Remote Sensing and Utilization of Water Hyacinth *(Eichhornia crassipes)*: A Comprehensive Review of Applications, Challenges, and Environmental Benefits

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Abstract:

One prospective free-floating aquatic plant that may be able to handle present challenges with food, energy, and the environment is the water hyacinth (Eichhornia crassipes). Invasive aquatic species jeopardize socioeconomic and ecological systems by disrupting freshwater ecosystems, altering their production and utility, and interfering with essential hydrological processes. From an ecological standpoint, water hyacinth can modify surface water clarity, induce hypoxia or reduced levels of related nutrients and contaminants such as nitrogen, phosphorus, and heavy metals, and influence the productivity of zooplankton and phytoplankton in freshwater ecosystems. Due to their remarkable flexibility and swift proliferation, these ecosystems face challenges. Nonetheless, this plant can generate useful commodities if it is handled. Water hyacinths can be utilized to manufacture a number of particle technologies, such as adsorbents, bioplastics, brake pads, fertilizers, bioenergy, animal feed, and phytoremediation agents. Water hyacinth (Eichhornia crassipes), a highly invasive floating aquatic weed, has proliferated in numerous subtropical water bodies, as indicated by field research and hydrological data. Numerous regions have effectively managed the weed since the 1970s due to the introduction of two weevils and the moth N. albiguttalis. In order to help create future strategies and analyze their effects on water hyacinth, it is now vital to identify traits that either facilitate or impede successful biological control. The primary factors contributing to this information gap include excessive dependence on traditional surveys, insufficient funding, and, most importantly, the absence of cost-effective satellite platforms with optimal spatial and spectral capabilities to differentiate water hyacinth from other coexisting plant species. This study provides a discussion grounded in the conducted tests and existing literature to enhance readers' comprehension. Water hyacinth *is a useful plant for phytoremediation because of its capacity to absorb both macro and micronutrients, such as phosphate and nitrogen. It is also a possible biomass energy source and animal feed due to its capacity to manufacture cellulose. Furthermore, it can be converted into high cellulose content particles suitable for usage in adsorbents, brake pads, and bioplastics.*

Keywords: Water hyacinth (Eichhornia crassipes), invasive species, freshwater ecosystems, zooplankton and phytoplankton productivity, hypoxia, nutrients and contaminants, particle technologies, biological control, satellite platforms, phytoremediation, bioenergy, bioplastics, adsorbents.

1.Introduction

The invasive species, water hyacinth *(Eichhornia crassipes),* proliferates and reproduces in aquatic ecosystems (Madizela et al., 2021). Water is an essential resource on Earth, providing numerous socioeconomic and ecological advantages at the household, agricultural, and global levels, with use in domestic, industrial, and agricultural contexts (Abbasi et al., 2014). Increased pressures from inadequate household waste management, along with heightened agricultural and industrial activities, are leading to a gradual decline in the world's freshwater supplies. This is inducing eutrophication in lakes, streams, rivers, and reservoirs (attributable to dams), along with a pervasive increase of aquatic weeds (Selman et al., 2008). This free-floating aquatic plant typically thrives in stagnant water bodies such as swamps, lakes, reservoirs, and rivers (Ganguly et al., 2019). It poses significant threats to biological diversity and socioeconomic factors at the environmental, individual, and genetic levels (Colautti & MacIsaac, 2004). The swift proliferation raises global concerns, as unregulated expansion may obstruct waterways and interfere with power generation facilities. Furthermore, water hyacinths diminish oxygen concentrations and obstruct sunlight penetration in aquatic environments, hence disrupting ecosystems due to insufficient atmospheric oxygen (Madikizela, 2021). Due of its rapid proliferation in aquatic ecosystems, water hyacinth is categorized as a weed or nuisance. Before any phenomenon undergoes extensive expansion, it initially exists in limited quantities. Water hyacinths are highly widespread in environments such as lakes, ponds, aquaculture ponds, and reservoirs. In its natural habitat, water hyacinth fosters habitat complexity and offers refuge and feeding opportunities for fish, zooplankton, and phytoplankton in freshwater ecosystems (Brendonck et al., 2003; Meerhoff et al., 2003; Villamagna and Murphy, 2010) Brendonck et al. (2003). assert that the roots and leaves of water hyacinth are essential for promoting macroinvertebrate colonization. The introduction of invasive species significantly affects aquatic animals, ecosystem production and function, ecological and hydrological processes, and human livelihoods, representing a critical global change phenomenon (Schneider and Geoghegan, 2006; Burgiel and Muir, 2010). Land development and rising human density present persistent challenges to environmental management and the integrity of river ecosystems. (Hardoy and Mitlin, 2001; Achankeng, 2003). A variety of methods for the management and utilization of water hyacinth have been researched and recorded (Thamaga & Dube, 2018).

