EDITORIAL

Options for the Utilization of Water Hyacinth (*Pontederia crassipes* Mart.) – An Update

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Abstract

The focus of this article is the utilization potential of the globally important species - water hyacinth (*Pontederia crassipes* Mart.), which has spread across continents and is now naturalized in most continents. Water hyacinth (WH) can be a menace in waterways, but it also offers a variety of utilization benefits for humans and animals. Learning from history, a fresh ‘re-think’ is needed to deal with WH, which is a highly successful species. Instead of focusing solely on its adverse effects, weed research must focus on the future management of the species that pragmatically integrates its utilization to meet ecological goals, as well as economic, societal and cultural needs.

This review finds several areas of WH utilization that must be explored further for wider application. They include the nutrient removal capacity that has been well developed in the USA but not elsewhere and the phytoremediation potential of the species to extract industrial pollutants. Other applications as low-cost raw materials have enormous but unheralded benefits that cannot be ignored in countries where WH is currently naturalized and is thriving.

WH, a colonial legacy that has affected all continents, is no more ‘invasive’ than we humans are. Its extraordinary capacity for growth can help in healing the wounds on the earth, torn apart by human activities. The species offers a glimpse of human follies in mismanaging our biological resources and the environment. The compelling evidence of utilization potential offers hope for societies to benefit from water hyacinth’s incredible capacities to overcome obstacles and produce biomass that can be put to multiple uses. The species represents the dilemmas human societies face with colonizing species but also exemplifies future options that should not be ignored further

Keywords: Water hyacinth; *Eichhornia crassipes*; utilization; ‘Living with Weeds’, colonizing species

Introduction

In an early article for *Nature*, a British biochemist, Norman Pirie (1960) highlighted water hyacinth’s incredible capacity to proliferate and cause economic damage, noting that instead of eradication, people must learn to ‘*live with it*’ and put it to good use.

> *“…An organism often multiplies explosively when carried to a new environment. Rabbits in Australia are a familiar example, and now we have water hyacinth (Eichornia crassipes) in South-East Asia, the Nile, and the Congo. In time, enemies of the invader will probably evolve in the new environment, or be introduced into it, and restore a balance, but that may take many years...”* (Pirie, 1960).
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> *“…In the meantime, there is disruption of old patterns of life and effort is therefore put into attempts to eradicate the invader and restore the status quo. This is obviously wise, but it is by no means certain that eradication will be successful, so it may be prudent to find how best to live in the new circumstances. The invader may often be useful…”* (Pirie, 1960).

Historically, the problems caused in waterways by the free-floating water hyacinth [*Pontederia crassipes* Mart.; syn. *Eichhornia crassipes* (Mart.) Solms.] began to be noted by the scientific community in the 1940s (Penfold and Earle, 1948). The extent of the problems in the USA was so vast that it led to the formation of the *Hyacinth Control Society* in 1961: “*to share information on the efforts to control water hyacinth in Florida’s lakes, rivers, and canals*”. In 1962, the Society launched the *Hyacinth Control Journal*, which evolved to be the *Aquatic Plant Management Society* journal (APMS, 1964).

In the treatise '*The World's Worst Weeds'*, Le Roy Holm et al. (1977a; b) compiled the biological knowledge of 76 of the most significant global species. In the book, water hyacinth (**Figure 1**) is No. 8 in the order of importance, under Group **I** ("*18 of the most serious and troublesome weeds in the world"*). Unfortunately, in undertaking what was a noble task, looking at species mainly from an agricultural viewpoint, Holm (1969) described many colonizing taxa, including water hyacinth, as '*terrible villains*'.

Figure 1 Water Hyacinth (*Pontederia crassipes* Mart.) of the Family Pontederiaceae [1]

The opinions of Holm et al. were based on information from across the globe. The listing of the 'worst' weed species also included estimates of yield losses in major crops, gleaned from the *Food and Agriculture Organization* (FAO) data and other sparse literature. The species and information compiled more than 50 years ago, reflect the time when **all** weedy species were considered 'bad news'. Times have changed, along with concepts related to weeds. The corpus of weed science literature is now replete with articles that provide a better understanding of colonizing taxa and their undisputed ecological roles.

As more and more species are recognized as 'beneficial' from both agro-agricultural and societal perspectives (Marshall, 2002; Altieri et al., 2015), several in Holm's list of '*The World's Worst Weeds*' may not be considered as particularly harmful in the sense Holm and others saw five decades ago. The evolution of weed control technologies and tools, including herbicides, biocontrol agents and integrated weed management (IWM) systems have also enabled land and waterways managers the opportunity to 'manage' most weedy species well when they go awry, or where their sheer abundance becomes problematic in agricultural landscapes, waterways or in terrestrial situations.

One of the important questions in *Weed Science* is the vexed issue of 'conflict species'. Many species, derided with a dubious and unsavoury label as '*invasive alien species*' (IAS), have undoubted ecological values and can be valuable bioresources for both humans and animals. This topic has already received a great deal of attention as a 'new' science (*Invasion Biology*) emerged in the late 1990s. Terms, such as '*alien*', '*feral*', '*invader*' and '*invasion*', are part of the *Invasion Biology* lexicon. These terms create fear in the public's mind and impede the sensible management of colonizing taxa. Instead of using such terminology, managing pioneer taxa, where they are problematic should be done with a greater understanding of their strengths and weaknesses and a balanced approach (Sagoff, 2009; Davis and Thomson, 2000; 2001; Guiaşu and Tindale, 2018).

This article explores the option of '*living with weeds*' with the example of water hyacinth (abbreviated to WH from here on). Colonization of the Americas, Africa and Asia by Europeans, between the 14th and 19th centuries, saw the introduction of vast numbers of colonizing taxa, both plants and animals, from their native areas to other places. The taxa so moved and introduced elsewhere were seen as new sources of food, fodder and energy, and also of ornamental value (Chandrasena, 2019; 2023).

A review of global literature, dating back to the 1940s shows that for the past seven decades, the management of WH has been a complex issue, affected by local environmental and social conditions as well as societal values and economic returns that are not always profitable (Mara, 1976). In terms of adverse effects on the local environment and the costs of management, perhaps, no other species is of greater concern, globally. Therefore, to shift the emphasis from a simple, control-oriented mindset to beneficial utilization of such a species requires a re-examination of the ecological, environmental and social services it can provide. Lessons learned in the

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[1] The Kew Plant List's updated review [*Kew Plants Of the World Online*: (**https://www.kew.org/plants/water-hyacinth**] accepts water hyacinth's name as *Pontederia crassipes* Mart., first collected in Brazil and named by the German botanist Carl Friedrich Philipp von Martius (1794-1868) (first published in *Nova Genera Et Species Plantarum per Brasiliam. 1: 9* (1823). In 1883, another German botanist Hermann Solms-Laubach (1842-1915) renamed the species as *Eichhornia crassipes* (Mart.) Solms, a name, now considered a synonym (Kew Plant List, 2023). WH's native range extends from the Amazon Basin and rivers to Venezuela, Peru and even Jamaica (Kitunda, 2018).

re-assessment should set a benchmark on how we should approach any other robust colonizing species.

In a recent article on '*Living with floating aquatic invasions*', Kleinschroth (2021) argued for a '*nuanced perspective'* on aquatic plant infestations, moving away from futile eradication attempts towards an aquatic ecosystem management strategy, minimizing negative effects while integrating environmental and socio-economic benefits. In addition, Pin et al. (2018), Su et al. (2018), Bakrim et al. (2022) and Nega et al. (2022) have also recently reviewed value-added products that can be derived from WH biomass. The reviews also discuss constraints, challenges and opportunities to expand product valorization for the benefit of rural communities. Given the vast amounts of WH globally available for utilization and the equally vast amount of global research on WH, the premise of this article is also *that the species should be put to good use through appropriate technology and socially responsible, community-driven programmes*.

