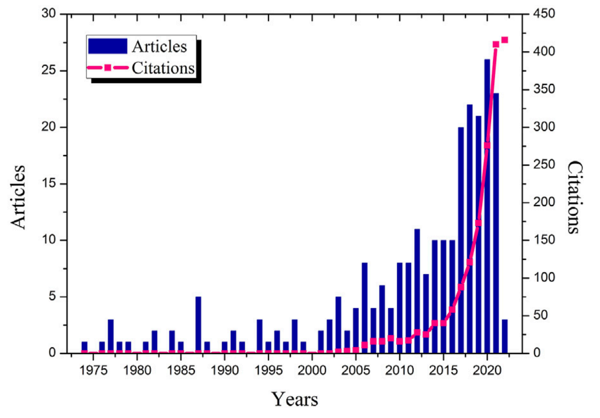


FIGURE 4 | Annual scientific production and citation.

to produce valuable products such as biopolymers fibers and composite. The biodegradable fibers of WH have proven to be an excellent way to treat wastewater via adsorption as compared to other expensive industrial technics (Arumugam et al., 2018). In addition, WH has been considered as a source of biofertilizers, animal feed and bioenergy (Jafari, 2010). It also exhibits robust biological activities including antioxidant, antimicrobial, antitumor, anti-aging, wound healing, anti-inflammatory, anticancer and antidiabetic (Kiristos et al., 2018; Sharma et al., 2020). Furthermore, WH biomass produces other valuables products such as enzymes and capacitors, and is used as a raw material to make furniture and handicrafts (Patel, 2012).

Given the complexity of the ecological system where the WH is proliferating as well as the sensibility of its habitat, the most suitable control methods must be well identified. Few literature studies have been conducted to evaluate the effectiveness of WH controlling programs. All papers published in this field described only experiences that have been adopted by the countries that faced this invasion. No study has analyzed these experiences outputs in order to identify the most cost-effective control programs.

To establish a road map for the best control methods to be adopted, this review highlights the control programs that have been tested worldwide and describes, through a deep literature analysis and comparison, the most effective and sustainable control programs for managing the proliferation of this aquatic weed. Through a critical analysis, this review evaluates the advantages and drawbacks of the main proposed control methods including biological, chemical and physical methods. In addition, this paper reviewed the most recent WH valorization pathways.

METHODOLOGY

An extensive search was conducted based on Scopus and Web of Science. The scope of the control methods research focused on published papers from 1980 to 2022, while the valorization has focused only on recent articles from 2016 to 2022. The following keywords were used: (water and hyacinth) and (control and methods); (water and hyacinth) and (biological and control); (water and hyacinth) and (chemical and control); (water and hyacinth) and (physical and control); (water and hyacinth) and (integrated and control); (water and hyacinth) and (run off and nutrients); (water and hyacinth) and (cost and benefits); (water and hyacinth) and (valorization). As a results, 990 sources of

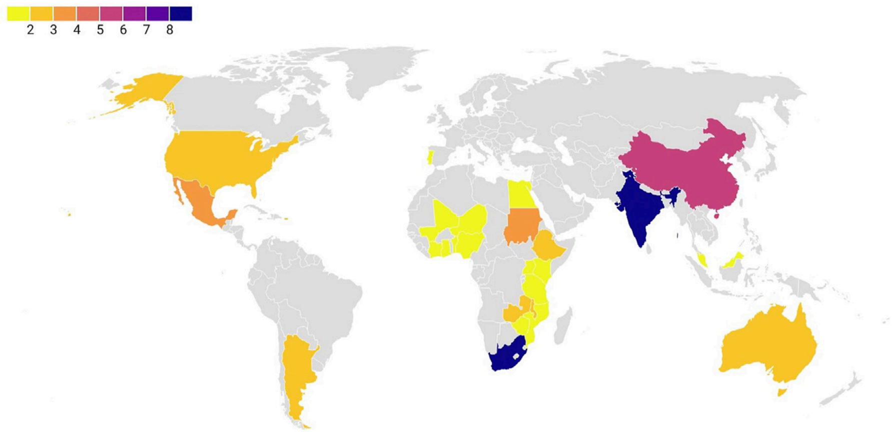


FIGURE 5 | Number of published research articles worldwide. Numbers in caption indicate the number of research articles published in the field of WH control. India and South Africa were the most frequently studied countries, followed by China.

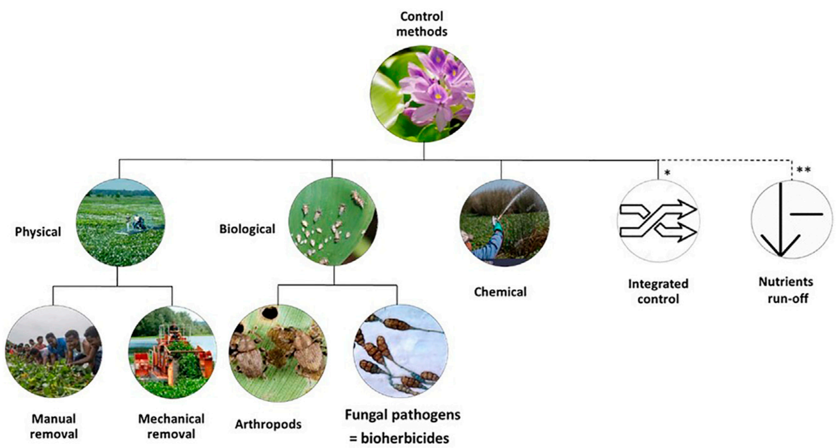


FIGURE 6 | Controlling mechanisms of water hyacinth. ***** Integrated control is the combination of two or more than one control method: Integrated biological and physical (IBP); Integrated biological and chemical (IBC); Integrated physical and chemical (IPC); Integrated physical, biological, and chemical (IPBC). ** Reduction of nutrient run-of, could be used with all kinds of control methods.

literature were identified from which 345 duplicates were removed and 105 were selected and analyzed. The screening process is described in **Figure 3**.

Evolution of the Articles and Citations Over the Years

Figure 4 shows the annual scientific production and citations related to WH control methods. The research is considered relatively old and started 50 years ago. In fact, the first paper in this research area was published in 1974. The number of published research papers and citations have fluctuated over the last 2 decades, reaching a peak of 26 paper in 2020. This leads us to infer that this rise in the number of articles and citations over the years represents an increasing interest in this research area.

Geographical Distribution of Articles

Our screening process reveals that accessible published research on the WH control methods in the world, is concentrated in India (9 articles), followed by South Africa (8 articles), and China (5 articles) (**Figure 5**). These three countries together published significant number of research papers in the past 2 decades.

WATER HYACINTH CONTROL METHODS

Nutrients drainage from agricultural and human activities towards water resources contributes to the rapid proliferation of WH. Hence, the first critical step for the management of WH would be the implementation of large-scale nutrient reduction solutions before eradication in order to minimize the amount of biomass to be removed. The main objective of this approach is to reduce the vegetation density and generate biomass to be used for the production of high value-added products.

The WH eradication consists of using chemical, physical (mechanical and manual removal), biological control and/or an integrated approach (**Figure 6**). However, no single method is suitable for all the infested area (Ajithram et al., 2020), and each method has its one limitations. The particularity of the infested area (size, spatial configuration, weather, water body uses, and the chronology of infestation) is one of the key elements for choosing a control method (Tewabe and Asmare, 2020).