Water hyacinth significantly impairs fisheries and navigational activities in tropical lakes (Gopal, 1987; Kateregga and Sterne, 2009). The experiments aimed at enhancing readers' comprehension and perspective concluded the literary debate of this study. It aims to provide detailed information on the utilization of invasive water hyacinth species for the production of beneficial products. This study is limited to examining and detailing a few potential applications of water hyacinths, despite the publication showcasing other possibilities, as illustrated in Fig. 1. Numerous supplementary applications exist, encompassing animal feed, water purification, soil rehabilitation, artisanal crafts, pharmaceuticals, the development of novel materials, fertilizers, bioenergy (such as biogas, biofuel, biodiesel, and bioethanol), among others.

2.Characteristics of water hyacinth

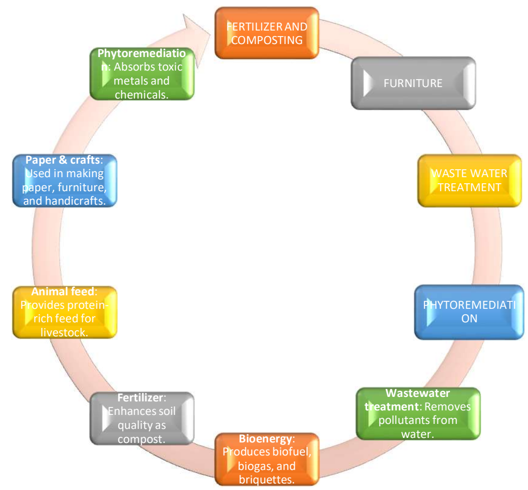
In their review study, they elaborate extensively on water hyacinth as a biomass. Its capacity to absorb water pollutants is a distinctive characteristic that sets it apart from other aquatic flora. Lignin, crystalline cellulose, and hemicellulose are structural carbohydrates that constitute the majority of water hyacinth (Zhang et al., 2020). The adsorption of water pollutants onto plant-based adsorbents is enhanced by the presence of prominent functional groups, including carboxyl, hydroxyl, and carbonyl, on the plant surface (El-khaiary et al., 2009). The fiber composition of water hyacinth consists of 33% hemicellulose, 25% cellulose, and 10% lignin (Salahuddin et al., 2021). The cellulose backbone of this aquatic plant comprises a substantial quantity of hydroxyl groups, which considerably influences its composition (Emam et al., 2020). The hydroxyl groups are crucial for adsorption and can be chemically modified to enhance adsorption efficacy. Researchers have utilized the water hyacinth's recognized porosity architecture to enhance the amount of active sites by carbonizing the plant into mesoporous carbon (Zhuang, 2020). Chemical modifications to water hyacinth are sometimes implemented, potentially increasing the surface area and so augmenting the adsorption capacity. Researchers consider the direct correlation between adsorption and specific surface area to be critical (Kumar and Chauhan, 2019).

3.Ecological impacts of water hyacinth

Freshwater aquatic organisms are adversely affected by the distribution and arrangement of water hyacinth (Murkin and Kadlec, 1986; Meerhoff et al., 2006; Mironga et al., 2014). From an ecological standpoint, water hyacinth influences the productivity of phytoplankton and zooplankton in freshwater ecosystems, alters surface water clarity, and may induce hypoxia or reduce the concentration of contaminants and nutrients, including nitrogen, phosphorus, and heavy metals. Research has shown that the effects of water hyacinth on zooplankton adversely influence fish populations and other aquatic organisms dependent on this algae (Mironga et al., 2014). The invasion of water hyacinth in freshwater systems significantly alters the structure, composition, productivity, and utility of aquatic ecosystems. Huang et al. (2007) assert that water hyacinth impedes photosynthesis in submerged vegetation by obstructing sunlight from reaching the deeper regions of freshwater environments. This creates adverse and hostile biological conditions, negatively impacting aquatic biodiversity (Wu et al., 2004). Furthermore, water hyacinth mats might diminish natural predation, perhaps leading to the increased prevalence of certain species over others (Kateregga and Sterner, 2009). Moreover, water hyacinth elevates evaporation rates due to its composition of approximately 90% water (Gopal, 1987). Moreover, the physical removal, dumping, and decay of these plants, which function as biological filters for heavy metals and other pollutants, pose significant health and environmental hazards.