A Colonial Legacy

The plant's common name, water hyacinth, and the botanical name - *Eichhornia crassipes*- arose in Europe in the early 19th Century. The botanical name honoured the Prussian Minister of Education, Culture and Medicine - John Albert Friedrich Eichhorn (Kitunda, 2018). The name was given by the German botanist - Karl Friedrich Philipp von Martius (1794–1868) who made an expedition to the Amazon basin during 1817-1820. On his return, Martius became the curator of the Munich botanic gardens and later, Professor of Botany at Munich (1826-1864).

WH is a lasting colonial legacy of the legendary explorer - Alexander Von Humboldt - who first collected its specimens and seeds from along the Orinoco River, a tributary of the Amazon, in the early 1790s. The French Botanist Alire Raffeneau-Delile cultivated it in Egypt in the 1790s under the auspices of Empress Josephine and Emperor Napoleon. Delile had obtained WH seeds or seedlings, sent to Josephine by Von Humboldt (Kitunda, 2018).

Delile introduced WH to Africa through an expanding French network of Botanic gardens on the continent, paving the way for its spread quickly into many countries. About 150 years after its initial introduction in Africa, WH began to have the most compelling economic and social impacts in the 20th Century. According to Kitunda (2018), it was between 1880 to 1980 when WH transformed from a much-admired flower to an economically damaging pest in Africa and elsewhere. Societies began to look at WH as a pernicious legacy of "*the white man's burden*" to beautify Africa. The spread of WH across the globe was hugely influenced by human introductions and expedited by hydrology changes (flow impediments) and pollution of the waterways. From an early date, European armies discovered that in addition to its aesthetic value, WH could be a military asset to enhance camouflage on battlefields.

As Kitunda (2018) explains, in the 1850s, a British Agricultural Officer cultivated WH in the Nile River in Egypt. Within 20 years, WH emerged as an ecological disaster affecting the Nile. It then caused a crisis in South Africa in the 1910s, Madagascar in the 1920s, Tanzania, Uganda and Kenya in the 1930s through to the 1970s. In the 1980s and 1990s, WH bloomed heavily on Lake Victoria, the Nile, the Congo and almost all watercourses of Africa.

The knowledge of the adverse effects in Africa did not stop the British from introducing WH to Sri Lanka in 1904, possibly as a military asset. Within five years, WH thrived in polluted lakes, canals, and dams all over the island, in the absence of natural enemies and favourable conditions (stagnant water and year-round high temperature). Impenetrable masses formed within a few years in polluted water. Until about the 1960s, it was typical for untreated sewage and industrial wastewater to be discharged into waterways directly, providing a nutrient-filled environment for WH (Room and Fernando, 1992).

Often, within days, multiplying vegetatively, WH supplanted other aquatic plants by the sheer size of the floating carpet it formed over water. The floating mats restricted light penetration and impeded oxygen dissolution in water, affecting fish and other aquatic animals. The offensive smells emanating from rotting vegetation interfered with fishing, navigation and life in Colombo (the Capital City) and its suburbs. The rulers reacted by enacting *The Water Hyacinth Ordinance* (1909), prohibiting the import of WH. Twenty years later, the *Plant Protection Act of 1924* continued the prohibition. Even so, 100 years later, large WH infestations still thrive in polluted waterways, and in many of the island's ancient, lakes and irrigation canals, slow-moving rivers and wetlands (Room and Fernando, 1992).

In India, WH was introduced in 1896 by the British, also as an ornamental, initially kept at the *Royal Botanical Garden*, Kolkata. Within the next 100 years, it spread throughout the country, infesting waterways and dramatically affecting livelihoods in pre-independent India. WH's impacts on the economy were so huge that by the 1950s, it was called '*The Terror of Bengal*'. Even today, massive WH infestations exist in rivers, man-made canals and lagoons across the sub-continent (Gopal, 1987).

In the USA, in 1975, Vietmeyer called WH the '*Beautiful Blue Devil'*. In a recent review of its utilization, Ray and Chandrasena (2015) suggested it could also be '*Cinderella*' depending on one's viewpoint. WH is almost the perfect example of the paradox colonizing taxa pose to humans. In a recent book on WH, Kitunda (2018) called it "*the flower of life and death*" and traced how the species spread in the 19th century from the Amazon Basin to the whole of the British Empire. Admiration for the '*enchanting beauty*' of the purplish flower was why it was introduced to various countries via Botanic gardens.

Growth Characteristics

Boyd (1976), Gopal (1987, 1990), Centre et al. (1999; 2002), OEPP/EPPO (2008) and Coetzee et al. (2017) provide comprehensive reviews of various socio-economic and ecological effects of WH. Other reviews describe WH's growth characteristics (Boyd and Vickers, 1971) under varying conditions (Centre and Spencer, 1981; Wilson et al., 2007; USEPA, 2000; Gunnarsson and Peterson, 2007), and its reproductive biology (Barrett, 1980; Barrett and Forno, 1982; Zhang et al., 2010).

WH's exceptional success as a species is largely due to its capacity for clonal growth, producing ramets vegetatively on stolons. This reproductive strategy allows populations to rapidly expand (**Figure 2**). Under favourable conditions (i.e. high sunlight, temperatures around 28-32 ^{0}C, nutrient-rich water), populations can double in 8-10 days through vegetative growth. In addition, WH can produce up to about 3000 seeds in an inflorescence and typically, there are several inflorescences per rosette. The seeds can remain viable in sediments for up to 20 years. Large root masses, bulbous petioles, stolons and rhizomes characterize a mother rosette, which typically has several offspring ramets attached to it.

High rates of photosynthesis and growth, under favourable conditions, characterize WH. Its unique morphology (gas-filled air chambers in roots, leaves and stolons) also allows for high gaseous transport of O_2 and CO_2 (Coetzee et al., 2017). The main factors limiting WH's growth are salinity, temperature, nutrients, disturbances and natural enemies (Wilson et al., 2007). Studies have also shown that low levels of phosphorus (P) can be a serious limitation for WH's growth (Kobayashi et al., 2008).

The species shows high genetic diversity in its native range. However, the species is characterized by genetic uniformity in much of the introduced range. This is likely to have resulted from genetic bottlenecks associated with WH's migratory history and the rarity of its sexual reproduction (Barrett, 1980; Zhang et al., 2010). Da Cunha et al. (2022) recently confirmed the very high heterozygosity in the WH genome but low genetic diversity at different locations in its native range (Brazil). This finding contrasted with the closely related, 'anchored' WH [*Pontederia azurea* Sw.; syn. *Eichhornia azurea* (Sw.) Kunth], which is also a floating aquatic with prolific clonal growth. With extensive, interconnected rhizomes and roots, *P. azurea* differs from *P. crassipes* by being attached to sediment, although it can also form large 'floating' colonies at the edges of water bodies.

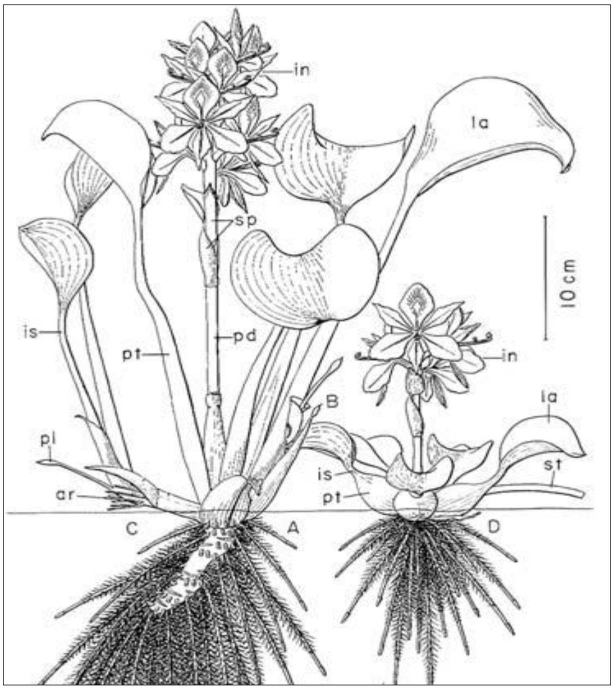

Figure 2 Morphology of *Pontederia crassipes* floating plants (From Center et al., 2002)

[**A**: the attenuated-petiole rosette form produced in crowded conditions; **B**: an expanding axillary bud; **C**: a developing ramet; **D**: bulbous-petiole rosette form produced as an offspring in open water conditions. **Abbreviations**: **ar**–adventitious root; **bb**–bud bract; **in**–inflorescence; **is**–leaf isthmus; **la**–leaf blade; **pl** –primary leaf; **pd**–peduncle of flower spike; **pt**–leaf petiole; **rh**–rhizome; **sp**–spathe; **st**–stolon]

However, even without much genetic diversity, in the introduced regions, the species can tolerate a broad range of adverse conditions in water. The basis of its high tolerance to a range of pollutants in water is through uptake and sequestration in roots or shoot tissues. The species can also resist pressure from herbivores, pests and diseases simply by the sheer mass of biomass it produces through clonal growth, complimented by fragmentation and spread by water.

