ACS Sustainable Chemistry & Engineering

Perspective

pubs.acs.org/journal/ascecg

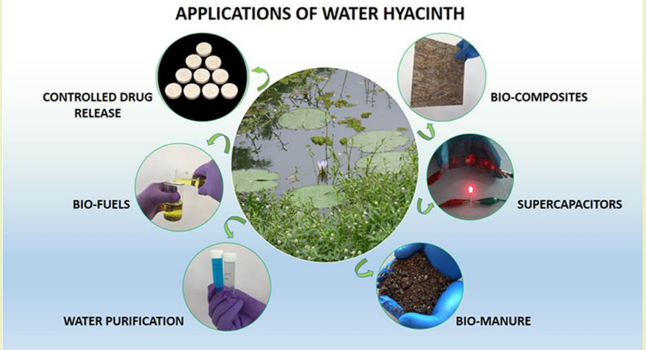
Water Hyacinth: A Unique Source for Sustainable Materials and Products

Vijaykumar Guna,[†,‡] Manikandan Ilangovan,[†] M. G. Anantha Prasad,[†] and Narendra Reddy*,[†]

[†]Center for Incubation, Innovation, Research and Consultancy, Jyothy Institute of Technology, Thataguni Post, Bengaluru 560082, India

[‡]Research Resource Centre, Visvesvaraya Technological University, Jnana Sangama, Belagavi 590018, India

ABSTRACT: Water hyacinth (*Eichhornia crassipes*) is a weed ubiquitously found in lakes, rivers, and other water bodies across the globe. With high rates of regeneration, survival, and growth, it is generally difficult to clear water bodies infested with water hyacinth. However, these features of water hyacinth can be considered as advantageous. Researchers have attempted to use hyacinth as an absorbent for heavy metals, water pollutants, and others. Although a large number of studies have been done on using the stems and leaves of water hyacinth as absorbent, there are several interesting and novel applications of water hyacinth. For example, water hyacinth has been demonstrated to be useful to develop supercapacitors, for production of ethanol, and to improve the immune resistance of plants and animals. In this review, we provide an opportunity for readers to realize the unique nature of water hyacinth and its potential to be used to develop products for various applications.



KEYWORDS: *Water hyacinth, Biomass, Renewable resource, Value addition, Bioproducts*

INTRODUCTION

Global warming due to unrestrained exploitation of natural resources has led to major concerns on the availability of food, feed, commodity products, and healthy living in the near future. Major concerns are the raising temperature and consequent effect on natural resources, food production, and security. It has been predicted that even a 2 °C rise in temperature would adversely affect production of major food crops. This would in turn lead to decreased availability or increased cost of natural products. Hence, maximizing utilization of natural resources and finding sustainable and ecofriendly sources for commodity products is of utmost importance. Since availability of natural resources is depleting at an alarming rate, it is inevitable that accessibility of agricultural land and production of food will be adversely affected. To overcome these limitations, considerable efforts are being made to develop crops that can provide high yields and tolerate extreme environments. Alternatively, nonconventional crops are being considered as potential sources for food, fuel, energy, and other products.

Water hyacinth is traditionally considered as a weed and is found to affect water bodies across the globe. The extremely rapid growth and ability to persist in water has made water hyacinth a notorious crop that is difficult to control. It has been estimated that water hyacinth can grow at a rate of 0.26 ton dry biomass per hectare per day under normal conditions.[1] On the basis of the conditions in which it prevails, water hyacinth is said to double its weight in 6−28 days and replicate in 4−58 days.[2] Another study suggests that under favorable conditions, water hyacinth could double its size in 5 days and yield could be up to 17.5 tons per hectare per day.[3] Other studies have suggested that production of water hyacinth varies from 60 to 150 tons per hectare with dry mass of about 6−10 tons per hectare.[4]

Due to its rapid growth, it depletes the water body of nutrients and oxygen thererby affecting other flora and fauna.[5] Rarely is any other species of plants capable of surviving in the vicinity of water hyacinth.[5] Water bodies infected with water hyacinth also cause problems in fishing, recreational activities, and flow of water.[6−8] Considerable money is spent for deweeding and controlling water hyacinth. For instance, in 2012, the Florida government spent about \$3.4 million to control water hyacinth in about 11,000 ha.[9] Even biological control of water hyacinth to avoid water loss may not be economically viable due to the high cost of decontamination.[10]

Although water hyacinth is considered a weed and found to affect water bodies including inland water ways and sources of potable water, several researchers have studied the potential of using water hyacinth as an inexpensive, abundantly available, and renewable and sustainable source for various applications.[11] Some of the applications considered for water hyacinth include fuel by direct combustion, ethanol and biogas production, sorbents for heavy metals and dyes, and reinforcement for composites.

Received: January 6, 2017
Revised: April 27, 2017
Published: May 11, 2017

DOI: 10.1021/acssuschemeng.7b00051
ACS Sustainable Chem. Eng. 2017, 5, 4478−4490

Table 1. Antioxidant Activity and Total Phenolic Content of *E. crassipes* Polar Extracts[16]

	yields of sequential extraction[a]			antioxidant activity (AA)		total phenolic content (TPC)	
biomass	$\eta_{Soxhlet}$ (wt %)	η_{SLE} (wt %)	η_{total} (wt %)	IC_{50} (mg L^{-1})	$mg_{AAE}\ g^{-1}{}_{biomass}$	$mg_{GAE}\ g^{-1}{}_{extract}$	$mg_{GAE}\ g^{-1}{}_{biomass}$
roots	1.12 ± 0.05	10.00 ± 1.41	11.12 ± 1.41	2340.91 ± 67.14	0.11 ± 0.00	21.88 ± 0.27	2.19 ± 0.03
stalks	2.65 ± 0.09	28.84 ± 1.46	31.49 ± 1.46	370.36 ± 7.70	2.04 ± 0.04	14.49 ± 0.18	4.18 ± 0.05
leaves	3.30 ± 0.14	20.93 ± 1.18	24.23 ± 1.19	113.44 ± 3.95	4.86 ± 0.17	39.28 ± 0.42	8.22 ± 0.09
flowers	4.45 ± 0.10	n.a.[b]	n.a.[b]	n.a.[b]	n.a.[b]	n.a.[b]	n.a.[b]

[a] Yields: η (kg extract/100 kg biomass); Soxhlet with dichloromethane; SLE with methanol:water:acetic acid mixture. [b] n.a. = not available.

Utilizing water hyacinth as a renewable and sustainable source will provide inexpensive and environmentally friendly bioproducts.[12] Demonstrating the usefulness of water hyacinth for various applications would help to realize its potential as a source for various bioproducts and overcome the conventional notion of treating it as a weed. In this review, we attempt to provide an overview of the various applications considered for water hyacinth. We hope that realizing the unique features and potential of water hyacinth as a useful agricultural crop will help to reduce global warming and dependence on unsustainable resources.

■ EXTRACTIVES FROM WATER HYACINTH

Considerable studies have been made to determine the structure and properties of water hyacinth and extract the unique compounds present. Broadly, leaves, stems, and roots of hyacinth are composed of cellulose, hemicellulose, and lignin. Cellulose fiber bundles in hyacinth stems have diameters in the range of 25−50 μm and purified single fibers had diameters of 7 μm.[13] Further purification and analysis has shown that cellulose in hyacinth can be obtained in the form of nanofibers with diameters in the range of 40−100 nm. Twenty organic acids, three steroids, and terpenoid were extracted from the leaves, stems, and roots of water hyacinth.[14,15] Higher levels of carboxylic acids could be extracted using methanol as the solvent. However, the distribution and amount of each extractant was not quantified.[14]

Roots, leaves, and stems of water hyacinth were treated with dichloromethane and methanol to obtain lipophilic extracts and analyze their antioxidant properties and potential for valorization.[16] Both Soxhlet and solid liquid extraction were done to obtain a total weight of extractants ranging from 11% to 31% (Table 1). Twenty-nine separate compounds were identified with 28 stigmasterol, 29 β-sitosterol, and 26 cholesterol components among others. Antioxidant and total phenolic content were considerably higher in the hyacinth extracts compared to standard (ascorbic acid) (Table 1).

