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Review Article

MULTIFACETED POTENTIAL OF *EICHHORNIA CRASSIPES* (WATER HYACINTH) LADENED WITH NUMEROUS VALUE AIDED AND THERAPEUTIC PROPERTIES

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Abstract

Being an aquatic weed which is growing dense and widespread across many lakes and water bodies, it is of paramount importance to utilize *Eichhornia crassipes* (commonly known as water hyacinth) for the benefit of the mankind, especially for its value added and medical properties, such as bio-fuel, biogas, bioremediation and therapeutics. Many of the bird sanctuaries and water-bodies have been drastically invaded by this aquatic weed which is really affecting ecological niche and bird migrations. Several researchers have successfully demonstrated the use of water hyacinth in the bio-remediation and as a potential source of renewable energy. Different heavy and toxic metals showing biomagnifications and therefore creating health hazards, could be remediated by using water hyacinth. The process of decontaminating agro-industrial waste polluted with heavy metals, organic and inorganic pollutants could possibly be done using water hyacinth. Current review focuses towards the efforts to utilize this weed for different value added and therapeutic properties. Furthermore the article emphasizes upon the need to gain more insight into the mechanism with concrete randomized controlled studies to find out the effects of this weed on human health and a sustainable solution to exploit and manage this invasive otherwise harmful weed into a beneficial entity for the mankind.
Keywords **:** Water hyacinth; value aided properties; bioremediation; bio-energy; bio-fuel; biogas; therapeutic

Introduction

Water hyacinth is known to have its origin from Brazil mainly in the rainforests of Amazon river along with some other regions of South America as well. One of the most invasive aquatic plant species worldwide, the water hyacinth (*Eichhornia crassipes*) is a perennial macrophyte monocot which belongs to Pontederiaceae family comprising of thick rounded green leaves, and lavender blue flowers while having dark purple to black roots with rhizomes and stolons (Patel, 2012; Gettys *et al.*, 2014). Nutrient rich water-bodies are the right spots for its multiplication with a doubling time of 1-3 weeks (Gopal, 1987a, Ndimele *et al.*, 2011). In terms of chemical composition, water hyacinth is enriched in nitrogen levels (3.2% of dry material) with a carbon to nitrogen ratio of 15. Given to their strong ability to uptake considerable amounts of nutrients and other chemicals, the chemical composition is likely to vary depending upon the environment (Gunnarsson & Petersen, 2007).

Characteristic features, factors and regulation

The cultivation of this otherwise invasive weed has reached more than 50 tropical and subtropical countries in the world with wide-abundance in Southeast Asia, Africa, Europe and United States as well having a mean biomass production of more than 140 tons per hectare per year (Abdelhamid & Gabr, 1991; Waeber *et al.*, 2015; Lindsey & Hirt, 1999; Brundu *et al.*, 2012; Bartodziej & Weymouth, 1995; Brendonck *et al.*, 2003; Lu *et al.*, 2007; Jimenez & Balandra, 2007; Toft *et al.*, 2003, Chabot). Both tropical and temperate environments have been reported to be equally suitable for the growth of the aquatic weed. Optimal temperature for growth of this invasive weed is between 25 to 27.5 °C while a pH range between 6 to 8 is considered optimal. While another study reported the optimal temperature for growth between 28-30^{o}C (Burton *et al.*, 2010). However, this plant is quite sensitive to salinity with 0.6% or more being vulnerable to the plant growth(Mangas-Ramírez & Elías-Gutiérrez). Moreover, the plant is not able to grow in the water having temperature either below 10^{o}C or above 30^{o}C. Being euryhaline in nature, it could growth both in fresh and marine water, though stationary or slow-flowing fresh water is most suitable for the infestation and further growth(Ojeifo *et al.*, 2000; Burton *et al.*, 2010). Some studies also reported about its ability to sustain adverse climatic conditions, and its ability to survive in damp soils for months, making it more invasive as well (Burton *et al.*, 2010). Water hyacinth seeds take about six months to germinate and remain viable for more than 15 years in the soil. In addition they have a remarkable capacity to regenerate rapidly even from stem fragments (Gunnarsson & Petersen, 2007; Ueki *et al.*, 1976; Malik, 2007). A salinity level of more than 0,6% is lethal for the plant.

Ecological dysbiosis

Water hyacinth because of its ability to grow in diverse nutrient conditions and fastidious in nature, it has become the fastest growing free floating hydrophyte in the world (Gopal, 1987a; Gopal, 1987b). Nutrient abundance and availability are indispensable for its growth and propagation with nitrogen, phosphorus and potassium required in larger amounts (Burton *et al.*, 2010; Xie *et al.*, 2004). There has been a direct correlation observed between the concentrations of nutrients with the rate of infestation of water hyacinth. This weed does have the capacity to store excess nutrients to be used further in later life stages (Heard & Winterton, 2000). There have been numerous ecological alterations in aquatic ecosystem, abiotic factors imbalance attributed to the hyper-invasion of this aquatic weed resulting in the formation of dense mats affecting water quality, reduced penetration of sunlight along with reduced availability of dissolved oxygen, leading to excessive evapo-transpiration rate and drying of water-bodies especially shallow lakes (Villamagna & Murphy, 2010, Gopal, 1987b). The negative consequences of such an ecological dysbiosis is quite vulnerable to the flora and fauna communities for e.g. because of the less penetration of the sunlight, the phytoplankton abundance tend to get decreased as a result of which the whole food chain comprising of aquatic invertebrates, fish and bird communities, is negatively affected (Gratwicke & Marshall, 2001; Villamagna & Murphy, 2010; Toft *et al.*, 2003). Furthermore, the water hyacinth can easily outnumber the submerged native species because of its aggressive and invasive nature (Midgley *et al.*, 2006).