Negative Effects

WH's negative effects include preventing navigation and fishing, causing aquatic biodiversity losses, oxygen depletion and fish kills when large infestations decay. Infestations also provide mosquito breeding grounds leading to an increase in vector-borne diseases, such as schistosomiasis and bilharzia in Africa. In addition, WH infestations also shelter rodents and other pests (Gopal, 1987; Gupta et al., 1996; Nega et al., 2022). However, the scale of these effects depends on the size of the infestations and how the mats are distributed over water surfaces (Coetzee et al., 2017; Honlah et al., 2022).

Villamagna and Murphy (2010) showed that the negative effects of WH are often non-linear to the infestation size. For instance, they found that the abundance and diversity of aquatic invertebrates generally increase in response to increased habitat heterogeneity and structural complexity provided by the large mats and root masses of WH but decline due to decreased phytoplankton (food) availability.

WH's adverse effects on fish are dependent on the original fish community composition and food-web structures. Abundant phytoplankton and epiphytic invertebrate communities are typically associated with the floating WH mats. These increase fish abundance and diversity. However, the opposite effect could also occur, especially with planktivorous fish. For instance, a decline in phytoplankton could have flow-on effects on the higher trophic levels. With waterbird populations, an increased abundance of fish and macroinvertebrates suggested a positive interaction, especially when WH populations were at moderate levels (Villamagna and Murphy (2010).

Control Options

The main options for managing WH infestations include physical removal either by hand or by machinery [2]. Manual removal is effective for small infestations, especially in well-contained small dams and lagoons. However, manual removal is unsuitable for large infestations over large areas, such as in Lake Victoria (Africa) and other lakes in affected countries or in large irrigation canals, such as in Florida (Mitchell, 1974; Cilliers, 1991).

Medium or large-sized aquatic weed harvesters have been available for more than six decades for the mechanical removal of WH. Newer designs of mechanical harvesters (Aquarius Systems, 2023), have been effectively deployed in many countries (i.e. Africa, India, Australia and USA). However, with mechanical removal, disposal of large quantities of the harvested biomass is a major obstacle, because of potential adverse environmental effects on canals, dams and river banks and the costs involved.

Since the 1960s, herbicides, such as 2,4-D, amitrol, diquat, paraquat and glyphosate have been used worldwide to reduce WH populations. While multiple applications are needed for effective control, herbicides provide only short-term relief (Center et al., 1999). Many hyacinth-infested sites are also used for drinking water, washing and fishing, so the use of herbicides contaminating such sites is also regarded as a threat to human health (Julien et al., 1999).

Biological control has long been the favoured method for WH control with several agents. Research on the biocontrol of WH was initiated by the USA in 1961, and the first control agents were released in Florida in 1972. Of the available agents, the most successful are the two Coleopteran weevils, *Neochetina eichhorniae* Warner and *Neochetina bruchi* Hustache [both Curculionidae] and the pyralid moth *Niphograpta albiguttalis* (Warren) [Lepidoptera: Pyralidae]. These agents are now well established in all of the countries where WH biocontrol has been implemented (Cilliers, 1991; Julien et al., 1999; Wilson et al., 2007; Coetzee et al., 2017). However, these agents do not wholly kill WH shoots but cause varying degrees of leaf mortality. Adult weevils, feeding on leaves, and larvae tunnelling through petioles and the meristematic tissue in the crown of the plant, can cause significant damage, preventing the populations from expanding (Julien et al., 1999).

In addition to insects, several fungal pathogens have also shown promise against WH (Charudattan, 1996; 2001). Among the most promising pathogens are: *Uredo eichhorniae* Fragoso and Ciferri, suitable as a classical biocontrol agent, *Acremonium zonatum* (Sawada) Gams, *Alternaria eichhorniae* Nag Raj & Ponnappa, *Cercospora piaropi* Tharp, *Cercospora rodmanii* Conway*, Myrothecium roridum* Tode and *Rhizoctonia solani* J. G. Kuhn. All of these fungal pathogens are widely distributed in different continents and can be developed further against WH for use in integrated management programs.

As reviewed recently by several research groups (Su et al., 2018; Pin et al., 2021; Udume et al., 2021; Nega et al., 2022; Karouach et al., 2022), none of the physical, biological and chemical control approaches, applied even in combination as 'integrated control' have been successful in the countries affected by the global spread of WH except at a very local and small scale. This is indeed the primary reason for a need to 'rethink' the WH control strategies and include WH utilization and product valorization as an integral part of its future management (Karouach et al., 2022),.

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[2] Controlling WH in affected waterbodies led to the founding of the *Hyacinth Control Journal* in 1962, which evolved to be the *Aquatic Plant Management Society* Journal in the USA in 1964 (APMS, 1964; (**https://apms.org/history/**).

Utilization Options

The socio-economic effects of WH on water bodies are clearly dependent on (a) the extent of the infestations, (b) the uses of the waterbody, and (c) the success of control methods used. However, despite being often branded as a villain, there is a *virtuous side* to this incredible colonizer that can be utilized for societal benefits. While the most effective strategies to control WH are known, control programmes often suffer from a lack of funding to have lasting impacts. Aquatic weed managers in most countries know that it is impossible now to eradicate WH where it has a foothold. Therefore, while efforts are made to contain the species where its local impacts are unacceptable, it is pragmatic to explore how utilization can be part of an integrated solution to controlling WH and also consider the obstacles to utilization.

Early Utilization Efforts

In an early study on utilization, an economist, Michael Mara (1976), used a fee of US$ 6.42 per wet ton of WH biomass in Florida, to estimate that the by-products do not defray the harvesting and transport costs of the weed. His view was that the high costs of harvesting, transport and conversion to compost, animal feed or other products would lead farmers to just ‘dump’ the material unless control programmes were subsidized or other ‘*economically feasible solutions’* were found for the harvested material.

In 1975, Vietmeyer reported how farmers in Bangladesh and Burma used large mats of WH to create floating vegetable gardens. This was done by heaping lake sediments and organic muck on top of packed carpets of WH and other reeds. The artificial beds were suitable for growing various popular vegetables. The ample nutrients in the polluted rivers also helped the water hyacinth to grow prodigiously.

In the USA, early utilization research focussed mainly on using aquatic weeds to remove nutrients, metals and other pollutants from wastewater. On assignment for the FAO, David Mitchell (1974) compiled a report on ‘*Aquatic Weeds*’ focusing on their uses and control. The report included Chapter 7 from Claude Boyd (1974), which demonstrated the enormous utilization potential of aquatic plants. Boyd and Mitchell's reviews (1974) summed up the opportunities for utilizing WH and other aquatics as fish and livestock feed, compost and mulch. The reports also discussed the potential for WH use in removing pollutants from effluents and the industrial uses of the biomass, for paper making, basket work, biogas, and alcohol production.

In 1978, Arnold Pieterse revised the information available, showing a remarkable increase in WH research over the previous 30 years. Discussing the *paradox* presented by WH, as a global pest and, also, as a useful species, Pieterse (1978) highlighted the need for balancing the costs of WH control in different situations versus the benefits of its utilization.

