Review

Opportunities and Management of Water Hyacinth (*Pontederia crassipes* Mart.) in India – An Update

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Abstract

In this article, we provide an update on the status of water hyacinth (WH) infestations in India with a discussion of its history and the problems it causes. In reassessing how best to manage the species, within a sustainable economic framework, we also discuss the future of its local control, as well as its more holistic management, with utilization options clearly in mind. It appears to us that WH is almost *the perfect species* to demonstrate how the strengths of a colonising species can be put to beneficial, societal uses. Given that WH is deeply entrenched in India and never likely to be eradicated because of the vastness of its spread, we also see that India is almost the perfect country to benefit from WH.

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. A vast amount of global literature highlights how WH biomass can be utilized for societal benefits. Therefore, the evidence for integration of WH management with utilization cannot be disputed. Some of the high-end utilization options discussed must move from proof-of-concept research to expedited adoption. Utilization options should balance the arguments about the conflicts aquatic weeds have with human interests. The high productivity, resilience and unique capabilities of WH simply cannot be ignored anymore. It is too valuable a resource not to be utilized further.

Keywords: Water hyacinth; *Pontederia crassipes; Eichhornia crassipes*; utilization, colonizing species

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Introduction

Historically, water hyacinth [*Pontederia crassipes* Mart.; syn. *Eichhornia crassipes* (Mart.) Solms.] began to cause problems in the waterways of the USA in the 1940s (Penfound and Earle, 1948). The extent of problems caused by water hyacinth (abbreviated to WH from here on) in the USA was so vast that it led to the formation of the *Hyacinth Control Society* in 1961. 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 and others (Holm et al., 1977) listed 76 of the most significant global weedy species. In Holm's list, WH (**Figure 1**) is No. 8 in the order of importance. Unfortunately, looking at species mainly from an agricultural viewpoint, Holm (1969) described many colonising taxa, including WH, as '*terrible villains*' (Chandrasena, 2023).

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

A Conflicted Species

The '*Worst Weeds*' listing by Holm et al. (1977) was based on yield losses in major crops that weeds cause. The listing of species, compiled more than 50 years ago, reflects the time when **all** weedy species were considered 'bad news'. Times have changed, along with concepts related to weed management.

In an early article for *Nature*, a British biochemist, Norman Pirie (Pirie, 1960), highlighted WH's incredible capacity to proliferate and cause economic damage. He was indeed the first to propose that people must learn to '*live with it*' and put it to good use. As more and more species are recognized as 'beneficial' from both agro-ecological and societal perspectives, many in Holm's list of '*Worst Weeds*' would not be considered particularly harmful in the way they were seen 50 years ago. The evolution of weed control technologies (i.e. herbicides, biocontrol agents and integrated systems) has also enabled managers to 'manage' most species well when they go awry or where their sheer abundance becomes problematic in waterways or in terrestrial situations.

One of the most important questions in *Weed Science* is the vexed issue of '**conflict species**'. Many species, derided as '*Invasive Alien Species*' (IAS), have undoubted beneficial values and can be bioresources for both humans and animals. This topic has ignited debate as *Invasion Biology* emerged in the late 1990s. Terms, such as '*alien*', '*invader*' and '*invasion*' (*Invasion Biology* lexicon), impede the sensible management of weedy taxa. Instead of deriding species, managing weeds, where they are problematic, should be done with a greater understanding of their strengths and weaknesses and a balanced approach (Chandrasena, 2023).

This article explores the difficulties in managing WH, an undisputedly aggressive, aquatic coloniser, contrasted with the possibilities of putting it to beneficial uses. The issues associated with WH are similar to those of other aquatic species as well. Our focus in the article is India, which has been exposed to WH for more than a century since its deliberate introduction in 1896.

A Colonial Legacy in India

The botanical name of WH - *Eichhornia crassipes*- arose in Europe in the early 19th Century. The 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.

WH, however, is a colonial legacy of the legendary German explorer, **Alexander Von Humboldt,** who first collected its seeds from the Orinoco River, a tributary of the Amazon, in the 1790s. The French Botanist **Alire Raffeneau-Delile** cultivated it in Egypt in the late 1790s under the auspices of Empress Josephine and Emperor Napoleon. Delile introduced WH to Africa via an expanding French network of Botanic gardens on the continent. Just over 100 years after the introduction in Africa, between 1880 and 1980, WH transformed from a much-admired flower to an economically damaging pest (Kitunda, 2018). Societies began to look at WH as a pernicious legacy of "*the white man's burden*" to beautify Africa.

The global spread of WH, due to human introductions, was expedited by hydrology changes (flow impediments) and pollution of the waterways.

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[1] The *Kew Plants Of the World Online*: (**https://www.kew.org/plants/water-hyacinth**) accepts WH'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).

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, especially on waterways. 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 across South Africa in the 1910s, Madagascar in the 1920s, Tanzania, Uganda and Kenya in the 1930s through to the 1970s. In the 1980s, WH bloomed heavily on Lake Victoria, the Nile, the Congo and almost all watercourses of Africa.

The known adverse effects in Africa did not stop the British from introducing WH to India. In India, WH was introduced in 1896, also as an ornamental, grown at the *Royal Botanical Garden*, Kolkata. Within the next 100 years, it spread across the sub-continent, infesting rivers, lakes, ponds, wetlands and irrigation canals, 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*' (Gopal, 1987).

In the USA, in 1975, Vietmeyer called WH the '*Beautiful Blue Devil'*. In an earlier review of WH utilization, Ray and Chandrasena (2015) suggested that WH could also be a '*Cinderella*' depending on one's viewpoint and is the perfect example of the paradox colonising taxa pose to humans. Jeremiah Kitunda (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 (1974), Gopal (1987, 1990), Center et al. (1999; 2002), and Coetzee et al. (2017) have reviewed various socio-economic and ecological effects of WH. Other reviews describe WH's growth under varying conditions (Center and Spencer, 1981; Wilson et al., 2007; Gunnarsson and Peterson, 2007) and its reproductive biology (Zhang et al., 2010).

WH's exceptional success as a species is due to its capacity for clonal growth, producing ramets vegetatively, allowing populations to rapidly expand (**Figure 2**). Under high sunlight, temperatures around 28-32 ^{0}C and nutrient-rich water, WH populations can double in 8-10 days through clonal growth. In addition, WH can produce up to about 5000 seeds in one inflorescence, and usually, there are several such inflorescences per plant. Large root masses, bulbous petioles and stolons characterize a mother rosette, which has several ramets attached to it.

High rates of photosynthesis and growth under favourable conditions characterise 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. The factors limiting WH's growth in a waterbody are space, salinity, temperature, nutrients, disturbances and natural enemies (Wilson et al., 2007). Low levels of phosphorus (P) can also be a limitation for WH's expansive growth.

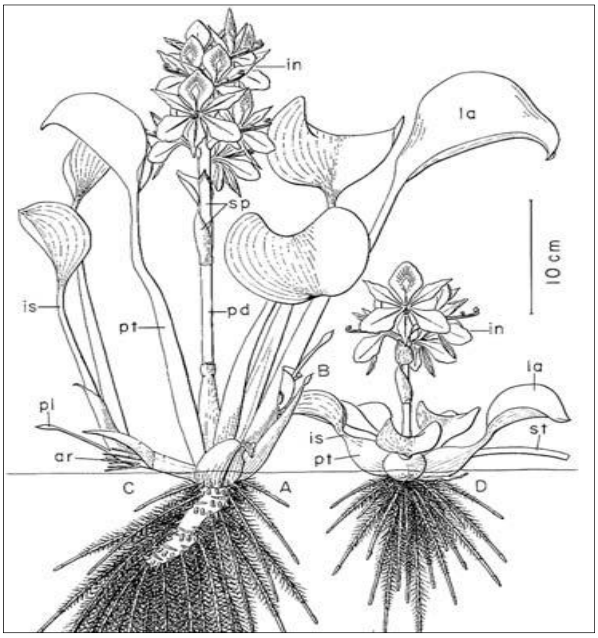

Figure 2. Morphology of *Pontederia crassipes* floating plants (From Center et al., 2002)

[**A**: the 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**–petiole; **rh**–rhizome; **sp**–spathe; **st**–stolon]

WH also shows high genetic diversity in its native range, although it is largely genetically uniform in much of the introduced range, resulting from genetic bottlenecks and the rarity of its sexual reproduction (Barrett, 1980; Zhang et al., 2010). Da Cunha et al. (2022) recently confirmed the high heterozygosity in the WH genome but low genetic diversity in its native range (Brazil). This finding, however, contrasts with the closely related 'anchored' WH (*Pontederia azurea* Sw.), which is also a floating aquatic with clonal growth. With extensive 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.

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

Negative Effects

WH's globally recognised negative effects include blocking navigation and fishing, causing biodiversity losses, oxygen depletion in water, and fish kills when large infestations decay. Infestations also harbour 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; 1990; 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.