Not only the native species which is affected by water hyacinth but even humans are impacted because of the ecological dysbiosis. Water-channels get blocked because of the deposition of the dense cell mass or mat formed by this weed resulting in disruption of the transportation, irrigation and hydropower generation (Honlah *et al.*, 2019). Nitrates and phosphate enriched nutrients accumulated in the water-bodies as a result of runoffs from rainwater from untreated wastewater, sewage and fertilized fields, have been known to enhance the growth of water hyacinth. Moreover, the construction of dams for hydropower, irrigation, water extraction and aquaculture are also known to reduce the flow of the river system, again providing ambient conditions for the water hyacinth colonies to grow (Hauser *et al.*, 2014; Honlah *et al.*, 2019). Fishing activity is also hindered resulting in huge economic losses as reported previously in literature (Calvert, 2002; Joffe & Cooke, 1997). Water hyacinth in the water-bodies also provides a rich platform and microhabitat for carriers/vectors of various diseases. Female anopheles mosquitoes which are the carriers of Plasmodium species causing malaria, rear in abundance in such microhabitats, threatening human lives (Joffe & Cooke, 1997). Many snakes, hippos and crocodiles are likely to hide in such water-hyacinth infested places, again proving dangerous for humans (Gunnarsson & Petersen, 2007).

Broad-Spectrum Applications

Many economic benefits could be derived from water hyacinth such as to produce biofertilizers, biogas, biofuel, bioremediation of heavy metals from waste-water and other contaminants, fodder, briquettes, furniture, and handicrafts along with therapeutic effects (Jafari, 2010; Patel, 2012) [Fig. 1]. Dried water hyacinth have been found to be much more economical for the developing countries. Because of the presence of high crude protein content, water hyacinth has been proved to be a suitable fodder as a part of the diet for ruminants, pigs and ducks (ELDIN, 1992; Jafari, 2010; Joffe & Cooke, 1997; Tham, 2012).

a. Phytoremediation

The plant's attributes certainly point towards this weed could be a hyperaccumulator mediating the process of removal of contaminants from the environment or wastewater, thus could be an attractive source as a low-cost, green, phytoremediation strategy (Jones *et al.*, 2018; Sharma *et al.*, 2016; Wolverton & McDonald, 1975). This cost-effective strategy holds promise in order to remove heavy metals, pesticides, hydrocarbons etc. from contaminated sites (Sharma *et al.*, 2016). Scientific community have focused on this particular organism because of its unique features such as its invasive growth, increased biogas production, ability to grow in polluted diverse environments, scavenger of heavy metals and ability to accumulate metal ions like cadmium, nickel, mercury etc. from industrial effluents (Malik, 2007; Sharma *et al.*, 2016). Water hyacinth has been extensively exploited for its capacity to absorb contaminants and nutrients; thus posing as a potential biological alternative for the improvement of wastewater quality and effluent quality as well (Ho & Wong, 1994; Cossu *et al.*, 2001). Water hyacinth was reported to accumulate many trace elements including nickel, copper, chromium and cadmium in a hydroponic study (De Souza *et al.*, 1999). Similarly leaves of the weed had been able to accumulate mercury as well indicating the possible association of water hyacinth in mercury remediation (Greenfield *et al.*, 2007). Furthermore another study revealed its role in the removal of arsenic and better removal rate in comparison to duckweed (Alvarado *et al.*, 2008).

Using appropriate water hyacinth based phytoremediation system, the ammoniacal nitrogen (AN) removal process was enhanced facilitating the design of an industrial scale phytoremediation system for the effluent treatment; hence paving the way for industry to reduce the AN level in their effluent discharge (Ting *et al.*, 2018). Water hyacinth root system is quite complex, which were also shown to remediate arsenic from waste water (Shabana & Mohamed, 2005). More so a lanthanide metal, europium was also remediated through the water hyacinth roots system as determined through scanning electron microscopy with highest concentration of the metal reported on root hairs (Kelley *et al.*, 1999). Also its dried roots and the ash and activated carbon derived from this weed were found to act as a decontaminating agent (Schneider *et al.*, 2001; Mahmood *et al.*, 2010; Mahamadi, 2011). Moreover this could act as a biological monitoring agent for heavy metal pollution as well (Zaranyika *et al.*, 1994). Many organic (e.g. phenol) and inorganic contaminants (nitrates, phosphates, cholrine, sulfur, silicates etc.) are also efficiently absorbed by this aquatic weed; though exact mechanism of action is still to be understood (Reddy, 1983; Ogunlade, 1992; Nora & Jesus, 1997; Zimmels *et al.*, 2007). In addition, *E. crassipes* was reported to be having highest capacity for nitrogen and phosphorus extraction (Kiran *et al.*, 1991).