Nutrient's Run-off

Declining freshwater quality, through land-based run-off, is recognized as one of the most significant threats to the long-term health of freshwater areas. Nutrient run-off, along with sediment run-off and pesticides, is particularly crucial in many freshwater bodies. Nutrient run-off is associated with algae and WH blooms, and changes in microorganism species, which pose a risk to aquatic organisms (Emirhüseyinoğlu and Ryan, 2019).

Lake Victoria, the world's second largest freshwater Lake, suffered from the high growth of WH. Soil erosion, nutrient runoff, as well as urban and industrial pollution have induced a rapid eutrophication of the Lake over the last 50 years. High levels of nutrients in the Lake caused a dramatic invasion of WH, considering that eutrophication is the main cause of the plant growth (Kaur et al., 2018). Reducing the loss of nutrients, sediments and pesticides surrounding freshwater bodies by managing the use of agricultural amendments, and by avoiding deforestation could reduce the end-of-catchment loads and enhance the resilience of freshwater bodies (Sharpley et al., 2006).

Drainage through agricultural soils can lead to the leaching of soluble nutrients and pesticides, which they could find their way to reach downstream waters as well as groundwater. Although nitrogen and phosphorus occur naturally, increased nitrogen and phosphorus from fertilizer leaching is harmful to the freshwater bodies and promote the proliferation of WH (George and Goldman, 2007).

The best way to manage the WH long-term effects is to better match nitrogen and phosphorus inputs to crop needs (Swallow et al., 2001). Furthermore, control of organic pollution can be also done by substituting synthetic chemicals fertilizers with organic fertilizers (Krisnawati et al., 2020). By optimizing nutrient application there is less chance of surplus nutrients being lost to waterways, where they can harm the environment, and increase the proliferation of WH.

Physical Control of WH

Physical methods consist of two kinds of control: manual and mechanical removal. Manual removal is done by human, to remove the WH plants from the water bodies (Ajithram et al., 2020), while the mechanical removal method is carried out by machines. Mechanical removal of WH consists of using weed cutters, harvesters, chaining, shredder boats, and dredging process. Mowing, netting, and barriers are also used as ways of mechanical removal. Barriers in the form of booms or cables have been effectively used in some countries such as Ivory Coast, Zambia, and South Africa to protect hydropower water intake pumps and water extraction pumps (Hill and Coetzee, 2008).

Physical control remains the only method through which WH can be transformed into value-added products. It allows the collection of the raw material and its potential valorization to compost or green energy and other uses. Physical control immediately opens physical space (habitat) for fish, boat traffic, fishing and recreation (Yigermal and Assefa, 2019). A study on mechanical harvesting of WH from an Australian lagoon has allowed an increase in dissolved oxygen, which was related to a potential increase of the water inflow (Perna and Burrows, 2005). Thus, physical control is the most suitable method to remove this plant, for economic and commercial benefits. Hand removal is most effective for small infestations while mechanical harvesting can be an effective tool for removing larger infestations. However, mechanical shredding and *in-situ* cutting processes, where plants are left to die and decompose in the water, can decrease dissolved oxygen in the water, and then catalyze the releases of phosphorus from the sediment. This process accelerates eutrophication phenomena, and can lead to a subsequent increase in WH or algae blooms (Mitan and Merry, 2019). A previous study carried out in laboratory using a water column, designed to mimic nutrient conditions of Lake Chivero (Uganda) reported that total nitrogen and phosphorus levels increased following mechanical (shredding) control of WH. Increased nutrient concentrations may be attributed to a release of these nutrients from decomposing plants (Villamagna and Murphy, 2010). Therefore, to overcome this eutrophication problem, the mechanical control must be associated with an integrated approach of valorization to produce biofertilizers and/or bioenergy from the plant (Tewabe and Asmare, 2020).

Chemical Control

Chemical control is an immediate and short time solution to remove WH using chemical herbicides. Chemical control has been used in several countries including Ghana, Nigeria, South Africa, Zambia, and Zimbabwe. The most effective and cheap herbicides used to reduce WH spread are glyphosate (Isopropilamine salt of N-phosphomethyl glycine), diquat (6,7-dihydrodipyridol pyrazinediumon) and 2,4-D (2,4-dichlorophenoxy) (Güereña et al., 2015).

Herbicides are very efficient to control WH (Villamagna and Murphy, 2010). However, they can affect and damage the aquatic system. It is considered harmful for the environment compared to the mechanical and the BC approaches (Ajithram et al., 2020). Furthermore, this method may lead to significant socioeconomic impacts if the quality of the freshwater is affected (Villamagna and Murphy 2010). For this reason, in many countries there are restrictions that prohibit the use of chemicals in water, intended for drinking purposes.

Using herbicides can be considered only under certain conditions such as in case of small-scale infestations and in emergency situations. Tewabe and Asmare (2020) reported

TABLE 1 | The most used herbicides against WH and some of their characteristics.

	Principle	Control effectiveness and duration	Treatment method	Dose	Cost	Advantages	Drawbacks	References
2,4-D (2,4-dichlorophenoxy)	2,4-D is absorbed by roots and shoots and readily translocated throughout the plant. Absorbed 2,4-d inhibits cell division of new tissue and stimulates abnormal, non-symmetrical growth of mature plant tissue, resulting in total cell disruption and plant death.	Plant death and sinking occurring within 3 weeks following application	-Applied by aerial spraying - Knapsack spray - High volume handgun spray	- Knapsack spray: 50 ml/ 10 L water/High volume overall spray coverage: 10 L spray solution/100 m^2 spray prior to flowering - High volume handgun spray: 1 L/200 L water/overall spray coverage: 200 L spray solution/ 1,000 m^2 spray prior to flowering - 1–12 kg ha^{-1}	700–1,000 USD/ ha	Systemic herbicide, 2,4-D can kill roots and shoots of aquatic plants, thus producing a more long-lasting effect amine formulations of 2,4-D has a low order of toxicity to zooplankton, benthic invertebrates, fish, and wildlife.	-Greater toxicity effects are apparent with both amine and ester forms of 2,4-D at lower pH (e.g., 6.5) than at higher pH conditions 10 of the water. -Is not suitable for treating a defined area within a large, open lake - Non-target plants may be affected, as a variety of plants do show degrees of susceptibility to 2,4-D treatment.	The State of Queensland, Department of Agriculture and Fisheries (2020). Osmond and Petroeschevsky (2013).
Diquat (6,7-dihydrodipyridol)	Causes a rapid inactivation of cells and cellular functions through release of oxidants	-Effective reductions in plant biomass can range from a few weeks to several months - Duration of control is a function of contact efficiency and regrowth from unaffected root systems or propagules	-High volume spot spray -DO NOT spray if plants are stressed or covered with dust or soil - DO NOT spray with misting machines or CDA applicators - Apply in dull weather or at the end of the day for best results	-4.0 L per 100 L of water 50–100 L/ha for Diquat 20 g/L - 400 ml per 100 L of water 5–10 L/ha for Diquat 200 g/L	600–1,000 USD/ ha.	Acts faster than translocating herbicides - Tissue death is often apparent in less than one week - Disappears rapidly from the water due to quick uptake by plant foliage	-Nonselective herbicide - Absorption by root systems is negligible -Kills only plant tissues it contacts/ temporary reductions in aquatic plant growth. - Efficacy is substantially reduced in turbid water or mud-coated vegetation because of rapid absorption by sediment particles	The State of Queensland, Department of Agriculture and Fisheries (2020). Osmond and Petroeschevsky (2013).
Glyphosate. 2,4-D	Absorbed through the leaves and are quickly transported throughout the whole plant,	- Symptoms of herbicidal activity may not be apparent for up to 7 days, and include wilting and yellowing of plants, followed	-Applied to the foliage of actively growing plants. - High volume application	- From 4 to 9 L/ ha solution form. -From 2 to 4.5 kg ha^{-1} granular form. It depends on	250 USD/ha	-Can kill the entire plant including roots, producing long-term control benefits. -Dissipates quickly from	- Non-selective herbicide -Not effective on submersed plants or those	The State of Queensland, Department of Agriculture and Fisheries (2020). Osmond and Petroeschevsky (2013).