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 depend on the fish community. Floating mats of WH usually harbour copious phytoplankton and invertebrate communities, which increase fish abundance. However, the opposite effect could also occur, especially with planktivorous fish. For instance, a decline in phytoplankton, due to the water surface being covered by WH mats, could have flow-on effects on higher trophic levels. With waterbirds, Villamagna and Murphy (2010) recorded an increased abundance likely related to the availability of fish and macroinvertebrates, particularly when WH infestations were at moderate levels.

Global Spread of WH

WH's native range extends from the Amazon Basin and rivers to Venezuela, Peru and even Jamaica (Kitunda, 2018). From its native range, it did not take much for this South American species to spread globally with the help of its human ally. The first record of WH outside South America was from a trade fair in New Orleans in 1884 (Penfound and Earle, 1948). Thereafter, WH spread around the USA and other countries. Introduced by the nursery trade, WH has now become deeply entrenched in Asia, South-East Asia, Papua New Guinea, Australia, almost all Pacific Islands (Oceania), almost the whole of Africa, several Mediterranean countries (Spain, Portugal, Italy), Central America, the Caribbean islands, and most tropical parts of the USA.

This global spread and pantropical distribution occurred within just over 200 years after it was 'moved' from its home base in Brazil to tropical regions. This distribution is primarily between 40^0 North and 45^0 South, including India. In addition, WH occurs as a 'casual' in several European countries with quite cold temperate climates, e.g. Belgium, Germany, the Netherlands, the U.K., Hungary, Romania and the Czech Republic (Coetzee et al., 2017). The heaviest of WH infestations occur in tropical climates (between 28°C and 32°C).

In India, WH ceases growth when the temperature drops below 10°C. However, WH tolerates a range of temperatures, lighting conditions, pH, drought and salinity (Gopal, 1987). As an erect, stoloniferous, perennial, WH can grow up to 1 m in height. The buoyant leaves allow it to stand erect and form dense mats. This morphology, however, varies according to conditions. Genetic polymorphism has led to tristyly in WH (Barrett and Forno, 1982). Of the three style lengths, in the native Amazonian basin, the short style (S-morph) predominates. However, in introduced areas, including India, the long (L-morph) and middle-length style (M-morph) are found (Barret, 1992).

Water Hyacinth in India

Historical Knowledge

The historical overview of WH in Colonial Bengal (ca. 1910-1947), provided by Iqbal (2009), citing Chaudhuri (1936) and MacLean (1922), shows that in the 1920s and 1930s, WH covered an area of over 4000 square miles of the active Delta of East Bengal (an area of ca. 35,000). During this period, the annual damage attributed to WH in Bengal was estimated at more than six crore (60 million INR).

A direct link between food, clean water, diseases and human and animal health was also drawn with WH infested waterways in Bengal during and after *World War I* (Iqbal, 2009). During *World War II*, crop failures in Bengal were also attributed to the myriad problems caused by WH. It has been suggested that WH contributed to the great *Bengal Famine* (1943-44), which killed about three million people.

A second historical aspect of WH's rapid spread in India was the promotion of its growth by *Shaw Wallace*, a Company that provided a range of goods and services to the colonial rulers. After *World War I*, the Company wanted to produce ash from WH, which contained ca. 15% potash that could be used as fertilizer (MacLean, 1922). Global access to potash had been severely limited by the War. The Company offered the Bengali Government INR 84 to 112 per tonne of unadulterated WH ash. While the original scheme failed (Iqbal, 2009), this history shows that since 1918, it might have led to people deliberately cultivating WH in Bengal for harvesting.

The rapid spread of WH in India, and elsewhere, is due to its extraordinary capacity to reproduce fast by vegetative and sexual methods. The species is insect-pollinated. In India, a single plant can produce a few thousand to 5000 seeds, which can remain viable in mud for up to 20 years. Even without seeds, WH can rapidly multiply. Gopal (1987) reported that two plants of WH could produce 30 offspring in 23 days and multiply to 120,000 in 120 days. Under ideal conditions, a doubling of WH infestations could occur in just 10 days. Severe infestations could reach up to 450 tonnes (wet weight) per ha.

Current Distribution in India

WH now occurs throughout India in small, medium or large freshwater lakes and reservoirs, lagoons, estuaries and wetlands, as well as streams, rivers, irrigation canals and paddy fields in most cities and villages (**Table 1**). The Table was constructed after a Questionnaire Survey of various weed research contacts in the different States and Union Territories through the ICAR-ARCIP-WM Network and the responses received. Information was also based on various articles cited in Indian references 9cited herein), abundant news media reports and on the authors' personal knowledge. Everywhere it has been found, especially on various large river systems, tributaries, lakes and wetland sites, some of which are protected by the RAMSAR convention, WH has been recorded as an aggressive coloniser.

In most Indian situations, there is sufficient water throughout the year to sustain WH populations. However, in drier situations, WH converts from an aquatic habit to a terrestrial one and survives. It has been estimated that in different States, ca. 20-25% of the total usable water surfaces are infested with WH, while in the States of Assam, West Bengal, Orissa and Bihar, the levels of infestation were much higher (Gopal, 1987; 1990; Sushilkumar, 2011a).

Table 1. Major Waterbodies, Rivers and Waterways Infested with Water Hyacinth in India *

State/Union Territory (UT)	Presence and extent	Responses on WH Occurrence and Locations
Andhra Pradesh	Widespread	Kolleru Lake, Sarvepalli Reservoir, Nellore Tank, Pynapuram Tank, Pennar Barrage and Nellore Water Supply Canal in Nellore District.
Andaman & Nicobar (UT)	Localised	Various freshwater ponds and streams on the islands.
Arunachal Pradesh	Widespread	Various small, medium, and large waterbodies.
Assam	Widespread	Bhadreti Lake, Deepor Beel Lake (Ramsar Site); widespread in most of the village ponds and Brahmaputra floodplains.
Bihar	Widespread	Ganga's tributaries, oxbow lakes (chauris), Moti and Kararai Lakes, Motihari and various small, medium and large waterbodies, Kusheshwar Sthan Lake (Darbhanga), Gogabill Lake (Kathihar).
Dadra & Nagar Haveli Daman & Diu (UT)	Widespread	Daman Ganga River network.
Chandigarh (UT)	Widespread	Various small, medium, and large waterbodies.
Chhattisgarh	Localised+	Arpa River, Dlapat Sagar Reservoir; Tandula River in Balod District.
Delhi (UT)	Widespread	Okhla Bird Sanctuary, Yamuna River.
Goa	Widespread	Mapusa River; Vast tracts of fields between Ambaji & Davondem, River Sal.
Gujarat	Widespread	Bilmora Lake; Sabarmati River, Bhadreti Lake; pond next to Bedi Marketing yard; Wier-Cum causeway – Surat; Tapi; widespread in city and village ponds.
Haryana	Widespread	Bhindawas Lake (Ramsar site, severe infestation); Ottu Lake (heavy infestation); widespread in city and village ponds.
Himachal Pradesh	Widespread	Widespread in all waterbodies; Nurpur Raja ka Talab reservoir.
Jharkhand	Widespread	Jamshedpur: in all rivers and tributaries, small and large water bodies.
Karnataka	Widespread	Bangalore: Doddabommasandra, Yelahanka, Jakkur, Rachenahalli, Nagavara and Hebbal, Bellandur Lake, Ulsoor Lake; Mysore: Karanji Tank; Kukkarahalli Lake; Dharwad: Unkal Lake; Uttara Kannada - Halyal Lake.
Jammu & Kashmir (UT)	Widespread	Dal Lake; various small, medium and large waterbodies (Azim, 2026; Srinagar, Dal Lake (personal communication – see later). Not present at higher altitudes.
Kerala	Widespread	Kuttanad, Alappuzha, Aleppy, Alappuzha-Changanassery canals, backwaters of Kumarakom, Vellayani Lake, Lake Vembanad (Ramsar site), Ashtamudi Wetland (Ramsar site); Sasthamkotta Lake, Thannermukkom Salt Water Barrier; all major rivers (Bharathapuzha, Periyar, Pamba).
Ladakh (UT)	Absent	No infestation reports due to cold, high-altitude desert climate.
Lakshadweep (UT)	Absent	No infestation reports as it does not have freshwater rivers or natural lakes — only small brackish ponds and groundwater lenses are present.