It was suggested that water hyacinth could be a useful source for production of antioxidants and other chemicals. To increase the yield of sterols, hyacinth stalks and leaves were treated with pure and modified carbon dioxide using ethanol as a cosolvent. Using 2.5 wt % of ethanol as cosolvent and 30 MPa pressue, the highest yield of total sterols achieved was 38.26 wt % and that of sigma sterol was 26.35 wt %.[17] Further, it was reported that supercritical fluid extraction (SFE) provided higher levels of stigmasterol compared to Soxhlet extraction. At 200 bar and 40 °C, SFE was found to be selective toward stigmasterol extraction.[18] A total extractive wt % of up to 1.88% based on weight of the hyacinth and a stigmasterol concentration of 32% in the total extracts could be obtained under the optimized conditions.[18]

■ WATER HYACINTH AS A SORBENT FOR HEAVY METALS

One of the most widely studied applications for water hyacinth is to use it as a sorbent for heavy metals in polluted water. The leaves, stems, and roots together or separately have been studied for sorption of heavy metals. Both the roots and stems of water hyacinth were studied for their potential absorption of Cr(VI) from solution.[19] The hyacinth roots and stems were dried and powdered in a 52 mesh screen. Batch absorption studies were done in a 250 mL conical flask at 25 °C for 450 min. Kinetics of absorption and adsorption isotherms at various sorption conditions were investigated. At 10 ppm, absorption increased linearly up to about 60 min, and later, it starts to saturate. A similar increase was observed when the sorbent dose was increased, but increasing pH from 1 to 5 decreased the removal efficiency from 95% to about 15%.[19] Absorption followed a pseudo-second-order reaction and Freundlich isotherm. Ability to remove up to 96% of the metal was considered to be good for practical applications.[19]

In addition to the leaves of hyacinth being generally considered for absorption and other studies, its long roots have been studied for its potential to absorb Pb, Zn, Cu, and Cd in aqueous solutions. The long roots of water hyacinth were powdered and used for sorption of the different metals. FTIR spectra confirmed the attachment of the metals, and SEM images showed that the adsorption was on the surface of the water hyacinth root powder. The powder had a specific surface area of 1.1 m^2/g and average pore width of 11.14 nm.[20] The level of adsorption of the various metals depends on the initial concentration, pH, and time. Maximum absorption was achieved for Pb followed by Cd, Zn, and Cu. The presence of Cu was found to adversely affect the absorption of Cd and Zn. A removal efficiency of up to 98% was achieved depending on the conditions used and whether single or multiple metals were present.[20] The roots of water hyacinth were also found to have excellent (up to 99%) absorption of acid and basic dyes. Both boundary layer absorption and interparticle diffusion were observed with rate constants for sorption varying from 0.042 to 0.069 per minute and interparticle diffusion constants being 0.082 to 1.554 mg/g $min^{1/2}$. It was suggested that the roots had higher absorption capability for basic dyes rather than acid dyes.[21] In another study, shoots of water hyacinth were powdered (150 μm) and used as a sorbent for removal of chromium and copper found in wastewater released from tanneries.[22] Almost complete removal of chromium and copper could be achieved both in the tannery waste and standard solution. However, the amount of metal ions that can be sorbed and the kinetics and thermodynamics were not reported.[22]

Instead of preparing activated carbon from biomass for absorbent applications, it was proposed that biochar made by pyrolyzing the biomass at different temperatures under inert atmosphere could be more economical and efficient for heavy metal absorption. With this view, Ding et.al. prepared biochars by carbonizing water hyacinth at 300, 450, and 600 °C. The potential of the absorbents for sorption of Cd^{2+} and Pb^{2+} and a mixture of the two metals in solution was studied. X-ray photon spectroscopy (XPS) studies revealed that two new peaks (Figure 1) were introduced with binding energies of 139.7 and 406.3 eV, which were supposed to be due to the presence of Pb and Cd.[23] Since the peak of Pb was higher than that for Cd, it was suggested that the biochar was more suitable for sorption of Pb.[23] The highest sorption for Pb was obtained at pH 5 and at pH 7 for Cd. In addition to high sorption, the biochar also showed excellent desorption capability with maximum desorption of 92% for Pb^{2+} when the biochar was prepared at 450 °C. As with the sorption, desorption was also higher for Pb. Also, Pb was preferentially taken up compared to Cd from a solution having a mixture of the two metals.[23] In another study, biochar prepared by pyrolyzing water hyacinth at various temperatures was studied for its potential to sorb Cd from aqueous solutions.[24] A maximum sorption of about 70 mg Cd per g of biochar was obtained. Absorption was considered to be pseudo-second-order, and ion exchange could contribute up to 79% of metal absorption.[24] Hyacinth was also able to retain most of the sorbed metals and did not desorb them. This was considered as a positive attribute for treating pollutants in the environment.

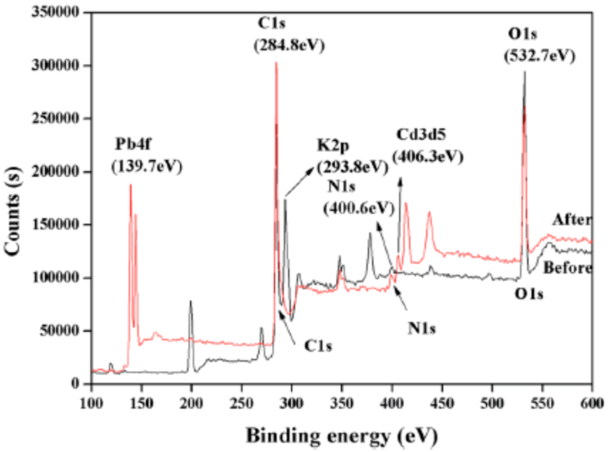


Figure 1. XPS curves for the biochar before and after adsorption.[23]

Various biomasses including water hyacinth were made into biochars and studied for their potential to sorb Cd, Cu, Pb, and Zn from aqueous solutions.[25,15] Removal of metal ions was greater than 95%. Hyacinth biochar had higher pH (9.2) and ability to exchange cations which would provide high sorption through ion exchange.[25] It was suggested that the biochars could be used in metal-contaminated soils for remediation and improving the quality of the soil.[25] Zhang et al. developed magnetized biochar for sorption of arsenic by treating the biochar with ferrous chloride and ferric chloride.[26] Treated material was subject to slow pyrolysis at 250 to 450 °C for 1 h and later washed and dried. The amount of Fe absorbed on the biochar was dependent on the ratio of Fe^{2+}/Fe^{3+} concentration in the initial solution. Consequently, the percentage of arsenic sorbed was also proportional to the Fe on the biochar. Up to 100% removal of arsenic was observed when biochar treated at 250 °C was used. Morphological and elemental analyses showed that absorption of arsenic was saturated at about 49 emu/g (7.4 mg/g). Biochar obtained at 250 °C had a coarse and granulated surface that contributed to higher surface area and hence better sorption of arsenic compared to the biochar obtained by treating at 450 °C which had fewer and finer granules. More importantly, arsenic sorbed by the biochar could be extracted (desorbed) just by using magnets. This would make the sorbent environmentally friendly without having the risk of re-releasing the arsenic into the environment.[26]

Heavy metals such as Cu(II), Co(II), and Fe(III) ions are released into the environment from industrial processing such as mining, electroplating, etc. It is necessary to develop low cost and highly efficient absorbents to remove metal ions from wastewater.[27] Water hyacinth was considered to be an ideal bioabsorbent due to its low cost and large availability. The ability of the hyacinth to sorb various metals was studied by powdering hyacinth and using metal solutions at various conditions. High sorption efficiency ranging from 90% to 99% was obtained for all three types of metal ions. The extent of sorption was dependent on the length of immersion, pH, temperature, and other parameters. Sorption was considered to happen via interparticle diffusion in three steps of adsorption, gradual inward diffusion, and equilibrium stage sorption. The absorbents showed considerably higher thermal stability after sorption due to the formation of metal ion complexes with the biopolymer.[27]

Although hyacinth has shown good ability to sorb various individual metals, a combination of metals and others salts coexist in most instances. Hence, it would be interesting to study the ability of water hyacinth to pick up (sorb) various metals in a mixed environment.[28] In one such attempt, studies were conducted to understand the behavior of water hyacinth roots to sorb Cu(II) and Cd (II) individually in a competitive environment. It was observed that Cu had slightly higher sorption than Cd in an individual solution, but Cd was sorbed to a considerably lower extent than Cu in a binary solution. Higher affinity of the Cu (II) for the sorption sites was postulated as the reason for its higher uptake. On the contrary, the presence of Cd(II) did not affect the sorption of Cu(II) but Cu(II) decreased the sorption of Cd(II) and even led to fast desorption of Cd(II).