Recent Utilization Efforts

The greatest majority of articles on WH describe laboratory or pilot-scale studies that provide potential evidence of utilization. A smaller number of articles comprise *in situ* water purification studies. Other articles emphasize how communities affected by WH infestations can reduce environmental impacts by putting WH to good use. The evidence from India, Africa, China, Indonesia, Philippines and other countries is convincing to argue that WH has numerous utilization options that communities can benefit from. As highlighted recently by John (2016), Feng et al. (2017) and Kleinschroth et al. (2021), people can clearly use this biomass as food for domestic animals, fertilizer and green manure, as well as raw material for various industries and as feedstock for biogas and bio-ethanol production

This review finds the most valuable WH practical utilization aspect to be the use of the plant’s strengths to extract N and P nutrients from wastewater. The same application can extend to extracting heavy metals from industrial effluents. Both applications could utilize WH, either alone or in combination with other pioneer species, such as cattails (*Typha* L. spp.) and common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] in constructed wetland treatment designs. In both these aspects, the effectiveness of WH in extracting pollutants in water depends on (a) having a sufficient population of colonies for uptake, (b) the concentrations of the contaminants, (c) the duration of exposure for uptake and (d) favourable growing conditions. These are factors that can be manipulated in well-controlled systems designed to optimize contaminant uptake while controlling the risks of the spread of WH. Regular harvesting of the WH biomass also assists its utilization for wastewater purification by allowing new growth to occur.

Nutrient removal from effluents

In the USA, WH has been used in constructed wetlands for wastewater treatment to remove N and P pollutants for several decades. In sewage treatment ponds, WH doubled every 6-18 days, producing 130-360 kg day^{-1} ha^{-1} of dry weight (DW) (Wooten and Dodd, 1976; Wolverton and McKown, 1976; Wolverton and McDonald, 1976; 1979).

Under tropical conditions, in nutrient-rich water, a single plant produced 65,000 offspring in a single growing season. One hectare of WH can have more than a million individuals. Such populations produced 3-6 tons of fresh weight (FW) ha^{-1} day^{-1} in the North American growth season (ca. 244 days) (Reddy and Tucker, 1983; Reddy and Debusk, 1987). No other plant on earth can produce such a colossal biomass. It is this vigour that makes WH ideal for utilization.

About 95% of WH's biomass is water, while the tissues contain ca. 2.5% of N and 0.5% of P. Under favourable conditions, the biomass produced in a day in one m^{2} can be as high as 60 g DW (1.2 kg FW m^{-2}) in nutrient-rich effluent. Such biomass (20-40 tons FW ha^{-1}) can remove N waste of over 2000 people and P waste of over 800 people. The nutrient removal rates from sewage water were 2.16 kg of N and 0.54 kg of P m^{-2} day^{-1} (equivalent to up to 5850 of N and 1125 kg of P ha^{-1} year^{-1}) (Debusk and Ryther, 1981; Debusk et al., 1983; Reddy and Debusk, 1987).

WH is a key component of the floating aquatic species in the Constructed Wetland Treatment Systems installed in the USA (USEPA, 2000). In 2002, a WH-based wastewater treatment system (WHS™) was patented by HydroMentia (2002), a Florida-based company. Installed at Florida's Lake Okeechobee, the system was successful in removing nutrients from non-point sources when combined with an *Algal Turf Scrubber* (HydroMentia, 2005). However, the uptake of this technology [ATS™-WHS™] has been slow largely due to the negative perceptions of WH and operational costs (Mark Zivojnovich, HydroMentia, *pers. comm*., 3 Dec 2023).

In India, growing in diary waste, WH significantly reduced the effluent's Biological and Chemical Oxygen Demand (BOD and COD), as well as Total Suspended Solids (TSS) and Total N (Trivedy and Pattanshetty, 2002). In Sri Lanka, free-floating WH growing in a wetland removed both N and P by nearly 100% in nine weeks (Jayaweera and Kasturiarachchi, 2004; Jayaweera et al., 2008).

Table 1 provides a summary of WH's nutrient removal efficiencies from wastewater (Vymazal, 2001), which shows that WH is suitable for small or medium-scale wastewater treatment units.

In a promising new development for domestic water treatment, Valipour et al. (2015) improved the efficiency of a continuous-flow, constructed wetland system further, based on combining WH's extractive capacity with microbial biofilms. In the pilot-scale '*Bio-Hedge*' units, nutrient-consuming bacteria grow on both WH roots and biofilm surfaces provided by a mesh-type matrix. In the 12-month study, WH grew slowly (growth rate of 1.2% day^{-1}) but extracted N and P effectively. The biomass contained 27 mg N g^{-1} (roots) and 44 (shoots) mg N g^{-1} DW, and 5 (roots) mg N g^{-1} and 9 mg P g^{-1} DW, respectively.

Table 1 Pollutant Removal Efficiencies of a typical WH-Based Constructed Wetland System

	Concentration (mg L-$^{`1}$)		
	Influent	**Outflow**	**Efficiency (%)**
TN	14-15	6-7	60
TP	3.8-4.0	2.0-2.5	47
TSS	48-50	9-10	64-65
BOD	80	14	76
	Loading (tons ha^{-1} year^{-1})		
	Influent	**Outflow**	**Removal**
TN	8.4	4.3	4.1
TP	2.0	1.3	0.7
TSS	109	56	53
BOD	96	20	76

The study isolated more than 23 strains of bacteria growing in the '*Bio-Hedge*' media (4.06 × 10^{7} colony-forming units, cfu cm^{-2}) and plant roots (3.12 × 10^{4} cfu cm^{-1}), consuming nutrients. The capital cost to treat 1 m^{3} d^{-1} of wastewater, was US\$78 m^{-3} (inflow) and US \$465 kg^{-1} of BOD$_5$ removed. Although the design is a promising low-cost technology, this system also needs further development (Alireza Valipour, *pers. comm.*, 20 Nov 2023).

The literature indicates that the harvested WH, following utilization for wastewater treatment, can be valorized for various industrial applications with some additional processing. To eliminate the risks of mineral imbalances and potential contamination (due to contact with human waste and other impurities), the harvested WH biomass should not be used for animal feed. However, the material can be easily processed to become raw material for industries, such as paper and pulp, construction materials and the production of biogas, bioethanol and biochar.

Phytoremediation potential

The second most promising utilization option appears to be the use of WH for a broad spectrum of phytoremediation roles. In early studies, Woolverton and Mckown (1976) showed that one hectare of WH can remove 160 kg of phenol in three days from a polluted source. In later research, the potential of WH for extracting and bio-accumulating heavy metals, such as cadmium (Cd), mercury (Hg), nickel (Ni), chromium (Cr), silver (Ag), lead (Pb) and zinc (Zn) from agricultural and industrial effluents has been amply demonstrated (Muramoto and Oki, 1983; Pinto et al., 1987; Zhu et al., 1999; Ingole and Bhole, 2000; 2003; Liao and Chang, 2004; Ebel et al., 2007).

Zhu et al. (1999) showed that WH efficiently extracted metals from wastewater, mostly when the metal concentrations were low (range of 0.1-1.0 mg L^{-1}). At higher concentrations (5-10 mg L^{-1}), plants grew much slower although they still bioaccumulated various metals. In phytoremediation, the efficiency of the uptake of a pollutant is usually measured by the Bio-Concentration Factor (BCF). BCF is the ratio of the concentration of the element taken up in roots or shoots against its external concentration. High BCF values (Cd, 2150; Cr, 1823, Cu, 595) showed that WH was efficient at phytoextraction of those metals and possibly, also Selenium (Se) (Zhu et al. (1999).

Similar studies have confirmed WH's impressive capacity for bioaccumulating Cd, Cr, Ni, Pb, Zn, Ag, Hg, copper (Cu), manganese (Mn) and arsenic (As), from various industrial effluents (Pinto et al., 1987; Ingole and Bhole, 2000; 2003; Liao and Chang, 2004, Lu et al., 2004). Adding to the studies, in Bangladesh, Misbahuddin and Fariduddin, (2002) argued that WH can form the basis of a low-cost method to remove As from domestic drinking water drawn from wells. In India, Tiwari, et al. (2007) showed that WH efficiently removed Pb, Cr, Zn, Mn and Cu from effluents and bio-accumulation was greatest with Pb, Zn and Mn.