Table 1 (Continued). Major Waterbodies, Rivers and Waterways Infested with Water Hyacinth in India

State/Union Territory (UT)	Presence and extent	Responses and Comments on WH Occurrence and Locations *
Madhya Pradesh	Widespread	Kotwal and Piluwa dams, Bhind; Tikamghad; Ranital pond and Mahanadda pond, Jabalpur; Machan River in Betul district of MP; Sarni reservoir; city ponds in Khandwa, Bhoj Wetland (Ramsar site), Sakhya Sagar (Ramsar site), Sirpur Wetland (Ramsar site), widespread in village ponds and canals.
Maharashtra	Widespread	Mithi River, Mumbai; Panchaganga River, Kolhapur; Powai Lake, Bombay; Mula River at Holkar bridge in Pune; Salim Ali Lake, Ujani Dam.
Manipur	Widespread	Lamphelpat wetland in Imphal, Lkop lake, Loktak Lake (Ramsar site), Pumlane Lake.
Meghalaya	Widespread	Varioius wetlands, Betasing region of South Garo Hills.
Mizoram	Localised	Tam Dil Lake, Saitual Sub-division, Aizawl District, Palak Dil (Pala Tipo)
Nagaland	Widespread	Various small, medium and large waterbodies and canals.
Odisha	Widespread	Ansupa Lake, Bhitarkanika Mangroves, Bindo Sarovar in Bhubaneswar, Chilika Lake (Ramsar site), Hirakund Reservoir, Mahanadi River.
Puducherry (UT)	Widespread	Various small, medium, and large waterbodies and canals.
Punjab	Widespread	Sutlej River, Kanjhli Wetland (Ramsar site, 90% covered); Old Bikaner Canal; Harike Wetland (Ramsar site), Ropar Wetland, widespread in irrigation canals.
Rajasthan	Localised	Keoladeo National Park, Pichola Lake, Talkatora Lake.
Sikkim	Not reported	No published reports of WH infestation, possibly due to predominantly high-altitude, cold-temperature terrain, which limits establishment of WH.
Tamil Nadu	Widespread	Sembakkam Lake (a 100-acre water body completely choked with WH); Bhavani River, Kaveri River, Amaravati and Valgai reservoirs.
Telangana	Widespread	Hussainsagar and several large lakes and reservoirs; various small and large water bodies, and canals in Hyderabad.
Tripura	Widespread	Rudrasagar Lake (Ramsar site), Dumboor Lake.
Uttar Pradesh	Widespread	Gomati River, various water bodies in most cities, towns and villages.
Uttarakhand	Localised	Asan Barrage / Asan Conservation Reserve (Ramsar site), Giritaal lake, Niranjanpur pond, Naini lake, Bhimtal.
West Bengal	Widespread	River Panchaganga, Hooghly River system, East Calcutta Wetlands (Ramsar site), Kusheswar Asthan, Kursaila and Daini Wetlands, and in various waterbodies in most towns and villages.

*Table 1 was compiled through a structured review combining peer-reviewed literature on WH distribution in India, official wetland and Ramsar Site management reports, and contemporaneous news media coverage of infestation and control efforts across Indian States and Union Territories. Records are current as of June 2026. Where no documented record of infestation could be located for a given State/Union Territory, this is indicated as “Not reported” (absence of evidence, no confirmed absence); where ecological constraints (e.g., cold climate, lack of freshwater habitat) make establishment of WH highly improbable, the entry is instead recorded as “Absent”.

Losses Caused by WH in India

WH infestations can have major environmental and socio-economic effects in India, as was reported 100 years ago (Iqbal, 2009; Gopal, 1987). These include all the effects previously mentioned from the global literature (see *Negative Effects)*. Other harmful effects include increased evapo-transpiration water losses, making fertile land near waterways unproductive, increased flooding risk due to blockages in canals, reducing water flows in water supplies to hydroelectric power stations, as well as blocking irrigation canals (Sushilkumar, 2011a, b; Ray and Chandrasena, 2015). Added to these are effects, such as reduced quality of drinking water and an increase in disease vectors (i.e., mosquitoes); increased health problems in infested regions (i.e., malaria, cholera and diarrhoea) and the decline in bird populations at wetland sites.

Where WH dominates and suppresses the available habitat and ecological niches of other aquatic life-forms, it disrupts critical plant-animal-environment interactions. The displacement of native plants adversely affects epiphytic, microbial, macroinvertebrate and phytoplankton communities. Fish kills have also been attributed to oxygen depletion, which occurs when large WH biomasses decompose in water (Ray and Chandrasena, 2015).

Reduced biodiversity in aquatic ecosystems, often claimed in literature as caused by WH infestations, could be due to obstruction to sunlight penetration. Decreased growth and productivity of phytoplankton could also occur under WH infestations, although there are no data available on direct measurements of these effects (Kato and Kato-Noguchi, 2026).

The rate of water loss from surfaces covered by WH, due to evapo-transpiration, is very high. In an early estimate, Van der Weert and Kamerling (1974) showed that water losses were 44-48% higher in a WH-covered lake in Surinam compared with open water. However, estimates vary greatly depending on waterway conditions and environmental factors (viz. humidity, sunlight, temperature and rainfall) (Lallana et al., 1987). Based on values in the literature (not fully discussed here), we contend that a WH-covered waterbody would lose water at a rate 3 to 6 times higher than that of open water. These are highly significant, especially in irrigation canals, some lakes and wetlands and drinking water supply reservoirs.

Our review finds that although the economic impacts of WH infestation are evident in India, they have not been comprehensively quantified at the national scale. Most Indian studies are limited by site-specific, subjective and qualitative assessment. Some studies are livelihood-focused, rather than providing monetary loss estimates attributable to WH.

In the State of Kerala (38,400 km^2), where the WH problem is most intense, major sectors of the economy (transport, tourism, navigation, fisheries, agriculture, production and trade of other goods) are affected but not quite quantified in economic terms. Sasidharan et al. (2013) reported that high degrees of nutrient pollution in water, viz. nitrates, nitrites and phosphates arising from agricultural runoff, sewage and industrial effluents, contribute to the prolific growth of WH across the State. More than 75% of waterbodies in Kerala are infested with WH, making large areas non-navigable and uncultivable.

As shown in a recent photo (**Figure 3**), a vast area of canals and waterbodies in the Central Kerala districts (Alappuzha, Ernakulam and Thrissur) is affected by WH infestations. WH infests rice fields, lakes, streams and canals, making large areas inaccessible, non-navigable and uncultivable. An estimated six lakh tonnes of cargo are moved every year using inland waterways in Kerala, which are seriously affected by WH, causing economic losses.

In Kerala backwaters, WH expands at the end of the rainy season when water bodies are less salty. Infestations disappear as rainfall decreases and water becomes saltier. However, during the time of its spread, WH disrupts navigation, bringing movement of both cargo and people to a halt (**Figure 3**), as boat engines are choked, especially during the opening months of the tourism season. The economic costs of these effects can only be surmised as substantial, although they have not been properly quantified.

Figure 3. Canals in Kerala, completely choked with WH, affecting tourism (Photo published on 16 March 2026) [2]

One estimate, made more than 15 years ago, showed that of the 8 lakh ha of freshwater (8000 km^2) available in India for aquaculture, ca. 40% has been rendered unsuitable for fish production, because of WH infestations. Most inland fishery reservoirs, in and around Bangalore and other major cities, have been badly invaded by WH. In West Bengal, WH created havoc in the State's fisheries, drinking water supplies, irrigation canals and rice fields. In Palta (West Bengal) and Baranagar (Telangana) waterbodies, WH and *Lemna* spp., along with some mollusc species, blocked water pipes (Sushilkumar, 2011a).

Climate Change Effects on WH

An increase in CO_2 produces an increase in net photosynthetic rates of many plants, especially those with C_3 photosynthesis (Leakey et al., 2009). WH is a C_3 plant. Unlike the shade-tolerant, submerged

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[2] *Mathrubhumi* E-Newspaper (**https://english.mathrubhumi.com/technology/science/water-hyacinth-impact-kerala-backwaters-video-euqguqjk**).

macrophytes, WH thrives on water surfaces with the capacity to utilise full sunlight for photosynthesis.

Studies conducted by Liu et al. (2010) using WH and two CO_2 concentrations (380 and 600 ppm) and four nutrient levels showed that in two months, growth was enhanced under nutrient-rich conditions. CO_2 enrichment increased the number of leaves per ramet and leaf area index of WH, but did not significantly increase leaf size or the number of ramets formed.

Root growth and assimilate allocation to leaves also greatly increased under high nutrient levels. The growth response proved that under elevated CO_2, the nutrients absorbed were mostly transferred to offspring ramets rather than maintained by the mother ramet. Such responses would benefit the plant's vegetative reproduction and the uptake of nutrients and other pollutants (Liu et al., 2010).

Water Hyacinth Management in India

A review of global literature, dating back to the 1940s, shows that for decades, the management of WH has been 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 management costs, no other species is of greater concern globally*. Therefore, it is necessary to shift the emphasis from a simple, control-oriented mindset to a more holistic management. In such an approach, beneficial utilization of WH has to be a priority, although this requires a re-evaluation of the costs vs. benefits in terms of ecological and environmental costs, as well as the social services WH can provide.