Efficient uptake of ethion, a phosphorus pesticide, recalcitrant organic chemicals such as herbicides and pentacholorophenol were also observed for accumulation and bioremoval by this aquatic weed (Xia & Ma, 2006; Roy & Hänninen, 1994). The sorption of uranium, copper and many basic dyes by the water hyacinth roots were also reported previously (Shawky *et al.*, 2005; Low *et al.*, 1994). Even waste water from pulp and paper industry, tannery and textile industry could be decontaminated using water hyacinth roots (Jayaweera & Kasturiarachchi, 2004). There have been many positive beneficial effects recorded on the abundance of zooplanktons, macro-invertebrates and fish communities as well (Villamagna & Murphy, 2010). Infect different plant parts have been reported for the bioadsorption of various metals and pollutants in the past (Sharma *et al.*, 2016). Keeping in view of the above facts, one might consider water hyacinth as an efficient and cost effective agent to hasten the process of decontaminating agro-industrial waste polluted with heavy metals, organic and inorganic pollutants.

b. Biofuel and Biogas Production

Keeping in view of the abundance of the weed in freshwater, marine, and aquatic ecosystems throughout the world, water hyacinth (*Eichhornia crassipes*) derived biodiesel (WHB) was proposed as a potential alternative energy source (Venu *et al.*, 2019). Another study also successfully showed the ability of water hyacinth to produce biodiesel(Sagar & Kumari, 2013). Increased industrialization and urbanization have been detrimental to our non-renewable energy resources resulting in energy crisis globally. Therefore we need fuels to be generated from renewable resources which are readily available. Owing to wider distribution and higher cellulosic and hemicellulosic contents in the water hyacinth biomass, it has the potential for bioethanol production tackling the growing problem of pollution attributed to fossil fuel emissions (Deka *et al.*, 2018).

Water hyacinth having low lignin content has been an attractive biomass source for the biofuel industry [Fig. 1]. Metal-contaminated water hyacinth was also shown to produce bio-ethanol in one of the studies reported earlier (Mahmood *et al.*, 2010). Another study reported that the ethanol generating capacity of water hyacinth was quite comparable to that obtained from agriculture waste (Mishima *et al.*, 2008). Genetic engineering technology has further enhanced the production of ethanol from hemicellulaose content present in this invasive weed which is fermented to oligosaccharides (Dien *et al.*, 2003; Mishima *et al.*, 2008). There have been few biological methods adopted to delignify the water hyacinth biomass for the large scale production of ethanol (Sari *et al.*, 2011). Majority of the studies have indicated that biofuel production from water hyacinth holds promise in terms of cost effectiveness, economic and environment friendly approach.

Similarly biogas which is primarily composed of methane and CO_2, the water hyacinth biomass could be an attractive source for biogas production because of its aggressive and invasive growth. Moreover the higher cellulose and hemicellulase contents along with larger C/N ratio makes it even more destined to produce biogas(Chanakya *et al.*, 1993). Many studies reported that on an average a tonne of semi dried water hyacinth biomass could produce about 4000 Liter of biogas with about 64% methanolic content (Gopal, 1987b). However a mixture of water hyacinth and animal waste (cow dung etc.) could yield even higher production of Biogas (Jafari, 2010; El-Shinnawi *et al.*, 1989b; El-Shinnawi *et al.*, 1989a). While the sludge or slurry left behind after biogas production is transported to be used as a liquid fertilizer. Similarly in vermicomposting, since water hyacinth loses the ability to reproduce vegetatively after passing through the earthworm gut but the presence of enzymes and hormones in the vermicast are known to stimulate plant growth and flowering as well (Gajalakshmi & Abbasi, 2002; Ansari & Ismail, 2012; Ramasamy & Abbasi, 1999). Pig dung blended and mixed with water hyacinth (1:3 ratio), were found to enhance the percent composition of methane in biogas (Adegunloye *et al.*, 2013). A mixture of water chestnut, water hyacinth and cow dung (in 1:1:2 ratio), after anaerobic digestion could produce biogas at an average of 0.326 L per day (Sudhakar *et al.*, 2013). Another study reported the biomethanation of fresh water hyacinth with varying amounts of water could produce even higher levels of biogas (Patil *et al.*, 2011).

The need is to make the biogas production cheaper, cost effective and less labour intensive. Moreover weed harvesting for the biomass and further for biogas production not only keep the weed under check for its growth and invasiveness but simultaneously fulfilling the energy availability and environmental sustainability as well.