Water hyacinth plants along with some parts (root, stem) also showed different levels of sorption for Cd(II) and Zn(II) in individual and mixed solutions.[29] Plants were exposed to solutions containing 1−6 ppm of Cd and 2−12 ppm of Zn and a mixed solution having 6 ppm of Cd and 12 ppm Zn. Plants were monitored and samples collected up to 16 days. Promotion and inhibition of growth of the plant were observed depending on the type and concentration of metal and time of exposure.[29] Sorption of Zn individually or from Zn and Cd from the combined solution did not have a negative effect on plant growth. However, at Cd concentrations of 4 and 6 ppm, plants had inhibited growth due to the toxicity of Cd. Further, most of the Cd was found to be in the roots with a concentration of up to 3900 μg/g.[29] Comparatively, the amount of Zn in the roots was as high as 10,300 μg/g after 16 days of exposure. After the same treatment, the amount of Zn in the stems was only 1300 μg/g indicating the preferential sorption capability. The overall removal percentage ranged from 82% to 92% for Cd and 87% to 95% for Zn. However, in a combined solution, the removal efficiency was around 70%.

Higher uptake of Cr (VI) by water hyacinth roots, stems, and leaves was also observed when a binary solution of Cr(VI) and phenol was used.[30] In this study, water hyacinth was grown in solutions containing various concentrations of Cr (VI) and phenol individually and in binary solutions. Elemental analysis (Table 2) showed that the uptake of the elements was higher in

Table 2. Elemental Composition of Water Hyacinth after Uptake of Cr(VI) and Phenol[30]

element	component	wt % roots	wt % stems	wt % leaves
C K	Cr(VI)	69.91	72.74	66.4
	phenol	50.43	52.25	51.24
O K	Cr(VI)	26.56	27.08	33.48
	phenol	45.97	47.54	48.59
Cr K	Cr(VI)	3.53	0.17	0.12
	phenol	3.61	0.22	0.18

the roots, stems, and leaves when phenol was present. At an initial concentration of 20 mg/L, the uptake of Cr (VI) from an individual solutions was 39% compared to 84% from a binary solution. Although uptake of phenol was also higher from a binary solution (Table 2), the difference was relatively much smaller compared to Cr (VI). It was suggested that reaction between Cr (VI) and phenol resulted in the formation of complexes that had greater affinity toward hyacinth and hence higher uptake.[30] The maximum uptake of Cr (VI) from the individual and binary solutions was 2.36 and 2.46 mg/g, respectively.

However, uptake of Cr(VI) at high levels was toxic to the plant resulting in a decrease in dissolved oxygen, sugar, and chlorophyll content and energy level of the plant. Roots of water hyacinth were found to have a specific area of 4.5 m^2/g, total pore volume of 0.027 cm^3/g, and average pore diameter of 25.4 nm.[31] This material showed good sorption to Cu(II) in aqueous solutions with sorption of up to 22.7 mg/g, higher than many other sorbents used for Cu (II). Spectra obtained using XPS clearly showed the presence of Cu(II) after sorption. Activation energy for the sorption process was found to be about 30.8 kJ/mol, and mechanism of sorption was suggested to be through complex formation and ion exchange.[31]

Uranium is one of the most toxic metal pollutants found in the earth. Several efforts have been made to use bioabsorbents for removal of uranium. Water hyacinth stems and leaves were made into powder, and the potential to remove uranium from aqueous solution was determined under various conditions.[32] Removal efficiency increased from 40% to about 85% when the pH was changed from 2 to 5.5. Sorption equilibrium was achieved within 30 min and followed pseudo-second-order kinetics. Highest sorption was 143 mg/g, and it was suggested that complexation and ion exchange were involved in the process of sorption.[32]

Instead of conducting laboratory trials, the ability of water hyacinth to sorb various metals (Ag, Ba, Cd, Mo, and Pb) released from a gold mine into water in a tailing area were studied.[33] Plants grown in green houses were planted in the polluted area and exposed to the contaminants for 4 days. Control plants were used downstream where there was minimum contamination. After exposure, the plants were collected, separated into various parts, and analyzed for changes. Accumulation of the contaminants in the plants was measured in terms of bioconcentration factors (BCFs). Very high concentration of Ag, Ba, and Pb was seen in the roots, whereas a uniform distribution of Mo and Cd was observed in the roots, stems, and leaves. It was suggested that some physical barrier in the plants could have reduced the transfer of the contaminants from the roots to the stems and leaves. Bioconcentration factors were highest for Mo followed by Pb and Ba. The plant was able to translocate Mo and Cd depending on the extent of accumulation and exposure.[33]

Although water hyacinth has been extensively studied for purification of water from metals, dyes, and other contaminants, the effect of absorption of metals on the physiological and biochemical aspects of the plant has not been well understood. To gain knowledge on these aspects, water hyacinth (*Eichhornia crassipes*) and *Pistia stratiotes* were exposed to Cd, and the changes in levels of protein expression were studied.[34] Considerable changes in the yield and morphology of the plant and ability to photosynthesize were observed. Antioxidant activity also increased in the water hyacinth plants with increasing exposure. Further, it was found that the plant was able to maintain the physiological changes even after exposure to up to 100 mg/L of Cd. Generation of antioxidant enzymes and reduction in oxidative stress were suggested to be the reasons for the ability of hyacinth to withstand stresses when exposed to Cd contamination.[34]

SORPTION OF DYES

Considerable studies have been done to chemically modify water hyacinth and improve the ability to sorb dyes. Hyacinth was soaked in nitric acid (2M) for 24 h and later washed, dried, and ground into powder having a particle size of 0.20−0.315 mm.[35] The amount of dye sorption by the modified hyacinth was dependent on the initial concentration, pH, time, and other parameters. Equilibrium sorption ranged from 54% to 99% depending on the initial concentration. Sorption was found to follow pseudo-second-order kinetics, and the overall dye uptake was through intraparticle diffusion.[35] Water hyacinth leaves were dried, powdered into various sizes, and used for sorption of Amaranth dye.[36] Kinetic and thermodynamic studies showed that the biosorption closely followed the Langmuir isotherm, and the maximum dye sorption was 70 mg/g. The abundant availability and low cost of water hyacinth were suggested to be ideal for removal of dyes from wastewater.[36]

Studies have also been done to determine the ability of alginate-modified hyacinth to remove methylene blue and crystal violet from dye wastewater.[37] In this approach, alginate solution was prepared in water to which the hyacinth powder was added and blended vigorously. Beads of alginate−hyacinth were formed when the mixed solution was dropped into 0.1 M calcium chloride solution. Size of the beads was controlled between 3 and 5 mm by extruding through a pipet tip. The amount of dye sorbed increased with an increasing amount of sorbent and pH up to 10. In all the studies, it was found that methylene blue sorbed to a larger extent than crystal violet. The bioabsorbent was found to have a considerably higher surface area of 226 m^2/g for methylene blue compared to 77 m^2/g for crystal violet, which provided higher sorption capacity.[37] Higher affinity for methylene blue was also due to the differences in the isoelectric point and hence net charge on the dye and the beads. However, both dyes had high affinity and could be sorbed up to 97% for methylene blue and 93% for violet. Alginate−hyacinth beads were also used to remove Cu from aqueous solutions in a packed bed flow-through column.[38] Immobilization of hyacinth powder on alginate was suggested to provide higher mechanical properties and dye sorption capability. The beads provided excellent sorption even after five sorption/desorption/regeneration cycles indicating that they are suitable for use in removing Cu from aqueous solutions.[38]