Preventative measures

Prevention plays a key role in keeping WH from spreading. In India, as in other countries, wire mesh barricading at several locations of a water flow pathway is used to reduce WH entry into other waterways. Continuous removal of small pockets of WH from the edges of water courses is also crucial in the preventative approach, recommended in India (DWR, 2019). DWR's research has shown the success of prevention, as in the case of WH management in Tikamgarh in Madhya Pradesh and in the Kharkai River at Jamshedpur in Jharkhand.

One case study, documented from the Kharkai River, showed how effective prevention can be even in a large river. The Kharkai used to be infested up to several km every year during summer, resulting in increased cases of malaria, dengue fever and other problems. Responding to public complaints, the municipality took management action. The river water usually stagnates in stretches after the monsoon rains in January. During the next few months, WH propagules germinate in such river reaches from buried seeds produced during previous years and clonal growth. The removal of the newly 'germinated' crop of WH offspring arrested its further proliferation (Sushilkumar – *personal observations*).

At many places, heavy iron mesh was installed to stop WH spreading from one part of the river to other parts. Teams of municipal labourers physically removed emerging WH colonies. This simple preventive approach arrested WH proliferation in the following summer. However, the case study showed how intensive the management effort required was. Nevertheless, the cost of implementation of the preventative programme was estimated at only 10% of the likely economic cost had WH covered the entire water surface of the river reach (Sushilkumar, 2011b).

Physical Removal

The main options for managing WH infestations at many locations include removal either by hand or by machinery. Both are most effective for small infestations, but are unsuitable for large infestations over large areas or in large canals. Medium- or large-sized aquatic weed harvesters have been available for more than six decades for the mechanical removal of WH. These machines were initially developed in the USA to tackle vast infestations in Florida. Newer designs of harvesters then came about and have been effectively deployed in India (**Figures 4-6**).

Figure 4. WH harvesting in Kerala (source: Matprop https://matprop.in/water-resource-restoration-program/)

However, with mechanical removal, disposal of large quantities of the biomass is a major obstacle, because of adverse effects on the banks of canals, dams and rivers and the costs involved.

In India, surveys indicate that manual removal of WH is the commonest form of control used in all States. However, labour is expensive, and the task is tedious. In small waterbodies, small-to-medium- sized excavators are used effectively, occasionally combined with a conveyor belt and locally modified lifting equipment. Often, the disposal of manually or machine-removed WH biomass is a significant problem for authorities.

Figure 5. Water Hyacinth harvesting in a Kerala canal (source: Pendse and Deshmukh, 2023)

Figure 6. Large biomasses of harvested WH pose a problem unless used as a bioresource (source: Pendse and Deshmukh, 2023)

Water weed cutters and harvesters are also used in India, although their success for WH management depends on the frequency and intensity of use. It is also known that if not properly conducted, mechanical harvesting may even aggravate a local WH problem by fragmentation and spreading of propagules. If machines are not properly cleaned after operations, contaminated mud could also spread WH from one location to another (Sushilkumar, 2011a).

Herbicides

Since the 1960s, herbicides, such as 2,4-D amine and ester, diquat, paraquat, glyphosate and metsulfuron, have been used in many countries to reduce WH infestations. While multiple and multi-year treatments are essential for long-term control, these herbicides do provide short-term relief. However, in India and many other developing countries, WH-infested sites are also used for drinking water, washing and fishing. This means that the use of herbicides at such sites may pose a public health risk (Center et al., 1999). It is also known that repeated treatments and the killing of large WH biomasses could adversely affect water quality, other vegetation and non-target organisms in aquatic environments.

In India, only three formulations of the auxin herbicide, 2,4-D (2,4-dichloro-phenoxy acetic acid; amine salt, sodium salt and ethyl ester) have been registered for use against WH (Choudhury, 2019). However, research trials have been done by different groups with paraquat dichloride, glyphosate and metsulfuron as potential candidates. Some of those formulations do not yet have aquatic registration in India and have only been used in trials.

Sushilkumar (2011b) reported that 2,4-D amine (2.0 kg ha^{-1}) was the best herbicide to control WH (98%), followed by glyphosate 2.5 kg ha^{-1} (96 %) and paraquat 1.0 kg ha^{-1} (93%). Tank mixes of paraquat (0.3%) and 2,4-D amine (0.3%) were effective in managing WH at Dolon Village (Ludhiana). The studies (**Table 2**) noted that while these herbicides were effective on WH and economical to use, they may have potential undesirable effects on non-target organisms and water quality.

Table 2. Herbicides used for Water Hyacinth control in India

Herbicide	Rate	Comment	Source (Reference)
2, 4-D Amine salt (58% SL)	1.0-2.0 kg ha^{-1}	• Provided ca, 75%-82% control at 25-30 DAT	Pradhan and Sushilkumar, 2019
2, 4-D Ethyl Ester (38% EC)	2.5 kg ha^{-1}	• Provided 88-93% control up to two months after application.	Yadav and Yadav, 2010
2,4-D Na salt (80% WP)	1.5 kg ha^{-1}	• Severe reduction in density after 21 days; Almost 100% kill at 35 DAT	Kathiresan and Deivasigaman, 2015
Paraquat	1.0-2.0 kg ha^{-1}	• Severe reduction at 21 DAT, but WH showed regrowth after 3 months.	Sushilkumar, 2011b
		• 62-68% control of WH, but longer persistence limits its suitability	Pradhan and Sushilkumar, 2019
Glyphosate	2.5 kg ha^{-1}	• 90-100% control at 35 DAT	Kathiresan and Deivasigamani, 2015
	2.0 kg ha^{-1}	• 75% control at 21 DAT	Sushilkumar, 2011b
	1.0-2.0 kg ha^{-1}	• 81-86% control at 25-30 DAT	Pradhan and Sushilkumar, 2019

Notes: Days after treatment (DAT); SL – Soluble Liquid; WP – Wettable Powder; EC – Emulsifiable Concentrate

Kathiresan and Deivasigamani (2015) concluded that 2,4-D sodium salt, glyphosate and paraquat offered efficient WH control, which was unaltered by the seasons (**Table 2**). However, their study noted undesirable effects, which included fish mortality and changes in water quality. Of the herbicides, glyphosate was the safest in terms of adverse effects, while also being the most effective in WH control. Pradhan and Sushilkumar (2019) also showed how 2,4-D, paraquat or glyphosate could be integrated with manual and mechanical control to control large infestations cost-effectively.

A recent study by the *Saguna Rural Foundation* (SRF), an NGO (SRT and SRF, 2021), reported that glyphosate was successfully applied by a drone to control large infestations of WH in the Ulhas River in the Thane District (Maharashtra) (**Figure 7**).

Analyses showed that glyphosate treatments did not leave any residues in the water, and the herbicide would be safe to use. WH in the treated areas collapsed over a short period, clearing the river reaches that were treated. **Figure 8** shows the use of a drone to treat a large lake in Telangana with a bioherbicide (not stated) and an anti-larval agent (Priya, 2019), which was claimed to be successful.

Figure 7. Drone spraying glyphosate in the Ulhas River control programme, 2021

Figure 8. A lake in Telangana, choked with WH and treated with a bio-herbicide and an anti-larval agent using drones. The project attempted to reduce the incidence of mosquito-borne diseases (Priya, 2019)

Despite the reported success with glyphosate, it is not approved for aquatic use in India. The *Central Insecticide Board & Registration Committee* (CIBRC) restricts glyphosate solely to terrestrial uses, such as in tea and weed control in non-crop situations. Also, several Indian States, including Kerala, have banned its use to protect water sources, which poses an obstacle for weed managers. Public opposition to glyphosate use is also very high in India, as shown by a spate of recent articles (Lele et al., 2025).

Biocontrol Agents

Biocontrol has long been the favoured method for WH control, with several agents released over the past 50 years. Biocontrol research began in the USA in 1961, and the first control agents were released in Florida in 1972. Of the agents, the most successful are the two Coleopteran weevils, *Neochetina eichhorniae* and *Neochetina bruchi* and the pyralid moth *Niphograpta albiguttalis* (Warren) [Lepidoptera]. These agents are well established in many countries where WH bio-control has been implemented (Wilson et al., 2007; Coetzee et al., 2017).

However, the insect 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 meristematic tissue in the crown of the plant, can cause damage, preventing populations from expanding.

In addition to insects, several fungal pathogens have also shown promise against WH (Charudattan, 2001). Among the most promising fungal pathogens of WH are: *Uredo eichhorniae* Fragoso and Ciferri, *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 pathogens are present in different continents and can be developed further against WH for use in the future (Ray and Hill, 2012).