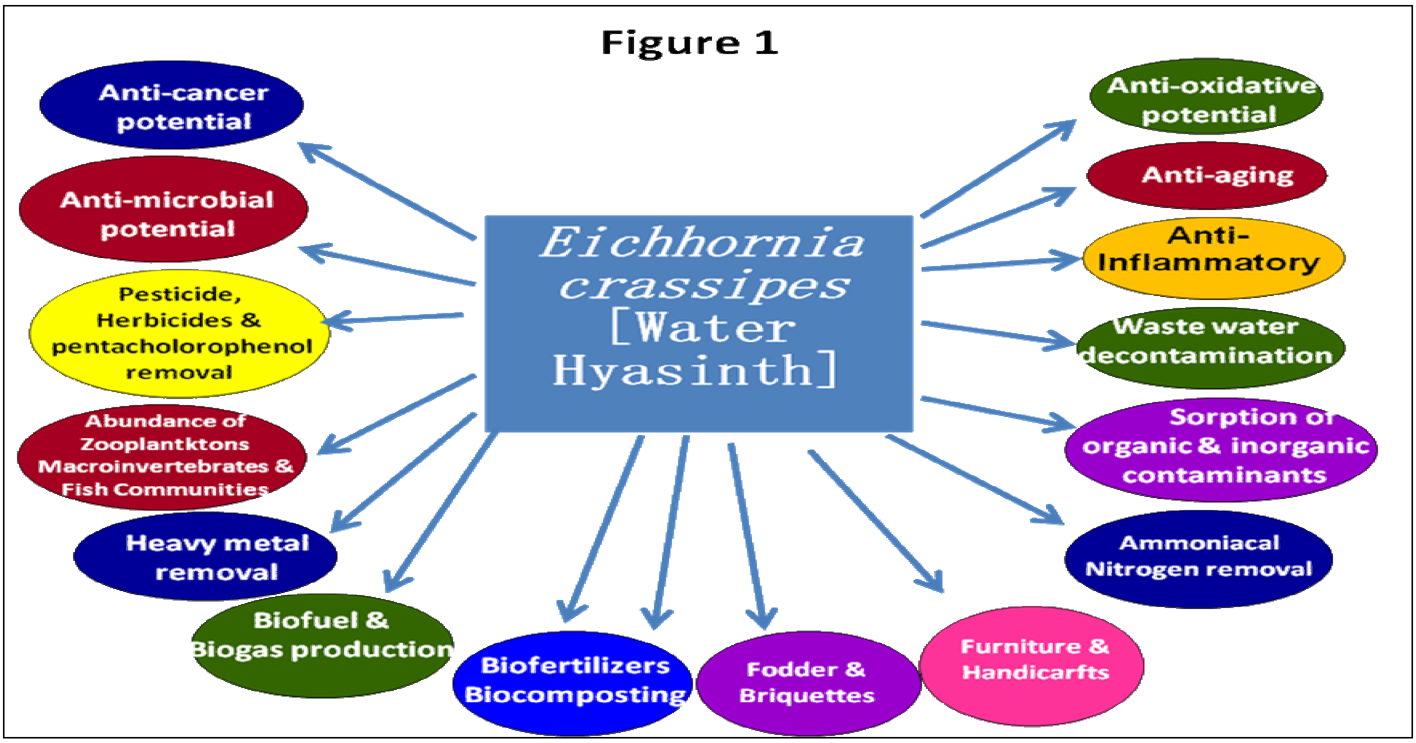

Fig. 1 : Broad spectrum applications of *Eichhornia crassipes*

c. Therapeutic Applications

It seems evident that antimicrobial, antifungal and antibacterial properties are associated with water hyacinth and many skin care products are known to contain hyacinth as well, good enough to treat many skin disorders [Fig. 1]. Water hyacinth was reported to have significant levels of vitamin C (ascorbate) as determined through cyclic voltammetry having underlying therapeutic applications in skin disorders and goiter as well (Ogunlesi *et al.*, 2010). Moreover water hyacinth in shampoos has been used to increase the fragrance to that of a fresh flower. Water hyacinth along with table salt and *Piper longum* has long been used for the treatment of goiter (Oudhia, 1999). Water hyacinth is now confirmed to be a great source of natural antioxidants with freeze dried leaves to be the richest source (Bodo *et al.*, 2004b; Bodo *et al.*, 2004a; Lalitha & Jayanthi, 2014). Moreover water hyacinth extracts have shown encouraging anti-aging effects as determined through DNA damage inhibition and DPPH radical scavenging assays. There was a pronounced increase in the DNA damage inhibition and DPPH radical scavenging ability with the increase in concentration of the ethyl acetate extracts of Water Hyacinth; thus having promising cosmeceutical industry prospects (Lalitha & Jayanthi, 2014). In Chinese traditional medicines, *Eichhornia* beans have been used for healthy spleen functioning. Similarly in Philipines, *Eichhornia* juice with lemon juice is traditionally used as an anti-inflammatory topical agent. Stir-fried hyacinth beans have been traditionally in use to treat digestive disorders, flatulence, diarrhea, intestinal worms and regulating cholesterol levels. Similarly stems of water hyacinth are traditionally used to treat cholera. Leaf extract of water hyacinth with rice flour and turmeric have been used for eczema. Also as traditional medicines, water hyacinth has been used to treat gonorrhea with the help of infusions prepared with the leaves of hyacinth plant. Some tribes in Kenya, use this herb beans to promote lactation while its flowers could help women who suffer from irregular periods. Even water hyacinth is known to contain some therapeutic compounds bearing anti-cancer properties (Aboul-Enein *et al.*, 2014). Therefore water hyacinth seems to have many broad spectrum properties of therapeutic significance.

Management of Water Hyacinth

There have been several adopted methods to control and manage the water hyacinth and to contain its spread (Sharma *et al.*, 2016). But still no effective control strategy has been developed till date. The management of *Eichhornia* still depends on efforts that focus on reducing the ecological and socio economic damage caused by it. In terms of physical methods, using machinery and human labor is widely followed because of its efficiency but due to cost issues, it may incur huge economic losses to the concerned farmer or individual (Alimi & Akinyemiju, 1991). However use of chemicals such as Glyphosate/ Diquate or 2,4D has been less expensive in order to eradicate water hyacinth but again many risks engendered to the populations and to the ecosystem, make them less favored for the said use(Charudattan *et al.*, 1996). Integrated management of this weed was also carried out using Glyphosate at a low concentration along with A. alternate (Ray & Hill, 2012). Similarly in another integrated weed management approach, microbial herbicide, natural populations of arthropods and chemical herbicides were used together (Charudattan, 1986).

