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"Science could help resolve the conflicting views regarding conflicted species"

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).

> *"…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

[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 19^{th} 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.

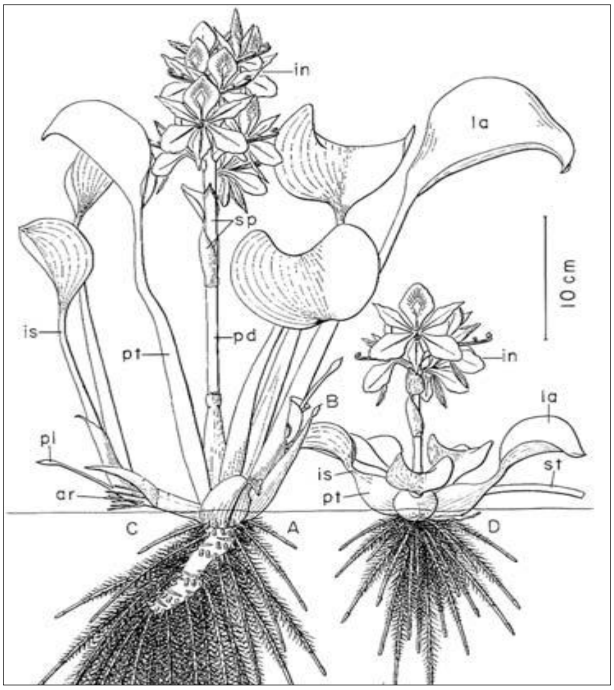

Figure 2 Morphology of *Pontederia crassipes* floating plants (From Center et al., 2002)

[**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),.

[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 30^0C 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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SHORT COMMUNICATION

First report of establishment of two weevils, *Neochetina bruchi* Hustache and *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae), released against water hyacinth [*Pontederia crassipes* Mart.] in the Philippines

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Abstract

Water hyacinth, *Pontederia crassipes* Mart. [syn. *Eichhornia crassipes* (Mart.) Solms.] of the family Pontederiaceae, is one of the world's worst aquatic weeds and a major problem in the Philippines, covering lakes, and blocking drainage and irrigation canals. Two weevils *Neochetina bruchi* Hustache and *N. eichhorniae* Warner (Coleoptera: Curculionidae) were introduced into the Philippines in 1992 to help control this weed. However, their establishment has never been confirmed.

In 2014, *P. crassipes* infestations at Laguna de Bay and Sampaloc Lake, San Pablo City were inspected but there were no signs of the beetles' presence, as indicated by distinct feeding scars. During weed surveys north of Manila during February 2023, feeding scars typical of *Neochetina* spp. were seen at San Quintin, Pangasinan although no beetles were seen. However, at several other sites, namely Baler, San Jose, Maria Aurora and Pulong Bahay, both *N. bruchi* and *N. eichhorniae* were found. To our knowledge, this is the first official record of both weevils establishing on *P. crassipes* in the Philippines and gives prospects to the biological control of this weed in the country. Sets of both weevils have been deposited at the Museum of Natural History, University of the Philippines at Los Baños, Philippines.

Introduction

Water hyacinth, *Pontederia crassipes* Mart. (Pontederiaceae) is one of the world's worst aquatic weeds, being found in over 80 tropical and subtropical countries throughout Africa, Asia and Oceania. It has also been reported in numerous countries in North America, particularly in the Caribbean (CABI, 2013). In the Philippines, *P. crassipes* is one of five major aquatic weeds (Bravo, 1991), covering lakes and hindering fishing activities, as well as blocking irrigation canals and drainage ditches, which can increase the risk of flooding.

Large infestations of *Pontederia crassipes* can lead to a decrease in oxygen content in water bodies, displacement of native aquatic plant species and reduced species diversity. In addition, it can also cause severe human health impacts by promoting diseases, such as malaria and dengue fever by creating suitable habitats for mosquitoes (Julien *et al.*, 1999). There are particularly large infestations in Laguna de Bay, especially near Taguig City (Figure 1A, B) and numerous infestations in Sampaloc Lake and in the Aurora region (Figure 2A, B).

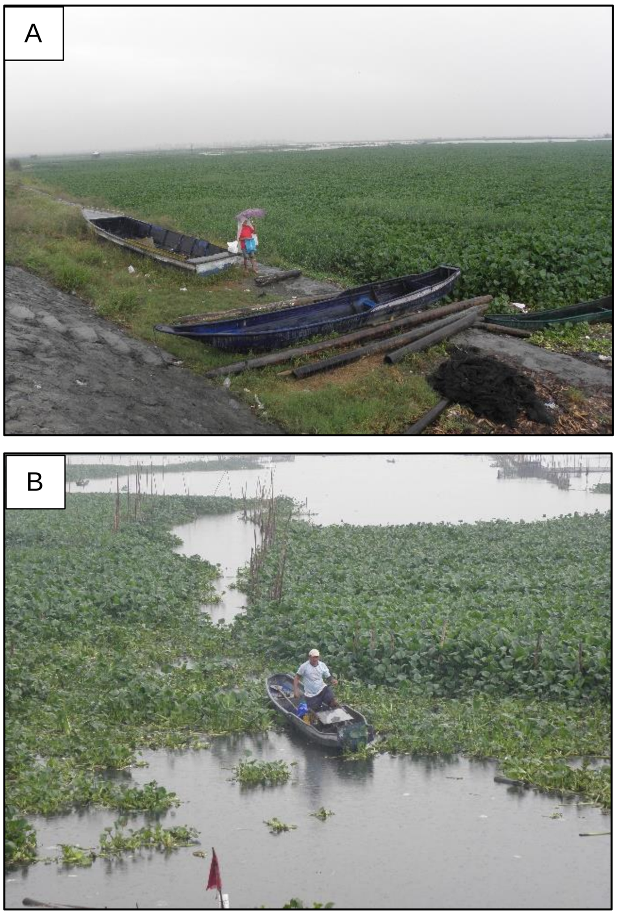

Figure 1. *Pontederia crassipes* infestations in the Philippines: Laguna de Bay (A & B)

Managing *P. crassipes* is particularly difficult as the plants grow very fast, doubling its biomass in 2-3 weeks, making manual control not feasible. The use of herbicides is also prohibitive in most waterbodies due to the effect of chemicals on water quality and fishing areas. With either manual removal or the use of herbicides, there is also the issue of viable seeds left in the muddy soil and reinfestation through daughter plants and fragments, which can take root and re-establish populations (Gopal, 1987; Wright and Purcell, 1995; Julien *et al*., 1999).

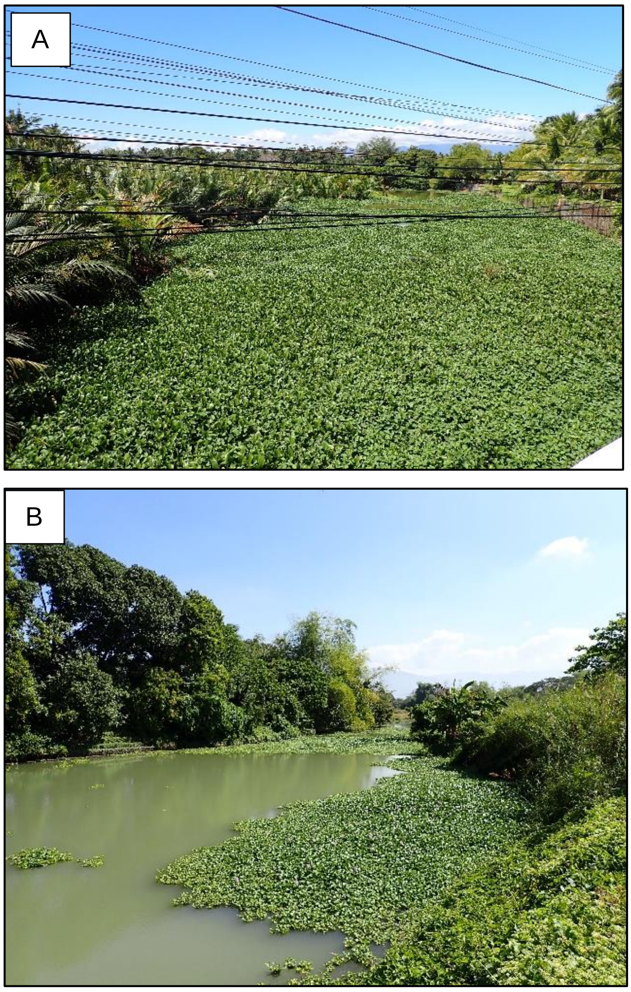

Figure 2. *Pontederia crassipes* infestations Pudoc Bridge, Baler-Casiguran Road Baler (A) and San Quintin, Pangasinan (B)

In 1992, two weevils, *Neochetina bruchi* Hustache and *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) were deliberately introduced into the Philippines by the Bureau of Plant Industry, Department of Agriculture from Thailand, where they had been released and established earlier. Both weevils were released in Laguna de Bay, as well as at unrecorded sites on Mindanao (Julien, 2001; Winston *et al*., 2014).

Establishment was never confirmed at any site in the Philippines and opportunistic field surveys at Laguna de Bay and Sampaloc Lake, San Pablo City by the first author in 2014 and 2019 failed to find signs (adult feeding scars) of establishment. Enquiries with researchers at several universities and government agencies could also not confirm the establishment of either weevil.

During surveys of several weed species in February 2023, opportunistic inspections of several *P. crassipes* infestations were conducted and the results of those surveys of *P. crassipes* in regions north of Manila are reported.

Results of Recent field inspections of Water Hyacinth

During a two-week visit to the Philippines in February 2023, funded by the New Zealand Government and managed by Manaaki Whenua - Landcare Research, looking for potential natural enemies of several invasive weed species, including *Decalobanthus peltatus* (L.) A.R. Simões & Staples (Convolvulaceae), *Solanum torvum* Sw. (Solanaceae) and *Urena lobata* L. (Malvaceae), opportunistic surveys were conducted on several other weed species, including *P. crassipes*, where biological control agents had previously been released and could be present.

The field surveys started in Clark, travelling north to Baguio, west to the coastal towns of Santo Tomas and San Fernando, east to Baler and Dinadiawan and south to Balanga, Mariveles, Bagac and Subic Bay. *Pontederia crassipes* was found at six sites (Table 1; Figure 3). *Neochetina eichhorniae* was found at three sites, while *N. bruchi* was found at only one site (Table 1).

The two weevil species (both about 4-5 mm long) can be distinguished from each other quite easily, with *N. bruchi* being usually brown in colour and possessing a chevron and two small parallel markings on the elytra, while *N. eichhorniae* is usually grey in colour, has two long parallel markings on the elytra but does not possess a chevron (Figure 4A).

Table 1. Sites during weed surveys where *P. crassipes* was observed and the presence or absence of both *Neochetina* spp.