Instead of using the raw roots, burned roots (carbon) from *Eichhornia crassipes* were studied for their ability to absorb a toxic

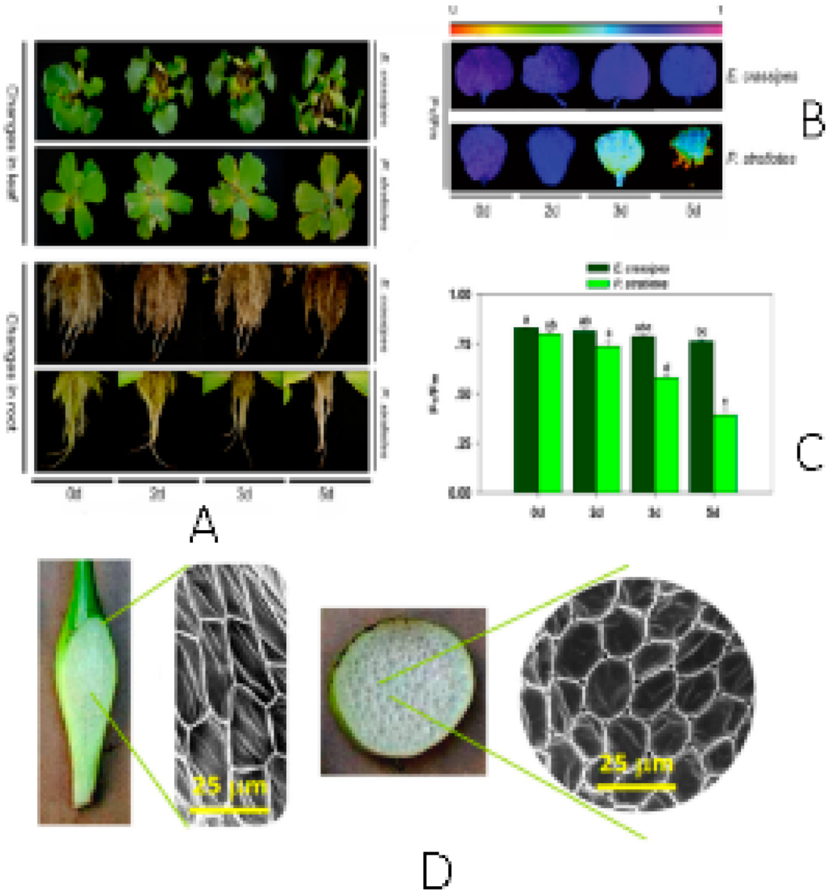


Figure 2. Exposure to Cd changes the morphology and the chlorophyll content in *E. crassipes* and *P. stratiotes* leaves. Panels B and C show the variations in the maximum chlorophyll flouorescence (Fv/Fm), and D shows the digital and SEM images of the surface and cross section of a water hyacinth petiole[34,46]

dye, congo red.[39] Roots were burned in a muffle furnace at 500 °C to prepare the absorbent. The absorbent had a porous morphology before absorption, but the pores were visibly less after absorption due to the presence of congo red on the surface.[39] The level of absorption was dependent on the initial concentration, time, and temperature with up to 95% removal of the congo red. A maximum absorption of 4.88 mg/g was achieved for the burned root powder. Compared to other absorbents, the level of absorption for the burned root powder was lower than that of Ceram (8.97 mg/g) and activated carbon from coir pith (6.75 mg/g) but higher than that of materials such as activated carbon from some marine algae and soil. However, the absorption depends on the material properties and the conditions used during absorption. Therefore, it may not be meaningful to compare data from different studies. Several other biomass-derived carbon sources have been studied and reported to have higher sorption capabilities.[39]

In a similar study, water hyacinth was carbonized, and the charcoal obtained was filtered to obtain particles with a size of around 53 μm.[40] The charcoal particles were further modified by either treating with a surfactant (SDS) or a surfactant along with sodium chloride (NaCl). Modifications of the carbon using SDS and salt resulted in an increase in the surface area to 31 $m^2\ g^{-1}$. When used as an adsorbent for the dye safranin, the amount of dye removal was much higher (up to 90%, about 85 mg of dye sorbed per gram of sorbent) for the SDS- and NaCl-treated samples. The extent of dye sorption was dependent on the contact time and more significantly on the pH. The highest sorption obtained for all three samples was at pH 12 with increasing pH from 2 to 12 continually increasing the amount of dye sorbed.[40] The adsorption process was considered to be physical for the unmodified, sodium dodecyl sulfate (SDS)-modified, and SDS–NaCl-modified samples, with activation energies being 2.26, 18.02, and 27.42 kJ/mol, respectively. A water hyacinth-based magnetic biochar was prepared by coprecipitating pyrolyzed water hyacinth with Fe^{2+} or Fe^{3+}.[41] Mineral crystals of Fe_3O_4 and Fe_2O_3 were formed on the surface of the biochar which assisted in removal of as much as 96% of P. A maximum sorption of 5 mg/g was obtained, and high affinity was also seen for As(V) even when eutrophic water from polluted lakes were used. It was suggested that electrostatic attraction and surface complexation via ligand exchange were contributing to the high sorption of P onto the biochar.[41] It was suggested that water hyacinth biochar could be used effectively and economically to reclaim phosphorus used in fertilizers and that released from industries.

Nanocrystallites were embedded into activated carbon prepared from water hyacinth to improve sorption properties. Powdered hyacinth was soaked in a cobalt nitrate solution for 24 h. Later, the treated biomass was converted into activated carbon by burning at 250 °C for 20 min.[42] Scanning electron microscope images and X-ray diffraction studies confirmed the presence of nanocrystallites. Considerable amounts of macropores and mesopores that could aid in sorption were observed due to the inclusion of nanocrystallites. A highest removal efficiency of 93% and sorption of up to 25 mg/L of the dye malachite green could

DOI: 10.1021/acssuschemeng.7b00051
ACS Sustainable Chem. Eng. 2017, 5, 4478−4490

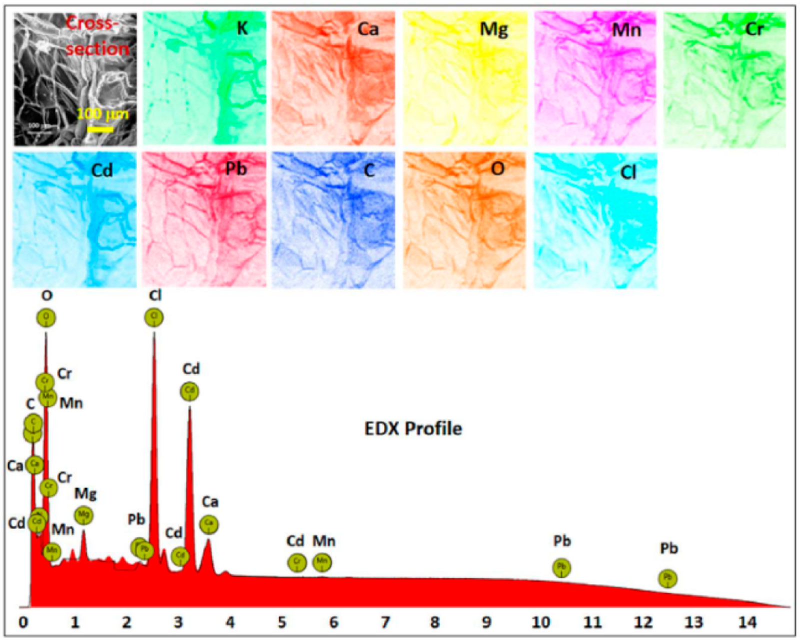


Figure 3. SEM and EDX profile (elemental mapping) for a green petiole in water hyacinth.[46]

be obtained.[42] Another option that has been considered to increase the sorption capability of water hyacinth is to treat with SDS. Charcoal prepared from hyacinth leaves was heated with the surfactant to create anionic sites for absorption and increase electrochemical interactions between the absorbate and the dye molecules. A relatively high surface area of 69 m^2/g was obtained after treatment. Treated hyacinth was introduced into the dye solution, and various sorption parameters were varied. Their effect on percent dye removal was studied.[43] Dye removal increased with increasing time but decreased as the concentration of the dye solution was increased. Highest removal was 98% at pH 12 with the absorption level being 116 mg/g.[43]