Though the initial focus was to control water hyacinth by eradication but due to the limitations of this approach, researchers tend to put more efforts on reducing the density of water hyacinth to levels that could minimize the economic as well as ecological impacts.

Biological control has been a good alternative as one could manage and restrict this weed by using some natural predators. Many weevil species such as *Neochetina eichhorniae*, *N. bruchi* or the moth species such as *Sameodes abligullatis* or the fungal pathogen, *Alternaria eichhornia* have been successfully tried in the past with positive outcomes (Shabana & Mohamed, 2005; Coetzee *et al.*, 2009). However, these natural predators may also hit non-target species as well, warranting their use because of the associated risks (Simberloff & Von Holle, 1999). Moreover their effects could be site-specific as well as has been seen in a study where two weevil species could effectively reduce water hyacinth population in one specific area but failed in the other (Schardt, 1986).

Challenges

There are many opportunities and challenges which the water hyacinth presents before the scientific community beyond the bio control (Sharma *et al.*, 2016). Lack of technological skills, skilled manpower, lower investments in machinery especially in developing countries and poor rural areas where this weed is largely spread and prevalent, have been the foremost challenges for exploiting this weed for good human use such as for biogas production, furniture, handicrafts and briquettes (Thomas & Eden, 1990; Gunnarsson & Petersen, 2007). Moreover we need sufficient market outlets as well in order to derive maximal benefits which is again a challenge for the poor countries (Patel, 2012). Further more intensive labor is required for transportation of the bio-compost which makes it unrealistic to be produced at a bulk scale especially for the low-income countries (Gunnarsson & Petersen, 2007). Extensive efforts with large cohorts of samples and randomized controlled studies and trials are needed to find out the effects of this weed on human health and a sustainable solution to exploit this invasive otherwise harmful weed into a beneficial entity for human applications.

Conclusions

This invasive weed is a threat to the biodiversity resulting in huge economic losses and a concern to the health of human beings as well (Degaga). However, there have been numerous value aided properties attributed to Water hyacinth as it is used for not only in the water purification process, biogas and biofuel production but also for the efficient removal of heavy metal contaminants of environmental concern from waste water in a cost effective manner. Many critical factors including temperature, pH, adsorbent dose etc. play a significant role in the biosorption capacities but still a lot to be done in this field especially to put forth bulk scale procedures in order to derive maximum benefits out of this invasive weed.

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Conflict Of Interest

Certified that there is no conflict of interest pertaining to publication of this manuscript in your esteemed Journal.

References

Abdelhamid, A. and Gabr, A. (1991). Evaluation of water hyacinth as a feed for ruminants. Archiv für Tierernaehrung, 41: 745-56.

Aboul-Enein, A.M.; Shanab, S.M.; Shalaby, E.A.; Zahran, M.M.; Lightfoot, D.A. and El-Shemy, H.A. (2014). Cytotoxic and antioxidant properties of active principals isolated from water hyacinth against four cancer cells lines. BMC complementary and alternative medicine, 14: 397.

Adegunloye, D.; Olosunde, S. and Omokanju, A. (2013). Evaluation of ratio variation of water hyacinth (Eichhornia crassipes) on the production of pig dung biogas. International Research Journal of Biological Sciences, 2: 44-8.

Alimi, T. and Akinyemiju, O. (1991). Effects of waterhyacinth on water transportation in Nigeria. Journal of Aquatic Plant Management, 29: 109-12.

Alvarado, S.; Guédez, M.; Lué-Merú, M.P. *et al.* (2008). Arsenic removal from waters by bioremediation with the aquatic plants Water Hyacinth (*Eichhornia crassipes*) and Lesser Duckweed (Lemna minor). Bioresource technology, 99: 8436-40.

Ansari, A. and Ismail, S.A. (2012). Earthworms and Vermiculture Biotechnology. In.

Bartodziej, W. and Weymouth, G. (1995). Waterbird abundance and activity on waterhyacinth and egeria in the St. Marks River, Florida. Journal of Aquatic Plant Management, 33: 19-22.

Bodo, R.; Ahmanache, K.; Hausler, R. and Azzouz, A. (2004a). Optimized extraction of total proteic mass from water hyacinth dry leaves. Journal of Environmental Engineering and Science, 3: 529-36.

Bodo, R.; Azzouz, A. and Hausler, R. (2004b). Antioxidative activity of water hyacinth components. Plant Science, 166: 893-9.

Brendonck, L.; Maes, J.; Rommens, W. *et al.* (2003). The impact of water hyacinth (Eichhornia crassipes) in a eutrophic subtropical impoundment (Lake Chivero, Zimbabwe). II. Species diversity. Archiv für Hydrobiologie, 158: 389-405.

Brundu, G.; Stinca, A. and Angius, L. (2012). *Pistia stratiotes* L. and *Eichhornia crassipes* (M art.) Solms.: emerging invasive alien hydrophytes in Campania and Sardinia (Italy). EPPO Bulletin, 42: 568-79.

Burton, J.; Van Oosterhout, E.; Ensbey, R. and Julien, M. (2010). Water hyacinth (*Eichhornia crassipes*): Weed of national significance. Department of Primary Industries, NSW., Australia.