Date	Site details	GPS location	Species present	Notes
21 Feb. 2023	Principe Bridge, Agoo, La Union	16.32897°N, 120.36595°E	Nil	Damage by grasshoppers
23 Feb. 2023	San Quintin, Pangasinan	15.95996°N, 120.74542°E	Undetermined	Feeding scars only
24 Feb. 2023	Baler-Casiguran Road, near Baler	15.77002°N, 121.55653°E	*N. eichhorniae*	Slight impact
26 Feb. 2023	Pantabangan-Baler Road, San Jose, Maria Aurora	15.78617°N, 121.47966°E	*N. eichhorniae*, *N. bruchi*	Slight impact
26 Feb. 2023	Pantabangan-Baler Road, San Jose, Maria Aurora	15.77396°N, 121.48398°E	Undetermined	Could not access site
27 Feb. 2023	Guimba-Aliaga Road, Pulong Bahay, Nueva Ecija	15.53860°N, 120.82439°E	*N. eichhorniae*	Slight impact

At the sites where the weevils were present, adult feeding scars were obvious and common (Figure 4B). However, despite the presence of larvae in the crown of plants (Figure 5), physical damage to plants by larvae appeared to be only slight.

Many of the plants at sites with beetles present were still quite tall (up to about 700 mm) and did not appear to show any signs of dieback, as usually seen when damage by the beetles is significant.

At one site in San Quintin, feeding scars were seen on several lamina but no weevils were recovered. As the feeding scars by both species (Figure 4B) are similar, it was not possible to determine which weevil species were present. Larvae of both species are indistinguishable in the field and feed in the crown of the plants (Figure 5), which can make plants water-logged and sink.

At some other sites where *P. crassipes* was found, there were no signs of damage by the weevils or plants were not accessible for a closer examination to determine if weevils were present (Table 1).

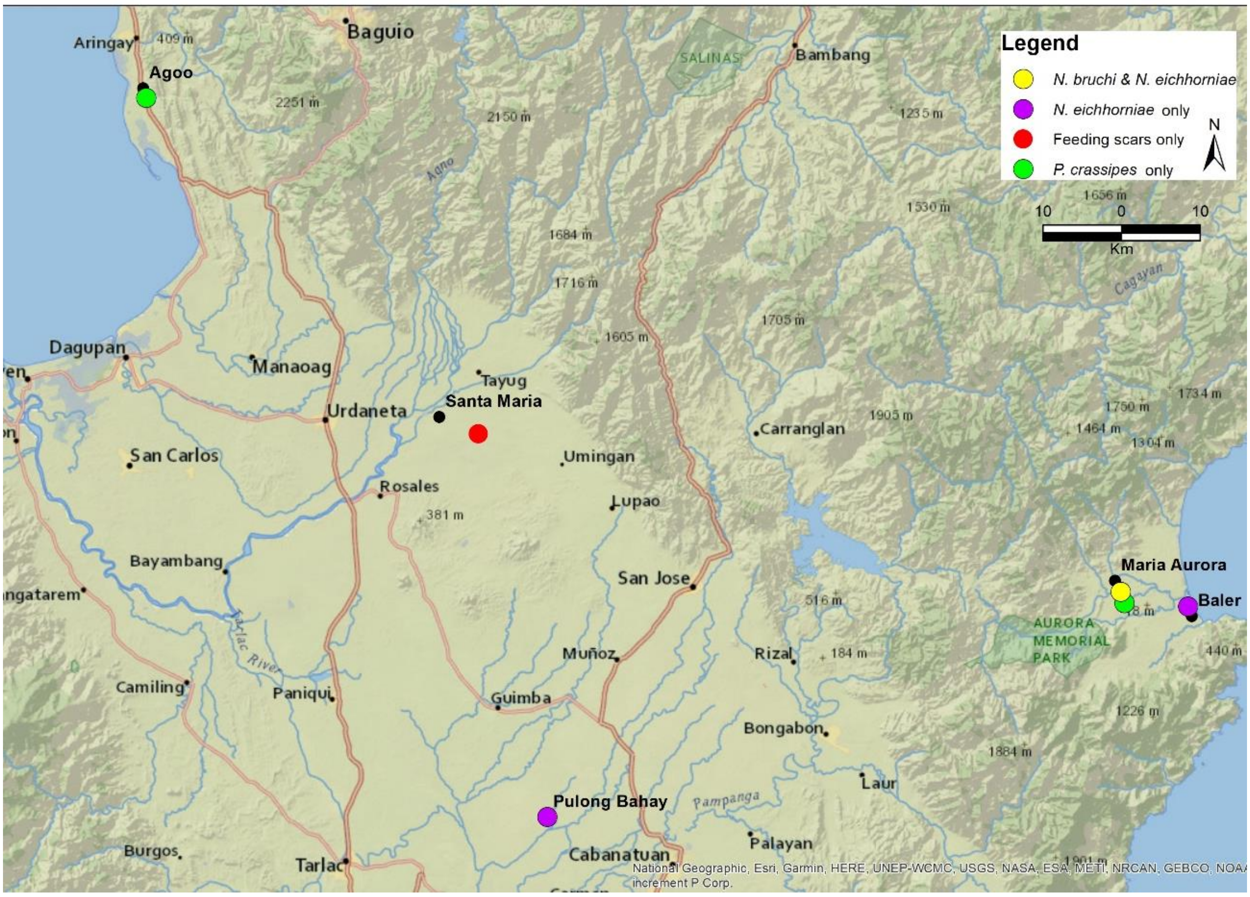

Figure 3. Map showing sites where *P. crassipes* was found, as well as where *N. bruchi* and *N. eichhorniae* were observed.

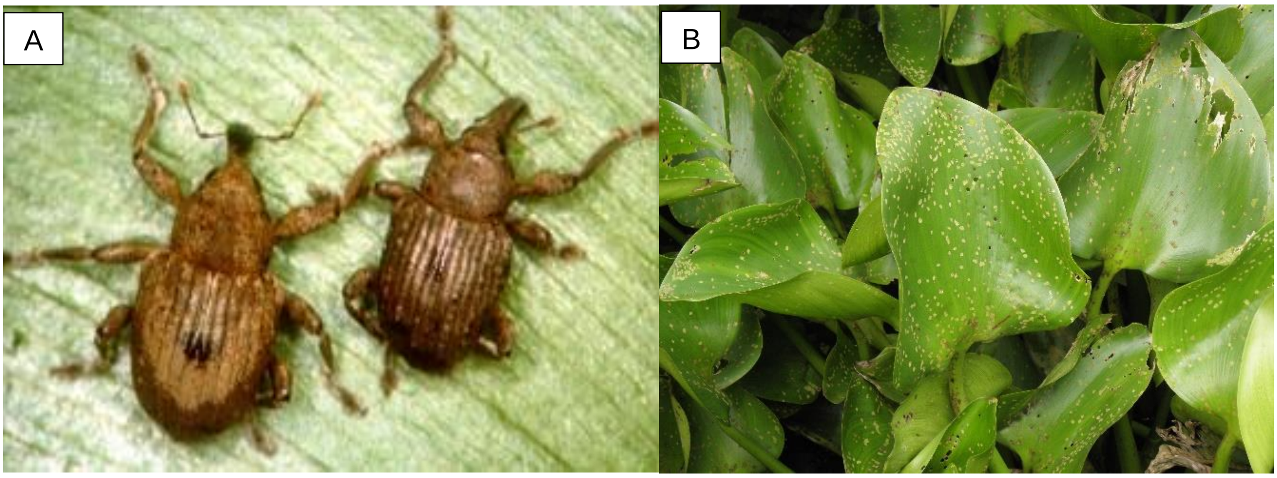

Figure 4. *Neochetina bruchi* (L) (orange arrows indicating chevron and parallel markings) and *N. eichhorniae* (R) (A), adult beetle feeding scars (B)

Discussion

The two weevils, *N. bruchi* and *N. eichhorniae* are recorded for the first time in the Philippines. These biological control agents were introduced in 1992 to control *P. crassipes* but their establishment had never been confirmed (Julien, 2001; Winston *et al*., 2014), prior to the current surveys. *Neochetina bruchi* has been deliberately introduced into 41 countries, with establishment now confirmed in 37 countries, while *N. eichhorniae* has been deliberately introduced into 43 countries, with establishment now confirmed in 39 countries (Winston *et al*., 2023).

Figure 5. Larvae tunnelling into the crown of *P. crassipes* plants

The impact of the two weevils on *P. crassipes* in these countries ranges from slight to high, with better control of the weed achieved if both species are present. In some countries e.g., Papua New Guinea and Vanuatu, biological control of *P. crassipes* has been particularly successful at some sites (Julien and Orapa, 2000; Day and Bule, 2016). However, in most other countries, detailed assessments of the beetles' impact on *P. crassipes* have not yet been conducted.

One of the factors that may limit successful biological control is the eutrophication of water ways, with levels of control by the beetles generally lower in heavily polluted waterways. It appears in these systems, *P. crassipes* can grow more vigorously and thus may outgrow any damage caused by weevils (Coetzee and Hill, 2011). This was particularly evident in Zimbabwe, where weevil numbers were high, but plants appeared to be quite healthy and still forming dense infestations.

In the Philippines, *P. crassipes* grows in natural lakes, as well as streams, irrigation canals and drainage systems. Only a few of these sites have been assessed for the presence of the weevils. Since the sites covered in the current surveys were only visited once, it is not possible to provide any meaningful long-term impact of the weevils on *P. crassipes* populations at the sites visited to date. It would be beneficial if further surveys could be conducted to determine the distribution of *P. crassipes* in the Philippines and to determine the presence and impacts of one or both of the weevils at these sites.

Weevils could be introduced to sites where they are not present and longer-term studies could be undertaken to assess the impact of the weevils on *P. crassipes* in the Philippines.

Where weevils are already present and *P. crassipes* is not under adequate control, other biological control agents against *P. crassipes* that have been tested for specificity and have established in other countries could also be introduced (Winston et al., 2023).

Acknowledgements

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Canada Goldenrod (*Solidago canadensis* L.): An Aggressive Colonizer or a Useful Resource?

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Abstract

Canada goldenrod (*Solidago canadensis* L.) is a controversial and misunderstood plant species. It is an example of both a maligned weed, even in its native lands, and a problematic colonizer at locations where it has become established. In both native and introduced environments, it tends to become a dominant species of high-density growth. In places where it is a native plant, goldenrod is tolerated to a limited extent as it is non-toxic to humans and, in general, not detrimental to fauna. Goldenrod has historically been used as a source of herbal medicine, especially by indigenous North Americans.

However, goldenrod is also an aggressive colonizing species characterized by prolific growth that crowds out other species, and this aspect is of concern at locations where it can invade and expand its territory of occupation rapidly. Regardless, in both native and non-native (invasive) environments, Canada goldenrod is often dealt with by pulling or digging out plants and either burning them or leaving them to rot. However, as a potential source of biomass, it is also a resource to be utilized.