(Continued on following page)

TABLE 1 | (*Continued*) The most used herbicides against WH and some of their characteristics.

	Principle	Control effectiveness and duration	Treatment method	Dose	Cost	Advantages	Drawbacks	References
	killing all parts of it	by complete browning and death. - Completely kills the plant 3–8 weeks after application	with handgun, knapsack, or boom -DO NOT use additional surfactant unless stated in the label and it is approved for use in aquatic situations	initial herbicide concentration.		natural waters, with an average half-life of 2 weeks in an aquatic system. -The herbicide has a low toxicity to benthic invertebrates, fish, birds and other mammals.	with most of the foliage below water.	Gutiérrez et al. (1996)

TABLE 2 | The natural enemy species established on WH at local, regional, and international level.

	Class: Insects				Class: Arachnida (mites)	Class: Dothideomycetes (Fungi)	References
Country	Order: *Coleoptera* Family: *Brachyceridae* Genus: *Neochetina* Species: *N. eichhorniae*	Order: *Coleoptera:* Family: *Brachyceridae* Genus: *Neochetina* Species: *N. bruchi*	Order: *Hemiptera* Family: *Miridae* Genus: *Eccritotarsus* Species: *E. catarinensis*	Order: *Lepidoptera* Family: *Crambidae* Genus: *Niphograpta* Species: *N. albigutallis*	Order: *Acarina* Family: *Galumnidae* Genus: *Orthogalumna* Species: *O. terebrantis*	Order: *Mycosphaerellales* Family: *Mycosphaerellaceae* Genus: *Cercospora* Species: *C. piaropi*	Cilliers et al. (2002)
Benin	×	×					
Burkina Faso	×	×					
Congo	×	×					
Ivory Coast	×	×					
Egypt	×	×				×	
Ghana	×	×				×	
Kenya	×	×				×	
Malawi	×	×	×	×	×		
Mali	×	×			×		
Mozambique	×	×					
Niger	×	×					
Nigeria	×					×	
Rwanda	×	×					
South Africa	×	×	×	×	×	×	
Sudan	×	×		×			
Tanzania	×	×					
Togo	×	×					
Uganda	×	×					
Zambia	×	×			×		
Zimbabwe	×	×			×		
United States	×	×					Ilo et al. (2020)
Vietnam	×	×					Shabana et al. (2018)
Australia	×	×					Osmond and Petroeschevsky (2013)
Mexico	×	×					Gutiérrez et al. (1996)
Malaysia	×	×					Ismail et al. (2019)
China	×	×					Julien (2001)
India	×	×					Jayanth (1988)

FIGURE 7 | Adult *Neochetina* spp. feeding scars on water hyacinth (Photo credit Willey Durde and Katherine Parys, USDA-ARS, Bugwood.org).

that herbicides such as 2,4-D, diquat, paraquat, and glyphosate have resulted in successful control in small, single-purpose water systems such as irrigation canals and dams of around 1 ha in size. However, Souza et al. (2020) reported that the use of glyphosate herbicide at its highest recommended dose of 7.0 L ha^{-1} or 3,360 g of acid equivalent per ha, showed a low potential of environmental impact in the control of WH in reservoirs, but it should be used properly in specific infested sites and never in overall application to the whole infested area. In addition, an integrated approach with other control methods is recommended and seems to be unavoidable in certain circumstances. For example, interactions between chemical and BCs have been demonstrated. Previous studies reported that herbicides can complement BC (Cilliers et al., 2002; Perna and Burrows, 2005; Villamagna and Murphy, 2010). Paraquat, glyphosate and 2,4-D have been used to enhance the effects of *Neochetina* spp. species. Herbicides reduce WH populations to low levels prior to the introduction of biocontrol agents, thereby giving the agents time to better establish itself and suppress the regrowth of the weed. Moreover, creating barriers where WH can accumulate as whole block makes herbicidal control more effective. Combining mechanical and chemical control methods is a good option that saves time and energy following small or individual plants targeted for spraying (Cilliers et al., 2002; Perna and Burrows, 2005; Villamagna and Murphy, 2010).

A recent experimental study carried out on the effect of different concentrations of acetic acid on WH, aquatic life, and the physicochemical properties of water under pond conditions on the shores of Lake Tana in Ethiopia showed that increasing acetic acid concentrations gradually by 5, 10, 15 and 20% removed WH. However, it did not affect the survival of Nile tilapia but reduced water quality. Spraying a 20% concentration of acetic acid caused complete damage to the WH, while 15 and 10% concentrations allowed the development of new daughter plants and requires follow-up spraying, whereas 5% was less effective (Birhanie et al., 2020). **Table 1** summarizes the world's most used herbicides against WH, their principles, effectiveness, duration, doses, pretreatment methods, cost, advantages, and drawbacks.

Biological Control

Biological control is also one of the processes employed to remove or stop the growth of WH plants. In this method, some organisms including insects, pathogenic bacteria, fungi and parasites, among others were used (Yigermal and Assefa, 2019). The aim of any BC is not to eradicate the weed, but to reduce its abundance to a level where it is no longer problematic.

Biological Agents Used to Control of WH

Five insects (two weevils, two moths and a sucking bug), and a mite are among the most used arthropods worldwide. Microorganisms such as fungus have been also applied as control bioagents (**Table 2**). The most enemy species used are *Neochetina eichhorniae* and *Neochetina bruchi* weevils (**Figure 7**). *Neochetina* weevils can have devastating effects on WH populations leading to reduction of the plant by more than 95% (Jayanth, 1988). Adult weevils feed on the external plant surfaces and petiole reducing photosynthetic capabilities and productivity of the plant (Julien, 2001).

Biological control was considered the only viable method for reducing the impact of WH on Lake Victoria (Kenya-Rwanda-Uganda), where two weevils *Neochetina eichhorniae* Warner and *Neochetina bruchi* Hustache (*Coleoptera, Curculionidae*) were used. Several million weevils individuals were released in the Lake via weevil-rearing stations resulting in a drastic collapse of the plant's extensive mats (Cilliers et al., 2002).

Agjee et al. (2016) reported that *Neochetina* spp. is effective to overcome the proliferation of WH in South Africa. Weevils induced both morphological and physiological damage to WH. Adult weevils feed by forming rectangular scars on the surface of the leaf, thus exposing the leaf to desiccation (Agjee et al., 2016). Over time, extensive feeding damage causes a reduction in plant growth and reproduction (Agjee et al., 2016). According to Tewabe, (2015) *Neochetina bruchi* populations grow better under eutrophic conditions. However, *Neochetina eichhorniae* is less dependent on good quality plants for growth than *N. bruchi*. Consequently, the relative abundance varies between sites: more *N. eichhorniae* at sites, lower quality of WH is observed, and *vice versa*. In polluted waterways, *N. bruchi* may complement the damage caused by *N. eichhorniae.*

TABLE 3 | Example of biocontrol experiences in some countries.