Ebel et al. (2007) showed that WH effectively cleaned up cyanide (CN) produced in small-scale (illegal) gold mining in South America. The studies showed that WH was much more effective than willows (*Salix* L. spp.) in CN removal and completely eliminated it from effluents (up to 10 mg/L) without plant growth being affected. They argued that since CN in aquatic ecosystems is fatal for fish in the ppb range, WH should be used in closed and controlled CN treatment ponds in regions where the species is already present with no risks. More recently, Newete et al. (2016) showed that WH bio-concentrated Cu, Hg, gold (Au) and Zn above the standard BCF index of 1000 $\mu g\ g^{-1}$ DW (1 $g\ kg^{-1}$ DW).

The evidence available from research, at both pilot scale and field applications, shows that it is possible to utilize this remediation potential of WH to reclaim aquatic habitats polluted by moderate levels of heavy metals. The process can be expedited by regular harvesting of spent plants. The proposition - that the biomass generated during phytoremediation could be used to produce biogas, bioethanol paper or other products – is valid (Feng et al., 2017) although, practical applications are still constrained by the unwillingness of countries to adopt WH technologies.

Despite decades of research, not much is known about the mechanisms by which WH tolerates heavy metals and other organic pollutants. The speculations are that WH may be sequestering potentially toxic compounds in non-living lignified tissues, including cell walls, which provide the structural support for the bulbous plant with air chambers. Pollutant molecules could also be adsorbed onto the surfaces of the extensive root biomass, where they decay or get chemically transformed. The mature plants usually slough off root materials, so any adsorbed material sinks to become benthic detritus.

Nearly 20 years ago, Ghabbour et al. (2004) isolated humic acids from leaves, stems and roots of water hyacinth growing in the Nile Delta in Egypt and suggested that these acids confer the strong metal and organic solute binding capacity to the species. However, future research will have to unravel this extraordinary capacity of water hyacinths.

In the CN extraction studies, Ebel et al. (2007) hypothesized that CN must be metabolized inside WH and released as CO_2 after uptake. They found no traces of CN or related metal complexes several days after uptake by WH cells. One possibility suggested was that CN may be getting converted to asparagine, an amino acid known to help plant cells detoxify ammonia (NH_4) and other compounds. Asparagine may then be mineralised to CO_2 and released into the atmosphere (Ebel et al., 2007).

A recent '*proof of concept*' paper from the UK by Jones et al. (2018) raised the possibility of WH use in Europe for pollution remediation. In bench-top studies, WH removed 63% aluminium (Al); 62% Zn; 47% Cd; 22% Mn and 23% As within six hours of exposure. Adding to the bench-top study findings, *in situ* experiments in a polluted river in the U.K., also showed that WH extracted Cr, Cu, Pb, antimony (Sb), vanadium (V) and titanium (Ti) while growing in less-than-ideal conditions. The results prompted Jones et al. (2018) to recommend the introduction of the species into EU countries where it is currently banned and for use in pollution removal. The authors also pointed out that WH will not survive the extremely cold northern winters, which will control its spread.

Bio-briquettes as Domestic Fuel

In several African countries, WH biomass is converted to bio-briquettes, which is an alternative domestic fuel source. Briquetting is the densification of biomass to increase the energy density of different biomass residues (Nega et al., 2022). In this utilization, carbonized WH (similar to charcoal) is converted into briquettes with algae, gum arabic or cassava starch, used as binders. The briquettes are low-cost fuel, comparable with charcoal in energy density (Rodrigues et al., 2014; Rezania et al. (2016).

A study in Nigeria (Davies and Davies, 2013) showed that carbonized WH biomass mixed with scooped-up and sun-dried phytoplankton scum made effective briquettes, to generate heat energy (calorific value of 18 $MJ\ kg^{-1}$). In addition, a Kenyan study (Rodrigues et al., 2014) showed that carbonized WH, converted to briquettes with gum Arabic, yielded a calorific value of 15.4 $MJ\ kg^{-1}$. Although the energy yield was about 45% of the calorific value of charcoal made with local wood (ca. 33 MJ kg^{-1}), given the abundance of WH, the study argued for the adoption of the technology to benefit local communities.

Figure 3 (A) An image of Bio-briquettes made up of WH charcoal and molasses (from Carnaje et al. (2018); (B) Bio-briquettes made with WH: EFB (from Rezania et al. (2016)

Adding to this research, in Malaysia, Rezania et al. (2016) mixed the left over refuse (empty fruit fibres, EFB) from the oil palm industry with dried WH biomass and cassava starch as a binder to make bio-briquettes that were effective for domestic use. The best calorific value was obtained by mixing the dried WH and EFB at a ratio of 25:75 (17.2 MJ kg^{-1}). The dried WH alone, formed into a briquette with cassava starch, also gave a calorific value of 14.4 MJ kg^{-1}.

Recent research in the Philippines by Carnaje et al. (2018) described the carbonizing of WH biomass at temperatures between 350-500°C, producing charcoal. The WH charcoal, blended with molasses at 30:70 (charcoal: molasses ratio), produced stable briquettes with high calorific value (16.6 MJ kg^{-1}) and compressive strength (19.1 kg cm^{-2}). Such research clearly shows that converting carbonized WH into an alternative fuel source should be a viable utilization option in developing countries aiming for technologies to reduce waste and the felling of trees as fuelwood.

Biofuel - Biogas and Bioethanol

Biogas is composed primarily of methane (CH_4) and carbon dioxide (CO_2) and is produced by anaerobic fermentation of lignocellulosic biomass left over from crops, manures, sewage, green waste and other plant material. Research over the past three decades (El-Shinnawi et al., 1989; Singhal and Rai, 2003; Feng et al., 2017) has proved that semi-dried WH biomass is highly suitable for fermentation to produce biogas. Mixing with animal manure, municipal waste, or sewage sludge increases the biogas yield. A usable quality gas (60% methane, CO_2 and ammonia) can be obtained within 15–20 days. WH, 100 kg of semi-dried shoots can yield up to 400 Litres of biogas daily. The leftover by-product has a high manure value and can be used as fertilizer.

WH biomass is typically rich in N (up to 3.2% of dry matter) with a C/N ratio of about 15-20, which makes it a suitable substrate for biogas production. The nutrient-rich sludge from the biogas can be used as a fertilizer for the nutrient-deficient soils in Africa, while the high protein content makes it suitable for use as fodder for cows, goats, sheep and chickens (Gunnarsson and Peterson, 2007; Feng et al., 2017).

A recent study from Kenya (Omondi et al., 2019) found that air-dried WH, mixed with slaughter house waste (SW) could be co-digested to produce high-quality biogas with high quantities of CH_4. The gas yield improved from 14 L kg^{-1} at 24ºC to 40-52 L kg^{-1} of air-dried WH at 32ºC and 37ºC. A WH: SW ratio of 30% showed optimum acclimatization and methane yield in a residence time of 60 days.

In an early study from Thailand, Isarankura-Na-Ayudhya et al. (2007) examined WH biomass as a feedstock for bioethanol production. The researchers used a two-sequential process of acid hydrolysis of dried WH biomass (hemi-cellulose content of 33% DW) with 10% H_2SO_4 (1:10 ratio), and the yeast *Candida shehatae* strain TISTR 5843 to produce liquid ethanol. Fermentation by the yeast at 30^{0}C for three weeks gave a maximum ethanol yield of 0.19 g of ethanol per gram of DW produced at a rate of 0.008 g L^{-1} h-1, which was comparable with the yields of other common bioethanol-producing feedstocks.

In India, Mannivannan and Narendhirakannan (2014) showed that the cellulose, hemicelluloses and lignin contents of WH ranged from 23-50%, 18-22% and 3-28%, respectively. When the dried biomass was pre-treated with dilute H_2SO_4, the hydrolysis produced a delignified substrate on which the fungal strain *Trichoderma reesei* grew strongly, producing ligno-cellulolytic enzymes (cellulase and xylanase). The enzymes degraded the substrate further to hexose and pentose sugars, which were then fermented aerobically by several yeasts (*Pachysolen tannophilus*, *Candida intermedia*, *Pichia stipitis* and *Saccharomyces cerevisiae*) yielding bio-ethanol.