Canada goldenrod has seen limited utilization, mainly as a source of natural compounds and extracts for medicinal or nutritional uses. The present report is an overview and perspective of Canada goldenrod in terms of its properties, characteristics, growth and habitat, as well as its positive and negative aspects. In our view, the utilization options of Canada goldenrod as a viable biological resource are real although broader opportunities for applications may require further development.

Keywords: *Solidago canadensis; goldenrod;* colonizing; biomass utilization; renewability; sustainability

Introduction

Many weedy species, including both long-established species ('natives') and newly arrived species, which can spread widely ('invasive') are treated by most people with disdain regardless of their inherent characteristics. As all weedy species are 'pioneering species' or 'colonizing plants', some of these viewpoints are controversial. The issue of how best to deal with them is a perpetual and often divisive subject. Considerable effort is often made to eradicate or at least control the proliferation of weeds in situations where they might be problematic. These efforts can be both costly and harmful to the environment. Elimination of weeds may in some cases disrupt the ecology of local ecosystems on both macroscopic and microscopic levels.

The debates about what is 'native' still rage on in ecology and must surely be related to how long a species has existed in an environment or a continent with or without human interference or introductions. *Are all such colonizing species undesirable? Do they not have redeeming values?* These are contentious issues (Chandrasena, 2023).

Certain 'native' weedy species have become established in local or larger ecosystems where they thrive and even proliferate. As colonizing plants, it is in their inherent nature to reproduce as prolifically as possible and perpetuate their species (genes). Such species may largely be ignored and taken for granted by the local human population if they do not interfere much with human endeavours.

On the other hand, 'likes' or 'dislikes', depending on how we perceive species, can lead to attempts to get rid of those considered problematic, often at great environmental costs. The latter is especially true where certain species have become aggressive colonizers of habitat, which can, at least temporarily, disrupt local ecosystems and, in some cases, have detrimental effects on the local economy or human activities (Chandrasena, 2023).

An example of such a weed species as described above, which is controversial for several reasons in its 'native' habitat and has become a problematic colonizing plant in areas outside its native range, is Canada goldenrod (*Solidago canadensis* L.). It is a species that has been in the North American continent for millennia. Therefore, it should be considered a 'native'. However, in many habitats and environments, goldenrod is considered a problematic 'weed' and is often reviled for several reasons.

It is an aggressive, fast-growing species, which can easily spread into new areas. It has spread from eastern North America to other parts of the world, becoming a problem species as it established quickly and begins to dominate in 'new' areas. While various attempts have been made to manage the spread of Canada goldenrod, the plant has proved difficult to control and even to manage to a reasonable extent. In some cases, the colonization has been so successful that it is now considered a 'naturalized' species on several continents (Foster, 2023).

Canada goldenrod is, in many ways, a unique weed. It is reviled by many people and desired by others, especially for its characteristic golden yellow flowers which can add colour to gardens or cultivated meadows. A large stand of flowering goldenrod plants, with their rich golden yellow blooms, can be pleasing to the eye. The blooming plants also attract pollinating insects, including bees and butterflies and may be welcomed in certain gardens or other habitats for those reasons (Eisenstein, 2019).

Canada goldenrod can pose problems in both urban and rural areas. In the latter, large, unchecked stands of growth may have a detrimental effect on the growth of certain field crops or on cultivated soils, as well as on animals that may forage on grasses in infested fields. While the species, in general, is not problematic to humans in terms of toxicity, its profuse flowering has been long associated with allergenic properties, which causes many to think of Canada goldenrod only with negative connotations (Pavek, 2012). Despite the reputation as a nuisance that may be justified by some of its inherent characteristics, the species is misunderstood from other points of view and needs to be re-evaluated.

An alternative to the elimination or aggressive management of weedy species, such as goldenrod, is to utilize them in ways that are not harmful to the environment and can provide some economic advantage on the local or broader level. Research over at least two decades has shown that whole plants of *Solidago canadensis* or certain parts may be utilized to make a variety of products, making it a valuable plant resource. Plants, which are composed of lignocellulosic biomass, contain many components which can be used directly or converted into useful end products (Ayoub and Lucia, 2018).

In a previous publication, Duns (2020) presented the case of smooth cordgrass (*Spartina alterniflora*) which has become a problematic colonizer in Asia and other parts of the world, but one that can be an invaluable resource. Smooth cordgrass is an example of the possibilities of successful utilization of its colonizing abilities for human benefit.

The article described how cellulose fibres from smooth cordgrass stems can be used to make a variety of moulded pulp products in China with economic benefits. Utilization allowed managers to avoid the harmful burning of the infestations and the potential environmental damage such aggressive control may bring about on China's eastern coastline. This example demonstrated what can be done with large biomasses from weedy taxa if proper efforts are undertaken with understanding, along with support from the local government, industry or population.

In addition to traditional sources of lignocellulosic biomass, from agriculture, forestry and fisheries and their wastes, other potential sources are the large numbers of colonizing plants that exist on any continent. Utilization of such species represents a vast pool of available lignocellulosic biomass and can be an environmentally advantageous alternative to the use of fossil fuels as a resource. For the most part, they are a vast untapped and unrealized pool of available biomass (Sharma and Pant, 2018).

The issue of some of these taxa becoming 'invasive species' is a common theme world-wide. There is a general perception that some colonizing taxa can crowd out desirable, native species both on land and in waterways and coastal areas. They may also have detrimental effects on local environments and economies. These plants are commonly removed and then buried or burned, which creates an additional environmental disturbance (Duns, 2020). Utilization of these problematic species would accordingly be a way to not only reduce pollution but to help local economies as well by providing raw materials to produce energy or other products (Sharma and Pant, 2018; Chandrasena, 2023).

The purpose of this perspective is to highlight the present status of Canada goldenrod as both a native and colonizing species and to indicate its potential as a useful resource that is either neglected or eradicated. is not to review in detail the various applications of goldenrod; An overview of the species, its taxonomy, colonizing abilities, negative and positive aspects and public perceptions is given, together with methods of management, and finally, utilization of the plant as a resource.

Taxonomy

Solidago canadensis L., a member of the Asteraceae, was named by Carl Linnaeus in his *Species Plantarum* (1773). Its taxonomy has long been a source of controversy and some confusion because it is morphologically a highly variable species (Werner et al., 1980; Popay and Parker (2014). One former taxon, *S. canadensis* spp. *altissima* (previously known as *S. canadensis* var. *scabra*) is now treated as a separate species, with the accepted name: *S. altissima* L., which is common in Europe. The morphologies of the two species are remarkably similar, except for the presence of short hairs on *S. altissima* leaves and the absence of hairs in *S. canadensis* (Zhao et al., 2014).

While there are many similarities in appearance and other characteristics between various *Solidago* species, differences do exist in terms of plant morphology (Pavek, 2012). There are also major differences in the phytochemical profiles and bioactivities of Canadian goldenrod populations (Kołodziej et al. 2011; Vrabiˇc-Brodnjak and Možina, 2022), as well as some differences in its preferred habitats (Eisenstein, 2019).

General characteristics

Canada goldenrod is an erect, perennial, terrestrial plant, reproducing by both rhizomes and by seed. The species is hermaphroditic, self-fertile and is also pollinated by insects. Its characteristics include strong fecundity, fast spreading, clustered growth, and a high degree of stalk lignification at the maturity period. Importantly, the plant is a major source of nectar and habitat for insects including pollinators (Ford, 2020). Individual plants have a tendency to grow large, with normal growth achieving dimensions of up to 1.8-2.0 m. It tends to grow in clusters. It is noted for attracting wildlife.

The stems branch only in the upper part, hairless near the base, but very finely pubescent toward the top. The stems are strong and are a useful source of fibre. The plant has numerous narrow leaves that are stalkless, and often crowded. They are generally 1-15 cm long and 1-22 mm wide, lanceolate, and widest in the middle, tapering to both ends.

Leaf margins vary from nearly entire to usually having fine or sometimes coarse, widely-spaced teeth. Most leaves have one prominent mid-vein on the undersurface and two distinct lateral veins that branch from it and parallel it nearly to the tip of the leaf. The lower and middle stem leaves of plants in thick patches of growth are often seen dying and falling off by the time flowering begins (Figure 1)

Figure 1 (a) ***Solidago canadensis*** **L.** ***growth*** **(Top) Young Canada goldenrod plants in spring, with no blooms. Upon close examination, the teeth or serrated edges of the leaves many be observed. (b) Plants in bloom in an urban area in late summer**

The inflorescence is a broad or occasionally narrow pyramidal panicle 5-40 cm in length and nearly as wide, with several to many horizontal branches. The upper sides of the branches carry numerous, densely-crowded small heads of golden yellow flowers, thus giving the plant its name. Each individual flower head is about 3 mm long and wide. In northern climates, the species flowers from mid-July to October in its native habitats, with the seeds ripening from September to October (Figure 2).

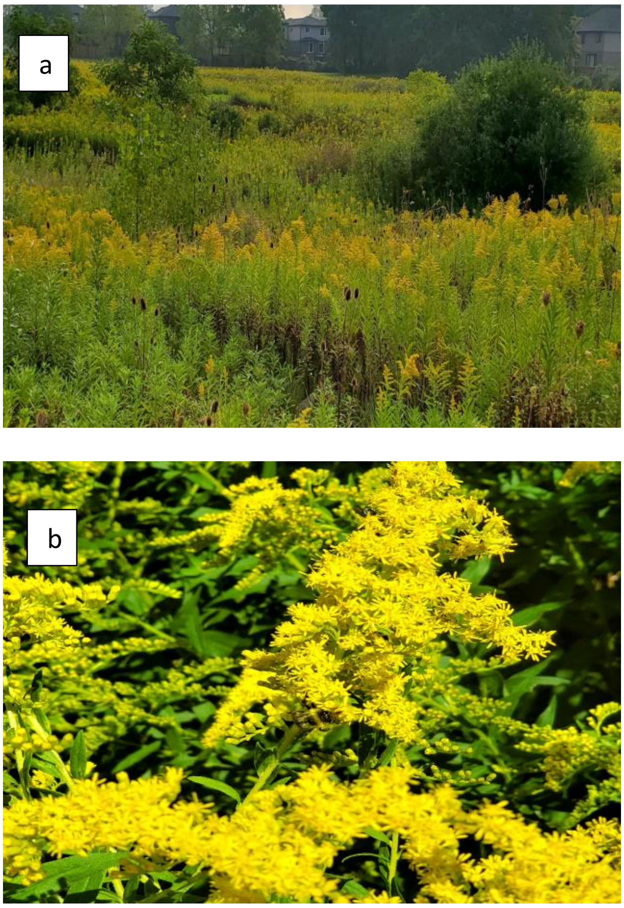

Figure 2 (a) The characteristic bright golden yellow florets of newly-blooming Canada goldenrod plants. (b) clusters of Canada goldenrods in urban fields and backyards near houses (author's collection)

Apart from profuse flowering, Canada goldenrod can reproduce from vegetative shoots that arise just below the root surface (Figure 3). Clonal growth and reproduction, from underground stem parts add considerably to the reproductive strengths of the species and also make its populations extremely difficult to control (Tang et al., 2013).