Countries	Species	Name	Release seasons	Individuals	Effectiveness	Lab/large-scale	Period	References
Benin (Lake Azili)	Two weevils	*Neochetina eichhorniae*	February, April - August	24,100	(+)	Large-scale	1991–1995	De Groote et al. (2003)
		Neochetina bruchi	August, March	7,700				
	1 moth	*Sameodes albiguttalis*	ND	2,400				
South Africa	Five arthropods	*Neochetina eichhorniae*	Winter (December)	1,400	90%	Large-scale	1990–1995	Jones (2009)
		Niphograpta albiguttalis		150				
		Orthogalumna terrabrantis		800				
		Eccritotarsus catarinensis		1,350 with 10 infested plants				
		Neochetina bruchii	Spring (March)	800				
	One pathogen	*Cercospora rodmanii (piaropi)*	ND	ND				
	Two fungi	**Acremonium zonatum*						
		**Alternaria eichhornia*						
Argentina (Reservoir)	1 weevil	*N. bruchi*	Spring (March)	284 (153 males and 131 females)	80%	Large-scale	1974–1980	Deloach and Cordo (1983)
	1 moth	*S. albiguttalis*	ND	ND				
Florida-United States	Two weevils	*N. eichhorniae* and *N. bruchi*	Spring (April) for the 5 experiments	0	(-)	Laboratory scale	1 year (all experiments)	Cofrancesco (1998)
		N. eichhorniae and *N. bruchi*		1,000	(- +)			
		N. eichhorniae and *N. bruchi*		2,000	(+)			
		N. eichhorniae and *N. bruchi*		3,000	(++)			
		N. eichhorniae and *N. bruchi*		4,000	(--)			

Neochetina spp. has been successfully used as biocontrol agents in several countries around the world. *Neochetina bruchi* has been released alone or with *Neochetina eichhorniae* in 30 countries, and *Neochetina eichhorniae* was released in another 32 countries (Julien, 2001). **Table 3** shows examples of biocontrol at large and laboratory scales with details on the bioagents and the individual numbers used, the seasons, the control periods and effectiveness of the control.

Because of the WH invasion problem in the biggest Lake in Ethiopia (Lake Tana), where the proliferation is increasing rapidly, a previous study was conducted to predict the possibility of applying BC with the two *Neochetina* weevils using a simulation model (Firehun et al., 2015). The authors evaluated the climatic similarities between Rift Valley (Ethiopia) and some other locations in West Africa, where biocontrol of WH using both weevils has been successfully used. The study results showed that *Neochetina bruchi* could be considered as a promising candidate for controlling the WH under the Ethiopian climate conditions. The country is currently, trying at the experimental level (greenhouse) to control the weed using *Neochetina bruchi* and fungi (*Rhizoctonia solani, Aspergillus flavus, Tricothcium roseum* and *Aspergillus niger)*. The biocontrol experiments have shown a high efficiency in controlling the weed (Yigermal and Assefa, 2019; Admas et al., 2020).

The most limiting factor of using the BC of WH is the long time required to achieve high performances (the process usually requires 2–4 years). Biocontrol methods can have inadequate results when there are factors affecting weevil growth such as weather, disease, predators, plant quality (host quality), and interferences after herbicide application. Consequently, it is mandatory to assess the infestation rate of weevil over time in order to ensure the process efficacy (Hauptfleisch, 2015).

Suitable Conditions and Limitations of Biocontrol

The biological control should be conducted in areas with **subtropical or tropical climate** because the low temperature reduces or stop weevil population increase and allow the weed to recover. It is effective on **floating plants** not on those retained in the mud beneath the water by the roots, and it is more successful

TABLE 4 | Advantages and disadvantages of WH control methods.

	Advantages	Disadvantages	References
Mechanical control (manual and *in-situ* cutting)	- Effective for short-term results/short-term solution -- Immediately opens physical space (habitat) for fish, boat traffic, fishing, and recreation - Effective for small infestations - Not require much technical expertise - Selective approach - No water-use restrictions - Provides a raw material for valorization	- Plants are left to die and to decompose in the water - Shredded WH bunch could move and start new proliferation in other unaffected area - Decrease of dissolved oxygen in the water - Release of phosphorus from the sediment - Alter trophic structure as a result of changes in nutrient and carbon balances - Increase algae blooms - Unpractical for areas larger than a hectare given the rapid rate of increase of the weed - The water depth limits this removal method.	Carvalho and Cerveira Junior (2019), Greenfield et al. (2007), Perna and Burrows (2005), Villamagna and Murphy (2010)
Mechanical control (harvesting)	- Effective for short-term results/short-term solution - Effective tool for removing larger infestations - Immediately opens physical space (habitat) for fish, boat traffic, fishing, and recreation - Selective approach - Increase in dissolved oxygen due to the increased water inflow - Not require much technical expertise - No water-use restrictions	- Costly and logistically difficult. - It heavy to transport because WH is composed of approximately 90% water. - Unpractical for areas larger than a hectare given the rapid rate of increase of the weed - The infestations soon return because a shredded bunch of the weed are carried by waves to other unaffected areas where they establish and start proliferating - The water depth limits this removal method.	Carvalho and Cerveira Junior (2019), Mangas-Ramírez and Elías-Gutiérrez (2004), Villamagna and Murphy (2010)
Chemical control	- Effective for short-term results - Reduce WH populations - Less labour intensive - Increase algae, pH and dissolved oxygen - Increase fish abundance - Removal of plant barriers to fish movement - Can relieve congestion of areas where access is obstructed	- Herbicides are less selective - kill non-target algae and macrophyte - Expensive because repeated applications are needed - Ecological impacts - Degrade water quality and put aquatic life at risk - Dangerous deoxygenation of water - Influence fish distribution - Water use restrictions (Socio-economic impacts if beneficial or designated uses of the waterbody are affected). - Introduction of toxic chemicals into the environment	Gutiérrez et al. (1996), Villamagna and Murphy (2010), Martínez Jiménez et al. (2007), Carvalho and Cerveira Junior (2019)
Biological control	- Efficient and safety - Avoids the introduction of toxic chemicals into the environment - Reduces WH buoyancy - Reduces the reproductive capacity of WH - Reduces WH photosynthetic capabilities, - Not labour or equipment intensive - Self-sustaining - Do not affect water quality in deep areas or where large mats of WH do not sink at once.	- Much of the cost is related to research and development. - Long time results - Commonly preceded by mechanical removal or chemical treatment to quickly reduce the plant population - Effective control takes many years - Potential to adversely affect non-target components of the ecosystem	Hill and Coetzee (2008), Simberloff and Stiling (1996), Villamagna and Murphy (2010), Wilson et al. (2005)
Combined physical and biological control	- Immediately opens physical space (habitat) for fish, boat traffic, fishing, and recreation - Efficient, safety and sustainable - Cost-effective - Reduces WH buoyancy and reproduction - Selective approach	- Require deep research and expertise in bioagent release and control - Costly if the biomass harvested is not valorized	Villamagna and Murphy (2010), Carvalho and Cerveira Junior (2019), Wilson et al. (2005)

(Continued on following page)

TABLE 4 | (*Continued*) Advantages and disadvantages of WH control methods.