4. Remote sensing of water hyacinth
Over the past three decades, data on water hyacinth and its implications for understanding biological activity in aquatic ecosystems have been collected using various satellite-based sensors (Cavalli et al., 2009). The capacity of remote sensing data to provide diverse and innovative applications for the comprehensive monitoring of extensive regions accounts for its growing utilization in mapping invasive species. Satellite photography facilitates the swift and economical documentation of the temporal and spatial distribution of aquatic macrophytes (Hestir et al., 2008; Shekede et al., 2008; Dube et al., 2014). Moreover, the continuous coverage of satellite sensors offers essential spatial data for both short-term and long-term monitoring, which is crucial for evaluating the effectiveness of existing management strategies. Penatti et al. (2015). Remote sensing technologies have proven indispensable in mapping land use, including agricultural and urban areas, as well as land cover, such as water hyacinth, vegetation, and grasslands, owing to the availability of sensors that deliver high-quality data (DeFries et al., 2004; Rindfuss et al., 2004). Numerous studies have recognized invasive alien plant species by multispectral remote sensing (Carson et al., 1995; Mladinich et al., 2006; Cuneo et al., 2009; Kimothi et al., 2010). Likewise, Shekede et al. (2008) and Dube et al. (2017) evaluated the efficacy of the newly introduced Landsat 8 OLI and Landsat series data in detecting and mapping the spatial distribution of water hyacinth in Zimbabwe's inland lakes. An analysis of variance (ANOVA) test was employed to assess spectral separability between water hyacinth and other land cover categories in the study area. In contrast to Landsat 7 ETM+, which exhibited a lower accuracy of 57%, Landsat 8 OLI achieved a superior total classification accuracy of 72%.

5. Application of water hyacinth



Due to its significant caloric and protein content, fibrous structure, and elevated water content, water hyacinth possesses several applications. This study piece thoroughly examines the diverse applications of water hyacinth, particularly highlighting its role in the energy sector, in light of the ongoing fuel crisis and the increasing demand for alternative energy sources. Furthermore, the plant can be utilized for the production of animal feed, compost, fertilizer, wastewater treatment, biomass and energy generation, biofuel, and even furniture. The diverse applications underscore the importance of utilizing water hyacinth to offer sustainable solutions.

5.1 Paper

Similar small-scale cottage industry papermaking ventures have prospered in several nations, including the Philippines, Indonesia, and India.

5.2 Fibre Board

Water hyacinth is also utilized in the production of fiberboards for diverse applications, along with a bituminized board intended for economical roofing solutions.

5.3 Yarn and Rope

The fibers derived from the stems of the water hyacinth plant can be employed to manufacture rope. The plant's stalks are longitudinally split to expose the fibers and subsequently permitted to dry for several days. The technique for producing this rope is analogous to that of jute rope manufacturing. The finished rope is treated with sodium metabisulphite to avert deterioration. A native furniture artisan in Bangladesh used rope to encircle a cane frame, resulting in an aesthetically pleasing finished product.

5.4 Basket Work

In the Philippines, water hyacinth is desiccated in sunlight and fashioned into baskets and mats for domestic purposes. The crucial element in producing a superior product is to guarantee that the stalks are sufficiently dried prior to utilization. In India, water hyacinth is similarly employed to manufacture products for the tourism industry. This procedure utilizes techniques from traditional basket weaving and craftsmanship**.**

5.5 Charcoal Briquetting

A proposal has been made in Kenya to tackle the increasing proliferation of water hyacinth in certain areas of Lake Victoria. The proposal aims to develop a suitable process for converting charcoal dust from the pyrolysis of water hyacinth into briquettes.

6.Water hyacinth as alternative biomass resource for energy production

Water hyacinth presents a compelling option as a biomass resource for energy production, attributed to its substantial biomass yield and rapid growth rate. This material is particularly advantageous for fermentation processes aimed at generating biofuel and bioethanol due to its composition, characterized by a low lignin concentration (10%) and elevated levels of cellulose (20%) and hemicellulose (33%). (Basha et al., 2021). The reduced lignin content in water hyacinth facilitates easier breakdown and conversion, while conventional biomass from terrestrial plants typically has higher lignin levels that can hinder fermentation. The biomass of water hyacinth can be converted into briquettes suitable for co-firing in coal power plants, alongside its use in biofuels, offering an eco-friendly alternative that reduces dependence on coal (Fh Nasir et al., 2004). This resource is readily accessible and sustainable due to its abundant and uncontrolled growth in aquatic environments. Utilizing water hyacinth for energy generation not only addresses the need for alternative energy sources but also mitigates its invasive nature, turning a problematic weed into a valuable asset. This dual benefit underscores its possible role in environmental management and sustainable energy efforts.

7.Water hyacinth as co-fuel

Experts have explored various alternative fuels, such as hydrogen, liquefied petroleum gas (LPG), compressed natural gas (CNG), and alcohols. Methanol and ethanol, along with vegetable oils, are considered beneficial renewable liquid fuels. Forhad Ibne et al. Nevertheless, the application of alcohols in diesel engines is limited due to their low cetane number, whereas vegetable oils are unsuitable for spark ignition (petrol) engines because of their low octane number and insufficient volatility. Utilizing bio-diesel, whether blended with diesel or employed as an independent fuel source, represents a viable strategy. (Saidar et al., 2011) Straight vegetable oil (SVO) and bio-diesel (SVO esters) represent two distinct options. (Garduño-Pineda et al., 2023) Given its abundance, perennial nature, non-crop status, biodegradability, and high cellulose content, water hyacinth meets all the criteria necessary for bioenergy production. The primary drawback is its high water content, exceeding 90%, which complicates harvesting and processing efforts. Biomass derived from water hyacinth has the potential to be transformed into biogas, providing energy for rural households. This approach addresses environmental and energy challenges by transforming an invasive weed into a valuable energy resource. (Ilo et al., 2020)