There are notable similarities between many goldenrod species, with some subtle differences. For example, *Solidago canadensis* can be distinguished from *Solidago missouriensis* Nutt. by its taller stature and its larger, more branched, open flower panicles. The Canadian goldenrod can also be distinguished from *Solidago gigantea* Ait. by its hairs on the stems and yellow bracts. (Pavek, 2012)

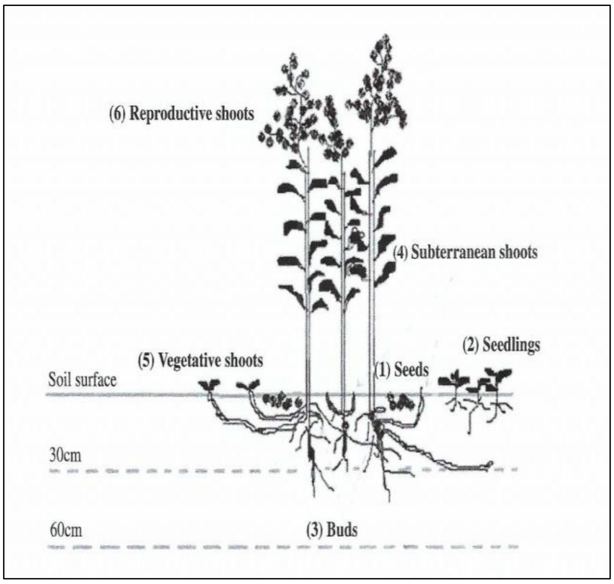

Figure 3 Canada goldenrod growth and reproduction - a depiction from Tang et al. 2013

Habitats and Biogeographical Distribution

Canada goldenrod generally grows easily and in abundance, as a robust plant. Growth will occur in any moderately fertile moist soil and in sunny conditions or semi-shade. The species is generally found growing naturally in many environments and locations, including in moist or moderately dry fields and meadows, edges of forests, swamps, clearings, orchards and compost piles, as well as along roadsides, streams, fencerows and shorelines, and as a weed in cultivated fields.

The fact that it grows well in diverse types of soil, especially in heavy or clay soils indicates its adaptability. In terms of soil pH, it can grow in mildly acid, neutral and basic (mildly alkaline) soils, while it avoids overly acidic soils. It can grow in semi-shade (light woodland) or no shade. Recently, Eckberg et al. (2023) demonstrated the dominance of Canada goldenrod in its local environment and found that it negatively correlated with the richness and combined biomass of all other plant species in that community. They attributed this dominance to the taller goldenrod plants reducing light availability for other types of plant growth. However, in the wild, goldenrods are often found mixed with other taller weedy species, such as milkweeds (*Asclepias* L. spp.), thistles (*Cirsium* Mill. spp.) and wild carrot (*Daucus carota* L.), and generally thrive in such situations.

In many rural areas of Canada and the USA, Canada goldenrod inhabits old or abandoned farm fields, pastures, and prairie lands, as well as undeveloped areas (Werner et al., 1980). In such localities, it is an early successional species. However, in well-managed prairies, pastures and cropland, Canada goldenrod typically consists of <5% of canopy cover (Smart et al., 2013). It is also important to note that goldenrods are a component of tall-grass prairies in provinces, such as Ontario in Canada. Unlike the grasses, introduced to Canada by farmers, such as Timothy (*Phleum pratense* L.) or bluegrass (*Poa pratensis* L.), native grasses have evolved to coexist with goldenrod (Ford, 2020).

Native range

Canada goldenrod is originally native to Eastern North America, from 26°N to 45°N, while it now extends to 65°N in the territory of Alaska. It primarily ranges from Newfoundland in the east to Ontario in the west and south to Virginia. This native range and main growth area encompasses much of the Great Lakes region, primarily in Ontario and Quebec in Canada and several northeastern United States where it undergoes a seasonal growth cycle.

Additionally, Canada goldenrod has spread to and now thrives in all US states except Alabama, Florida, Georgia, Hawaii, Louisiana and South Carolina. The species has also now extended its range to all Canadian provinces except for Nunavut in the far north (Pavek, 2012; Canadensis, 2020).

World-wide Spread

Canada goldenrod has now spread to various parts of the world and has been called an ‘invasive species’ of significant concern. Its abundant seeds, rapid vegetative reproduction ability, and allelopathy to other plants are the main reasons for its successful invasion. (Tang et al., 2013; Zhu et al., 2022).

Canada goldenrod was introduced to Britain and Europe from North America as an ornamental plant in the 17th to 18th centuries. It then spread from gardens to the surrounding natural environments in Central and Eastern Europe expanding at a rate of 741 km^2 per year in Europe. The species then spread to become naturalized in many countries, including Australia, Brazil, China, India, New Zealand and Japan (Zhang and Wan, 2017).

Canada goldenrod was introduced to China in 1935 as an ornamental plant for the gardens of Shanghai (Liu et al., 2005). Since then, it has become a significant and problematic colonizing plant widely distributed in China, especially along the southeast coast and the Yangtze River Basin (Dong et al., 2006; Yang et al., 2011).

In China, Canada goldenrod proliferated to the extent that it accounted for around 35% of the total weed infestations affecting China. It is now extensively distributed in most provinces of China and is listed as one of the most destructive and widespread weeds in China, having negative impacts on native environments (Zhao et al., 2014).

Dong et al. (2006) concluded that a lack of natural enemies in the invaded ecosystems made Canada goldenrod highly invasive and that abiotic factors, such as niche opportunities created by habitat disturbances, human activities, and nitrogen deposition, promoted its establishment and spread through seed dispersal and vegetative structures. In a recent review of Canada goldenrod (Lin et al., 2023), the ‘invasion’ success of the species in China was attributed to the combination of human activities and its inherently competitive nature.

A detailed study by Zhao et al. (2014) of the genetic diversity among native and invasive populations of Canada goldenrod in China, using AFLP markers, concluded that populations originated from multiple introductions and then spread through long-distance dispersal associated with human activities. They also noted that high genetic variability in the species in the invaded range has favoured its establishment and spread, factors that may well provide a challenge for its successful control. They also suggested that North American populations were possibly of a single genetic group.

Allelopathy

The allelopathic properties of Canada goldenrod have been studied for more than four decades (Zhu et al., 2022). Allelopathic polyacetylenes and diterpenes have previously been isolated from the plant’s roots. In some early studies, Fisher et al. (1977) showed that Canada goldenrod reduced the germination and growth of sugar maple (*Acer saccharum* Marshall) in the absence of competing vegetation. In a recent review of allelochemicals of two *Solidago* species Kato-Noguchi and Kato (2022) reported that the extracts, root exudates, essential oil and rhizosphere soils of Canada goldenrod suppressed the germination, growth, and establishment of several native plant species.

Allelochemicals, such as fatty acids, terpenes, flavonoids, polyphenols and their related compounds have been identified in the extracts and essential oils of *Solidago canadensis.* The concentrations of total phenolics, total flavonoids and total saponins in the rhizosphere soil of *S. canadensis* obtained from the invaded ranges were also greater than those from the native areas and ranges, which the species occupied. Kato-Noguchi and Kato (2022) and Zhu et al. (2022) concluded that the strong allelopathic activity of both species supports their 'invasiveness' and the formation of thick monospecific stands.

Abhilasha et al. (2008) found that the Canada goldenrod root exudates inhibited the growth of mouse ear-cress [*Arabidopsis thaliana* (L.) Heynh.]. The magnitude of the inhibition increased with the concentrations of the extract. In their analysis of 40 different root extracts, Abhilasha et al. (2008) found four main secondary compounds with allelopathic properties and different molecular masses that were consistently present in the samples. The levels of the four allelochemicals were lower in *Solidago* populations from newly invaded ranges than in populations of the same ploidy level in their native range. This prompted the authors to suggest that the production of these secondary compounds by the colonizer, invading a new area was lower, possibly because of the higher susceptibility of other plants in such habitats to these substances.

Environmental Effects

Positive Effects

As Eisenstein (2019) recently discussed, several benefits of Canada goldenrod justify growing it in various local environments without trying to control it. This is mainly because the species is known to attract a variety of pollinator insects and other wildlife, including birds that may feed on the insects or seeds. From this point of view, the plant is considered an asset even by farmers who appreciate its ability to attract pollinators who will then pollinate the crops. Together with its distinct golden yellow flowers, goldenrods are also a colourful and desirable species in garden beds, parks or natural settings.

Just like many other high biomass-yielding and fast-growing plants, goldenrods, with their tall and dense stands, can be a good agent for carbon sequestration by absorbing atmospheric CO_2. Removal of large goldenrod stands on a large scale could therefore be detrimental to the environment from the point of view of greenhouse gas reduction, in addition to habitat disruption. While not primarily a wetlands plant, Canada goldenrod can establish itself on the periphery of wet and moist areas. As a consequence, the goal of preserving wetlands may also be adversely disrupted by excessive attempts at removing dense stands of Canada goldenrod.

Negative Effects

While there are positive aspects to Canada goldenrod, it certainly has negative effects on both its native habitats and in newly invaded environments. Its prolific and dense growth can cause moisture and nutrient deficits to other neighbours, which may decline in abundance. This may cause a reduction in local biodiversity and economic losses to agriculture in both crop and livestock farming (Canadensis (2020). If not controlled, dense stands and clusters of Canada goldenrod can reduce grasses or hay on pastureland (Figure 4).

Figure 4. A Photo showing the impact of late summer/fall mowing on Canada goldenrod. The headland of this field (to the right) was mowed for hay in June of the previous year. The area to the left was knocked down in late August, encouraging goldenrod to break dormancy and produce stalks (dark green clumps) (Ford, R., 2020)

Broadly, as a known producer of a variety of terpenoids, phenolics, flavonoids and a large number of essential oils, goldenrod could also affect soil properties and soil microorganisms (Zhu et al., 2022). Some people, especially those with urinary tract or heart disorders may be allergic to various goldenrods; upon touching the plant, some may experience a skin reaction (allergic contact dermatitis) (Macleod, 2013).

Public Perceptions

Given the aforementioned positive and negative effects of Canada goldenrod, it is not surprising that the public perceives it as a controversial species (Canadensis, 2020). In the public mind, the negative aspects of its growth may outweigh the positive aspects. Where it has largely co-existed with humans for a considerable time, if not exactly welcomed every spring, people have come to tolerate the species to a certain extent in many gardens.

A main reason that Canada goldenrod is despised by the public is that it has not been known to live harmoniously with many other plants, particularly in recreational areas, such as public parks and home gardens. Since it can reproduce vegetatively by rhizomes and also by seed, the species can easily take over areas that are otherwise agriculturally productive (Eisenstein, 2019).