In India, the available biocontrol agents of WH are summarised in **Table 3**. However, research shows that it takes a long time (20-36 months after the introduction of an agent) to control one cycle of WH. Nevertheless, the Coleopteran weevils, *Neochetina bruchi* and *N. eichhorniae*, have successfully cleared WH from many aquatic bodies (Jayanth, 1988; Ray et al., 2009; Sushilkumar, 2011a, b; 2022). The Indian experience is that after the release of bioagents in a water body, biocontrol of WH may occur in 4-5 cycles in a span of 5-7 years (Sushilkumar, 2022).

Once the infestation of WH becomes weak after 2 to 3 continuous cycles, the space and ecological niche vacated by the WH due to its suppression by the weevils could be taken up by other strongly colonizing species, such as alligator weed [*Alternanthera philoxeroides* (Mart.) Griesb.], water lettuce (*Pistia* *stratiotes* L.) or salvinia (*Salvinia molesta* D. S. Mitchell). Such weed succession has been observed to occur in water bodies in India, unless those species are also managed at the early infestation stages.

Broadly, as in large African lakes (Opande et al., 2004), in many situations in India, especially in the extensive infestations, such as in Kerala, WH control by biocontrol agents is often inadequate and short-lived. In Kerala, even high numbers of weevils per plant (5-7) were not able to kill WH completely, although weevil foraging reduced flower production drastically (Sushilkumar, 2011a;b). The bioagents are usually successful only in perennial waterbodies where water remains throughout the year. In contrast, they usually do not work in rivers and canals, where, during floods after the monsoon, all the WH gets washed away with the available weevil populations.

Table 3. Biocontrol agents in India used against Water Hyacinth

Biocontrol Agent	Comments	Source
Arthropod herbivores		
Mites - *Orthogalumna terebrantis* Wallwork (*Acarina: galumnidae*)	• Considered to be safe for field release in India.	Jayanth et al., 1988
	• Injurious effects involved leaf mining by the larvae (instars), leading to leaf wilting and reduced dry weight.	Haq and Sumangala, 2003
Weevil - *Neochetina bruchi* Hustache (Coleoptera: Curculionidae)	• Adults feed on leaves; larvae bore into petioles/rhizomes. Well established on WH in different parts of the country, achieving good control of WH along with *N. eichhorniae*.	Jayanth, 1988; Ray et al., 2009; Sushilkumar, 2011a, b, 2015
Weevil - *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae)	• Adults feed on leaves; larvae tunnel into petioles and root crowns, disrupting vascular tissue. Well established throughout India. It is successful in stagnant ponds and lakes but not effective in running water, such as a river.	Ray et al., 2009; Sushilkumar, 2011a, b, 2015
Plant hopper - *Megamelus scutellaris* (Hemiptera: Delphacidae)	• Recently brought by DWR, Jabalpur, from South Africa for host-specificity testing against WH. The bioagent is under trial at the quarantine facility of ICAR-National Bureau of Agricultural Insect Resources (ICAR-NBAIR), Bengaluru	Archana Anokhe, 2026 (personal communication)
Fungal pathogens (Ascomycetes)		
Fusarium oxysporum Schlecht.	• Causes vascular wilt by colonizing xylem and producing fusaric acid and other phytotoxins. Showed good results within 10-15 days of application with good future prospects.	(Dutta et al., 2023), Pathak and Kannan, 2011
Fusarium roseum (Link) Snyder & Hansen		
Alternaria japonica Yoshii	• Causes leaf spot and blight in WH, which was the only species strongly susceptible to spore suspension (5 × 10^5 conidia/ml) of *A. japonica*. Needs further research.	Dutta et al., 2015
Alternaria alternata (Fr.) Keissler	• Causes leaf spot and blight, followed by dieback disease in water hyacinth	Aneja and Singh 1989, Ray et al. 2008, Dutta et al. 2015

Integrated Control

As reviewed recently by Su et al. (2018), Pin et al. (2021), Udume et al. (2021) and Nega et al. (2022), none of the physical, biological and chemical control methods, applied alone or in combination, have been successful in any country that has been affected by WH except at a very local level and small scale. This is indeed the primary reason why we should 'rethink' the WH control strategies and include WH utilization and product valorization as an integral part of future WH management (Karouach et al., 2022).

In India, limited attention has been paid towards studying the responses of herbivore insects on WH plants treated with sub-lethal doses of a herbicide. In one study (Sushilkumar, 2011b). The integration of herbicides with the bioagents resulted in control of two cycles of WH within a period of 21 months after the initial release of weevils, whose application alone would have taken 2-3 years to control one cycle of WH. This integrated approach also drastically reduced the herbicide load in the waterbody.

Charudattan (2001) had already reported that the Integration of the fungal pathogen *Cercospora rodmanii* with natural populations of *N. eichhorniae* and *N. bruchi*) provided complete control of WH, while combinations of *C. rodmanii* with low rates of 2,4-D and diquat also showed compatibility.

However, a study in South Africa (Katembo et al., 2013) showed that a sub-lethal dose of glyphosate (8% of the lethal dose of Monsanto's 'Round-Up', 360 g a.i. L^{-1}) on WH resulted in a decrease in leaf N content of the treated infestation but had no effect on its C content. Thus, glyphosate sub-lethal treatments increased the leaf C: N ratio, but the reduced N content did not alter the weevil's feeding behaviour. The findings demonstrated the potential for integrating control with the Coleopteran weevils and glyphosate, where the weevil population needs to be conserved. By taking out the centre of a WH infestation with a lethal dose of glyphosate, the borders are likely to receive spray drift at a sub-lethal dose, which will retard WH growth while providing a refuge for the weevils (Katembo et al., 2013).

The trials at DWR, Jabalpur, for the integration of *Neochetina* spp. and the fungus *Alternaria alternata* showed that the fungus alone was not effective on WH. However, it enhanced the biocontrol efficacy of *Neochetina* spp. In either a one-time treatment or several monthly treatments, the fungus was ineffective if applied alone. However, when the fungus was applied with the weevil, flower production in WH was considerably reduced due to their combined effect (DWR, Annual Report, 2019).

In other 'integrated control' studies, the manual-cum-mechanical removal of WH had a higher cost because of labour hire but gave the highest weed control efficiency (WCE) of 81-92%. Glyphosate (2.0 kg/ha) was the most cost-effective (84-86% control) with a cost of INR. 18,080 to 19,660 ha^{-1}. Applying the herbicide over the WH floating weed mat loosened it significantly, which led to its efficient removal, manually or mechanically, 25 to 30 days after treatment (DAT) (Pradhan and Sushilkumar, 2019).

Utilization Options

For a long time, WH has posed a dilemma for weed managers, although the spate of recent research in India and elsewhere appears to indicate a very strong change in that position. Discussing field-obtained evidence, Opande et al. (2004) said: "*There being both negative and positive socio-economic impacts, it is more correct to state that Water Hyacinth is not just an enemy but a friend of the lakeshore communities in the Winam Gulf*" (Kenya).

In a recent article on '*Living with floating aquatic invasions*', Kleinschroth (2021) argued the case for moving away from futile eradication efforts of species, such as WH, towards a pragmatic '*aquatic ecosystem management strategy*', *minimizing negative, local effects while integrating environmental and socio-economic benefits.'* We agree with this proposition.

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 '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, which grew prodigiously in the polluted river water. These practices have expanded in the last 50 years.

In the USA, early utilization focused on using WH to remove nutrients, metals and other pollutants from treated sewage (Boyd, 1974; Mitchell, 1974; Pieterse, 1978). These reviews also supported the use of WH as fish and livestock feed, compost and mulch. The reports also showed the potential for WH use in removing pollutants from industrial effluents and the commercial-scale uses of the biomass for paper and pulp, biogas and bioethanol production. Discussing the *paradox* presented by WH, the reports highlighted the need *for balancing the costs of WH control in different situations versus the benefits of its utilization*.

Recent Utilization Efforts

Chandrasena (2023) pointed out that the majority of articles on WH describe laboratory or pilot-scale studies and evidence of the utilization potential of WH that could be developed further. Many reviews emphasize how communities affected by WH can reduce environmental effects by putting WH to good use (Gunnarsson and Peterson, 2007; John, 2016; Feng et al., 2017; Kleinschroth et al., 2021; Karouach et al., 2022; Nandiyanto et al., 2023; Canning, 2025).

The use of WH for water purification remains doubtful as an application. However, Valipour et al. (2015) reported this possibility, assembling a continuous-flow wetland '*Bio-Hedge*' with WH and nutrient-consuming bacterial biofilms on WH roots and a mesh-matrix. In the 12-month study, WH grew slowly at a rate of 1.2% day^{-1}, but extracted N and P at 60% and 47% efficiency (influent vs. outflow).

One of the most valuable practical ways by which WH can be utilized is the use of its strengths to extract N and P nutrients and heavy metal contaminants from any effluent or treated wastewater. For such applications, WH could be utilized either alone or in combination with other pioneer species in treatment wetland designs. However, despite the compelling evidence, mostly from the USA, most other countries, including Australia, are hesitant about such systems for fear of causing further spread.