The bioethanol yields were in the range of 0.021-0.043 g g^{-1} of WH biomass and were comparable with other low-cost materials that are used to produce bioethanol. The results of such studies prove the suitability of WH biomass as feedstock for bioethanol production (Feng et al., 2017). Despite the potential and the environmental advantages, the available evidence is that this utilization option is also yet to be widely adopted in different developing countries, possibly due to technological constraints.

Compost and Green Manure

WH biomass has been considered invaluable for conversion to compost since the 1940s. With high moisture retention properties and high levels of N, P and K nutrients, WH compost, which is typically, alkaline, makes a good soil supplement for acidic and sandy soil. In the USA, it takes 3-6 months to make a good compost, depending on temperature and aerobic conditions (Wolverton and McDonald (1976; 1979). In India, composting takes only about 50-60 days and decomposition is expedited by urea and lime, each at 2-5%, or cow manure (10%) added to the chopped-up WH. Frequent turning over is necessary to keep the decomposing biomass aerated. However, Indian farmers are reluctant to convert WH to compost because the process is labour-intensive (Hasan and Chakrabarti, 2009).

One ton of WH compost has about. 20 kg of N, 11 kg of P and 25 kg of K (equivalent to 105 kg of ammonium sulphate, 69 kg of phosphate and 50 kg of potash, respectively). This compost, fortified with mineral fertilizer at 20:1 gives high crop yields. WH biomass can also be mixed with cow manure and domestic waste to make high-quality compost. Given that fresh WH has a low C/N ratio of 16-20, mixing with other cellulosic material and raising the C/N ratio to about 60 gives microbes a balanced substrate to produce the best quality compost (Montoya et al., 2013; John, 2016; Ayanda et al., 2020).

Udume et al. (2021) recently confirmed that WH compost is alkaline (pH 7.4-8.1) and can be bio-converted to both compost and biochar as part of ‘green’ inexpensive technologies and used as soil amendments for acidic soils. In their view, combined with molasses or cattle manure slurry, WH compost can also be used in the restoration of hydrocarbon-polluted sites in Africa (Udume et al., 2021). Yan et al. (2017) suggested that the high biomass produced by WH (ca. 150 tons DW ha^{-1} $year^{-1}$) makes it suitable for use as green manure as well. Soil incorporation of biomass may give better crop yields, although the evidence of this utilization is not common.

Animal fodder

The case studies from Africa and other developing countries show that the availability of crude protein (about 20-30 % of DW) and sugars make WH a good fodder, although stalks contain calcium oxalate crystals. The best fodder or silage is obtained by chopping up WH and mixing it with other hay (grasses or legumes) (Abdelhamid and Gabr, 1991; Tham and Udén, 2013).

Fresh WH leaves, cooked with rice grain and fish feast and blended with vegetable waste, rice bran, salt and copra meal are utilized as feed for pigs, ducks, and fish in many countries, including Thailand, Malaysia, China, and the Philippines (Nega et al., 2022). In Sri Lanka, a recent study by Fouzi and Deepani (2018) demonstrated that dried and powdered WH leaves could make up to 20% of fish meal (mainly contributing concentrated protein) fed to Nile tilapia (*Oreochromis niloticus* L.), thus making a considerable saving on standard fish meal.

Raw Materials for Industries

WH provides raw materials for various handicraft industries, including paper-making, paper pulp, grease-proof paper, several kinds of fibre-board, yarn and rope and the world-famous WH furniture (Olal et al., 2001; Olal, 2003; Nega et al., 2022). In recent years, international funding has been focused on a renewed and significant interest in such uses of WH to create a variety of products and employment opportunities for communities (Montoya et al. 2013; Pin et al., 2021; Udume et al., 2021; Kleinschroth et al., 2021; Honlah et al., 2022; Xu et al., 2022).

In many countries, including Sri Lanka, women’s groups and others (such as handicapped groups) have come together to form “*Community-Based Organizations*” to harvest and process WH and manufacture a variety of products, such as WH paper, diaries, cards, lampshades, baskets, footwear, ropes and cordage. Reports from Africa indicate that along the Nile, WH is turned into ropes, which are used to make makeshift bridges across the mighty river.

Various research groups have documented that weaving and crafting are low-cost economic activities for rural villagers around WH-affected lakes in Central Africa. These crafts require only simple inborn skills. In Africa, crafted products from WH have a market from the resident populations as well as tourists from overseas and visitors at large. Added to crafting are the extensive and large-scale uses of dried WH as compost and animal fodder. These means of practical utilization have led to a general perception prevalent in African villages that WH is really a ‘*blessing*’ that empowers both women and men and is ‘*not always a menace’* (Olal et al., 2001; Olal, 2003; John, 2016).

Numerous initiatives for WH utilization are already underway in Africa and South-East Asia, from low-technology cottage industries to large, livelihood programmes. Many projects aim to minimize the local impacts of the species on waterways. In Thailand, King Bhumibol (1927-2016), Thailand's 9th Monarch, favoured WH utilization and his initiatives for 'eco-friendly' technologies gave impetus for the use of WH for pollution remediation (Chunkao et al., 2012).

Additionally, in Thailand, Vietnam and Indonesia, many companies produce WH furniture. basketry and other woven household items as part of sustainable '*nature-based*' solutions. In addition, WH forms the core raw material for a popular brand, '*Yothaka',* which was created by a pioneer design architect in Thailand - Suwan Kongkhunthian. As he explained:

> *"…The challenge* [with water hyacinth] *is to transform what people perceive as Sawa ('floating garbage') into something of economic use, and even more so, into aesthetically pleasing designs. The transformation has to meet lifestyle trends to be marketable…"* (Chanasongkram, 2016).

While many countries have been producing WH products for decades, the boldest move to promote the utilization of the species has come from Bangladesh, which has vast areas of waterways affected by WH In 2021, Bangladesh's *The Business Post* reported that at least 50-60 types of products are made using water hyacinth, including baskets, table mats, notebooks, toys and gift items, which have a huge demand in America, France, Spain, Germany, Ghana, South Korea, Taiwan and Kenya.

Labelling water hyacinth as '*Once a Weed Now a FOREX Resource*' Entrepreneurs estimated that: '*Bangladesh can earn Bangladesh Taka 20-30 crores (US $ 1.86 to 2.72 million) yearly while nearly 1 lakh of people will find jobs in this sector within several years*'. Vietnam, China, Thailand and Indonesia are key players in the global market saturated with products based on water hyacinth. One local company (***Eco Bangla Jute Limited***) sells products worth US $ 60-70,000 made from water hyacinth per year and is planning to further expand its market to Japan, Germany, the USA and Hong Kong only to draw buyers' attention (**Figure 3**).

Figure 4 A Schematic showing how Water Hyacinth is being promoted for cultivation in Bangladesh "Once a weed, now a new source of forex" (Credit: *The Business Post*, 21 Aug 2021 https://businesspostbd.com/national/once-a-weed-now-a-new-source-of-forex-23304

To support the industry and its foreign revenue earning capacity, instead of just relying on the naturally growing WH, Bangladesh entrepreneurs are planning to formally cultivate the plant commercially or preserve the harvests with a view to utilization all year round. Many entrepreneurs have identified the shortage of raw materials to meet the soaring demand from foreign clients as a significant obstacle. Such an attitude, supported by industry leaders, scientists, governments and civil society, bodes well for the required paradigm shift of '*living with weeds*'. This applies to not just WH but also other colonizing species from which large volumes of inexpensive plant biomass can be guaranteed for human benefits.

Other Potential Utilization Options

Apart from the above-mentioned utilization options of WH, this review finds several other potential uses, which have moved beyond the '*proof-of-concept'* stages. Several uses are related to chemicals that can be extracted from the species and other chemical characteristics of the WH biomass. As shown by the available literature, there is notable research interest in these uses, which involve various forms of pre-treatments and chemical processing. However, most are still in the experimental stages and are yet to be fully developed for commercial use.