One major stigma that goldenrod has long been associated with is that it has been accused of being the cause of allergies or hay fever. However, this accusation is largely unproven. Goldenrod is insect-pollinated and its heavy and slightly sticky pollen does not blow on the wind. Rather, it is common ragweed (*Ambrosia artemisiifolia* L.) that is the usual culprit (Eisenstein, 2019; Canadensis, 2020).

Management of Canadian Goldenrod

Canada goldenrod can be a difficult plant to manage due to its inherent tendencies of rapid, dominant growth. As is the case with many weedy species, several different control methods have been used for its control with varying degrees of success.

Mechanical control

The traditional method of mechanical control is unsurprisingly widely used to deal with Canada goldenrod infestations. Mechanical control includes pulling, digging or hoeing out plants and then disposing of them by various means. This tedious method is suitable for small clusters of plants and is practised by homeowners who wish to eliminate the plants from their properties. However, Canada goldenrod can withstand heavy cutting and will regrow if cutting is done during the growing season. Thus, complete removal of the plants is preferred. To prevent seed dispersal, flower heads also need to be removed before seed ripening (Pavek, 2012).

Large stands of Canada goldenrod may also be dealt with by the removal and burning of the plants. The resulting ashes or char residue can be used as a fertilizer or soil amendment if the land is to be used for growing purposes. This physical control method is widely practised in China, normally after the stems have died (**Figure 5**). This burning represents the wastage of a vast amount of potentially useful biomass, and the smoke from the burning of large stands of plants can be a source of air pollution presenting a significant health risk to those with respiratory problems.

Figure 5 Canadian goldenrods removed by hand from a stand of growth in an area in eastern China (upper) and being burned (lower) (courtesy J. S. Chen).

Chemical control

Several selective, broad-leaf herbicides are available to control Canada goldenrod. However, it is a ‘hard-to-kill’ species without harming other broad-leaf vegetation. In addition, herbicides are not very practical for Canada goldenrod infestations that can cover large areas. Goldenrods can be killed with the selective herbicide triclopyr, which has a relatively short half-life in soil (Foster, 2023). At heights of 10-15 cm, glyphosate and other selective herbicides, such as 2,4-D and picloram can also be used to control several *Solidago* species.

A mixture of fluroxypyr and metsulfuron has proven selective in wheat, while Canada goldenrod growth on waste land can be effectively treated with other selective broadleaf herbicides, such as sulfometuron, imazapyr, flazasulsufuron and chlorsulfuron. In some cases, selective treatments could be followed by glyphosate and fluroxypyr to increase the effectiveness of control and recovery (Popay and Parker, 2014). In general, multiple herbicide applications are required to treat infestations because they are inherently difficult to control (Foster, 2023).

Biological control

Canada goldenrod is susceptible to many pathogens and insect pests, which reduce biomass production as well as seed production. Thus, biological control presents an alternative to managing the species. In Europe, herbivore pressure is generally low. Snails and small rodents rarely feed on goldenrod stems and leaves. In Switzerland, 18 phytophagous insects feeding on *S. canadensis* are known (Popay and Parker, 2014).

Tang et al. (2013) investigated various non-chemical methods for controlling Canada goldenrod in heterogeneous environments. These included cutting and hoeing and the inoculation with an indigenous pathogen, the fungus *Sclerotium rolfsii* SC64, which was isolated from *S. canadensis* and applied as a solid formulation. The research found that *S. rolfsii* SC64 caused 70% of plant mortality of *S. canadensis* under 150 cm growth stage.

The efficacy of control increased to 80% when the above-ground material was removed. Individually, the methods of cutting, hoeing or treating with *S. rolfsii* SC64, did not provide sufficient control of *S. canadensis*. However, a combination of cutting, hoeing and treating with isolate SC64 during the growing season in May, July and September was able to kill more than 90% of the ramets.

The combinations not only eliminated the plant's sexual reproduction but also killed the underground stems, preventing regrowth. Tang et al. (2013) concluded that such an integrated approach may provide an optimal strategy for the control of *S. canadensis.* These findings support those of Dong et al. (2006) and Lin et al. (2023) who also concluded that combined control methods, and minimizing seed production seem to be critical for effectively controlling Canada goldenrod and these control measures need to be taken before flowing.

Utilization of Canada Goldenrod

Instead of attempting to eradicate or control large infestations of a species, such as Canada goldenrod, an alternative is to take advantage of them as a freely available resource to be utilized (Ciesielczuk et al., 2016; Duns, 2020; Chandrasena, 2023) for a variety of applications. As with other large biomass-producing colonizing species, Canada goldenrod has been utilized for some traditional applications over the years. However, there are various other possible utilization opportunities also, which are under investigation. Some applications utilize the entire above-ground biomass of the plants, while others make use of only specific parts or even specific chemicals extracted from the plant (Figure 6).

In this brief review, the intention is to give the reader a sense of which applications have the greatest value and what could be done in the future. In the utilization of Canada goldenrod, the whole biomass may be utilized, such as burning it for heat or fuel in its most simplistic form, or only one or a few components may be utilized, e.g., carbohydrates for bioethanol. Some applications involve the conversion of biomass into its various constituent components (e.g., cellulose, hemicellulose, and lignin), which can then be further converted into other products by chemical, mechanical (pressure, agitation, grinding) and/or biological processes (enzymes, microbes) to produce many possible products.

The products that can be derived from fast-growing and large biomass-producing colonizing species include biofuels, such as bioethanol, biomethanol, biodiesel and biogas, cellulose fibres for pulp and paper, lignin, carbohydrates and proteins, as well as smaller chemical building blocks to synthesize other larger chemicals that would otherwise be obtained from petroleum refining (Ayoub and Lucia, 2018; Chandrasena 2023).

Zihare and Blumberga's review (2017) of Canada goldenrod utilization was a quantitative study of the number of publications related to this objective. Their hypothesis was that such weedy species could be a valid resource for high-value-added products and instead of eliminating them, great benefit could be obtained from their use. A breakdown of the major areas of utilization of Canada goldenrod that they determined is shown in the pie chart of Figure 6.

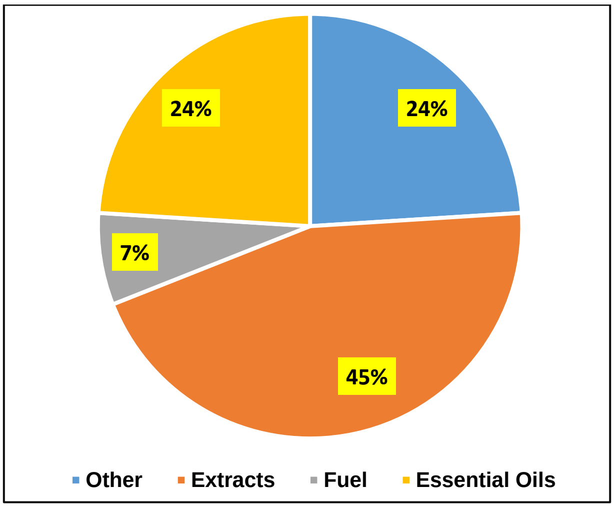

Figure 6. Proportions of studies reported on different utilization modes of Canadian goldenrod (Source: Zihare and Blumberga 2017).

It is to be noted that extracts make up 45% of the total utilization modes, with essential oils and the “Other” category making up 24% each, and fuel (biofuel) applications at 7%. The “Other” category is composed of assorted uses such as cellulose, compost, animal litter, honey production, isolated compounds, pest control, and rubber incorporation, in approximately equal proportions of 3.4% each of the total 7% of this category.

Figure 7 below provides an overview of different Canada goldenrod plant parts that can be utilized beneficially. ‘Extracts’ obtained from the plant are the most dominant utilization category for various practical applications, although this aspect also appears to have immense potential for further development. Some of the more historical and significant practical uses of Canada goldenrod, and other uses, which are at the developmental research stages, are discussed below.

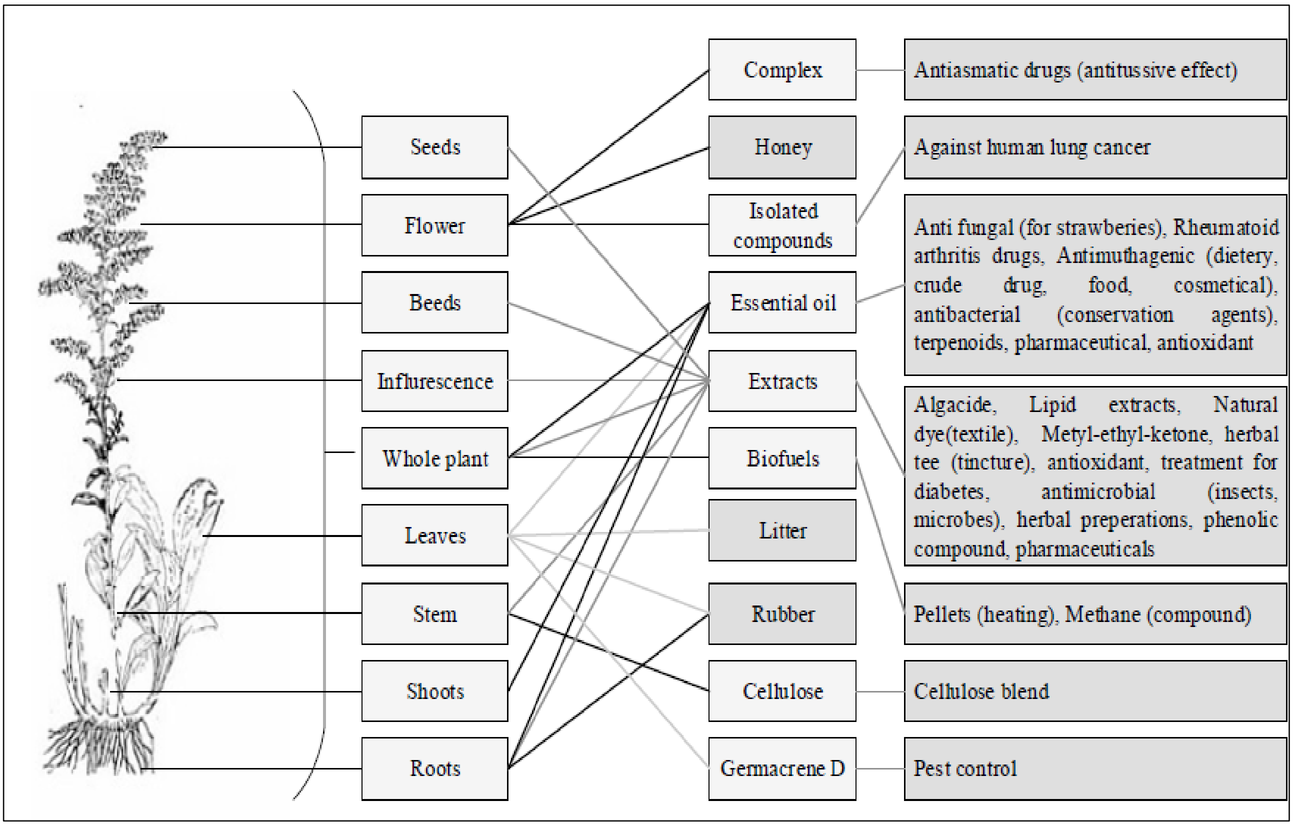

Figure 7. Classification of *Solidago canadensis* plant parts used as resources for various applications and products (reproduced from Zihare and Blumberga, 2017)

Medicinal and Nutritional uses

The best-known traditional use of Canada goldenrod is in the area of herbal medicine. Parts of the whole plant or extracts have been used to cure various ailments for centuries. The origin of the Latin name also reflects the plant’s many traditional medicinal uses; the genus name *Solidago* comes from the Latin *solidus* meaning “whole” and *ago* meaning “to make”. In effect, *Solidago* means “to make whole or cure” (Macleod, 2013).