In addition to the removal of dye using absorbents, another critical aspect is the disposal of the absorbed biomass. Degradation of the methylene blue-sorbed water hyacinth powder through semicontinuous anaerobic−aerobic bioreactors was studied. Several bacteria and fungi were screened for their ability to decolorize the sorbed powder. A consortium of *S. cerevisiae* and *Bacillus sp. STIS* was found to be most suitable for decoloration and degradation. Water hyacinth powder that has sorbed methylene blue to three different levels was exposed to the microorganisms for the degradation studies.[44] Complete decoloration of the dye was possible using the consortium. It was found that the consortium of microorganisms and the anaerobic−aerobic system of treatment was most optimal for removal and degradation of textile dyes in wastewater.[44]

Instead of using hyacinth as a passive sorbent for metals in wastewater, a unique approach of adopting hyacinth leaves as separators in an electrodeposition reactor to recover nickel from electroplating wastewater was studied.[45] Water hyacinth leaf was used as a membrane to separate the anode and cathode. The reactor setup was immersed into an artificial electroplating wastewater. Various electrical measurements and deposition of nickel on the plates was observed by passing current through the system. About a 5% increase in nickel recovery was achieved when hyacinth was used as a separator. Considerably heavy deposition of nickel and clear water could be seen when the hyacinth was used as a separator.[45] The portioned reactor had 27% higher separation of nickel, current efficiency of 88%, and specific energy of 5.2 kWh/kg, considerably higher than that of the reactor without the separator. In a similar approach, water hyacinth petioles were studied for their structure since their unique structure was considered suitable as a substrate to develop biomimicked oxygen separation membranes.[46] Scanning electron microscope images of the surface and cross section of the petiole revealed hexagonal porous surfaces which reduce its density and provide buoyancy (Figure 2). Considerable amounts of metals such as Cd, Cr, and Mg were found in the petiole (Figure 3). For preparation of the membranes, dry petioles were immersed in a precursor gel, dried, and later calcined at 950 °C.[46] The calcined powder obtained had a 3D microstructure with nanorods having diameters of 50−80 nm. Pellets were formed from the calcined powder to act as the membrane. Oxygen permeation flux and electrical conductivity was nearly 2-fold higher for the membrane prepared using hyacinth petiole as the template compared to conventional membranes.[46] It was concluded that the approach of biomimicking using petioles of water hyacinth as the template could result in novel multifunctional materials for various applications.

■ CONTROLLED DRUG RELEASE

The petiole part of the water hyacinth was collected, dried, and powdered for potential use as a rate retarding material for controlled release of drugs (metformin).[2] Water hyacinth powder was combined with a drug and wet compressed and formed into a pellet. Mechanical properties, ability of the pellets to release drugs, and the kinetics of release were studied. The amount of drug released from the tablets ranged from 50% to 70% depending on the amount of hyacinth powder. An in vitro dissolution study conducted using simulated intestinal media showed that dissolution time ranged from 1 to 5 min depending on the amount of hyacinth present. Although combining water hyacinth powder (5%) with a drug provided desired release rates, the biocompatibility and any possible adverse effects of the water hyacinth powder were not investigated.[2]

Table 3. Parameters That Indicate Changes to Composition and Crystal Structure of Cellulose in Hyacinth before and after Alkali-Peroxide Treatment[51]

	pretreatment			relative content (%)						
	temp. (°C)	time (h)	solid recovery (%)	cellulose	hemicellulose	lignin	lignin removal (%)	crystallinity (%)	cellulose hydrolysis (%)	reducing sugars (mg/g dry)
untreated			100	25.64	31.81	3.55	–	22.80	17.09	48.67
water treated	30	24	71.8	27.19	41.90	9.56	0	38.12	14.95	45.18
treated by 3% NaOH/1.5% H_2O_2 (w/v; v/v)	30	12	49.7	37.43	16.53	5.97	16.36	21.71	52.70	219.23
	30	24	49.0	37.08	15.88	4.71	35.09	17.17	58.91	243.4
	30	36	45.1	36.31	16.71	4.85	38.41	14.95	46.15	186.18
	25	24	51.0	36.33	17.72	6.17	11.43	12.18	55.37	223.53
	42	24	41.3	35.67	16.70	3.63	57.77	13.88	45.66	168.97

FUEL APPLICATIONS

Water hyacinth has been considered as a viable and renewable source for fuel applications. The plant has been studied as a potential source for bioethanol and biodiesel and has also been directly burned as fuel. It was suggested that production of ethanol from water hyacinth typically involves three steps (pretreatment, saccharification, and fermentation).[47] Economical production of xylanase was considered to be critical for obtaining bioethanol at affordable rates. Similarly, water hyacinth has been considered to be suitable for production of biohydrogen. Stems of hyacinth were hydrolyzed and used for hydrogen production. A maximum hydrogen production of 126.7 mmol H_2/L was obtained.[48] Water hyacinth has also been used to produce methane by thermal treatment of hyacinth using a microwave, hot air oven, autoclave, and hot water bath to improve solubilization.[49] Treating in a hot air oven provided the highest solubilization of 55% followed by a microwave, hot water bath, and autoclave. Methane production of 3039 mL/g of volatile solids was obtained after treating the hyacinth for 90 °C for 1 h compared to 2396 mL/g for untreated hyacinth.

Cellulosic ethanol is considered to be one of the most promising alternatives to fossil fuels. Various biomass sources have been studied as potential sources for bioethanol. The potential of using water hyacinth as a biomass for ethanol production has also been studied.[50,15] To prepare the ethanol, a typical process of acid hydrolysis and fermentation by yeast was done. Various amounts of the bioethanol from water hyacinth was combined with regular fuel, and the torque generated and other parameters were evaluated. Mixing up to 10% of bioethanol provided higher torque compared to similar blends of bioethanol produced using different sources of biomass. It was concluded that water hyacinth could be used as a renewable and inexpensive source for production of ethanol. Pretreatment of water hyacinth was done with sodium hydroxide and hydrogen peroxide to increase accessibility and higher sugar and ethanol yields.[51] For the pretreatment, hyacinth powder was heated with 1.5% v/v hydrogen peroxide and 3% v/v sodium hydroxide at varying temperatures and time (Table 3). Pretreated samples were subject to enzyme hydrolysis using 17.43 FP/ml of cellulase at 50 °C for 3 days. Hydrolyzed samples were analyzed for glucose conversion and further subject to fermentation for ethanol production. Fermentation into ethanol was done using a thermotolerant yeast isolated from winery orchards. Both simultaneous saccharification and fermentation (SSF) and separate hydrolysis and fermentation (SHF) were studied for their ability to convert the glucose into ethanol under various conditions. Ethanol yield of up to 45 g/L was obtained under optimum conditions. Ethanol produced at 0.21 g/g of biomass using the extracted yeast was considerably higher than that obtained using other sources of yeast. The SSF process produced a higher level of ethanol than the SHF process. Alkali-peroxide treatment of hyacinth and the new yeast system were found to be highly promising for production of cellulosic ethanol.[51] In another study, enzymatic hydrolysis was found to have a profound effect on the yield of total reducing sugars and hence bioethanol production. A total reducing sugar content of about 0.57 g/g was obtained using a cellulose concentration of 50 U/g, 280 U/g of xylanase, and 0.13% of surfactant.[52] Further fermentation of the sugars using *Pichia stipitis* yielded an ethanol concentration of 10.4 g/L.