The effectiveness of WH in extracting other environmental pollutants in water depends on having sufficient colonies for uptake, the concentrations of the contaminants, the duration of exposure for uptake and favourable growing conditions. These are factors that can be manipulated in systems designed to optimize contaminant uptake while controlling the risks of the spread of WH. In a study conducted in South Africa, Newete et al. (2016) reported that WH stems and leaves bio-concentrated Cu, mercury (Hg), gold (Au) and Zn above the standard bioconcentration factor (BCF) index of 1000 µg per g dry weight (equivalent to 1 g per kg dry weight).

Regular harvesting of the WH biomass assists in pollution reduction by allowing new growth to occur. The literature indicates that the harvested WH, following its use for wastewater or effluent treatment, can be valorized for various industrial applications with additional processing. To eliminate the risks of potential contamination (due to contact with human waste and other impurities), the harvested WH biomass should not be used for animal feed. Nevertheless, the material can be easily processed to become raw material for a wide range of industrial products, such as paper, construction materials and the production of biogas, bioethanol and biochar.

Utilization Experiences in India

India presents one of the most impressive and diverse national case studies on WH utilization, mainly because of the scale of the resource and the diversity of its applications (Pendse and Deshmukh, 2023; Abba and Sabarinath, 2025; Abba et al., 2025). Combined with attitude changes driven by ‘green’ technologies, as well as institutional and community engagement, India is witnessing a genuine paradigm shift in utilizing WH as a means of managing vast infestations. India harvests an estimated 200 metric tonnes of WH biomass ha^{-1} $year^{-1}$, a figure that, if even partially valorised, would represent an enormous renewable feedstock resource for multiple industries.

The following sub-sections review the principal utilization pathways that have been investigated or implemented within India, with attention to both established findings and recent developments.

Wastewater Treatment and Phytoremediation

In India, Trivedy and Pattanshetty (2002) showed that WH growing in dairy waste significantly reduced Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids and Total Nitrogen in the effluent. Adding to this, Chaudhuri et al. (2008) also reported effective WH-based treatment of municipal wastewater in urban settings, reporting substantial reductions in N and P nutrient loads under optimal hydraulic retention times.

A relevant recent contribution is the comparative study by Pendse and Deshmukh (2023), which reviewed WH phytoremediation performances in India and found that the species consistently reduced BOD by 60–80% and COD by 55–75% in domestic wastewater. Most importantly, these results are on par with the effectiveness of WH for wastewater treatment in the USA (Wolverton and McDonald, 1979; Debusk et al., 1983; Reddy and DeBusk, 1987).

Heavy metal uptake is a particularly significant utilization capability of WH that can be applied in reducing pollution caused by various industries. In India, as in other countries, the processes of textile dyeing, tanning of leather, electroplating, and pharmaceutical manufacture generate effluents contaminated with lead (Pb), chromium (Cr), zinc (Zn), cadmium (Cd), copper (Cu), silver (Ag) and arsenic (As). Ingole and Bhole (2003) provided early results of WH's high degree of tolerance and bioaccumulation of these metals in shoot tissues.

Galgali et al. (2023) reviewed and provided compelling proof that WH could be utilised as a key component of phytoremediation systems in future designs, especially in India, in constructed floating wetland configurations. A recent comparative study on the Nag River in Maharashtra found removal efficiencies of 79–83% for iron, 74–76% for zinc, 70–73% for copper, and 62–74% for lead using WH under field conditions (Bramhankar et al., 2026). There is clearly great potential for utilizing WH for phytoremediation of industrial effluents to extract inorganic ions (Pb, Cr, Zn, Mn, Cu, As, etc.) by designing small systems. Similar applications could be used to reduce phenols, dyes and other organic pollutants discharged in untreated effluents. What the literature shows is that WH is quite simply the best aquatic species that can be used for this task.

Biogas Production

Indian research on biogas production from WH biomass spans from bench-scale studies to community-scale pilot studies. Early studies of Singhal and Rai (2003) established a benchmark: 100 kg of semi-dried WH yielding ca. 400 Litres of biogas per day. The relatively low lignin content of WH, compared to terrestrial biomass feedstocks, accelerates digestion kinetics, although the high water content of WH (ca. 94%) necessitates pre-treatment or co-digestion with denser substrates.

Community-level biogas enterprise models have also emerged in India, most notably the initiative '*Payal Jwala*' launched in Kerala in 2021 by social entrepreneur Anuroop G., working with the *Centre for Research on Aquatic Resources* (CRAR). The initiative converts WH from the backwaters and canals of Thanneermukkom into biogas distributed to households as a cooking fuel alternative to LPG, simultaneously addressing WH infestation, energy poverty, and indoor air pollution (Krishnan, 2022). Such models demonstrate that the technology is both feasible and socially scalable under Indian conditions, but require government support for replication.

Bioethanol and Biofuel Production

As India successfully reaches its 20% ethanol blending target in 2025, five years ahead of the original 2030 schedule, WH has a huge scope as a second-generation feedstock for bioethanol production under the *National Biofuel Policy* (Awashti et al., 2013). Researchers at IIT Kharagpur and other institutes like ICRISAT established a method utilizing pore-scale phenomena to extract a high percentage of fermentable sugars and bioethanol from the hemicellulose in WH, achieving significant yield increases (Cherwoo et al., 2025). Thus helping in aquatic ecosystem cleanup without competing with food crops and avoiding the "food vs. fuel" debate.

Recent reviews (Abba and Sabarinath, 2025; Abba et al., 2025) found that WH biofuels can reduce the levelized cost of energy (LCOE) by up to 25%, increase ethanol yields by 40%, and improve sugar release by 50% through optimised pretreatment. Such metrics place WH within reach of commercial viability for bioethanol production under Indian conditions.

In an important study, Mannivannan. and Narendhirakannan (2014) reported that cellulose, hemicelluloses and lignin contents of WH ranged from 23-50%, 18-22% and 3-28%, respectively. The study showed how the dried WH biomass could be first hydrolysed with dilute H_2SO_4 to a delignified substrate, further degraded by fungi (*Trichoderma reesei*) and then fermented aerobically by yeasts (*Pachysolen tannophilus*, *Candida intermedia*, *Pichia stipitis* and *Saccharomyces cerevisiae*) to yield bio-ethanol. This bio-conversion yielded bioethanol in the range of 0.021-0.043 g g^{-1} of WH biomass. Given that such a biofuel yield is competitive with other common low-cost sources, this utilization needs to be further developed and optimised for adoption by industries.

Composting, Vermicomposting, Green Manure and Soil Amendment

WH's utility as a green manure for crop production has been studied in India by incorporating freshly chopped WH into rice fields to improve soil organic carbon. However, direct field application of fresh WH carries the risk of re-establishment from viable plant fragments and potential allelopathic effects from residual chemicals in WH tissue. Composting or vermicomposting effectively eliminates such risks (Sushilkumar and Bhan, 2000).

Composting is the most widely practised WH utilization method in India, requiring no specialised infrastructure and yielding a product (compost or vermicompost) that farmers can readily use. In India, composting of WH requires about 50–60 days, with decomposition accelerated by adding urea (2–5%), lime (2–5%), or cow manure (10%) to the chopped WH biomass (Gajalakshmi and Abbasi 2002). One tonne of WH compost contains ca. 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), making it a nutrient-rich organic fertilizer that can partially replace synthetic fertlizer inputs.

Co-vermicomposting of WH with fly ash using the earthworm *Eisenia fetida* improved the water holding capacity, cation exchange capacity and available nutrient fractions relative to conventional organic waste vermicompost, a particularly relevant finding given the co-location of coal fly ash generation and WH infestations in India (Mishra et al., 2025).

Compost and vermicompost making from WH has great potential in India. This utilization option does not require any specific machinery or skills. However, in spite of the huge WH biomass available, composting and vermicomposting are not sufficiently prevalent in India owing to misconceptions. Even the vast biomasses removed mechanically by municipalities are left unattended to decompose and decay unused. Nevertheless, some smart farmers in several States have been observed to collect the decaying WH biomass and use the material in their farms.

One Indian company, "*CEF Srinagar Biofuel Private Limited*", established in 2021, has recently commercialized enriched compost made from WH and other aquatic weeds, harvested from the Dal Lake in Srinagar (Jammu & Kashmir). In this project, about 200 tonnes of WH-dominated aquatic weed biomass were harvested per day. In the recent de-weeding, up to June 2026, the company processed about 37,0000 metric tonnes of WH and other aquatic weeds to produce ca. 5600 metric tonnes of compost. The product has been sold to farmers in Kashmir, Uttar Pradesh and Punjab with success, showing promise that it can be replicated elsewhere in the world (Azim, 2026, *pers. comm.* - Sushilkumar) [3].