Canadian goldenrod has been used by North American First Nations peoples for millennia for its medicinal and nutraceutical benefits. Its flowers and roots have traditionally been used to treat a wide range of ailments or symptoms, such as burns, fever, snake bites and sore throats (Wetzel et al., 2006).

Other traditional medicinal benefits of the species include asthma prevention, treatment for fever, fungal infection and inflammation of the mouth. (Canadensis, 2020). The plant extracts have also been used for urological, antiphlogistic and analgesic applications, gastro-intestinal and liver treatments, as well as for treatment of burns and ulcers. Infusions from goldenrod were used to relieve intestinal cramps and headaches. Broadly, Canada goldenrod extracts exhibit a spectrum of activities, including diuretic, anti-microbial, cytotoxic and antioxidant properties and also stimulate the immune system.

The nutritional or food uses of Canada goldenrod are linked with its medicinal usage. Flowers and leaves are edible and can be considered a modest source of nutrition (or nutraceuticals) (Wetzel et al., 2006). The plant has been brewed as a tea for centuries and the seeds can be used for thickening soup (Canadensis, 2020). Canada goldenrod is also an important source of the plant flavonol and antioxidant quercetin (3,3′,4′,5,7-pentahydroxy flavone. These chemicals are currently being studied and promoted by nutritionists and natural health practitioners to help combat chronic malnutrition and diabetes (Macleod, 2013).

Essential Oils

Many of the medicinal effects of Canada goldenrod and other goldenrods have been attributed to its essential oils and other components. Earlier studies on the plant have led to the isolation of a wide range of flavonoids, phenolic acids, saponins, alkaloids, polyacetylenes, mono- and di-terpenes and sterols (Lu et al., 1993; Bakia et al., 2019; Shelepova et al., 2019).

An extract of the flowers of a European goldenrod (*Solidago virgaurea* L.) was recently launched commercially in the Egyptian market under the trade name Cystinol® at a dose of 400 mg. It is used for the treatment of urolithiasis by promoting the excretion of water more than the electrolytes and increasing renal blood flow. This facilitates the washing out of bacteria from the urinary tract and prevents crystal formation, and hence kidney stones (Bakia et al., 2019).

In their review, Zihare and Blumberga (2017) determined that approximately 70% of the research on Canada goldenrod relates to the extraction of essential oils from the plant. The essential oils have both cytotoxic and anti-microbial activities. Zhu et al. (2009) compared the antimicrobial activities of volatile, essential oils from *Solidago decurrens,* a traditional wild medicinal plant and *S. canadensis* from east China. The most abundant component of the volatile oil from the leaves of *S. canadensis* was germacrene D (44.24%), while the most abundant component of the volatile oil from the leaves of *S. decurrens* was δ-elemene (21.73%). Overall, the antibacterial activity of the oil from *S. canadensis* was lower than that from *S. decurrens*.

El-Sherei et al. (2014) examined the effect of seasonal variations on the composition of the hydro-distilled essential oils of fresh flowers and green aerial parts of *Solidago canadensis* cultivated in Egypt over the four seasons of the year. The major compounds detected in the oil samples of all seasons were: germacrene D (9.9-29.5 %, (in agreement with Zhu et. al., 2009), α-pinene (3.4-29.2 %), γ-cadinene (0.4-20.4 %), myrcene (3.0-13.7%) and limonene (4.8-11.5 %). In addition to these dominant terpenes, reports indicate significant amounts of 6-epi-β-cubebene, a taste-generating sesquiterpene also in Canada goldenrod essential oils (Wang et al., 2006).

El-Sherei et al. (2014) reported a seasonal variation effect with the summer samples containing the highest amounts of monoterpene hydrocarbons, while the winter samples yielded the highest amounts of sesquiterpene hydrocarbons. While all oil samples showed considerable potential cytotoxic activity against human liver, breast and cervix carcinomas (Hepg2, MCF7 and Hela, respectively), the winter samples showed relatively higher cytotoxic activity compared to the summer samples. Thus, essential oils and other chemicals extracted from Canadian goldenrod have the potential to be developed further for obtaining beneficial health effects.

Anti-Oxidant Activity

The leaf and bark of Canada goldenrod contain a wide range of bioactive compounds (Wang et al., 2006; Deng et al., 2015; Shelepova et al., 2019), which show antioxidant, antimicrobial, antifungal and anti-inflammatory properties. However, this review finds that the properties of these molecules and/or their mixtures are yet to be fully understood and explored for beneficial, practical applications.

Deng et al. (2015) investigated the total phenolics, tannins and flavonoids and the antioxidant and antimicrobial activities of ethanolic extracts from the leaves and bark of Canada goldenrod at three ripening stages - vegetative growth only; full bloom; and mature after flowering. Extractions were made with either high-pressure (HP) or ultra-sonication.

The antioxidant activities, as well as the phenolic, tannin and flavonoid contents varied with ripeness stage, tissue type and extraction method. Overall, the ultra-sound extracted leaves of the full bloom stage exhibited the highest phenolic content (3.8. mg GAE g dry matter^{-1}), 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging capacity (0.547. mg AAE g dry matter^{-1}), and oxygen radical absorbing capacity (ORAC) value (57.86. mmol TE g dry matter^{-1}). The high-pressure extracts of mature plant samples had the highest flavonoid content (2.45. mg RE/g DM and reducing power - 3.38) as well as the highest tannin content (4.17. g/100. g DM) (Deng et al., 2015).

All leaf extracts exhibited antimicrobial activity against *Listeria monocytogenes* and *Staphylococcus aureus*, but only the HPE extracts of the VG samples showed activity against *Salmonella* spp. (Deng et al., 2015). The UE leaf extracts at the MF stage demonstrated the maximum inhibitory potency against *Escherichia coli*, *L. monocytogenes* and *S. aureus*. These results highlight the potential of using Canada goldenrod extracts as natural antimicrobial and antioxidant substances for food applications.

As part of a study examining the anaerobic degradation of Canada goldenrod by sulphate-reducing and methane-producing bacteria, Havryliuk et al. (2023) analysed the plant's phenols, flavonoids and total carbohydrates in 70% ethanol extracts and whole plant samples. The results (Table 1) showed that goldenrod extracts contained an exceptionally large amount of carbohydrates (4.54 mg mL^{-1} of extract or 511.5 mg g^{-1} of dry matter). The concentration of phenolic compounds was also high (4.3 mg mL^{-1} of GAE, gallic acid equivalents or 485.6 mg of GAE g^{-1} of extract). Flavonoids were 3.4 mg mL^{-1} or 385.7 mg g^{-1} of extract. The authors also showed that antioxidant activity was also high in the Canada goldenrod extracts, reaching a value of 86.3%. Overall, they demonstrated that goldenrod plants contain a large concentration of organic compounds, and, in particular, carbohydrates, vitamins and flavonoids. The study concluded that Canada goldenrod was a valuable substrate for the growth of anaerobic microorganisms and biogas synthesis with major applications in the production of biofertilizers, bio-ethanol and biofuels.

Table 1. Total phenols, flavonoids and carbohydrates contents in plant extracts and plant biomass of *Solidago canadensis L.* (from Havryliuk et al., 2023)

Type of Analysis	Value mg/mL of Extract	Value mg/g of Extract	Value mg/g of Plant
Phenols (GAE)	4.3 ± 0.3	485.6 ± 28.4	105.7 ± 6.2
Flavonoids (RUE)	3.4 ± 0.1	385.7 ± 16.4	84.0 ± 3.6
Total Carbohydrates	4.5 ± 0.2	511.5 ± 23.1	111.4 ± 5.0
DOC	8.5 ± 0.5	956.8 ± 45.5	208.3 ± 17.7
Anti-oxidant activity %	86.3 ± 4.2	-	-

Kołodziej et al. (2011) had already reported significant antibacterial and antimutagenic activity of hexane and ethanolic extracts of three *Solidago* species (*Solidago virgaurea*, *Solidago canadensis*. and *Solidago gigantea*). They observed that both extracts of all three species were antibacterial. However, the extracts were stronger in inhibiting Gram-positive bacteria (i.e., *Staphylococcus aureus*, *Staphylococcus faecalis* and *Bacillus subtilis*) than Gram-negative bacteria (i.e., *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*).

Hexane (lipophilic) extracts of Canada goldenrod were the strongest against Gram-positive bacteria, while the other extracts were weaker. However, ethanolic extracts of *S. gigantea* and *S. canadensis* showed relatively strong activity against Gram-positive bacteria. In general, alcohol extracts were stronger in antibacterial activity compared with hexane extracts. Nevertheless, hexane extracts of the three goldenrods exhibited antimutagenic activity at a concentration of 2.5 mg mL^{-1} whereas ethanolic extracts, in the range of concentrations tested, did not show antimutagenic activity (Kołodziej et al., 2011).

Biofuels and Bioenergy

The most significant non-food application of biomass-based materials has undoubtedly been in the area of biofuels and bioenergy, as the search for environmentally benign, non-toxic, renewable and sustainable alternatives to fossil fuels widens. The large biomasses of several fast-growing colonizing species are ideal for this purpose (Young et al. 2011; Sharma and Pant, 2018; Chandrasena, 2023).

However, Zihare and Blumberga (2017) noted that unlike some other weeds and other organic waste materials, Canada goldenrod biomass has yet to be subjected to adequate investigations and applications as a source of bioenergy or biofuels. Only 7% of studies on different application modes of goldenrod have been in the fuels area (Figure 6).

The study of Ciesielczuk et al. (2016) who examined the possibility of using Canadian goldenrod, wormwood (*Artemisia absinthium* L.) and common tansy (*Tanacetum vulgare* L.) as sources of biofuels is an important contribution. The authors studied field harvested yields, density of growth, dry matter contents of the harvest, bulk density, ash content and calorific values obtained from the species. Their results revealed that all species, with their capacity for fast growth, could be great energy sources due to their favourable characteristics, such as high calorific value (over 16 MJ kg^{-1}), low moisture, low costs and abundant availability.

Canadian goldenrod, in particular, was found to be especially promising as a fuel source since it is capable of covering large areas of land and could be efficiently harvested and burned without much heating system changes (Ciesielczuk et al., 2016).