Source of Biochemicals

More than five decades ago, Shibata et al. (1965) isolated Eichhornin as a new anthocyanin pigment from the purple flowers of WH and Gibberellin-like substances from WH roots. Although Eichhornin, a 3-diglucoside of delphinidin, has anti-oxidant, anti-inflammatory and nutraceutical properties, these properties are yet to be used for medicinal purposes.

A review of phytochemicals in WH by Lalita et al. (2012) showed an impressive list of chemicals that can also be extracted in commercially viable quantities from plants. These include carbohydrates (glucose, D-xylose, D-glucose and L-arabinose), cellulose, proteins, amino acids and vitamins, especially Vitamin A. Roots and stolons of WH also yield stigmasterol and diosgenin, both of which are used to synthesize progesterone and cortisone. Nonetheless, recent literature on WH as a source of biochemicals is limited, which leads to the conclusion that technological barriers may be limiting these experimentally justified utilization options.

Utilization for Biopolymers

In recent years, research has been focused on using WH biomass for developing cement composites and degradable biopolymers. A study conducted by Salas-Ruiz et al. (2019), showed that WH root ash could be used as an alternative to 'pozzolans' (finely ground silica and aluminous materials) in cement matrices to manufacture particleboard and other construction materials. These composites are cheap and eco-friendly products that can help in promoting waste recycling and pollutant elimination.

In addition, WH can be combined with several other agricultural residues (i.e. bagasse and rice straw) and transformed to produce bioplastic with biodegradable qualities that can readily be used as substitutes for synthetic plastics (Nandiyanto et al., 2023). In an important '*novel approach*', Saratale et al. (2020) showed how alkali and acid pre-treated WH biomass hydrolysate could be converted by saccharification into Poly-β-hydroxybutyrate (PHB) by the Gram-negative bacterium - *Ralstonia eutropha*. PHB is a high-value, degradable, crystalline bio-polymer with high tensile strength and durability. As Saratale et al. (2020) argued, sustainable PHB production using abundant, non-edible and renewable carbon sources, such as WH biomass, will contribute to reducing waste and the up-cycling of potential waste to high-value products. However, producing degradable biopolymer molecules in this way is sophisticated technology, as it involves fermentation by a specialist bacterium.

Extending the biopolymer to produce 'eco-friendly' 'bio-plastic' requires an additional step of combining the polymer with different kinds of starches, such as cassava, sago and corn starch. While this complex application is promising for the future of WH biomass utilization, it is still under development and yet to be optimized for commercial scale applications.

Utilization as 'Biosorbent'

Early studies by Schneider et al. (1995) proved that WH leaves were strong candidates for use as an inexpensive 'biosorbent' material to remove industrial dye discharges from polluting waterways. Dried WH leaves or root biomass have a high affinity and large sorption capacity for the removal of metal ions, such as Cu, Cd, Pb, Cr and Zn. The high adsorption affinity appears to be due to hydroxyl and carboxylate groups on the surface of WH biomass. Schneider et al. (1995) further suggested that dried WH biomass might be placed in simple bags and used in a very low-cost metal ion removal system for decontamination of mining industrial wastewater.

A recent study by Ramirez-Rodrigues et al. (2021) showed how effective dried and powdered WH leaves were as a biosorbent for removing pollutants from industrial effluents, on a large scale. The pore size of the powdered WH material (2.25 nm) indicated that it was a mesoporous biosorbent. In the specific application, the powdered WH, placed in a 'packed-bed column', efficiently extracted and removed Acid Red AR27, an anionic dye. AR27 is one of the most common dyes used in colouring textiles, leather, paper, confectionary, pharmaceuticals, food and beverages, and often linked to polluting waterways. Ramirez-Rodrigues et al. (2021) highlighted that the high effectiveness, versatility, ease of use, as well as low fixed and operating costs, made WH eminently suitable as a future biosorbent for industrial uses.

However, as discussed by Mahmood et al. (2010), Mahamadi (2011) and Hasan et al. (2010), utilization of the dried and powdered WH biomass in industrial-scale applications is still far from being realized. Factors, such as pH, temperature and adsorbent dose, affect the biosorption capacities of the WH biomass. Despite this promising utilization option, more research appears to be still required on optimizing the adsorbent processes and resolving technical issues, such as structural properties of the biosorbent, desorption with chemical eluants and biosorbent modification for continuous flow utilization.

Obstacles to Utilization

As with any technology, there are barriers to WH utilization, which need to be overcome. Some obstacles require technological solutions, while others need community support and political will for implementation. Some developing countries are slow to utilize WH because the systems to deal with its spread from an existing, infested area are not well developed. This means that education is a key component in the integration of utilization of WH with its management, where required, in different settings.

The literature shows that WH could be harvested at an affordable cost for biomass processing on a large scale (about one million tons year^{-1}) in developing countries, including Africa and India. Scientists and policy-makers would have to put forward a case-by-case analysis of cost-benefits, under local conditions, before utilization can become more widely accepted (Coetzee et al., 2017).

In some countries, there are challenges related to efficient harvesting and dehydrating WH biomass without making unacceptable local environmental impacts. The deliberate cultivation of WH for utilization will also be challenging in some situations without adequate safeguards to manage the known undesirable effects of WH on aquatic ecosystems to which it can spread. In addition, developing portable, high-efficiency facilities for harvesting, processing and dehydration are needed, as well as further improvements in product valorization (Su et al., 2018; Pin et al., 2021; Nega et al., 2022).

Despite the well-published successes, this review finds that the WH-based wastewater pollution removal technologies are yet to be adopted widely by many countries where possibilities exist. Among the main obstacles to adoption are concerns about increased risks of spread, other misconceptions about utilizing a well-known colonizing taxon and costs involved in transferring the technologies.

In Australia, the zero-tolerance attitude towards WH prevents people from exploring its utilization. The entrenched view is that the costs of managing outbreaks far outweigh any beneficial uses. In most advanced economies, labour is expensive and also not readily available for weed management and other laborious tasks. Furthermore, the costs of mechanical harvesting, machinery and transport of any ‘green’ material and processing are also usually prohibitive. Consequently, efforts for the practical utilization of WH as an inexpensive plant biomass will most likely be made only in developing countries.

Given the abundance of WH in South and Southeast Asia, and Latin America, including the Caribbean, and Africa, various practical applications are likely to be utilized simply because people need cheap and plentiful raw materials to generate income. Even then, utilization may be best practised as small-to-medium scale enterprises (paper pulp, compost) or as cottage industries. However, even in these countries and regions, WH utilization will need government support and policy changes within frameworks of creating sustainable economies.

Other obstacles to WH utilization are related to the optimization of effective technologies, which require investment. Local solutions for product valorization should ensure an effective supply chain and market opportunities for WH by-products (Pin et al., 2018). Such challenges need to be overcome in different countries with knowledge exchange and technology transfer, especially in industrial-scale applications. Well-trained people with aquatic weed management and ecological expertise, as well as ecological literacy, are required to monitor and manage any spread risks. The literature on WH also indicates the important role non-governmental actors and civil society can play in taking the lead in utilizing the power of this incredible colonizing species.

Australian climate modellers (Kriticos and Brunel, 2016) recently showed that there is a high potential for future WH range expansion in Europe and the Northern Hemisphere, under global warming. However, cold temperatures will contain the species. In the Southern Hemisphere, WH will most likely expand southwards in Argentina, Australia and New Zealand, threatening waterways in those regions. In inter-connected European countries, it will be hard to stop the spread of WH because of the limited biosecurity capacities within the EU countries and porous borders (Kriticos and Brunel, 2016).

Globally, large and small-sized machines that can effectively harvest WH are now available. The steps to efficient harvesting, drying, processing and conversion of WH biomass to usable raw material are also well documented and attested by a large volume of articles. Countries should use this knowledge to address any unacceptable risks that infestations may pose in different situations. If practical use can be merged with appropriate (low-cost and low-energy) technologies, WH utilization options can indeed be expanded for societal benefits. Broadly, WH utilization should a part of a “green” ecosystem-based climate adaptation strategy. The species and its strengths are too valuable to be ignored.