WH fibre products – 'Eco-Friendly Livelihoods

WH stems yield cellulose fibre suitable for paper pulp, grease-proof paper, yarn, ropes, cordage and fibre-board production. The WH biomass provides raw materials for various other handicraft industries and the world-famous WH furniture (Olal et al., 2001; Nega et al., 2022). As in Africa (Ayanda et al., 2020) and many South-East Asian countries, NGOs across India produce WH paper diaries, cards, and stationery — products that command premium pricing in the eco-friendly and sustainable goods markets.

In recent years, global funding has focused on a renewed interest in such value-added uses of WH to create a wide variety of products and employment opportunities for communities. WH-based products include attractive and colourful mats, hats, handicrafts, bags, baskets, laundry bins, necklaces, head caps, diaries, greeting cards, lampshades and

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[3] Project Coordinator – Mohd. Tariq Azim; CEF House, B-II/58, Mohan Cooperative Industrial Estate, Mathura Road, New Delhi – 1100.

footwear (Montoya et al., 2013; Pin et al., 2021; Udume et al., 2021; Kleinschroth et al., 2021).

In India, women's groups and others (such as handicapped groups) have come together to form "*Community-Based Organizations*" to harvest and process WH to manufacture a similar range of products, which have a market among resident local populations, as well as tourists from overseas and visitors at large. Reports from Africa also indicate that along the Nile, WH biomass has been turned into ropes for makeshift bridges across the river.

There are many case studies of WH fibre providing an eco-sensitive livelihood for rural communities in India, explored by non-government organisations (NGOs). Apart from coarse yarn and rope, the use of treated and refined WH fibre for high-value textiles and sanitary napkins (Vijayakumar et al., 2026) is particularly praiseworthy in India. Such uses have also been reported from Africa and other South-East Asian countries (Chandrasena, 2023).

While still in early commercial stages, many of these applications show the diversity of value-added products that can be generated from WH. These programmes, under the banner of transforming 'waste-to-wealth', are expanding across many States of India. The projects work closely with *Self Help Groups* (SHGs), "*training women to convert WH into eco-friendly products, fostering both environmental preservation and economic empowerment in their communities*" (*The Better India,* 2026)

It is also noted that these increasingly popular WH-based products (**Figure 9**) minimize the local impacts of WH on choked waterways. They are also low-technology, cottage industry products from which communities benefit. The production requires only simple inborn skills and can readily be components of nationwide livelihood improvement programmes.

Figure 9. A sample of WH-based fibre products

Complementing the cottage industries are the large-scale uses of dried WH as compost and biogas for rural households. Olal et al. (2001) and John (2016) reported that such means of practical utilization have led to a perception prevalent in African villages that WH is really a '*blessing*' that empowers both women and men and is '*not always a menace*'. India is not far behind in this attitude change.

Other Utilization Options with Potential in India

The following utilization options have the potential for further development in India. However, as far as we are aware, some are only under laboratory or pilot-scale investigation in collaborative projects, especially between researchers in India, China, Japan and Korea. Nevertheless, these options reinforce our belief in the value of WH biomass valorisation for societal benefits and industrial applications.

Biochar

Pyrolysis of dried WH biomass yields biochar, which can be used for soil amendment, for improved water retention and enhanced cation exchange capacity. Biochar also provides pH buffering, nutrient retention and carbon stabilising in soil (Canning, 2025). Biochar production also provides a safe disposal pathway for metal-contaminated WH biomass from phytoremediation systems, with metals stabilised in the char matrix rather than released to the environment. Practical applications are likely to be developed with further research and cost evaluations.

Biobriquettes

Briquetting is the densification of biomass to increase the energy density of biomass residues. In several African countries, WH is converted into Biobriquettes with dried algae as a binder. The briquettes are la ow-cost fuel, comparable with wood-based charcoal. WH briquettes have heat energy (calorific value of 18 MJ kg^{-1}). Carbonized WH (charcoal) can be 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 (Davies and Davies, 2013; Rodrigues et al., 2014; Carnaje et al., 2018). However, surprisingly, we find that Indian research has not yet explored this highly desirable option.

Animal fodder

WH dried biomass is a source of crude protein (ca. 20% of dry matter) and carbohydrates and has been used as cattle and fish fodder in many Asian-Pacific countries (Nega et al., 2022). The presence of calcium oxalate crystals in stems requires the biomass to be chopped and mixed with other fodder, such as legumes and grasses. In India, there is evidence that dried WH has been incorporated successfully into mixed rations without adverse animal health effects. Nevertheless, the practice is not common, although stray animals have been observed to feed on WH.

Source of Chemicals, Biopolymers, Bio-absorbents and Bio-Plastics

Global research reveals that WH biomass could be extracted for a variety of invaluable chemicals (Lalita et al., 2012; Bakrim et al., 2022). These remain much under-exploited in India. However, cellulose extracted from WH is widely used in high-value biopolymers, bioplastics and bio-absorbents in several countries (Schneider et al., 1995; Mahamadi, 2011; Saratale et al., 2020; Ramirez-Rodrigues et al., 2021).

Biopolymers and bio-plastics derived from WH cellulose are already used in high-end car manufacturing for internal trims, dashboards and panels (Prasanth et al., 2021), replacing materials that are otherwise made from fossil fuel-driven processes. Such applications appear to have commenced in materials research in India. Given that global literature points to spectacular achievements that are already in commercial use, cellulose fibre extraction needs to be considered as one of the most useful future applications of WH biomasses.

Supercapacitors and nanomaterials

An emerging and technically sophisticated application in India is the use of WH-derived activated carbon in supercapacitor electrodes (Prasanth et al., 2021; Mahata et al., 2025). Activated carbon derived from WH biomass has specific capacitance values suitable for lithium-iron batteries - a finding that positions WH as a precursor feedstock for advanced materials manufacturing and sustainable industries. The process involves carbonizing the cleaned and dried stems, followed by chemical activation using KOH. Mahata et al.'s research (2025) revealed that the activated carbon derived from WH has a useful high surface area of 1600–2450 $m^2\ g^{-1}$.

Integrated utilization concept

An estimated 200 tonnes ha^{-1} $year^{-1}$ of WH biomass is available across 8 million ha of water bodies in the country. The ability to fully utilize this resource requires not just technology but infrastructure, harvesting machinery, drying facilities, rural supply chains, and market linkage mechanisms.

A few decades ago, India saw the disposal of WH biomass with accumulated heavy metals and other pollutants as a major constraint to its management. This position has changed nowadays with a clearer understanding that such risks can be easily managed.

The proposition that WH biomass, contaminated with metal ions or organic molecules, contaminated WH biomass generated during phytoremediation, could be used to produce biogas, bioethanol and plaster board is valid in India. Clearly, the harvest of WH biomass, if handled appropriately, generates multiple co-products across energy, agriculture, and materials sectors, offering a compelling economic case for commercial-scale utilization. The financial viability of any single product stream (for example, biogas alone or compost alone) is often marginal. Hence, the integrated utilization of WH as a resource requires planning the manufacture of a combination of co-products that would substantially change the economics of dealing with WH in a positive direction.

Two of the most socially embedded utilization models in India are the *Assam Pani Meteka Craft Industry* (ASRLM, 2024) and the *Kerala Kudumbashree WH Weaving Networks* (The Secretariat, Kerala, 2025). They are success stories today because they integrate livelihood creation with sustainable resource extraction and community ownership in continued WH harvesting and utilization. Scaling up such models through *State Rural Livelihood Missions*, NABARD-linked microfinance, and export promotion under the GI framework offers a replicable template for other WH-infested States.

Obstacles to Utilization

As with any technology, there are barriers to WH utilization that 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 WH utilization with its management, where required, in different settings.

In some countries, there are challenges related to efficiently harvesting and dehydrating WH biomass without making adverse local impacts. The deliberate cultivation of WH for utilization will also be challenging in some situations without adequate safeguards to manage the undesirable effects of WH on aquatic ecosystems to which it can spread. In addition, developing 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 published successes, we find that the WH-based wastewater pollution removal technologies are yet to be adopted widely by many States of India where possibilities exist. Among the main obstacles to adoption are concerns about increased risks of spread and costs involved in transferring the technologies from pilot-scale to field applications.

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 laborious tasks. Furthermore, the costs of mechanical harvesting, 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.

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.

Managing Water Hyacinth – Looking Ahead

Specifically for India, our review finds that reliable data and information are lacking in the country for a proper assessment of WH, either as a problem to solve or as a resource for exploitation. As shown in the first-ever *Water Bodies Census* 2018-19, India has 15.98 million ha of freshwater bodies (ca. 4.86% of India's total landmass). The largest freshwater areas are ponds and tanks (18.22 lakh ha), followed by reservoirs (31.5 lakh ha), lakes (1.44 lakh ha) and wetlands (5.64 lakh ha) (Government of India, 2018).