Yao et al. (2014) had earlier observed that the methane production of Canadian goldenrod digested with cattle slurry was highly stable and efficient. Their results are supported by Havryliuk et al. (2023), who examined methane production, as well as copper immobilization through the degradation of Canada goldenrod plants by methane-producing and sulphate-reducing bacteria. Recording highly efficient methane production and copper detoxification in the degradation of goldenrod biomass by methanogenic bacteria, the study recommended that harvested biomass be easily fermented for biogas without the use of additional fermentation co-substrates.

Another application in the biofuels area is the bio-conversion of plant biomass to ethanol (bio-ethanol). While bio-ethanol has become a major commodity in the "green" fuels sector, the need for non-food sources of sugars to ferment to ethanol is required to avoid land use conflicts with food crops, such as corn and sorghum. Consequently, organic waste materials, such as crop residues, food waste, brewers' dregs and other materials have been examined to produce "second generation" bio-ethanol. Weedy species, a source of lignocellulosic biomass, are thus an appropriate potential source of bio-ethanol (Chandrasena, 2023, p. 273-277).

In a recent study, Wiatrowska et al. (2022) examined the energy production potential of several weedy species in Poland. The species were: Asian knotweed (*Reynoutria japonica* Houtt.), *Reynoutria sachalinensis* (F. Schmidt) Nakai and a hybrid *Reynoutria* × *bohemica* Chrtek & Chrtkova; Canada goldenrod, *Solidago gigantea*, and steeplebush (*Spiraea tomentosa* L.). The higher heating value (HHV) and lower heating value (LHV) of the plants were calculated. *Solidago canadensis* and *S. gigantea* had high heating values of 19.9 MJ·kg−1 and 19.4 MJ·$kg^{-1,}$ respectively. The observed heating values ranged from 18.5 MJ·kg^{-1} for *R. japonica* to 19.9 MJ·kg^{-1} for *R. sachalinensis.* For the remaining species, heating values were also approximately 19.0 MJ·kg^{-1}; indicating the possibility of using the biomass of such species for energy purposes, via combustion. The authors also noted that these high heating values were comparable with the values obtained for some common, energy-yielding species, such as willow (*Salix* L.) species (19.4–19.6 MJ·kg^{-1}) and the grass -*Miscanthus* (17-20 MJ·kg^{-1}).

Wiatrowska et al. (2022) also investigated the above species as sources for obtaining bio-ethanol using an alkaline pretreatment with 1% sodium hydroxide, followed by simultaneous saccharification and fermentation. While the highest bio-ethanol yield was obtained at 2.6 m^3 ·ha^{-1} for the *Reynoutria* × *bohemica* biomass, the remaining species, including the two *Solidago* species, also gave ethanol yields around 2 m^3 ha^{-1}, proving that the studied weedy species could be an inexpensive, potential raw material for the production of bio-ethanol.

Pulp and Paper

A significant application of biomass from various large-sized weedy species is their use as a source of cellulose fibres for paper pulp and other related products (Zihare and Blumberga, 2017; Duns, 2020; Vrabiˇc-Brodnjak and Možina, 2022). Colonizing species, including Canadian goldenrod, are a readily available source of lignocellulosic biomass. They are eminently suitable as renewable alternatives to traditional wood sources of cellulose fibres that can be used in the manufacture of paper and paper products, such as personal hygiene products and packaging materials.

In the area of papermaking. Li et al (2006; 2007) determined the chemical composition and fibre morphology of Canada goldenrod plants in China. Their results showed that the chemical composition included - ash content (2.92%), lignin (18.78%), holo-cellulose (80.28%), and pentosan (19.34%). The ash content was much lower than that of wheat straw (*Triticum* L. spp.), and close to that of common reed [*Phragmites australis* (Cav.) Trin. ex Steud.]. The lignin content was similar to that of wheat straw, while its holocellulose content was equivalent to that of poplar (*Populus* L. spp.).

Goldenrod fibres were on average, 9.8 mm long, with a length-width ratio of 0.86. The fibrous cell wall thickness was 3.03 µm, and the ratio of cell wall thickness to lumen of 0.36. These measurements indicated that the Canada goldenrod fibres were suitable for pulping and papermaking. Studying the effectiveness of bleaching for the production of chemical pulp from Canada goldenrod fibres, Li et al. (2007) reported that standard alkaline-anthraquinone bleaching was sufficient and suitable for producing the bleached chemical pulps from those fibres.

Despite the suitability for producing chemical pulps from its cellulose fibres, this particular utilization of Canada goldenrod has yet to see full commercialization to any extent, unlike *Spartina alterniflora* (smooth cordgrass). As discussed by Duns (2020), an industrial facility was successfully established and operates in China (WHERE?? xxxx) to produce moulded pulp products from smooth cordgrass, taking advantage of extensive and large stands. The possibility exists to extend a similar technology to the harvested stands of Canada goldenrod without letting the biomass go to waste.

Wood-Polymer Composites

Another significant and growing application of biomass from colonizing species is in wood-polymer composites, or specifically, those that are designated wood-plastic composites (WPCs). In effect, they are mixtures of wood fibres and thermoplastic resins, such as polypropylene (PP), polyethene (PE), or polyvinyl chloride (PVC). The composites are thermoplastics, reinforced with filler consisting of natural plant fibres and prepared under controlled temperature and pressure, and mixing. The cellulose fibres from plant sources partially replace the synthetic polymer in the composite material.

WPCs have many excellent properties, such as high durability, wear resistance, and specific strength and stiffness and can also attain a texture similar to that of solid wood. In many cases, the cellulose fibres impart improved mechanical and chemical properties in the composite compared to the original polymer matrix, such as improved tensile strength, density, weight reduction and moisture absorption. The main application of WPCs was initially in the manufacture of exterior decking and fencing. However, WPC applications have greatly expanded to other industries, such as the automobile, aerospace and electronics sectors, and advanced building construction materials (Ayoub and Lucia, 2018).

WPCs have also been fabricated from other environmentally friendly materials, such as wood waste, waste paper, agricultural residues, such as wheat straw, other unused natural resources including various plant species, and recycled thermoplastic resins. Fibres from diverse sources of biomass, including colonizing plants, have accordingly been investigated for use in composites.

The average individual fibre properties are an important requisite for the use of a particular type of fibre in composites. The characteristics of the particular filler used for manufacturing WPCs influence the physical and mechanical properties of the obtained composite. Filler materials include wood-based filler, other natural fibres, and recycled materials

In an important, first-ever report from China, Liu et. al. (2017) provided details of the chemical composition and fibre characteristics of Canada goldenrod (Table 2). They also investigated the potential of goldenrod fibres as a filler to produce high-density polyethylene (HDPE) composites. The filler consisted of goldenrod stem fibres pulverized into powder and chemically modified by the addition of a silane coupling agent to render the polar fibres more non-polar to be compatible with the non-polar HDPE. The treated fibres were mixed with HDPE in various proportions to prepare composites.

When the composites were prepared, scanning electron microscopy (SEM) analysis revealed good contact and interaction between the fibre-matrix interfaces, forming a three-dimensional network structure, a property which is essential for good composite construction. The resulting mechanical properties of the composites showed that a maximum tensile strength could be obtained at a loading of 30% Canada goldenrod biomass replacing the HDPE.

Table 2. Chemical composition and fibre morphology of Canadian goldenrod (from Liu et al., 2016)

Chemical composition	
Cellulose (%)	36.69
Pentosan (%)	18.68
Lignin (%)	16.37
Ash (%)	2.35
Extractives (%) *	4.58
Fibre Morphology	
Length (um)	720.72
Width (um)	212.24
Aspect Ratio	3.397

* Ethanol-Toluene extractives

The study by Liu et. al. (2017) has proved how useful the biomass content, chemical/physical characteristics and fibre properties of Canada goldenrod can be. The strength and other properties of the HPDE composites that can be made with Canada goldenrod fibres also show the potential for expanded utilization of the species as a natural material for filler for composites.

Biochar Applications

Biochar is a carbonaceous material, a type of charcoal with high carbon content, which can be made from biomass via pyrolysis under low oxygen or anaerobic conditions. Due to its large specific surface area, and well-developed pore structure, biochar is an excellent adsorbent material. When added to soil, biochar can improve the soil porosity, air content, water holding capacity and fertilizer efficiency of soil (Cha et al., 2016).

The carbon in biochar is stable and no longer participates directly in the carbon cycle, so this is a significant approach to carbon sequestration, which has the potential to help mitigate climate change and reduce the greenhouse effect via carbon sequestration (Panwar et al., 2019). Biochar is also relatively cheap to produce on a large scale and has become increasingly popular for various environmentally-friendly applications.

The use of biomass from weedy species, such as Canada goldenrod and many others, as a source of biochar has been under investigation for more than two decades. In a recent study, Zhang et al. (2018) prepared biochar from Canada goldenrod and showed its effective use for alleviating the inhibition of tomato seed germination by allelochemicals in soil. The biochar-amended soils also promoted the germination and growth of tomatoes compared with soils, which were not amended.

Phytoremediation Potential

Canada goldenrod plant biomass may also serve in environmental applications as a biofilter medium or phytoremediation agent for removing heavy metals from contaminated soils or water. This was proved in a study in Poland by Bielecka and Królak (2019) who analysed Pb and Zn contents of above-ground and below-ground parts of Canada goldenrod from an agricultural and previously mined, industrial area. Lead contamination in the agricultural area was low (median of 22 g kg^{-1}), while the industrial area was heavily contaminated (median of 201 mg kg^{-1} but up to 1626 g kg^{-1}) of Pb in soil. In addition, Zn levels in the contaminated soils were: in the agriculture area – 42 mg kg^{-1} and in the industrial 350 mg kg^{-1}.

The results showed that Canada goldenrod tolerated and bio-accumulated both metals. Pb accumulation was mainly in the roots and rhizomes (estimated to be up to 540 g Pb ha^{-1}) whereas above-ground parts had 70 g ha^{-1} of Pb. Concerning Zn, in the heavily contaminated industrial soils, both above and below-ground parts of plants accumulated similar amounts (ca. 450 g Zn ha^{-1}). However, in the agricultural area, with a natural Zn content in the soil, goldenrods bio-accumulated Zn in larger amounts (ca. 250 and 110 g ha^{-1}) in the above-ground and under-ground parts, respectively.

This result prompted Bielecka and Królak (2019) to suggest that Canada goldenrods could be used to phyto-extract Zn from the soil. In discussing their results, the authors also recommended that Canada goldenrod be used as a phytostabilizer of Pb and Zn in soils heavily contaminated with these elements.

Dyes for Various uses

One of the earliest non-food applications of plants has been as a source of dyes, which are naturally occurring colouring materials. A wide range of natural plant dyes gives rise to a spectrum of colours ranging from yellow to black. These dyes arise from various organic and inorganic molecules in the plant, which absorb light in the visible region of 400-800 nm. Based on archaeological evidence, nontoxic and renewable natural dyes and pigments have been used for colouring food substances, leather, wood, natural fibres and fabrics from the dawn of human existence (Chandrasena, 2023a,).