The literature shows that no single country into which WH has been introduced has managed to contain its establishment and biogeographical range expansion. In other words, WH epitomises successful colonizers, who should be admired for those qualities and, where possible, put to good use. The incredible capacity of WH to convert solar energy to biomass, along with its reproductive ability, are the reasons why its infestations are hard to control. Nutrient-laden waterways ensure its luxuriant growth on water. Fragmentation of colonies readily occurs, ensuring further expansion and spread of the species.

‘Seeing’ Water Hyacinth with ‘New Eyes’

Way back in the 1960s and 1970s, aquatic weeds were seen as ‘‘*the symptoms of human failure to manage our resources*’ (Pirie, 1960; Holm, 1969; May, 1981). In those days, the utilization of aquatic weeds, mainly as biofertilizers and animal feed, was an incidental ‘spin-off’ from which farmers could recover some costs of control (Mara, 1976). However, purposeful utilization of WH for sewage and industrial wastewater treatment then evolved in the 1970s decade, proving how valuable the species can be (Wolverton and McDonald, 1976; 1979).

This vast literature on WH available from across the continents provides a comprehensive *knowledge base* of its biology and ecology, either as an individual species or in mixed populations, as well as resistance to control. The factors that contribute to the spread of WH across regions and containment are also well known. Despite this knowledge, there are justifiable concerns in some countries about the further spread and the environmental risks WH poses, given that its unmanaged populations have created havoc over more than a century in most countries. This dominant narrative continues to be the main obstacle to utilization despite the vast evidence from research, which shows that WH is *unlikely to engulf* the world.

In managing WH infestations, science-based aquatic weed management strategies are needed to get their full benefits. Country-by-country approaches are needed in developing countries, which are affected by vast populations of WH. Biogas, bioethanol, compost, and use in pollution removal all appear as viable options, despite the absence of cost-benefit analyses or life-cycle assessment studies.

As discussed in this essay, the conversion of WH biomass into other industrial raw materials is a well-proven application. It all comes down to society’s preparedness, backed by science, to accept the potential of a colonizer to provide immense benefits in an uncertain future and ‘*learn to live*’ with it (Kleinschroth et al., 2021). The ideal solution should be the utilization of WH, either as raw material in high-technology applications or low-technology cottage industries, which should not encourage its further spread. Instead, utilization should aim to help control its vast growth potential to manageable and acceptable levels in different situations.

WH is one of the best examples for use in educational and public discourses related to creating a 'weed-literate' society. The wide variety of practical utilization options of WH, highlighted herein, should be sufficient to demonstrate how its abundant growth and biomass can be an asset for boosting economic development among needy populations, especially in developing countries. The undesirable environmental effects of vast populations of WH on waterways are well-documented and predictable in most aquatic ecosystems. How to manage those effects with ‘integrated control’ is also known, despite under-achieving the control objectives in most settings.

Kleinschroth et al. (2021) pointed out that the economic and environmental gains from the utilization of WH and other aquatic weeds are impressive, based on decades of research. This alone should be the most crucial consideration in putting colonizing aquatics including WH to good use, with shared knowledge and experiences.

Frugal Innovations

Some of the WH utilization options, reviewed in this essay, may qualify as ‘*frugal innovations*’ that societies may benefit directly from. As explained by a recent *Nature Editorial* (2023), the emphasis of ‘*frugal innovations*’ is not the proliferation of low-quality products but *those that can be produced with local knowledge and abundant, locally available materials for the mass market. The products, or by-products must be produced at an affordable cost and add considerable value to societies through technology-driven low-cost and sustainable solutions*.

Utilization options should balance the arguments about the conflicts aquatic weeds have with human interests. The high productivity, resilience and unique capabilities of WH and most colonizing aquatic species simply cannot be ignored anymore. They are too valuable a resource not to be exploited further.

Given this, the real challenge for aquatic weed research is to ‘*integrate*’ the management of WH with practical utilization, where the possibilities are so obvious. Aquatic weed research groups should be proactive in communicating those possibilities and demonstrating that utilization is possible, which may, in some cases, require controlled conditions to contain the risks of further spread of the species.

Often the reluctance to utilize WH is based on environmental concerns and the economics of harvesting, transport and processing, which are not trivial. Thankfully, in the last three decades, many technological solutions have been developed to make such processes efficient and economically viable.

Although aggressive colonizing species, such as WH, '*affect people's livelihoods and human well-being*', Shackleton et al (2019) argued that '*They provide both benefits and costs in different contexts leading to complexity. A better understanding of this is therefore needed to aid decision making*'.

WH and Sustainable Development

This review finds that WH could be an exemplar to help humanity deal with a changing globe and create an '*environmentally literate*' society that enacts decisions based on both sound science and the needs of humanity. The contribution WH utilization can make to the UN's *Sustainable Development Goals* (UN, 2023), cannot be ignored. The evidence on adverse environmental effects of WH is dependent on scale and is equivocal in most situations, with knowledge gaps on whether moderate populations can actually help maintain aquatic ecosystems.

Concerning SGDs, utilization of WH holistically contributes to (1) reduced gender inequalities, poverty alleviation and sustainable employment (SDG1, 5 and 10); (2) economic growth (SDG8); (3) industry and innovation, including 'clean' energy (SGD7 and 9); (4) responsible material consumption (SGD12) and (5) climate change adaptation, through reduced greenhouse gas emissions, reducing waste and recycling of materials (SGD13).

A change in attitude towards colonizing taxa, epitomized by WH, appears crucial as we face an uncertain future, complicated by climate change, which is already upon us. Humans are the most potent agency that must take responsibility for actions with a deeper appreciation of past mistakes. A relic of colonialism, WH is now naturalized in many countries and may never ever be fully eradicated. More than 100 years of control efforts to remove WH in affected regions and countries have failed because the species is just too successful as a colonizer in new environments. Seeing the species with 'new eyes', along with utilization options, appears prudent.

Efforts to remove the human footprint from heavily populated landscapes appear increasingly counterproductive. Instead, we must accept the fact that the waterways affected by WH, and other similar aquatic colonizers reflect their watersheds, often dominated by human activities. In such cases, the focus should be on maintaining the health and critical ecosystem services and managing the plant communities best adapted to these novel conditions.

Science helps us approach the '*world of weeds*' with both wonder and humility. Science may also help to remove the unconscious bias some people have against weedy colonizers. Scientific ethics call for us to have an honest dialogue with *Nature* and what we find in life. Science will also help us fight mis-information, and also navigate the troubled waters and find a more reasonable position concerning weeds. What we must all strive for is to '*rethink Nature*' (Hill and Hadly, 2018) and find the '*middle ground*' in the weed discourses (Shackelford, et al., 2013). Instead of continuing to blame WH and other globally important colonizing taxa for human follies, the role of such species in shaping local livelihoods and human well-being should become a central theme for discussion (Shackleton et al., 2019).

Not all weedy species are harmful, certainly not all the time, nor in all situations. The evidence of ecological and environmental values, as well as the potential for utilization of weedy taxa for societal benefits cannot be disputed. Therefore, cultivating an attitude of '*living with weeds*', even with those, such as WH, that may, from time to time, cause some environmental concerns, is pragmatic. Such a tolerant attitude will help us reduce the environmental and social costs of taking unsustainable control actions against colonizing taxa and navigate a precarious future unfolding rapidly around us.

Hill and Hadley (2017) recently wrote: '*As the world stumbles deeper into the Anthropocene, the novel biogeographic dynamics (globalization, mass disturbance, and climate change) will progressively warp habitats*'. Under such disturbances, colonizing taxa will not just thrive but also change the habitats, which they occupy. However, improved education, balanced discourses and knowledge-sharing should help create more 'environmentally-literate' and 'weed-literate' societies, which will understand that *weedy species are no more villainous than we humans*. An important lesson for humanity is to *learn from Nature*. With or without humans on the planet, WH and other colonizing taxa will play vital roles in stabilizing the earth's damaged ecosystems. *They will also survive catastrophes on Earth. We may not.*

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