To achieve optimum ethanol yield, hyacinth was pretreated using a combination of mild acid and biological treatment using white rot fungus *Echinodontium taxodii* or brown rot fungus *Antrodia sp.* 5898. The combined treatment was expected to degrade the outer surface and better expose the hemicellulose for hydrolysis into sugars.[53] The yield of the reducing sugars from the combined treatment was between 209 to 366 mg/g of dry matter compared to 113 to 322 mg/g for the unmodified hyacinth. Similarly, the ethanol yield was 0.192 g/g compared to 0.146 g/g for the untreated sample. It was suggested that a combined chemical and biological treatment would be more suitable for ethanol production from hyacinth.[53] Since water hyacinth contains a considerably large amount of water, it was suggested that hydrothermal liquefaction would be a better alternative than the conventional chemical and physical approaches of producing lignocellulosic ethanol.[5] Up to 23% conversion into bio-oil and two types of bio-oil could be produced from hyacinth, one that was rich in both aliphatic and aromatic content and the other which was rich in aliphatic content. On the basis of this study, it was suggested that the carbon and hydrogen in water hyacinth could be used for production of hydrocarbons.[5] Interestingly, it was found that the presence of Pb increased the yield of bio-oil from water hyacinth. About 56% higher oil yield was obtained from water hyacinth containing lead since the Pb^{2+} ions could stabilize the carboxyl and carbonyl groups which lead to the formation of more fatty acids. Most of the Pb remained in the char and did not contaminate the oil.[54]

Although hyacinth could be considered as an ideal source of biomass for cellulosic ethanol production, storage of the biomass and problems in degradation should be addressed. Since even the dry hyacinth or for that matter most biomass is composed of high levels of moisture, it would be dificult to store the biomass and prevent degradation. One solution to this problem was proposed

Table 4. Proximate Analysis and Calorific Value of Hyacinth and Fruit Bunch Fiber Composites[58]

composition ratio WH:EFB	moisture content (%)	volatile matter content (PVM) (%)	ash content (PAC) (%)	fixed carbon content (PFC) (%)	calorific value (MJ kg^{-1})
25:75	9.3 ± 0.03[a]	80.3 ± 1.02[a]	3.73 ± 0.54[a]	15.97	17.17 ± 0.05[a]
50:50	9.4 ± 0.04[a]	74.12 ± 0.15[a]	4.53 ± 0.27[a]	21.35	16.14 ± 0.01[a]
75:25	9.7 ± 0.03[a]	70.58 ± 0.91	6.23 ± 0.09[a]	23.19	15.83 ± 0.04
90:10	10.1 ± 0.03[a]	69.62 ± 0.42[a]	4.80 ± 0.21[a]	25.58	14.39 ± 0.06
100:0	9.9 ± 0.00	66.27 ± 0.1	6.90 ± 0.11	26.83	14.58 ± 0.05

[a] Significant difference: $p < 0.05$.

by Cheng et al. who treated hyacinth with calcium peroxide and proposed that the treatment would not only preserve the biomass but also help in removing the lignin and other substances that would be helpful for further hydrolysis.[55] A considerable decrease in lignin content and increase in yield of reducing sugars was observed due to the calcium hydroxide treatment. The concurrent pretreatment and storage (for 90 days) with 10% peroxide of water hyacinth having about 80% moisture content provided an ideal yield of sugars, suggesting this to be useful for large-scale application.[55]

Although several technologies and raw materials have been used for the production of cellulosic ethanol, current cellulosic ethanol production is not economically competitive compared to fossil fuels mainly due to the high cost of raw material and low conversion from cellulose to glucose. Due to the high rate of growth and availability of biomass, water hyacinth was considered as a potential source for production of biofuels. In this respect, production of xylanase from water hyacinth was studied.[47] It was suggested that water hyacinth contained relatively high levels of hemicellulose (49% of total soluble sugars) and was hence more suitable for ethanol production.[56] Dried powder prepared from water hyacinth was treated with 10 volumes of 2% v/v sulfuric acid for 7 h to hydrolyze the biomass. After hydrolysis, the liquid hydrolysate was filtered and used for fermentation. Up to 18.8 g of reducing sugars were obtained per 100 g of hyacinth used. These sugars were fermented using *Pichia stipites* to produce ethanol. Ethanol yield was 0.425 g_p/g_s, and productivity was 0.176 g_p/L/h. Water hyacinth was found to be more favorable for ethanol production than other biomasses.[56]

Leaves of hyacinth were reported to contain considerable amounts of oil, and efforts have been made to convert the oil into biodiesel. Up to 65% oil content with free fatty acid content of 45.3 mg KOH/g were also found in the hyacinth leaves. Some of the lipids in water hyacinth include 9-hexadecenoic acid, 12-15-octacecadienoic acid, hexadecanoic acid, and 9-octadecenoic acid. A high conversion rate of 87% oil to biodiesel could be achieved using novel gum Arabic-coated magnetic Fe_3O_4 nanoparticles.[1]

Instead of converting into ethanol or biodiesel, attempts have been to directly use hyacinth as a source for fuel.[57] Water hyacinth was cleaned, sorted, and made into briquettes by compression molding. The ability of the briquettes to be used as a source for fuel was determined by measuring the gross calorific value using a bomb calorimeter. Compared to other sources of biomass, water hyacinth had lower calorific value (14.6 MJ/kg) but comparable to that of coal (15−27 MJ/kg).[57] However, the hyacinth sample released lower amounts of sulfur, nitrogen, and chlorides, which was considered to be particularly suitable for fuel applications. A combination of water hyacinth and oil palm empty fruit bunch fibers were studied for potential use as briquettes for fuel production.[58] The two biomasses were combined using cassava starch as the binder. Increasing the percentage of hyacinth increased the ash and fixed carbon content. Calorific values ranged from 14 to 17 MJ/kg and decreased with increasing hyacinth content (Table 4). High calorific value and low carbon and toxic gas emissions were obtained when the ratio of hyacinth and fruit bunch fibers was 25:75.

Combining sewage water sludge and water hyacinth (10% to 40%) was considered to provide better combustion performance.[59] Some of the parameters obtained during the cocombustion in CO_2/O_2 atmosphere showed that inclusion of water hyacinth increased the combustibility up to 2 times. Activation energy, ignition temperature, and combustion performance were dependent on the ratio of CO_2/O_2 and the hyacinth/sludge.[59]

Instead of direct burning of the biomass, hyacinth was treated with various ionic liquids to make them more suitable for production of biogas. Hyacinth was solubilized by treating with the ionic liquids and a cosolvent and heated from 20 to 140 °C for up to 240 min. The precipitate obtained after treatment was collected and used for production of biogas. Anaerobic batch digestions were carried out to produce biogas.[60] Treating with ionic liquids resulted in considerable changes to the composition of the hyacinth and the level (%) of degradation. Biogas and methane yield also varied depending on the level of treatment. Combination of 1-butyl-3-methylimidazolium chloride/dimethyl sulfoxide (Bmim]Cl/DMSO) provided the highest methane yield. Most of the ionic liquids used could be recovered resulting in a green process for the production of biogas, particularly methane.[60] However, the high cost of ionic liquids and relatively harsh conditions necessary for production of the biogas would make commercial application economically prohibitive.