These colour-producing compounds commonly include a vast array of flavones and flavonoids, quinones, polyenes (carotenoids), and nitrogen-containing organics, such as pyrroles, pyrimidines and alkaloids. Dyes have traditionally been used to impart specific colours or mixtures of colours to various textiles, such as silk and cotton, leather and yarn, including jute, while non-toxic dyes are used in the food and cosmetic industries (Choudhury and Chandrasena, 2022; Chandrasena, 2023b, p. 297).

Many colonizing species have been the most important sources of plant dyes for millennia and some species have more value in this regard than others (Choudhury and Chandrasena, 2022). Canada goldenrod has traditionally been used as a source of natural dye, mainly yellow dye from the carotenoids present in the flowers (Chandrasena, 2023b, p. 297).

Canada goldenrod has also been used as a model plant for investigating and standardising industrial dye production methods and properties of plant dyes. For example, Bechtold et al. (2007) studied aqueous solutions containing flavonoid dyes extracted from goldenrods employing absorbance measurements by photometry after the addition of FeCl2, analysis of total phenolics (TPH) in the extracts and the depth of dyeing of wool yarn. In this study, TPH calculated as gallic acid equivalents ranged from 62-97 g kg^{-1} of plant material with one sample exceeding this range with a value for TPH of 142 g kg^{-1}.

Correlation among TPH, photometry in the presence of FeCl2 and lightness of the dyeing have been used to characterise plant sources for dyes.

However, the study found a poor correlation between the photometric results and the colour depth of the final dyeing of yarn Bechtold et al., 2007).

Leitner et al. (2012) used Canadian goldenrod as a representative case to study the production of a concentrated solid plant dye as opposed to the direct use of more dilute natural plant extracts for dyes. The authors concluded that using such a concentrated naturally produced dye offers novel approaches concerning the standardisation of dyestuff quality, handling and applicable dyeing techniques.

Natural growth elicitor/pesticide

The large variety of chemicals produced as secondary metabolites by Canada goldenrod may also serve as growth elicitors or a natural pesticide that can be put to practical use. One of the best-documented examples is the algicidal activity reported by Huang et al. (2013; 2014). In their studies, concentrated ethanol extracts of Canada goldenrod controlled the toxigenic cyanobacterial blooms of *Microcystis aeruginosa* in a natural water column (pond). Extracts of 0.3-0.5 g L^{-1} inhibited *Microcystis* biomass by more than 70% after 5 days after treatment (DAT) and more than 80% after 25 DAT, without any long-lasting negative effects on water quality parameters. Moreover, the extracts had lower toxicity to *Daphnia magna* and zebrafish than to *Microcystis aeruginosa*. With hardly any adverse effects on the aquatic ecosystem, the study suggested that it was feasible to use Canada goldenrod extract as an algicide to control *Microcystis* blooms in static bodies of water.

Adding to these findings, Liu et al. (2017) investigated the anti-fungal properties of Canada goldenrod essential oil against the highly virulent, pathogenic fungus ‘grey mould’ (*Botrytis cinerea*) in a range of in vitro studies. The practical application investigated was to determine whether the vapour from the oils could be used to prevent the post-harvest decay of strawberry (*Fragaria* × *ananassa* Duchesne) fruits, caused by the grey mould. The essential oils from the leaves of Canada goldenrod plants exhibited a highly potent and dose-dependent, antifungal activity against *B. cinerea*. Compounds in the vapour profoundly altered the pathogen’s mycelial morphology, cellular structure, and membrane permeability. The study suggested that Canada goldenrod oils could be developed further for the control of post-harvest fungal diseases while maintaining taste and other qualities in strawberries.

Animal husbandry

As well as being a natural food source for many insects such as butterflies, the prolific growth of Canada goldenrod in rural fields and pasture lands suggests that it could be an asset for farmers. It may serve as a cheap and readily available source of food, bedding or litter for farmers and others who raise animals, as well as for certain wild animals.

Zihare and Blumberga (2017) noted that Canada goldenrod leaves have been used as a source of animal litter as well as fodder. The plant is grazed by animals such as cattle, sheep, horses and whitetail deer (Pavek, 2012). However, many farmers, especially in North America dislike Canada goldenrods because of the potential detrimental effects of unchecked infestations on pasturelands and competition with traditional forage crops (Ford, 2020). In such cases, farmers would do well to avoid dense stands from forming. To avoid such conflicts with other fodder crops, Pavek (2012) recommended seeding Canada goldenrod at low densities or planting in small, manageable areas. However, despite the potential, the species is not popular as fodder for animals, especially in North America.

Landscaping and Gardening

Canadian goldenrod is tolerated and even welcomed by some people in their gardens, primarily due to its attractive, golden yellow flowers that can attract butterflies and moths. The plant also attracts other beneficial insects, such as ladybirds, lacewings and hoverflies, which are known to help control insect pests in home gardens. The species, therefore, has landscape uses, including as a perennial for urban and woodland gardens. It is also suitable for cut or dried flowers and has also been used along roadsides for soil containment, and along seashores and riverbanks to mitigate erosion.

Canada goldenrod can also be used for rangeland revegetation of disturbed areas, mine spoil reclamation, and soil stabilization (Pavek, 2012). Utilized in this manner, Canada golden plays a modest ecological role with some environmental benefits. Although it is not typically favoured by horticulturists and gardeners for landscaped settings, due to its rapidly spreading growth, some consider it a worthwhile addition to beautifying gardens. Managing the species in garden settings may require controlling seed dispersal by removing flower heads before seed ripening (Pavek, 2012).

Conclusions and Outlook

As discussed above, with both negative and positive aspects, Canada goldenrod has become a somewhat controversial species. As an extraordinarily successful colonizer, capable of prolific and unbridled growth, the species can quickly become dominant in different habitats and soil types.

As such, it has botanical traits, which make it a nuisance, especially in rural areas where it may compete in agricultural lands in which primary agricultural crops could be grown. Canada goldenrod has been wrongfully accused of being a source of allergies and hay fever and has also been maligned by the public for this reason. The species has spread from North America rather readily to various distant parts of the world, including Europe and China, where it is often considered a significant problem.

Where it is a problem, mechanical control of Canada goldenrod, or indeed many other similar weed species, is likely to be the least harmful to the environment. In the case of relatively small infestations, mechanical or manual control is the most practical, provided the residues are not simply burned but used for other purposes.

Mechanical methods are especially suitable for small stands, or in places where labour is inexpensive and plentifully available (such as in parts of China). Spot treatments with herbicides are also effective in controlling small to medium stands of goldenrods, in cases where the threat of expansion poses a risk to landscapes. However, it should be noted that in many locations I North America, where Canada goldenrod is native, the stands are now largely left alone and, as a result, have proliferated in both urban and rural areas.

Canada goldenrod plants are a rich source of chemicals, which are its secondary metabolites. While some of these chemicals may contribute to its inherent allelopathy and dominance in its local environment, several chemicals clearly have therapeutic values that can be exploited.

While there are many negative aspects to Canada goldenrod, on the positive side, the stands of Canada goldenrod are an enormous source of lignocellulosic biomass that can also be beneficially exploited. Based on analysis of the fundamental chemical and physical properties, this biomass can be a natural raw material for applications, such as wood fibre-polymer composites. Research is certainly moving in the direction of proving that the species could be converted into a new bioresource, which can be of excellent value for industrial applications.

The question as to whether or not a particular colonizing species should or could be purposefully cultivated to serve as a source of biomass is contentious. The traditional solution to weedy species by relentless control is a mindset that is difficult to change. In this situation, controlled cultivation on land less suitable for food crops may serve the two-fold purpose of supporting a local economy while at the same time managing any adverse effects pioneering species may have on local environments. If treated as valuable bioresources, they will not be left to rot and waste away or disposed of by burning, becoming a source of pollution or environmental contamination.

As Chandrasena (2023a, b) has discussed with examples, some countries and jurisdictions have already begun to '*see*' colonizing species as bioresources and not as enemies. Many countries and regions appear ready to use selected species judiciously in many eco-friendly applications and as invaluable raw materials for industries. However, in advanced economies, especially in North America, including the USA and Canada, the UK, Australia and New Zealand, the bioresource potential of colonizing species is largely ignored because of inadequate 'eco-literacy and 'weed-literacy'. It is abundantly clear that the prevailing discourses on weedy species are largely skewed towards '*seeing*' them only as problems (Chandrasena, 2023 a).

Rather than attempting to eradicate colonizing species with costly and environmentally hazardous control methods and tools**,** *is it time to look at other available choices*? Humans can learn to live in concert with many species, simply by learning to utilize the strengths of most species.

The choices are certainly not unique to Canada goldenrod, but this species can certainly serve as an example of what can be done. Based on the scientific evidence available, '*re-thinking'* should allow societies to reach a common consensus, if not a strategy, towards utilization as a management tool for many of the species that are perceived as 'problematic' on a global basis and not just locally.

Utilization, as bioresources, should be a viable option for many colonizing species, such as Canada goldenrod. Their attributes of rapid growth, high biomass production and proliferation together with strong characteristics of root and stem growth render them a reliable source of lignocellulosic biomass. While this particular source of biomass has seen some utilization as a source of raw material to produce energy and a variety of industrial products, it largely remains yet to be exploited to its full potential.

The advantages of using weeds as raw materials are not just related to their robust and fast growth and tolerance of a range of ecological conditions, but also to their resilience. These species are amenable to repeated harvesting, leaving behind sufficient rootstock that may regrow for continual, sustainable harvesting. Ease of harvesting is a key factor in the utilization of weedy species for practical applications (Vrabiˇc-Brodnjak and Možina, 2022).

The utilization of Canada goldenrod is, however, not the complete solution to the problems it may cause in some situations. There could be situations where utilization is not possible, or the populations of the species may have grown out of control on a scale that causes concern to both farmers and the public.

Sufficient knowledge, tools and techniques are available for deployment in these instances, where control is needed. *Control where needed is not in conflict with utilization, where there is potential. Control methods selected should only be the ones that are the most ecologically and environmentally-sound for the specific landscape or situation*.

An integrated management strategy would be ideal in many circumstances. This would consist of judicious management, combined with responsible and environmentally-friendly harvesting techniques and utilization. Large quantities of plant biomass generated by the growth of Canada goldenrod and similar weedy species should not be wasted.

With the increased need for biomass as an alternative to petroleum as a feedstock for energy, chemicals and other products, the outlook for Canada goldenrod to fill at least a part of this need is promising. Increased awareness on the part of the general public, as well as industry, and promotion of the utilization of weedy species, will help to solve the age-old question of how to deal effectively and practically with weeds. There should be a common consensus, if not a strategy, towards utilization on a global basis and not just left as an issue to deal with by local governments or civic organizations.

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