The limitation of lignin molecules in their conversion to sugars hinders the effectiveness of microorganisms in the fermentation process. Due to their elevated energy breakdown process, plants that possess a high lignin concentration are consequently not suitable for biofuel production. Water hyacinth serves as a significant biomass resource for the biofuel industry due to its low lignin content, which enhances the conversion of cellulose and hemicellulose into fermentable sugars. A novel technique for ethanol extraction from fermented sugars is proposed, involving saccharification, diluted sulfuric acid pretreatment, and the use of specific yeast extraction to enhance fermentation efficiency. Water hyacinth is utilized to generate biogas, demonstrating diverse fermentation potentials across several nations. Combining 25% cow manure with 75% dry water hyacinth yields the highest methane production rates, highlighting the significant potential of water hyacinth as an alternative energy source. One ton of dried water hyacinth has the potential to yield approximately 370,000 gallons of biogas. Biomass densification, commonly referred to as briquetting, has been utilized in numerous countries for an extended period (Rezania et al., 2015).This process converts biomass scraps into uniform, solid fuel briquettes, enhancing their properties and elevating their worth. In comparison to their fundamental components, biomass briquettes exhibit increased density, enhanced energy content, and reduced moisture levels. Local markets often offer a variety of commercial biomass briquettes, such as those made from sawdust, wood wastes, and rice husks. Lakeside villages in Kenya utilize briquetting as a method to manage the excessive growth of water hyacinth (Sinha et al., 2001). The water hyacinth, recognized for its rapid growth, presents an opportunity to serve as a sustainable energy source, potentially substituting conventional fossil fuels(Wu et al., 2001).Biomass waste generally possesses significant weight and low density, resulting in high transportation costs and difficulties in its application within burners. The process of biomass densification, such as briquetting, effectively addresses these challenges. The density of briquettes serves as the main criterion for assessing their quality. Briquettes offer several advantages compared to firewood, including higher heat intensity, user-friendliness, cleanliness, and reduced storage requirements. Corn cobs, sawdust, water hyacinth, and cowpea chaffs represent excellent materials for briquetting in the production of fuel energy (Tirupathy et., al).Alongside addressing an environmental concern, the conversion of water hyacinth into briquettes offers a renewable energy solution that presents considerable benefits for energy production and ecological conservation.

8.Other applications

8.1Wastewater Treatment (Phytoremediation)

One of the primary techniques utilized to mitigate lake pollution involved the harvesting of aquatic vegetation to extract nutrients from wastewater. Rotimi et al. (2009) Although all aquatic plants are appropriate for this purpose, the harvesting of smaller species, such as phytoplankton or submerged plants, is generally more costly and labor-intensive than the collection of floating and emergent vascular plants Emerhi et al. (2013). Eichhornia crassipes, or water hyacinth, exhibits significant effectiveness in the remediation of many contaminated water bodies. The utilization of Waste Stabilization Ponds (WSP) for swine wastewater treatment has gained heightened attention in recent decades (Tran TT et al., 2003).Research conducted in both natural and controlled environments has demonstrated that water hyacinth effectively reduces various contaminants in swine effluent. A diverse array of aquatic flora, such as Lemna minor (duckweed), Salvinia rotundifolia, Pistia stratiotes (water lettuce), and Eichhornia crassipes, has been extensively studied by numerous specialists in the discipline (Supatata et al., 2009). Water hyacinth has shown greater effectiveness in eliminating phosphate and nitrogen than other alternatives. Phosphorus pollution in aquatic ecosystems generally originates from three main sources: domestic wastewater, agricultural methods, and industrial operations. Water hyacinth thrives in polluted aquatic environments due to its absorption and sedimentation capabilities. The heightened productivity levels substantially enhance its widespread use in the treatment of industrial wastewater in Southern France. Studies demonstrate that water hyacinth can attain a nitrogen removal efficiency between 10% and 90%. Water hyacinth, water lettuce, pennywort, duckweed, water peanut (*Alternanthera philoxeroides*), and lidded cleistocalyx (*Cleistocalyx operculatus*) are prominent floating plants that have shown highly successful in the purification of eutrophic water in recent decades. Duckweed and water hyacinth have been evaluated for their efficacy in treating wastewater originating from dairy and pig manure, demonstrating their potential in phytoremediation initiatives.