■ REINFORCEMENT FOR COMPOSITES

Agricultural residues such as straws, stalks, and husks and even biomass such as switchgrass have been extensively studied as reinforcement for composites. Water hyacinth has been processed into various forms and used as reinforcement. In one such attempt, hyacinth was collected, cleaned, dried, and powdered into particles with an average size of 63 μm. The powdered hyacinth was treated with sodium hydroxide at room temperature for 2 h then washed, neutralized, and dried.[61] After treatment, the particles were compounded with low density polyethylene and natural rubber. Extrudates obtained were compression molded at 160 °C into sheets suitable for tensile testing. The ratio of hyacinth in the composites varied from 5% to 25%. Increasing the amount of fibers in the composites marginally increased the strength. Similarly, treating with NaOH provided better strength compared to using untreated hyacinth due to better interactions between fibers and matrix. Modulus of the composites showed a very high increase after treating with alkali. Further, treating with alkali also showed an increase in thermal stability. X-ray diffraction studies showed a decrease in interparticle spacing and amount of crystalline phase after treating with alkali which provided better interfacial adhesion and hence improved properties.[61] Although hyacinth-containing materials may provide enhanced tensile and flexural properties, the hydrophilicity of cellulosic substances makes the composites susceptible to moisture. It was observed that hyacinth-containing unsaturated polyester composites had lower tensile and flexural properties after immersion in water compared to before immersion. Composites containing higher amounts of hyacinth had a larger decrease in properties suggesting that the fibers were responsible for the decrease.[62]

One of the most common approaches to improve the water resistance of biocomposites is to blend with synthetic polymers, use compatibilizers, or chemically modify the reinforcing biofibers. Water hyacinth fibers were used as reinforcement for high density polyethylene with polyethylene-grafted maleic anhydride as the compatibilizer.[63] Although the compatibilizer did not provide noticeable improvement in tensile properties, considerable improvement in resistance to water was observed. Enhanced interfacial adhesion and a decrease in the amount of hydrophilic sites were suggested to be the reasons for the higher resistance to water after using the compatibilizer.[63]

Stems of water hyacinth were cut into 3 cm long pieces and later powdered in a wiley mill to pass through a 40 mesh screen. The powdered hyacinth was blended with polyester resin in four different weight ratios to form the composites by pouring into predesigned molds.[64] Inclusion of the water hyacinth decreased the modulus of rupture, modulus of elasticity, and compression strength. It was suggested that the hyacinth and polyester resin had poor compatibility due to the differences in their hydrophilicity. Also, powdering the hyacinth results in fibrous materials with small aspect ratios and hence inferior properties.[64] To improve compatibility between hyacinth and polyester, various pretreatments have been considered. Stems of water hyacinth were powdered and treated with water. Fibers formed were washed and collected for further treatment with alkali. For the alkali treatment, fibers were immersed in solution containing 2%, 5%, 7%, and 10% of alkali for 1 h. The treatment resulted in an increase in cellulose and decrease in lignin content. A considerable decrease in fiber diameter from 89.9 μm to about 40 μm was observed after treating with 10% alkali.[65] Treated and untreated fibers were used as reinforcement for unsaturated polyester composites.[65] Tensile strength and modulus of the composites generally increased with increasing treatment with alkali, which was suggested to be due to the strengthening of the fibers and increase in contact area due to fibrillation after treatment. Unlike the tensile properties, flexural strength and modulus decreased for the composites containing fibers treated with 10% alkali compared to those treated with 7% alkali. Morphological analysis showed good interaction between the fibers and matrix, particularly after treatment.

Poly(methyl methacrylate) (PMMA) was used to modify fibers (64 μm) obtained by grinding water hyacinth stems. These modified fibers were combined with low density polyethylene (LDPE) and natural rubber in various ratios and injection molded to form pellets. The pellets were later compression molded to form the composites.[66] Increasing concentration of the fibers in the composites increased the tensile strength up to 20% due to strengthening of the composite. Modified fibers showed higher tensile properties at all the concentrations studied. Higher tensile properties of the modified fiber composites were due to the better interaction and interfacial adhesion between fibers and matrix. Morphological analysis showed no fiber pull out, indicating better binding in the modified fiber composites, whereas considerable fiber pull outs were observed when the fibers were not modified.[66] Similar to using PMMA, water hyacinth fibers were also treated with poly(vinyl alcohol) (PVA). In this approach, fibers were immersed in a solution of PVA and later dried and combined with natural rubber and low density polyethylene to form pellets which were compression molded into the required shape.[67] Similar to the results with PMMA-modified hyacinth, treating with PVA increased mechanical properties. Better adhesion and no fiber pull outs were observed in the composites containing the modified fibers.

Cellulose was extracted from the water hyacinth and combined with a chitosan solution to form a biocomposite along with TiO_2 nanoparticles. The nanoparticles were supposed to act as chelating agents and form a network that increases the hydrophilicity and polydispersity. Efficiency of the biocomposite to remove reactive dyes from textile wastewater was studied.[68] Surface area of the biocomposite was considerably higher at 173 m^2/g compared to 133 m^2/g for the untreated samples. Similarly, micropore volume had increased from 0.0774 to 0.0913 cm^3/g. Considerably higher dye (up to 95%) could be absorbed at low pHs (2−3) due to the presence of protonated amine active sites that could lead to higher interaction between them and the sulfonate groups in the dye. Absorption of the dye onto the biocomposite was closer to the Langmuir isotherm with a monolayer adsorption capacity of 0.606 mg/g.[68,12] Although high dye removal was achieved, the ability of the biocomposite to desorb the dye was not studied. In addition, extensive modification using nanoparticles could make the absorbent expensive and also reduce the biodegradability.

■ SUPERCAPACITORS

Carbon microspheres for supercapacitor applications were developed from sugars obtained after hydrolyzing water hyacinth.[69,12] A unique approach of using supercritical water for carbonization was followed in this study. For the carbonization, hyacinth powder was placed in a bioreactor and sulfuric acid was added, maintaining a pressure of 20 bar. A temperature of 130 °C was used for 2 h to complete the hydrolysis process, and the hydrolysates formed were carbonized using subcritical water at temperatures ranging from 160 to 200 °C and times from 6 to 10 h under an inert atmosphere. Such treatment resulted in the formation of a solid carbon useful for supercapacitor applications. The solid carbon obtained was further activated using KOH and formed into a slurry along with 10% polytetrafluoroethylene (PTFE) and 10% carbon black. The slurry was applied onto electrodes to act as supercapacitors.[69] Up to 10% of carbon was obtained from the hyacinth with diameter of the carbon being 2−4 μm. Morphological analysis revealed that the carbon had a surface area of 852 m^2/g after treating with KOH. After being subjected to 1000 loading and unloading cycles, the performance of the activated carbon supercapacitors decreased but was considerably higher compared to the unmodified carbon. Its high electrochemical stability, ready availability, and inexpensive nature were considered as positive attributes for using water hyacinth as a source for supercapacitors.[69]

■ OTHER APPLICATIONS

Cellulose extracted from water hyacinth stems was found to be suitable as the reducing and stabilizing agent for fabrication of silver nanoparticles.[70] To obtain the cellulose, cleaned hyacinth was treated twice with 5% sodium hydroxide and 11% hydrogen peroxide at 60 °C for 1 h. This cellulose was homogenized in distilled water, and the pH was adjusted to 4, 8, or 11. Silver nitrate solution was added into the cellulose solution, and the formation of nanoparticles was measured and characterized. Instant formation of particles was observed at pH 11, whereas it took up to 6 h to form nanoparticles in acidic medium. Also, the size of the nanoparticles obtained in the alkaline medium (2.7 nm) was much smaller than those in the acidic medium (5.7 nm). X-ray diffraction and transmission electron microscopy showed that the nanoparticles obtained were spherical and highly crystalline. It was suggested that using cellulose from water hyacinth could be the most economical approach to produce silver nanoparticles.[70]

In a unique application, water hyacinth stems were used to sorb essential oil (bergamot oil) and later treated with ultraviolet light. The treated material was used as an inhibitor against mold (*A. flavus*) and increase the storage life of brown rice.[71] Cleaned water hyacinth stems were immersed in an oil solution for sorption to occur. The sorbed stems were exposed to UV rays at a wavelength of 253.7 nm for 10 to 20 min and made into 20 mm diameter discs. Brown rice was inoculated with *A. flavus*, and later, the water hyacinth pellets were placed in the inoculated petridish. Considerable reduction in spore germination could be observed, particularly for the stems treated with UV rays. Fungal activity of the hyacinth was found to be dependent on the temperature of exposure and the extent of UV irradiation. Water hyacinth acts as an absorbent for the oil with prolonged release rates. It was concluded that bergamot oil-treated water hyacinth could be used to protect rice from mold growth.[71]

Peat used for growing tomato seedlings and cabbage was substituted with compost made from water hyacinth.[72] Addition of the water hyacinth compost to tomato plants decreased the stem diameter, plant height, and biomass, whereas there was no significant effect on the addition of water hyacinth on the growth of cabbage.[72] It was suggested that up to 50% hyacinth could be used in the peat with pig manure as a substitute for synthetic polymer-based peat.