	Advantages	Disadvantages	References
	- Ecofriendly, and do not affect water quality - Provides a raw material for valorization - Balanced approach contributes to self-generating and restoration of ecosystems. - Conserve freshwater bodies and biodiversity		
Combined physical and chemical control	- Immediately opens physical space (habitat) for fish, boat traffic, fishing, and recreation - Increase pH and dissolved oxygen - Reduce WH populations - Easy to implement - Effective for short-term results - Provides a raw material for valorization	- Dangerous to the environment - Affect water quality - Not selective - Not sustainable - Dangerous deoxygenation of water - Water use restrictions - WH proliferation could reappear in any time - Costly approach	Carvalho and Cerveira Junior (2019), Villamagna and Murphy (2010)
Combined chemical and biological control	- Immediately opens physical space (habitat) for fish, boat traffic, fishing, and recreation - Efficient and sustainable - Reduce WH populations	- Require research and expertise in bioagent release and control. - Dangerous to the environment - Not safety - Affect water quality - Require deep research and expertise in bioagent release and control - Don't provide a raw material for valorization - Herbicide increased mortality of the biological control species	Hill et al. (2012), Carvalho and Cerveira Junior (2019), Wilson et al. (2005)

in **larger water bodies** where wind and wave action increases the mortality of agent-stressed plants. In addition, the stable mats for long periods contribute to the multiplication of bioagents. Among biocontrol limitations, the **cold winters**, which increase the time for controlling the weed, and **periodic or annual floods and drought** which reduce the host plant leading to the high reductions of the weevil populations and their local extinction. Moreover, the **high pollution**, contamination by nutrients and concentrations of heavy metal pollutants reduce the host plant quality for bioagents establishment, because the uptake of heavy metals by WH may reduce the fecundity of the weevils that feed on those plants. Finally, biological control should not be combined with other control method in the same place and time, its **interference** from other controls notably inappropriate herbicide applications will directly or indirectly kill the bioagents by reducing the number of plants necessary for weevil's growth and survival.

Integrated Control of WH

Integrated control is the use of two or three control methods together (**Table 4**). Its includes aspects of BC, herbicide applications, physical removal as well as the management of nutrients feeding the aquatic ecosystem (Van Wyk and Van Wilgen, 2002). It was reported that the key element of this approach is first the appointment of an organization to drive the control program, the involvement of all interested and affected parties, the division of the study area into management units, and finally, the application of the appropriate control methods. The control methods combination promotes weed stands reduction and growth of natural enemies for effective BC. Moreover, the use of combined control methods, in many cases, shows that it can be cost-effective than the application of only one control method in the entire study area (Hill and Coetzee, 2008). **Table 4** summarizes the advantages and disadvantages of WH control combined methods.

Valorization of WH

After WH removal, this plant constitutes a valuable biomass for biofertilizers and bioenergy production (biogas, biohydrogen, bioethanol, liquid, and solid biochar), water treatment, charcoal briquettes, paper making, fish feed, animal feed, furniture making, fiberboard making, yarn and rope manufacture. All these potential ways have been deeply reviewed (Lu et al., 2008; Ratnani et al., 2020; Harun et al., 2021).

The water hyacinth is a potential candidate for bioenergy production because it is a lignocellulosic biomass. which could be used for sugar production, and fermentation to bioethanol and biohydrogen (Rezania et al., 2017). Another research has evaluated the bioconversion of fermentable sugars derived from WH into microbial lipids and single cell proteins by an oleaginous yeast. This study indicated the feasibility of sustainable valorization of WH-derived liquid hydrolysate towards a biorefinery framework Alankar et al. (2021). By the way, Arutselvy et al. (2020), have conducted a sequential valorization strategy for dairy wastewater (DW) and WH to produce fuel and fertilizer. Anaerobic co-digestion of WH and DW improved the process efficiency and increased biomethane production. Biomethane yield from the codigestion was higher compared to the monodigestion. The residual digestate was used for pyrolysis to obtain bio-oil and biochar. Another study indicated that the biochar obtained from WH pyrolysis could serve for heavy metal adsorption, and could be used for bioremediation application (Hasan et al., 2021). In addition, an integration strategy of hydrothermal carbonization (HTC) and anaerobic digestion (AD) using WH, showed that hydrochars and process waters from HTC process, could be valorized for a solid combustion fuel and biomethane production (Brown et al., 2020).

Besides bioenergy, WH valorization showed its importance in the agricultural sector as well. A novel approach of formulating an enriched N-P-K (nitrogen-phosphorous-potassium) fertilizer from WH and other residues (wet blue leather and poultry bone) has been performed. The developed organic N-P-K fertilizer resulted in significantly higher plants compared to commercial fertilizers (Majee et al., 2019). Moreover, WH could be transformed to a high-quality forage for animal feed. A previous study showed that the cultivation of edible mushrooms on WH biomass degrades almost all the lignin-cellulose of the substrate through enzymes, and enriches it with high protein content, making the spent substrate an excellent forage (Araiza et al., 2016).

Water hyacinth has been a subject for the development of cement composites and bioplastics. A study conducted by Salas-Ruiz et al. (2019), showed that WH root ash could be used as an alternative to pozzolans in cement matrices to fix these pollutants. This developed composite is cheap, green, and promotes waste and pollutants recycling and elimination. WH with other agricultural residues (bagasse and rice straw) could be transformed to produce bioplastic with a high biodegradability rate. This ecofriendly product could be used as an alternative to synthetic plastics (Ungprasoot et al., 2021).

Results obtained from this bibliographic research showed how it is beneficent to adopt these kind of strategies for efficient WH management. An economic feasibility study performed by Wang et al. (2019), showed that integrated valorization approaches could be beneficial, especially in the case of costly valorization technics such as bioethanol production. The study confirmed that coupled use of WH as a phytoremediation plant and bioethanol feedstock is a potential response to green development strategies.

RESULTS AND DISCUSSION

Effectiveness of WH Control Programs

The water hyacinth in the absence of its natural enemies, causes serious problems worldwide and especially in Africa, where it has rapidly invaded rivers and freshwater bodies, especially in tropical and temperate-warm regions. It has grown enormously in the last decades, becoming an agricultural, environmental, and public health problem.

Control of this weed is difficult, and all appropriate options available should be considered. If necessary, a variety of control measures can be used, depending on the nature of the problem and the local conditions of the affected area. Therefore, available environmentally friendly, and sustainable methods should be adopted (Labrada and Fornasari, 2002).

Different control programs of this weed have been applied worldwide on large-scale. Some countries have adopted the mono-control approach, by using one control method for the whole invaded area, while others have applied integrated control approach, which consists of combining the available control methods, at the same time but separated in space, according to the site's specificity and conditions.

According to our extensive bibliographic research carried out on the different control methods and their use worldwide, BC appeared to be effective and sustainable for controlling WH. Ndunguru et al. (2001) reported that the *Neochetina* weevils had an effective and long-term impact, leading to a gradual reduction in the WH vigor and thus increasing its susceptibility to competition from other aquatic vegetation. Moreover, a study conducted by Firehun et al. (2015) has shown that *Neochetina* weevils are a promising candidate for BC of WH under tropical conditions.