8.2 Removal of organic pollutants

The capacity of water hyacinth, a floating aquatic plant, to assimilate organic matter from wastewater has been extensively examined at laboratory, pilot, and larger scales. Although it is a resilient plant in numerous countries, it also serves as a valuable resource for waste management and agriculture. According to Wu et al., water hyacinth cultivated in ponds or natural water channels is primarily utilized for water purification. It is recommended to implement shorter harvesting intervals to enhance biomass yield. Water hyacinth has demonstrated considerable efficacy in the treatment of dairy wastewater. Substantial reductions were observed in several physico-chemical parameters following a 25-day treatment with water hyacinth. The reductions for total solids, calcium, magnesium, and overall hardness were 37%, 5%, 47.5%, 54%, and 33%, respectively. Water chloride, chromium, nitrous nitrogen, nitric nitrogen, pH, alkalinity, COD, BOD, and bicarbonates shown a considerable reduction. In 2001, Palanisamy and colleagues. This phytoremediation technology serves as an economical solution for the cleanup of contaminated soils, groundwater, and wastewater, and may effectively treat industrial effluent. Water hyacinth represents a viable choice for sustainable wastewater management because to its efficacy in pollution removal.

8.3 Removal of toxic pollutants and heavy metals

Plants capable of remediating heavy metals provide an efficient and ecologically sound approach for sequestration and elimination as heavy metal pollution escalates globally. Phytoremediation is an economical green method that use plants to absorb metals, thereby extracting radionuclides and other detrimental substances from soil and water. (Costa et al., 2000) This technology utilizes the ability of growing plants to function as solar-powered pumps to extract and concentrate specific components from the environment. These plants enhance water quality by extracting metal pollutants from wastewater via their roots. (Wu et al., 2001) The capacity of water hyacinth (Eichhornia crassipes) to eliminate pollutants from surface water, particularly toxic metals, has garnered interest. An effective detoxification technique for phytoremediation is the in situ reduction of heavy metals by vegetation. The phytotoxic effects and the capacity of water hyacinth to absorb heavy metals have been extensively studied. Aquatic macrophytes, including water hyacinth, have been extensively employed to monitor pesticide and heavy metal pollution in water bodies (Jabenaesen et al., 1997). Due of its substantial biomass output and prevalence in tropical and subtropical regions, water hyacinth is an optimal selection for this application (Klumpp et al. and Delgado et al). have conducted comprehensive reviews of this species' ecology and practical applications. In sewage systems, the root systems of water hyacinth and other aquatic flora create an environment favorable to aerobic bacteria. Through nutrient consumption, these bacteria generate inorganic compounds that assist plant growth. It is feasible to gather this rapid plant growth to produce nutrient-dense compost. Water hyacinth has demonstrated significant potential in phytoremediation and wastewater treatment by effectively eliminating or diminishing nutrients, heavy metals, organic compounds, and pathogens from water.

8.4 Composting and fertilizer

In contrast to untreated water hyacinth, the study indicated that mulching with water hyacinth subjected to high quantities of glyphosate and 2,4-D herbicides impeded tomato growth. Mahmood Q. et al., 2005 Consequently, while employing water hyacinth for mulching or composting, meticulous management is necessary to avert pesticide contamination. Combining dried water hyacinth with ash, soil, and animal manure or organic municipal waste enables reliable composting suitable for labor-intensive, low-capital production (Anzeze AD et al., 2005). Vermicomposting is highly advantageous as water hyacinth loses its ability for vegetative growth after traversing the digestive system of earthworms. Furthermore, water hyacinth biomass can be directly employed as compost or green fertilizer. Furthermore, water hyacinth biomass can be directly employed as compost or green fertilizer. Vegetative waste generated from biogas generation can be collected and utilized directly on farms or amalgamated with other organic materials. The roots of water hyacinth have been effectively pulverized into a coarse powder to enhance agricultural yield, particularly for lucrative crops such as vegetables Oguniade et al. assert that water hyacinth possesses a C/N ratio of approximately 15 and contains a significant nitrogen content of up to 3.2% of dry matter. Water hyacinth possesses significant promise as a fertilizer for nutrient-deficient soils due to its elevated nutrient contents and vigorous development.

8.5 Animal feed (livestock

The demand for alternative protein sources, such as water hyacinth leaf protein concentration (LPC), has risen due to the escalating costs of food production and population growth (Lyte C. et al., 1998).This plant has demonstrated its efficacy as a superior protein source for animal feed when combined with other feed concentrates. (Lenzi et al., 1994). Due to its elevated water and mineral composition, the nutrients of water hyacinth can be administered to certain animals. In China, suitable pig feed is composed of chopped and cooked water hyacinth mixed with rice bran, copra cake, vegetable waste, and salt. In Indonesia, China, the Philippines, and Thailand, water hyacinth serves as a superior fodder for non-ruminant livestock, poultry, and aquaculture. Upon sun-drying, it becomes rich in protein, vitamins, and minerals.
Pigs, ducks, and fish are nourished with water hyacinth in Malaysia, Indonesia, the Philippines, and Thailand. Oguniade et al. assert that water hyacinth serves as a viable roughage feed for ruminants, characterized

by its dry matter including low acid detergent fiber (33%) and high crude protein (18%). Nonetheless, weight gain and the protein efficiency ratio diminished as the proportion of water hyacinth meal increased in the diets administered to grass carp (Ctenopharyngodon idella) containing 0–100% water hyacinth meal. Fish have also been indirectly nourished by water hyacinth. Dehydrated water hyacinth has been administered to channel catfish fingerlings to stimulate growth. Moreover, the decomposition of water hyacinth after chemical control releases nutrients that promote phytoplankton growth, hence enhancing fish output. The impact of water hyacinth on egg quality, including eggshell thickness and strength, has been evaluated when utilized as duck feed. The strength of eggshells was discovered to be augmented by water hyacinth, which is rich in protein and minerals, notably calcium, constituting 2.0% of dry matter. The mass of the egg and eggshell increased upon the incorporation of water hyacinth into the diet.