Calvert, P. (2002). Water hyacinth control and possible uses. Technical brief. International Technology Development Center, United Kingdom.

Chabot, J.F. Foreign Invaders: Non-Native Species and Their Effect on North America's ecosystems. Jeannett Julich.

Chanakya, H.N.; Borgaonkar, S.; Meena, G. and Jagadish, K.S. (1993). Solid-phase biogas production with garbage or water hyacinth. Bioresource technology, 46: 227-31.

Charudattan, R. (1986). Integrated control of waterhyacinth (*Eichhornia crassipes*) with a pathogen, insects, and herbicides. Weed Science, 34: 26-30.

Charudattan, R.; Labrada, R.; Center, T. and Kelly-Begazo, C. (1996). Strategies for water hyacinth control. Report of a Panel of experts meeting, 11-14 September, 1995, Fort Lauderdale, Florida, USA.

Coetzee, J.; Hill, M.; Julien, M.; Center, T. and Cordo, H. (2009). *Eichhornia crassipes* (Mart.) Solms–Laub.(Pontederiaceae). Biological Control of Tropical Weeds using Arthropods. Cambridge University Press, New York, NY, 183-210.

Cossu, R.; Haarstad, K.; Lavagnolo, M.C. and Littarru, P. (2001). Removal of municipal solid waste COD and NH_4–N by phyto-reduction: A laboratory–scale comparison of terrestrial and aquatic species at different organic loads. Ecological Engineering, 16: 459-70.

De Souza, M.; Huang, C.; Chee, N. and Terry, N. (1999). Rhizosphere bacteria enhance the accumulation of selenium and mercury in wetland plants. Planta, 209: 259-63.

Degaga, A.H. Water Hyacinth (*Eichhornia crassipes*) Biology and its Impacts on Ecosystem, Biodiversity, Economy and Human Well-being.

Deka, D.; Das, S.P.; Ravindran, R.; Jawed, M. and Goyal, A. (2018). Water Hyacinth as a Potential Source of Biofuel for Sustainable Development. In. Urban Ecology, Water Quality and Climate Change. Springer, 351-63.

Dien, B.S.; Cotta, M.A. and Jeffries, T.W. (2003). Bacteria engineered for fuel ethanol production: current status. Appl Microbiol Biotechnol, 63: 258-66.

El-Shinnawi, M.; El-Din, M.A.; El-Shimi, S. and Badawi, M. (1989[a]). Biogas production from crop residues and aquatic weeds. Resources, conservation and recycling, 3: 33-45.

El-Shinnawi, M.M.; El-Din, M.N.A.; El-Shimi, S.A. and Badawi, M.A. (1989b). Biogas production from crop residues and aquatic weeds. Resources, conservation and recycling, 3: 33-45.

Eldin, A.T. (1992). Utilization of water-hyacinth hay in feeding of growing sheep. Indian Journal of Animal Sciences, 62: 989-92.

Gajalakshmi, S. and Abbasi, S.A. (2002). Effect of the application of water hyacinth compost/vermicompost on the growth and flowering of Crossandra undulaefolia, and on several vegetables. Bioresour Technol, 85: 197-9.

Gettys, L.A.; Haller, W.T. and Bellaud, M. (2014). Biology and control of aquatic plants. A Best Management Practices Handbook: Third Edition. Aquatic Ecosystem Restoration Foundation, Marietta, GA.

Gopal, B. (1987a). Water hyacinth. Elsevier Science Publishers.

Gopal, B. (1987b). Water Hyacinth Elsevier. Amsterdam, The Netherlands 471.

Gratwicke, B. and Marshall, B. (2001). The impact of Azolla¢ liculoides Lam. on animal biodiversity in streams in Zimbabwe.

Greenfield, B.K.; Siemering, G.S.; Andrews, J.C.; Rajan, M.; Andrews, S.P.; Spencer, D.F. (2007). Mechanical shredding of water hyacinth (Eichhornia crassipes): Effects on water quality in the Sacramento-San Joaquin

River Delta, California. Estuaries and Coasts 30: 627-40.

Gunnarsson, C.C. and Petersen, C.M. (2007). Water hyacinths as a resource in agriculture and energy production: A literature review. Waste management, 27: 117-29.

Hauser, L.; Wernand, A.; Korangteng, R.; Simpeney, N. and Sumani, A. (2014). Water hyacinth in the Lower Volta Region: Turning aquatic weeds from problem to sustainable opportunity by fostering local entrepreneurship. Report New-Business Challenge Netherlands-2014-Ghana Sustainable Trade, 1-4.

Heard, T.A. and Winterton, S.L. (2000). Interactions between nutrient status and weevil herbivory in the biological control of water hyacinth. Journal of Applied Ecology, 37: 117-27.

Ho, Y. and Wong, W-K. (1994). Growth and macronutrient removal of water hyacinth in a small secondary sewage treatment plant. Resources, conservation and recycling, 11: 161-78.

Honlah, E.; Yao, S.A.; Odame, A.D.; Mensah, M.; Atakora, P.O. and Sabater, A. (2019). Effects of water hyacinth invasion on the health of the communities, and the education of children along River Tano and Abby-Tano Lagoon in Ghana. Cogent Social Sciences 5: 1619652.