While this national statistic is important, an estimate of how much of these inland water resources are affected by WH and to what degree is yet to be established. A comprehensive assessment would be desirable, given the issues discussed herein. It would require a GIS analysis that would give an estimate of the total areas of canals and small waterways, as well as rice paddies. These relatively easy steps should be followed by an estimation of major river reaches, tributaries and areas affected by WH. As shown in **Table 1**, the ICAR-AICRP-WM Network respondents could then be requested to provide a reasonable estimate of the total infestation area.

Brij Gopal, in 1987, cautioned against the utilization of WH, saying that: '*Developing countries should not encourage the propagation of this weed for utilization. The interests of humanity can only be safeguarded by seeking effective long-term control of WH, rather than by its utilization* (Gopal, 1987).

Interestingly, utilization of WH was well underway in the USA by the time Gopal made those comments. Perhaps Gopal's extreme caution was based on the Indian historical experiences of people cultivating WH in Bengal for making potash (as discussed by Iqbal, 2009). We contend that Gopal was handicapped without the scientific evidence we now have of utilization options. Multiple projects across India are a testament to the success of community-based approaches to managing WH, integrated with utilization (*The Better India*, 2026). We suggest that utilization can be implemented without necessarily causing further spread, but as part of a long-term, locally adopted WH management strategy.

Recent reviews of 'value-added products', derived from WH biomass, discuss the constraints as well as the compelling opportunities in WH product valorization for the benefit of communities (Pin et al., 2018; Su et al., 2018; Bakrim et al., 2022; Nega et al., 2022; Chandrasena, 2023; Abba and Sabarinath, 2025; Abba et al., 2025). Given the vast amounts of WH available as a major bioresource, we also believe that this *virtuous side* of WH cannot be ignored anymore and should be put to practical uses.

WH arrived in India not of its own accord. Humans were responsible not just for its introduction but also for facilitating its spread and deep entrenchment. Given that WH will never be eradicated from India or from the Asian-Pacific region, the time is upon societies to *benefit from the species by putting it to good use through appropriate technology and socially responsible, community-driven programmes*.

The socio-economic effects of WH are dependent on the size of infestations, the uses of the waterbody, and the success of control methods used. While effective strategies to control WH are known, control programmes often suffer from a lack of funding to have lasting impacts. Weed managers in most countries, including those in advanced economies (i.e. the USA and Australia), acknowledge that it is impossible now to eradicate WH where it has more than a foothold. Therefore, while efforts are made to contain it where its local impacts are unacceptable, it is pragmatic to explore how utilization can be part of an integrated solution to controlling WH and plan to overcome the obstacles to doing so.

As we have discussed, the corpus of literature on WH problems, management and opportunities is vast. Encouragingly, the subject does not appear to lack interest, as shown in so many recent reviews, even in the last few years. Our experiences show that each management strategy (i.e., physical, chemical, biological, or any combination as 'integrated control') has its own set of advantages and disadvantages and could be modified and applied in different situations. The success of each method, on its own or in various combinations, cannot be disputed. They do work, but only in small or very localized infestations.

We agree with the broad generalisation in the literature that effective long-term control strategies for WH have not yet been developed in any country. However, given the limitations of the biocontrol agents, our view is that an effective long-term control strategy should be much more 'location-specific', based on the conditions of each site. This requires taking into account the size of the infestation and its spatial distribution over the waterbody, the designated use of the water, its size, and its spatial configuration. Weather patterns affecting WH are not critical in India.

This vast literature on WH available from across the continents provides a comprehensive *knowledge base* of its biology and ecology, as a monoculture or in mixed populations. The factors that make WH resist control efforts are also well documented (Britto et al., 2026). With this knowledge, we believe that the highly successful coloniser is *much too strong for humans to manage in the long run without causing further unnecessary disturbances and damage to already fragile aquatic ecosystems*. Perhaps we should be prudent and *learn to live with it*.

We also contend that 'control' will not work alone at any infested site, even over a medium-term scenario, unless the primary factors that contribute to WH's proliferation are mitigated. The critical external factors that authorities can influence include reducing, via legislation or otherwise, nutrient pollution of waterways, which is rampant in Indian cities, burdened with heavy populations. India is no exception here. Severe infestations of WH are a manifestation in many other densely populated cities, especially in tropical and sub-tropical countries.

Waterways in most cities in India, large and small, as well as peri-urban townships and rural areas, suffer from being unclean and spoiled by direct discharges of untreated or partially treated sewage, industrial and domestic effluents. Away from the densely populated areas, in rural India, excessive runoff of fertiliser used in agriculture is the main cause of WH dominance in many lakes, swamps and smaller tributaries of major rivers. Unless action is taken to mitigate these human-related habitat 'disturbances', WH management will continue to be an almost impossible goal to achieve.

Research across India has shown that in any State that has waterways seriously affected by WH, action on the ground needs a 'location-specific', integrated plan that includes all possible management options. Implementation also requires a citizen's participatory approach that combines the efforts of the non-governmental sector, comprising small or large environmental groups, along with government departments and University researchers.

We strongly recommend that authorities and civic bodies, particularly in urban areas, engage the services of professional vendors to remove WH using heavy machinery for managing WH at different locations in India. The utilization of WH, '*turning waste into wealth*', as raw material for a wide variety of industries or for other uses, must also be done under scientific and administrative supervision and accountability to mitigate any risk of spread. There is abundant literature and many examples, from Africa in particular, cited herein, that should be used to facilitate such WH management discourses.

There is also an urgent need to monitor the existing infestation and map its spread using modern GIS tools, remote sensing, drones and artificial intelligence. Departments in National, State and Local Governments, including municipalities, must step up to keep their data and information updated, as has been done in the USA and Australia.

Conclusions

Way back in the 1960s, 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, proving the value of the species (Wolverton and McDonald, 1979).

The factors that contribute to the spread of WH across regions and containment are now 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 (Kriticos and Brunel, 2016). This dominant narrative continues to be the main obstacle to utilization.

In a recent globally focused bibliometric analysis of WH literature, Brito et al. (2026) analysed 3,845 articles that have been published in five continents (ca. 30 countries) [4]. Their objective was to identify the patterns, trends, and impact of WH in those affected countries and societies. One conclusion they drew was that there is an urgent need for international cooperation in both research and management of WH. For instance, Brito et al. (2026) argued for comparative studies between temperate and tropical regions to generate insights into the ecological and socio-environmental factors that shape the 'invasive dynamics' of the species.

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[4] Brito et al. (2026) retrieved In total, 6,496 articles, covering a period from 1927 to December 2024. Of these, their study used 3845 peer-reviewed articles in 1422 journals that were relevant to the research questions they asked: i.e. (1) what makes WH so aggressive ("invasive") in different situations and (2) what functional traits best explain WH's success beyond its native range.,

We agree that progress toward effective WH management requires interdisciplinary and multi-scalar approaches capable of integrating ecological, social, and economic dimensions and adapting strategies to the specific conditions of each region.

Relevant to our assessment and discussion on WH is the fact that Brito et al. (2026) found Indian research publications accounting for 21% of all research on WH, followed by China. Together, India and China, the two most populous nations in the world, were responsible for one-third (32%) of all WH publications. In India, the largest number of articles fall within the phytoremediation research landscape area (ca. 2.5% of total publications). This, in our view, is research in the right direction, prompted by the crucially important realisation of a bioresource, freely available, that has been much under-utilized.

In managing WH infestations, science-based aquatic weed management tactics and strategies are needed. Country-by-country approaches with utilization 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 comprehensive cost-benefit analyses or life-cycle assessment studies. Such studies have been done elsewhere and can be adopted in India.

As discussed in this essay, the utilization of WH as part of management is a well-proven approach. 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 '*learning to live*' with it (Kleinschroth et al., 2021). The ideal solution should be the utilization of WH, which would not encourage its further spread, but 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 effects of vast populations of WH on waterways are predictable in most aquatic systems. How to manage those effects with 'integrated control' is also known, despite under-achieving on the control objectives in most settings.

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*'.

This review of WH in India shows that the species 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. A change in attitude towards colonizing taxa, epitomized by WH, appears crucial as we face an uncertain future, complicated by climate change.

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 so deeply entrenched in India and may never ever be fully eradicated. More than 100 years of control efforts to remove WH in infested regions have failed because the species is just too successful as a pioneer species in new environments. Seeing the species with 'new eyes', along with utilization options, appears to be the only prudent way forward, while maintaining the health of critical ecosystem services and managing the plant communities best adapted to the human-disturbed environments.

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, 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. Instead of continuing to blame WH and other 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).

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 actions against specific taxa and navigate a precarious future unfolding around us.

Hill and Hadly (2018) 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, WH and other colonizing taxa will not just thrive but also change the habitats they occupy. Learning from Nature, it is also important to realise that with or without humans on the planet, WH and other colonizing taxa will play vital roles in stabilizing the earth's disturbed and damaged ecosystems. *They will also survive catastrophes on Earth. We may not.*

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