8.6 Furniture

Despite the production of commercial items from water hyacinth in China, Thailand, Indonesia, and India, the plant's potential for furniture manufacturing has not been thoroughly explored by academic researchers. The production of furniture from water hyacinth constitutes a distinctive field of inquiry, as it remains largely unexamined by many individuals (Abdel et al., 2014). The rigorous standards for material quality and the complexity of the manufacturing process render the use of water hyacinth for furniture challenging. Jafari elucidated that biomass may be skillfully transformed into handicrafts and furnishings that are both visually appealing and durable. In the Philippines, the stalks of water hyacinth are desiccated and woven into mats and baskets. Likewise, the plant is employed in India to produce various domestic goods and decorative objects that are favored by tourists (Jafari et al., 2010). This innovative application of water hyacinth not only mitigates the plant's invasiveness but also provides an eco-friendly source of materials for crafting aesthetically pleasing and functional items.

9.Conclusion

Recent research on the water hyacinth has enhanced our comprehension of both its fundamental and practical characteristics. This understanding will facilitate the advancement of future water hyacinth applications. A suitable large-scale initiative could effectively mitigate the proliferation of water hyacinth. The study has investigated the water hyacinth's adaptability in processing wastewater from various residential and commercial sources, along with the plant's efficacy in removing pollutants from wastewater. An additional energy source that can be utilized is the water hyacinth. The optimal application of water hyacinth, as indicated in the literature, is in biofuel production, particularly in Brazil, India, and certain African countries. One kilogram of cellulose yields 1.1 kilos of glucose and 0.56 kilograms of ethanol. The engineering aspect is crucial in various commercial applications due to enhanced consumption opportunities, including the manufacture of animal feed, compost/fertilizer, and energy generation from water hyacinth-based power plants. The primary focus of future projections should be on energy from power plants. It may assist in diminishing the utilization of fossil fuels. Nutritional deficiencies in underdeveloped nations may be mitigated by utilizing water hyacinth as animal feed. Value will be generated by leveraging the abundant availability of water hyacinth and its significant calorific content to educate the local community about its potential as an alternative biomass resource, offering both economic and ecological advantages. Employing the plant for various functions concurrently may be an innovative idea. The biomass can be employed to generate biofuel or electricity for power plants after the phyto-remediation of water hyacinth and nutrient absorption from wastewater. Nonetheless, apart from minor cottage enterprises or assisting disadvantaged individuals in sustaining their livelihoods through biogas production, large-scale activities have yet to develop. The government may reduce the barriers, provide resources to educate the public on this non-fossil energy source, and promote scientific research to explore the potential of plants.

References

1) *Abdel-Rahman, E.M., Mutanga, O., Adam, E. and Ismail, R., 2014. 'Detecting Sirex noctilio grey-attacked and lightning-struck pine trees using airborne hyperspectral data, random forest and support vector machines classifiers". ISPRS Journal of Photogrammetry and Remote Sensing, 88:48-59.*
2) *Abbasi SA, Ramasamy EV. Biotechnological methods of pollution control. Hyderabad: Orient Longman (Universities press India Ltd.); 1999; 168.*
3) *Adelabu, S., Mutanga, O., Adam, E. and Sebego, R., 2014. 'Spectral discrimination of insect defoliation levels in Mopane woodland using hyperspectral data'. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 7:177-185.*
4) *Anzeze AD. Biosorption of heavy metals using water hyacinth Eichhornia crassipes (Mart.) solms-Laubach: adsorption properties and technological assessment. Online available at: (http://erepository.uonbi.ac.ke:8080/xmlui/ handle/123456789/6844); 2011.*
5) *Aoyama I, Nishizaki H. Uptake of nitrogen and phosphate and water purification by water hyacinth. Water Sci Technol 1991;28(7):47–53.*
6) *Aquatic Ecosystem Restoration Foundation. Best Management Practices in Support of Fish and Wildlife Habitat. 3272, Sherman Ridge Road Marietta, Georgia; 2005. p. 30064.*
7) *Basha SA, Gopal KR, et al. A review on biodiesel production, combustion, emissions and performance. Renew Sustain Energy Rev 2009;13(6):1628–34. [23] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Science 2011;37(1):52–68.*
8) *Bariou, R., Lecamus, D. and Henaff, F., 1985a. Indices de végétation. Dossiers de télédétection, Centre régional de télédétection, Université de Rennes 2, Rennes, France, 80.*
9) *Banapurmath NR, Tewari PG, Hosmath RS. Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methylesters. Renew Energy 2007;33:1982–8.*
10) *Bartodziej, W. and Weymouth, G., 1995. Waterbird abundance and activity on water hyacinth and Egeria in the St-Marks River, Florida. Journal of Aquatic Plant Management, 33:19-22.*
11) *Berberoglu, S., Lloyd, C.D., Atkinson, P.M. and Curran, P.J., 2000. The integration of spectral and textural information using*

neural networks for land cover mapping in the Mediterranean. Computers and Geosciences, 26(4):385-396.