The applications of herbicides over wide areas results in large quantities of WH biomass sinking into the water (Ajithram et al., 2020). The anaerobic decomposition of this biomass decreases dissolved oxygen in the water and results in massive biodiversity damage and greenhouse gas emissions. In addition, herbicides kill non targeted plants that are native, beneficial, and necessary for healthy functioning of the Lakes's ecosystem (Rosic et al., 2020). In Mexico a combined chemical-mechanical program, using the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) and a mechanical harvester, was implemented to control WH on the Trigomil Dam. Reasonably successful results were obtained (Gutiérrez et al., 1996). In China, integrating Roundup at different concentrations (41% salt of glyphosate) and Caoganlin (10% salt of glyphosate)) with weevils (*N. eichhorniae* and *N. bruchi*) greatly suppressed the plants. The tests indicated that herbicides had to be used at a lower concentration than normal, to not kill the plants too rapidly and not deprive the insects of food and habitat. The combined biological-chemical approach was effective (Mallya et al., 2001). Nevertheless, herbicide application on WH is forbidden in many other areas of China. For this reason, an asexual reproduction inhibitor named KWH02 was invented for controlling WH. The results indicated that KWH02 is a suitable control agent in areas, where water is used for drinking and in Lakes, pools, and creeks, where the water flow rate is slow (Chu et al., 2006).

On the other hand, it was reported that only physical removal, either manual or mechanical, of WH can eliminate the plant's biomass from the water. It is considered as a selective approach and short-term solution (George and Goldman, 2007). However, disposal of the WH biomass after the physical removal remains problematic and creates terrestrial disposal issues. Plant disposal leads to a new bloom, causing environmental risks (Gunnarsson and Petersen, 2007). If WH is properly disposed of and collected, it could be used as a primary source to generate high value-added products and energy (Ayanda et al., 2020). It can offer the economic incentives to facilitate a sustained and effective WH management program. Although, recent studies

TABLE 5 | Examples of some large-scale experiences of WH control programs conducted in 26 countries.

N	Country	Physical control (PC)	Biological control (BC)	Chemical control (CC)	Integrated control (IC)	Effectiveness	Control period	Observations	References
1	Ethiopia	(–)				PC was not effective	2012–2018	- No systematic evaluation has been done after the removal campaign. - Control's failure: because the dense mats of the weed have been harvested in the lakeshore.	Enyew et al. (2020), Van Oijstaeijen et al. (2020), Abtew and Dessu (2019)
2	Egypt	(–)	(+)			- PC was not effective - BC was effective	2000–2002	- WH on Lake Edko was reduced by 90% - Lake Mariout, reduction was slower due to water pollution - The pathogen *Alternaria alternata* (Fr.) Keisser (*Ascomycotina*) has been utilized	Shabana et al. (2018) Gebregiorgis (2017)
3	Sudan	(–)	(+)			- PC was not effective - BC was effective	1978–1984	Drastic reduction in the growth of WH	Beshir and Bennett, (1984)
4	Kenya	(+)	(+)		(+)	- Integrated PC and BC was effective	1998–2005	95% reduction of the WH	Swallow et al. (2001) Gebregiorgis (2017)
5	Uganda	(+)	(+)		(+)	- Integrated PC and BC was effective	4 years	80% reduction of the WH Maintaining a clear passage for ships to dock at Port Bell	Cock et al. (2000). Ogwang and Molo (1999)
6	(Kenya-Uganda-Tanzania) Lake Victoria	(+)	(+)		(+)	- Integrated PC and BC was effective	2 years	Biomass was reduced by 100%	Julien (2001), Swallow et al. (2001), George and Goldman (2007), Valk (2015)
7	Tanzania	(+)	(+)		(+)	- Integrated PC and BC was Effective	3 years	70% reduction of WH/The source of the WH coming into the lake has also been targeted with the construction of three weevil-rearing stations along the Kagera river in Rwanda - Quarantine regulations and management of nutrient enrichment	Mallyae et al. (2001)
8	Zambia	(–)	(–)	(+)		- PC was not effective - BC was not effective - CC was effective	ND	—	Nang'alelwa (2008)
9	Zimbabwe	(–)	(–)	(+)		- PC was not effective - BC was not effective - CC was effective	ND	BC was not effective on lake Chivero because of high pollution levels	Cilliers et al. (2002), Moyo et al. (2013)
10	Mozambique	(–)	(–)	(–)		- PC was not effective - BC was not effective - CC was not effective	ND	Biological control in progress	Langa et al. (2020)

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TABLE 5 | (*Continued*) Examples of some large-scale experiences of WH control programs conducted in 26 countries.

N	Country	Physical control (PC)	Biological control (BC)	Chemical control (CC)	Integrated control (IC)	Effectiveness	Control period	Observations	References
11	Malawi	**(–)**	**(+)**			- PC was not effective - BC was effective	ND	—	Phiri et al. (2001); Mellhorn (2013)
12	South Africa		**(+)**	**(+)**	**(+)**	- Integrated control was effective in some area	1995–2011	- Low temperate in high-altitude climatic areas and interference from other control options has retarded biological control. - South Africa invested a sum of 6.8 million USD in research and development of biocontrol of IAPs from 2014 to 2017	Cilliers et al. (2002), Hill et al. (2012), Zachariades et al. (2017), Paterson et al. (2019), Miller et al. (2020), Rogers et al. (2020), van Wilgen et al. (2020)
13	Nigeria	**(+)**	**(+)**	**(+)**	**(+)**	- BC in 1994 et 1995 followed by PC in 2001 were effective - CC was effective - Integrated was effective	1994–2001	- Decline in WH populations - Booms were used to collect the weed for manual removal	Cilliers et al. (2002)
14	Niger	**(–)**	**(+)**			- Physical was not effective - BC was effective	ND	Decline in WH populations following the release of the weevils in 1994	Cilliers et al. (2002)
15	Ghana	(–)	(+)	**(–)**		- Physical was effective - BC was effective - CC was not effective	1993–1995	—	De Graft (1995)
16	Benin		**(+)**			- BC was effective	1991–2003	- WH cover was reduced from 100 to 5% in Ouémé and lake Azili.	De Groote et al. (2003)
17	Mali	**(–)**	**(+)**			- PC was not effective - BC was effective	ND	—	Julien (2001)
18	Ivory Coast	**(–)**	**(+)**			- PC was not effective - BC was effective	ND	Decline in WH population	Cilliers et al. (2002)
19	United States (California and Florida)		**(+)**	**(+)**	**(+)**	- Integrated CC and BC was effective	3 years	90% weed reduction with BC control with *N. bruchi.*	Van Driesche et al. (2002), Frieman (2004), Nesslage et al. (2016),Tobias et al. (2019), Reddy et al. (2019), Ilo et al. (2020)
20	Australia	**(+)**	**(+)**	**(+)**	**(+)**	- Integrated was effective	ND	- PC increases dissolved oxygen in lagoon	Osmond and Petroeschevsky (2013)
21	Mexico	**(–)**	**(+)**	**(+)**	(+)	- Integrated was effective	ND	Cyanobacteria blooms	Gutiérrez et al. (1996), Perna et al. (2011), Waltham and Fixler (2017)
22	China	**(–)**	**(+)**	**(+)**	**(+)**	- Manual control was not effective - Integrated BC-CC control was effective	1995–2000	- From 1995 introduction of weevils 1996 Roundup (41% IPA salt of glyphosate) and Caoganlin (10% salt of glyphosate), were	Julien (2001), Chu et al. (2006), Lu et al. (2007)

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TABLE 5 | (*Continued*) Examples of some large-scale experiences of WH control programs conducted in 26 countries.