Jafari, N. (2010). Ecological and socio-economic utilization of water hyacinth (*Eichhornia crassipes* Mart Solms). Journal of Applied Sciences and Environmental Management 14.

Jayaweera, M.W. and Kasturiarachchi, J.C. (2004). Removal of nitrogen and phosphorus from industrial wastewaters by phytoremediation using water hyacinth (*Eichhornia crassipes* (Mart.) Solms). Water Sci Technol, 50: 217-25.

Jimenez, M.M. and Balandra, MaG. (2007). Integrated control of Eichhornia crassipes by using insects and plant pathogens in Mexico. Crop Protection, 26: 1234-8.

Joffe, S. and Cooke, S. (1997). Management of water hyacinth and other invasive aquatic weeds. Issues for the World Bank. Washington, DC. World Bank internal report.

Jones, J.L.; Jenkins, R.O. and Haris, P.I. (2018). Extending the geographic reach of the water hyacinth plant in removal of heavy metals from a temperate Northern Hemisphere river. Scientific reports, 8: 1-15.

Kelley, C.; Mielke, R.E.; Dimaquibo, D.; Curtis, A.J. and Dewitt, J.G. (1999). Adsorption of Eu (III) onto roots of water hyacinth. Environmental science & technology, 33: 1439-43.

Kiran, M.; Srivastava, J. and Tripathi, B. (1991). Capacidad de retiro del nitrógeno y el fósforo de cuatro plantas elegidas en las charcas de aguas dulces tropicales. Diario Conservación Ambiental, 18: 143-7.

Lalitha, P. and Jayanthi, P. (2014). Antiaging activity of the skin cream containing ethyl acetate extract of *Eichhornia crassipes* (Mart.) solms. Int. J. PharmTech Res., 6: 29-34.

Lindsey, K. and Hirt, H.M. (1999). Use water hyacinth!: a practical handbook of uses for the water hyacinth from across the world. Anamed.

Low, K.; Lee, C. and Tai, C. (1994). Biosorption of copper by water hyacinth roots. Journal of Environmental Science & Health Part A, 29: 171-88.

Lu, J.; Wu, J.; Fu, Z. and Zhu, L. (2007). Water hyacinth in China: a sustainability science-based management framework. Environmental management, 40: 823.

Mahamadi, C. (2011). Water hyacinth as a biosorbent: A review. African Journal of Environmental Science and Technology, 5: 1137-45.

Mahmood, T.; Malik, S.A. and Hussain, S.T. (2010). Biosorption and recovery of heavy metals from aqueous solutions by *Eichhornia crassipes* (water hyacinth) ash. BioResources, 5: 1244-56.

Malik, A. (2007). Environmental challenge vis a vis opportunity: the case of water hyacinth. Environment international, 33: 122-38.

Mangas-Ramírez, E. and Elías-Gutiérrez, M. Effect of mechanical removal of water hyacinth (*Eichhornia crassipes*) on the water quality.

Midgley, J.M.; Hill, M.P. and Villet, M.H. (2006). The effect of water hyacinth, Eichhornia crassipes (Martius) Solms laubach (Pontederiaceae), on benthic biodiversity in two impoundments on the New Year's River, South Africa. African Journal of Aquatic Science, 31: 25-30.

Mishima, D.; Kuniki, M.; Sei, K.; Soda, S.; Ike, M. and Fujita, M. (2008). Ethanol production from candidate energy crops: water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes* L.). Bioresour Technol, 99: 2495-500.

Ndimele, P.; Kumolu-Johnson, C. and Anetekhai, M. (2011). The invasive aquatic macrophyte, water hyacinth {*Eichhornia crassipes* (Mart.) Solm-Laubach: Pontedericeae}: problems and prospects. Research Journal of Environmental Sciences, 5: 509-20.

Nora, M. and Jesus, R. (1997). Water hyacinth [*Eichhornia crassipes* (Mart.) Solms-Laub], an alternative for the removal of phenol in wastewater. Acta Biologica Venezuelica 17: 57-64.

Ogunlade, V. (1992). Chemical and nutritional evaluation of water hyacinth in Nigerian waterways: Ph. D Thesis, Obafemi Awolowo University, Ile-Ife.

Ogunlesi, M.; Okiei, W.; Azeez, L. and Obakachi, V. (2010). Vitamin C contents of tropical vegetables and foods determined by voltammetric and titrimetric methods and their relevance to the medicinal uses of the plants.

Ojeifo, M.; Ekokotu, P.; Olele, N. and Ekelemu, J. (2000). A review of the utilisation of water hyacinth control measures for a noxious weed. Proceedings of the Proceedings of the International Conference on Water Hyacinth, 27-1.

Oudhia, P. (1999). Medicinal weeds in rice fields of Chhattisgarh, India. International Rice Research Notes, 24: 40.

Patel, S. (2012). Threats, management and envisaged utilizations of aquatic weed Eichhornia crassipes: an overview. Reviews in Environmental Science and Bio/Technology, 11: 249-59.

Patil, J.H.; Lourdu, M.; Raj, A. and Gavimath, C. (2011). Impact of dilution on biomethanation of fresh water hyacinth. International Journal of Chemical Sciences and Applications, 2: 86-90.

Ramasamy, E. and Abbasi, S. (1999). Utilization of biowaste solids by extracting volatile fatty acids with subsequent conversion to methane and manure. Journal of Solid Waste Technology and Management, 26: 133-9.