12) *Bolenz S, Omran H, Gierschner K. Treatment of water hyacinth tissue to obtain useful products. Bio wastes 1990;33:263–74*
13) *Busk TA, Peterson JE, Reddy KR. Use of aquatic and terrestrial plants for removing phosphorus from dairy wastewaters. Ecol Eng 1995;52(3) 371–90.*
14) *Costa RHR, Bavaresco ASL, Medri W, Philippi LS. Tertiary treatment of piggery wastes in water hyacinth ponds. Water Sci Technol 2000;42(10):211–4.*
15) *Cohen Y, Plaut Z, Meiri A, Hadas A. Deficit irrigation of cotton for increasinggroundwater use in clay soils. Agron J 1995;87:808–14.*
16) *Clark TA, Mackie KL. Fermentation inhibitors in wood hydrolysates derived from wood Pinus radiata. J Chem Technol Biotechnol 1984;34b:101–10*
17) *Chuang YS, Lay CH, Sen B, Chen CC, Gopalakrishnan K, Wu JH, et al. Biohydrogen and biomethane from water hyacinth (Eichhornia crassipes) fermentation: effects of substrate concentration and incubation temperature. Int J Hydrogen Energy 2011;36:14195–.*
18) *De Casabianca M, Laugier T, Posada F. Petroliferous wastewaters treatment with water hyacinths (Raffinerie de Provence, France): experimental statement. Waste Manag 1995;15(8):651–5.*
19) *Dominguez H, Nunez MJ, Chamy R, Lema J. Determination of kinetic parameters of fermentation processes by a continuous unsteady-state method: application to the alcoholic fermentation of D-xylose by Pichia stipitis. Biotechnol Bioeng 1993;41:1129–32.*
20) *Epstein P. Weeds bring disease to the east African waterways. Lancet 1998;351:577*
21) *Fernández OA, Sutton DL, Lallana VH, Sabbatini MR, Irigoyan JH. Aquatic weed problems and management in South and Central America. In: Charudattan R, editor. Aquatic weeds the ecology and management of nuisance aquatic vegetation. New York: Oxford University Press; 1990. p. 406–25.*
22) *Herfjord T, Osthagen H, Saelthun NR. The water hyacinth. Norwegian Agency for Development Cooperation. Water Resources and Energy Administration, Oslo. ISBN 1994;82-410- 0207-6.*
23) *Hossain R, Chowdhury MK, Yeasmin S, Mozammel MH. Production of ethanol using yeast isolates on water hyacinth and azolla. Bangladesh J Microbiol 2010;27:56–60.*
24) *Ganguly A, Chatterjee PK, Dey A. Studies on ethanol production from water hyacinth – a review. Renew Sustain Energy Rev 2012;16:966–72.*
25) *Ikhtyar O, Shmsuzzamana F. Kinetics of gas formation from water hyacinth biomass. In: Proceedings of the international conference on water hyacinth, Hyderabad, India; 1984. p. 475–85.*
26) *Jafari N. Ecological and socio-economic utilization of water hyacinth (Eichhornia crassipes Mart Solms). J Appl Sci Environ Manag 2010;14(2):43–49.*
27) *Jayaweera MW, Kasturiarachchi JC, Kularatne RK, Wijeyekoon SL. Contribution of water hyacinth (Eichhornia crassipes (Mart. Solms) grown under different nutrient conditions to Fe-removal*

mechanisms in constructed wetlands. J Environ Manag 2008;87(3):450–60.