N	Country	Physical control (PC)	Biological control (BC)	Chemical control (CC)	Integrated control (IC)	Effectiveness	Control period	Observations	References
								screened to supplement the activity of the weevils.	
23	Malaysia	(+)	(+)		(+)	Integrated control was effective	ND	—	Ismail et al. (2019)
24	Argentina	(–)	(+)			- PC was not effective - BC was effective	6 years	90–95% control with *N. bruchi*	Deloach and Cordo (1983), Cabrera Walsh et al. (2017)
25	Portugal	(+)				- PC was effective	2005–2008	Removal of 200,000 tons of the WH	Julien (2001)
26	India	(–)	(+)			-PC was not effective -BC was effective	32 months	More than 95% of the infestation was cleared	Jayanth (1988), Malik (2007), Simpson et al. (2020)

(–) not effective, (+) effective, (ND) not defined, (PC) physical control, (BC) biological control, (CC) chemical control, (IC) integrated control.

have shown that it has diverse uses (Mathew et al., 2015; Hernández-Shek et al., 2016; Sindhu et al., 2017; Priya et al., 2018). These studies further recommended that the potential of this macrophyte should be fully harnessed, which could generate significant incomes. In wide infested areas the exploitation of this plant should no longer pose problems of profitability since productivity will be ensured by harvesting a surplus of the plants. Frequent and controlled harvesting of excess WH is essential to better control the rate of water plant coverage of the water surface. Additionally, using BC combined with the physical one improved the management process. Ndunguru et al. (2001) reported that WH infestation in Lake Victoria was reduced by 78% using integrated management strategies such as BC using the *Neochetina* weevils and manual removal. Since the physical control leads to an immediate elimination of WH, the BC ensures the establishment of bioagents in the study area and maintain the program sustainability in case of future proliferation of the plant. To visualize the approaches feasibility, and to evaluate their effectiveness in terms of application and performance, a descriptive analysis on WH control approaches and programs used worldwide was conducted.

The objective of this analysis was to identify successful control programs around the world and to evaluate the most used and effective ones. Results obtained from previous large-scale WH control experiences were considered. The analysis was carried out in 26 countries, in America, Asia, Australia, Europe and Africa. **Table 5** summarizes the bibliographic research results.

As shown in **Table 5**, in the 26 large-scale trials, 70 control methods have been applied. Each country adopted one or more control methods throughout the invasion period of the plant. In the experiments performed, the control methods have been used either separately or in combination.

Control methods classification in terms of application for the studied countries is presented in **Figure 8**. Out of the 70 control methods, the biological control method has been used 25 times with a percentage of 36%, followed by the physical treatment which has been applied 23 times with 33%, and finally the chemical and the integrated control have been applied 11 times (16%) for each one in all experiments. The most adopted control methods consisted of using the biological and the physical controls separately, followed by the integrated approach, and then the separated chemical control.

Most countries started with physical control alone followed by the biological one, and few countries have adopted the chemical and integrated control. The mono-physical control has failed in most of the case studies, while the mono-biological has been successful in the major cases. The chemical control has been successful as well; but has not been used many times. The integrated control has been used in few countries but it was successful in all of them.

The classification of the control methods in terms of effectiveness for the studied countries is presented in **Figure 9**. From 25 biological control programs, 21 were effective. The biological control has shown its effectiveness in some cases where it has been used alone, and has been 100% effective in all integrated program cases.

For the separate physical control, despite being used widely in several countries, only few cases (9 countries out of 23) were successful while, the chemical control has not been too much adopted, because it's costly, harmful for the environment, and forbidden in some countries (Cabrera Walsh et al. (2017)). As shown in **Figure 9**, despite its negative impact, and being adopted only in few countries, the chemical control was effective.

The integrated control approach is the combination of one or more control method. It involves the test of at least two control methods simultaneously but separately in space, according to the site's specificity and conditions. The combinations consist of integrated biological and physical control methods (IBP), integrated biological and chemical control methods (IBC), integrated physical and chemical methods (IPC) and integrated biological, physical and chemical methods (IBPC). In all case studies, 11 integrated

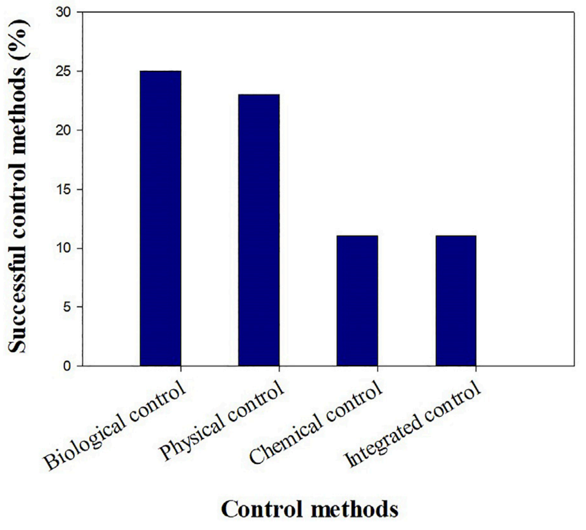

FIGURE 8 | Classification of separate and integrated control methods, in terms of application based on 26 large-scale trials.

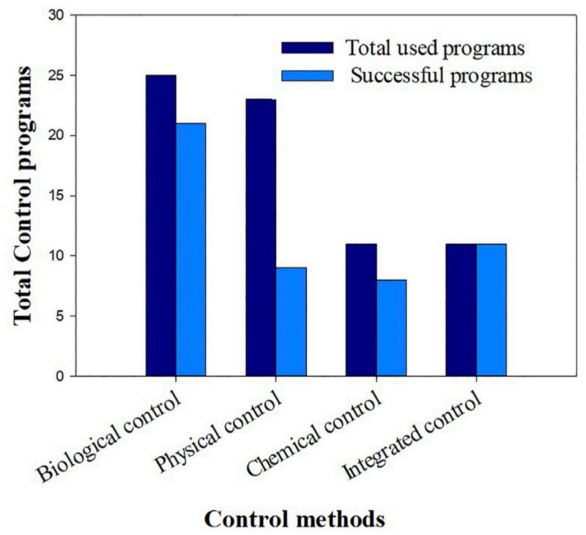

FIGURE 9 | Classification of separate and integrated control methods, in terms of effectiveness based on 26 large-scale trials.