Ray, P. and Hill, M.P. (2012). Impact of feeding by Neochetina weevils on pathogenicity of fungi associated with waterhyacinth in South Africa. Journal of Aquatic Plant Management, 50: 79-84.

Reddy, K. (1983). Fate of nitrogen and phosphorus in a waste-water retention reservoir containing aquatic macrophytes. Journal of Environmental Quality, 12: 137-41.

Roy, S. and Hänninen, O. (1994). Pentachlorophenol: uptake/elimination kinetics and metabolism in an aquatic plant, Eichhornia crassipes. Environmental Toxicology and Chemistry: An International Journal, 13: 763-73.

Sagar, C.V. and Kumari, N.A. (2013). Sustainable biofuel production from water Hyacinth (*Eicchornia crassipes*). Int J Eng Trends Technol., 4: 4454-8.

Sari, E.; Syamsiah, S.; Sulistyo, H. and Hidayat, M. (2011). The kinetic of biodegradation lignin in water hyacinth (*Eichhornia crassipes*) by Phanerochaete Chrysosporium using Solid state fermentation (SSF) method for Bioethanol Production, Indonesia. World Academy of Science, Engineering and Technology, 78: 249-52.

Schardt, J. (1986). "1984 Florida Aquatic Plant Survey," Florida Department of Natural Resources, Tallahassee, Fla. Schardt, JD 1985.

Schneider, I.A.; Rubio, J. and Smith, R.W. (2001). Biosorption of metals onto plant biomass: exchange adsorption or surface precipitation? International Journal of Mineral Processing, 62: 111-20.

Shabana, Y.M. and Mohamed, Z. (2005). Integrated control of water hyacinth with a mycoherbicide and a phenylpropanoid pathway inhibitor. Biocontrol science and technology, 15: 659-69.

Sharma, A.; Aggarwal, N.K.; Saini, A. and Yadav, A. (2016). Beyond biocontrol: water hyacinth-opportunities and challenges. Journal of Environmental Science and Technology, 9: 26-48.

Shawky, S.; Geleel, M.A. and Aly, A. (2005). Sorption of uranium by non-living water hyacinth roots. Journal of Radioanalytical and Nuclear Chemistry, 265: 81-4.

Simberloff, D. and Von Holle, B. (1999). Positive interactions of nonindigenous species: invasional meltdown? Biological invasions, 1: 21-32.

Sudhakar, K.; Ananthakrishnan, R. and Goyal, A. (2013). Biogas production from a mixture of water hyacinth, water chestnut and cow dung. International Journal of Science, Engineering and Technology Research, 2: 35-7.

Tham, H.T. (2012). Water hyacinth (*Eichhornia crassipes*).

Thomas, T. and Eden, R. (1990). Water hyacinth-a major neglected resource. Proceedings of the Energy and the Environment. Into the 90s. Proceedings of the 1st World renewable energy congress, Reading, UK, Pergamon, 2092-6.

Ting, W.; Tan, I.; Salleh, S. and Wahab, N. (2018). Application of water hyacinth (*Eichhornia crassipes*) for phytoremediation of ammoniacal nitrogen: A review. Journal of water process engineering, 22: 239-49.

Toft, J.D.; Simenstad, C.A.; Cordell, J.R. and Grimaldo, L.F. (2003). The effects of introduced water hyacinth on habitat structure, invertebrate assemblages, and fish diets. Estuaries, 26: 746-58.

Ueki, K.; Ito, M. and Oki, Y. (1976). Waterhyacinth and its habitats in Japan. Proceedings of the Proceedings of the fifth Asian-Pacific Weed Science Society Conference, Tokyo, 424-8.

Venu, H.; Venkataraman, D.; Purushothaman, P. and Vallapudi, D.R. (2019). *Eichhornia crassipes* biodiesel as a renewable green fuel for diesel engine applications: performance, combustion, and emission characteristics. Environ Sci Pollut Res Int., 26: 18084-97.

Villamagna, A. and Murphy, B. (2010). Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshwater biology, 55: 282-98.

Waeber, P.O.; Ralainasolo, F.B.; Ratsimbazafy, J.H. and Nievergelt, C.M. (2015). Consequences of lakeside living for the diet and social ecology of the lake Alaotran gentle lemur. Primates in Flooded Habitats: Ecology and Conservation. A. Barnett, I. Matsuda and K. Nowak (eds.). Cambridge University Press.

Wolverton, B. and Mcdonald, R. (1975). Water hyacinths and alligator weeds for removal of lead and mercury from polluted waters.

Xia, H. and Ma, X. (2006). Phytoremediation of ethion by water hyacinth (*Eichhornia crassipes*) from water. Bioresource technology, 97: 1050-4.

Xie, Y.; Wen, M.; Yu, D. and Li, Y. (2004). Growth and resource allocation of water hyacinth as affected by gradually increasing nutrient concentrations. Aquatic Botany, 79: 257-66.

Zaranyika, M.F.; Mutoko, F. and Murahwa, H. (1994). Uptake of Zn, Co, Fe and Cr by water hyacinth (*Eichhornia crassipes*) in lake Chivero, Zimbabwe. Science of the total environment, 153: 117-21.

Zimmels, Y.; Kirzhner, F. and Malkovskaja, A. (2007). Advanced extraction and lower bounds for removal of pollutants from wastewater by water plants. Water Environment Research, 79: 287-96.