28) *Jebanesan A. Bilological treatment of dairy waste by Eichhornia crassipes Solms. Environ Ecol 1997;15(3):521–3.*
29) *Jinlin X, Grift TE, Hansena AC. Effect of biodiesel on engine performances andemissions. Renew Sustain Energy Rev 2011;15:1098–116.*
30) *Jianbo Lu, Zhihui Fu, Zhaozheng Yin. Performance of a water hyacinth (Eichhornia crassipes) system in the treatment of wastewater from a duck farm and the effects of using water hyacinth as duck feed. J Environ Sci 2008;20:513–9.*
31) *LichtsFO, Industry Statistics. World fuel ethanol production. Renewable Fuels Association; 2010. Available at: 〈http://www.ethanolrfa.org/news/entry/glo bal-ethanol-production-to-reach-88.7-billion-litres-in-2011/〉 [retrieved 30.04.11].*
32) *Lytle C, Lytle F, Yang N, Qian J, Hansen D, Zayed A. Reduction of Cr(VI) to Cr (III) by wetland plants: potential for in situ heavy metal detoxification. Environ Sci Technol 1998;32(20):3087–93.*
33) *Lenzi E, Luchese E, de Lima Barbosa S. Improvement of the Eichhornia crassipes water hyacinth-use in the decontamination of chromium contaminated solution. Arq Biol Technol 1994;37(3):603–9.*
34) *Masami GO, Usui I, Urano N. Ethanol production from the water hyacinth Eichhornia crassipes by yeast isolated from various hydrospheres. Afr J Microbiol Res 2008;2:110– 3.*
35) *Methy M, Alpert P, Roy J. Effects of light quality and quantity on growth of the clonal plant Eichhornia crassipes. Oecologia 1990:84.*
36) *Nigam JN. Bioconversion of waterhyacinth (Eichornia crassipes) hemicellulose acid hydrolysate to motor fuel ethanol by xylosefermenting yeast. J Biotechnol 2002;97:107–16.*
37) *OECD-FAO Agricultural Outlook and OECD/FAO2011/〈http://www.agri-out look.org/dataoecd/23/56/48178823. pdfS〉; 2011–2020.*
38) *Nishikawa N, Sutcliffe R, Saddler JN. The influence of lignin degradation products on xylose fermentation by Klebsiella pneumoniae. Appl Microbiol Biotechnol 1988;27:549–52.*
39) *Palanisamy E,Manoharan N. Performance studies on vegetable oils and their derivative as alternate fuels forcompression ignition engines: an overview. In: Proceedings of the 19th national conference on IC engine and combustion; 2005. p. 95–100.*
40) *Poddar K, Mandal L, Banerjee GC. Studies on water hyacinth (Eichhornia crassipes) – chemical composition of the plant and water from different habitats. Ind Vet J 1991;68:833–7.*
41) *Rushang JM, Michael JP. Flow properties of bio diesel fuel blends at low temperatures. Fuel 2007;86:143–51.*
42) *Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. Areviewon biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15(5):2262–89. [34] Seyed Ehsan Hosseini, Wahi Mazlan A, Saber Salehirad, Seis Mohsin M. Evaluation ofpalmoil combustion*

characteristics by using the chemical equilibrium with application (CEA) software. Appl Mech Mater 2013;388:268–72.
43) Sharma YC, Singh B. Development of bio diesel from Karanja, a tree found in rural India. Fuel 2007;87:1740–2.
44) Sinha AK, Sinha RK. Sewage management by aquatic weeds (water hyacinth and duckweed): economically viable and ecologically sustainable biomechanical technology. Environ Educ Inf 2000;19:215–26.
45) Sooknah RD, Wilkie AC. Nutrient removal by floating aquatic macrophytes cultured in anaerobically digested flushed dairy manure wastewater. Ecol Eng 2004;22:27–42.
46) Sandip S, Sandeep M, More M, Nadaf AA. Biochemical conversion of acidpretreated water hyacinth (Eichhornia crassipes) to alcohol using PichiaStipitis NCIM3497. Int J Adv Biotechnology Res 2012;3(2):585–90.
47) Tran AV, Chambers RP. Ethanol fermentation of red oak acid prehydrolysate by the yeast Pichia stipitis CBS 5776. Enzyme Microb Technol 1986;8:439–44.
48) Vaillant N, Monnet F, Sallanon H, Coudret C, Hitmi A. Treatment of domestic wastewater by an hydroponic NFT system. Chemosphere 2003;50(1):121–9.
49) USEPA. Design manual – constructed wetlands and aquatic systems for municipall wastewater treatment. U.S. Environmental Protection Agency. Report No. EPA/625/1-88/022. Office of Research and Development, Cincinnati, OH, 83, 1988.
50) Van ZC, Prior BA, Preez JC. Acetic acid inhibition of $_D$-xylose fermentation by Pichia stipitis. Enzyme Microb Technol 1991;13:82–6
51) Valero MAC, Johnson M, Mara DD. Enhanced phosphorus removal in a waste stabilization pond system with blast furnace slag filters. In: Proceedings of the second international conference smallwat, Seville, Spain; 2007.
52) Williams SR. Apparatus and method for agricultural animal wastewater treatment. United States Patent Application Number 2009. p. 250–393.
53) Wu D, Wang ZF, Feng L. The harm of over-reproduction of water hyacinth and preventative measures. Environ Sci Technol 2001;24:35–7.
54) Yang DQ, Jing YX, Chen ZP, Cheng HQ. Study on the removal effect and regulation of Cleistocalyx operculatus to N and P in a eutrophic water body. Acta Sci Circumst 2001;21(5):637—9.
55) Xiaomei L, Kruatrachue M, Pokethitiyook P, Homyok K. Removal of cadmium and zinc by water hyacinth, Eichhornia crassipes. Science Asia 2004;30: 93–103.