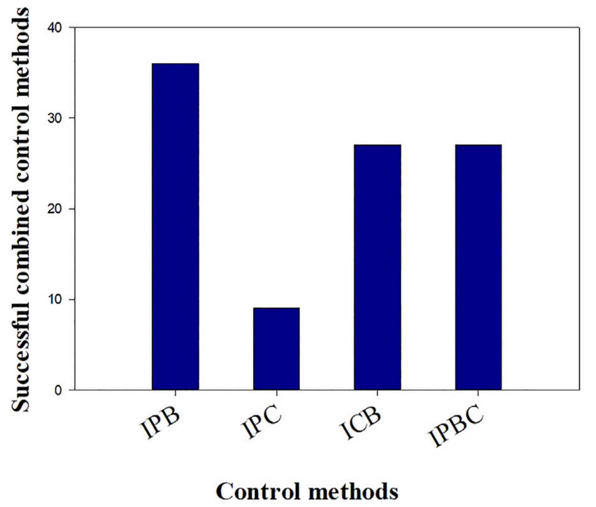

FIGURE 10 | Classification of integrated control approaches, in terms of application based on 26 large-scale trials.

control programs have been used and all of them were successful. The integrated methods IPB, ICB, IPCB, and IPC have been used 4, 3, 3 and 1 times respectively. As shown in **Figure 10**, the IPB was the most used program (37%) compared to the other integrated approaches. Although all integrated programs were successful, the combined physical and biological approach was the most effective. Therefore, it is recommended to adopt this integrated approach or to switch to an integrated "**biological-physical and chemical**" approach in case of emergency. In this latter case, the chemical control should be used properly in very specific and limited infested sites. Control methods must consider such scale dependent characteristics of WH invasions and ecosystem structure (Lu et al., 2007). Moreover, an integrated "**control-valorization**" approach is highly recommended. Awareness about WH benefits by developing new product locally based on this plant should be raised. This approach has two objectives: it will allow both WH removal and income generation. In addition, nutrient run-off reduction should be considered in management programs of WH. Because nutrient run-off is the major factor leading to the proliferation of WH in freshwater bodies, its control is necessary to decrease the vigorous growth of this plant (Chen et al., 2021). It was reported that an integrated control strategy is considered as the most effective method in South Africa, including biological control, manual removal, herbicide applications, and nutrient reduction (Paterson et al., 2019). Mitigation measures of nutrients' input from agriculture activities and the monitoring of the streams feeding the freshwater systems should be implemented. All stakeholders and policy makers should be aware of the need to reduce the impact of pollution on freshwater bodies to succeed in managing the WH invasion.

Economical Evaluation of Water Hyacinth Controls Program

Table 6 shows the cost/benefit of the 3 separate control methods and that of the integrated approach. It is worth mentioning here that the monetary investment per hectare (US$/ha) cleared for each separate control method was calculated based on research data (surface area infested and control cost in different countries) except for South Africa and Sudan, for which the cost of the manual and mechanical removal has been taken from previous studies (Van Wyk and Van Wilgen 2002; Jones, 2009; Tayeb and Nagat Mubarak, 2012; Ilo et al., 2020).

TABLE 6 | Economical evaluation of the most used control methods.

Country	Infested area by WH (ha)	Cost (USD)	Physical control cost per hectare (USD/ha)	Integrated approach cost per hectare (USD/ha)	Biological control cost per hectare (USD/ha)	Integrated approach cost per hectare (USD/ha)	References
Ethiopia	30,728	- Manual removal: (2.1 million USD) - Mechanical removal: 1 million (USD) spent for procurement and transport of harvester's machines	**100**	—	—	Not applied	Admas et al. (2020)
Sudan	300,000	- Manual removal: 160 (USD/ha) - Mechanical removal: 115 (USD/ha) - Biological removal: 1 Million (USD)	**275**	—	**16.6**	Not applied, Sudan started with only the physical, and it was not effective	Tayeb and Nagat Mubarak (2012)
Benin	100,000	- Biological control: 2.09 million (USD)	—	—	**20.9**	Not applied	De Groote et al. (2003)
South Africa	—	- Chemical control: 0.25 million (USD) - Biological control: 0.01 million - Integrated Control: 0.02 million	—	**86**	**18**	Applied and it costs **16** (USD/ha)	Ilo et al. (2020); Van Wyk and Van Wilgen (2002); Jones (2009)
United States	3.2 million	- Biological control: 29.5 million (USD) - Chemical control: 115 million (USD)	—	**50**	**12.8**	Applied but the cost is not defined	Wainger et al. (2018)

As shown in **Table 6**, the use of the physical or the chemical control separately requires high investment. However, in Sudan, Benin, South Africa and United States, the cost of the biological control was about (16.6), (20.9), (18) and (12.8 US$/ha) respectively (Van Wyk and Van Wilgen et al., 2020; De Groote et al., 2003; Tayeb and Nagata Mubarak, 2012; Wainger et al., 2018). The cost of the separate biological control seems to be the lowest compared to the other control methods. Furthermore, all successful programs consisted mainly of biological control that is considered the most cost-effective and sustainable control method but long-lasting and a slow-acting one. For example, in Benin, biological control has been conducted from 1991 until 2003 (De Groote et al., 2003). As a result of this large-scale experiment, *Neochetina eichhorniae* showed a significant reduction of the WH covered area.

However, biological control cannot be suitable for all regions, especially in areas that experience periodic floods and frost that cause high mortality of the bioagents since the plant is able to regrow after winter. In these regions, it is necessary to switch from a purely biological to a more integrated management approach, which includes also herbicide applications, mechanical and manual removal in addition to the biological treatment. For an effective biological control, the combined control methods promote weed stands reduction and growth of natural enemies (Hill and Coetzee, 2008).

A review on the benefits of WH (*Eichhornia crassipes*) for Southern Africa conducted by Ilo et al. (2020) clearly showed the economic feasibility of WH using control methods. The paper revealed that the integrated control (biological with chemical) of WH was the most cost effective method (16 US$/ha) followed by the biological (18 US$/ha) and the chemical (86 US$/ha) methods. Similar results were found in China where more than US$ 10 million/year was spent for the physical control even though it was not effective. From 2002 to 2006, the Shanghai government invested US$ 1.2 million for integrated management of WH that was effective (Chu, et al., 2006). From the obtained results, we can deduce that the separate physical and chemical controls require a big investment, while the integrated control approach gives the best return on investment and decreases the period of the program achievement.

CONCLUSION

Water Hyacinth is reported as an invasive aquatic plant causing many dramatic problems, mainly on the environment and the socioeconomic activities, in lakes, rivers, and many reservoirs around the globe, particularly in Africa.

The current research described and compared the existing solutions for managing and controlling WH worldwide, provided a concise conclusion on the most used, cost-effective, and sustainable programs, and highlighted the most recent and innovative studies on the WH valorization pathways.

This review demonstrated clearly that an integrated control program using different methods, nutrients run-off monitoring and biomass valorization seems to be the most effective and balanced approach for WH management. Water hyacinth management plans should be multi-scaled, integrated, and adaptive. Reduction of nutrient levels leaching into fresh water bodies should be considered as an integral part of any large-scale WH management because polluted water bodies promote WH infestations. Valorization technics of the harvested WH should be scaled up to remove the biomass and generate additional incomes.

In summary, this review has three main objectives: 1) help local stakeholders and decision makers of each infested area to deliver sustainable WH management, 2) encourage researchers to develop new technics to valorize the weed, and 3) motivate industrials to set up new commercials units for the valorization of the harvested WH, or to incorporate it in their present conversion processes.

AUTHOR CONTRIBUTIONS

FK: Conceptualization, Methodology, Investigation, Analysis, Interpretation, Writing-Original Draft, Review and Editing WB: Methodology, Review and Editing AE: Methodology, Review and Editing MS: Methodology, Review and Editing MK: Methodology, Review and Editing AY: Methodology, Review and Editing Project administration, Supervision. MH: Conceptualization, Methodology, Validation, Review and Editing, Supervision LK: Conceptualization, Methodology, Validation, Review and Editing, Project administration, Supervision.

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