When water hyacinth treated by various means were fed into prawns, significant increase in immune response and disease resistance was observed.[73] Crude protein content of up to 12.4%, presence of essential amino acids such as lysine and methionine, and fat of 4.7% in water hyacinth were considered to be preferable for animal feed. The survival rate of prawns fed with the hyacinth was up to 77.7% higher than the control after 4 months. In addition, several nonimmuno-specific responses such as total hemocyte count, different hemocyte count, phenoloxidase activity, etc. had shown considerable increases. A simple method of treating hyacinth and their ability to provide better immune resistance and survival were reported to be ideal for use as prawn feed.[73] Cellulose purified from water hyacinth could be made into membranes and used for water purification.[74] Concentration of cellulose and evaporation time played a critical role on the membrane properties, and higher cellulose concentration resulted in denser and smaller pores.

A material called as liquid tar was prepared by condensing the vapors and liquids generated after pyrolysis of water hyacinth at various temperatures.[75] Further, the liquid tar could be formed into a resin by polymerizing using formaldehyde in the presence of acid catalysts. The resin was also converted into carbon fibers by carbonization at 900 °C with a conversion rate of about 29%. Properties of the carbon fiber obtained (strength of 600 MPa and modulus of 42 GPa) were similar to that of commercially available carbon fibers.[75,12]

CONCLUSIONS

The need for sustainable materials and products is gaining significance across the globe. Increasing population, decreasing availability of natural resources, and health concerns due to use and disposal of synthetic polymer-based products makes it necessary to find renewable, sustainable, and inexpensive materials. Although large quantities of renewable biomass is available, it is difficult to process and develop products from the biomass, particularly lignocellulosic agricultural residues. Most biomasses are nonthermoplastic, do not dissolve easily, and also are a combination of cellulose, hemicellulose, and lignin making them difficult to be processed. Water hyacinth is a unique biomass, and its components have been used to study and develop a multitude of products. Their rapid growth, potentially low cost, and renewable nature make hyacinth very attractive as a raw material for various sources. Although feasibility of using hyacinth for various applications has been demonstrated, most studies have been done as an academic interest, and no hyacinth-based products or technologies are currently available on the market. Until now, water hyacinth has been mainly studied as a source of fuel, sorbent for metals and dyes, composites, and others. It is necessary to have a new perspective toward water hyacinth as a resource than a weed. Better understanding of the composition, studies on processability, and more importantly, new avenues for application have to be studied. Among the various biomasses currently available, water hyacinth seems to be the most promising source for renewable, sustainable, and inexpensive bioproducts.

AUTHOR INFORMATION

Corresponding Author

*Phone: +919611233707. E-mail: narendra.r@ciirc.jyothyit.ac.in.

ORCID

Narendra Reddy: 0000-0002-8053-4867

Notes

The authors declare no competing financial interest.

Biographies

Vijaykumar Guna received his B.E in mechanical engineering from VTU, Belgaum, and MTech in Energy Engineering from Jain University−Bengaluru in the years 2012 and 2015, respectively. He is currently pursuing his Ph.D. from VTU, Belgaum. He is a CSIR-sponsored Senior Research Fellow working in the Centre for Incubation, Innovation, Research and Consultancy since 2016. Prior to this, he was a Research Fellow in the Centre for Emerging Technologies, Jain University, for two years. He also has to his account a two year industrial experience. His research interests include developing green and ecofriendly composites, industrial automation, and thermal management.

Manikandan Ilangovan obtained his bachelor's degree in mechanical engineering from Jain University, Bangalore, in 2016. Soon after his graduation, he joined the Centre for Incubation, Innovation, Research and Consultancy as a Research Fellow. He is currently working on fabrication and characterization of composites, especially biodegradable composites developed from agricultural residues and byproducts. His other research interests include biomimetic materials, extraction of fibers from nontraditional sources for different applications, utilizing biomass for heavy metal and dye adsorption, etc.

Dr. M. G. Anantha Prasad graduated with a Ph.D in Mechanical Engineering with a specialization in Product Design and Advanced Materials from Visvesvaraya Technological University, Belgaum. He has published more than 48 papers in international/national journals and conferences and also has a patent. He was a recipient of the prestigious Commonwealth Professional Fellowship (2015) to undergo specialized training at Loughborough University, U.K. In addition to his regular responsibilities, he has served as a key member of BOS, BOE, and Academic Councils of several technical institutions. He has facilitated and chaired many faculty development programs and has played a pivotal role in identifying key personnel as chief guest, guest of honor, and keynote speakers. He has also served as the convener of many national and international workshops and conferences on various topics and has the credit of presenting papers in similar events organized by other institutions.

Dr. Narendra Reddy's work is mainly related to developing green and sustainable products using agricultural residues and other biomass. He obtained his bachelor and Master degree from Bangalore University and later his Ph.D. from the University of Nebraska-Lincoln. He is currently a recipient of the prestigious Ramalingaswami Felllowship from the Department of Biotechnology, Government of India. He has published more than 100 research papers, two books, and several book chapters. His current focus is to convert agricultural residues into value-added bioproducts for practical applications.

■ ACKNOWLEDGMENTS

The authors thank CIIRC, Bengaluru, Sri Sringeri Sharadha Peetam − Sringeri, and Jyothy Institute of Technology for their financial support. Dr. Narendra Reddy is thankful to the Department of Biotechnology, Ministry of Science and Technology, Government of India, for funding through the Ramalingaswami reentry fellowship.

■ LIST OF ABBREVIATIONS

AA: antioxidant activity
AAE: ascorbic acid equivalents
BCF: bioconcentration factors
(Bmim]Cl): 1-butyl-3-methylimidazolium chloride
DMSO: dimethyl sulfoxide
EDX: energy-dispersive X-ray spectroscopy
EFB: empty fruit bunch fibers
FTIR: Fourier transform infrared spectroscopy
IC50: required extract concentration for 50% reduction or inhibition
LDPE: low density polyethylene
PAC: ash content
PFC: fixed carbon content
PMMA: poly(methyl methacrylate)
PTFE: polytetrafluoroethylene
PVA: poly(vinyl) alcohol
PVM: volatile matter content
SDS: sodium dodecyl sulfate
SEM: scanning electron microscopy
SFE: supercritical fluid extraction
SHF: separate hydrolysis and fermentation
SLE: soxhlet with dichloromethane
SSF: simultaneous saccharification and fermentation
TPC: total phenolic content
UV: ultraviolet
WH: water hyacinth
XPS: X-ray photoelectron spectroscopy

DOI: 10.1021/acssuschemeng.7b00051

REFERENCES

(1) Sai, R. S.; Gangadhar, V. R.; Vijayalakshimu, S.; Ranjitha, J. A novel gum Arabic coated magnetic Fe3O4 nanoparticle catalyzed transesterification of Eichhornia Crassipes oils for the production of biodiesel. *Int. J. Pharm. Sci. Rev. Res.* **2015**, *32* (2), 82−84.

(2) Khatun, S.; Sutradhar, K. B. Water hyacinth: a possible alternative rate retarding natural polymer used in sustained release tablet design. *Front. Pharmacol.* **2014**, *5*, 1−8.

(3) Kunatsa, T.; Madiye, L.; Chikuku, T.; Musademba, D. Feasibility study of biogasproduction from water hyacinth a case of lake Chivero − Harare, Zimbabwe. *Int. J. Eng. Technol.* **2013**, 3 (2), 119−128.

(4) Guerena, D.; Neufeldt, H.; Berazneva, J.; Duby, S. Water hyacinth control in Lake Victoria: Transforming an ecological catastrophe into economic, social and environmental benefits. *Sust. Prod. Consumpt.* **2015**, *3*, 59−69.

(5) Singh, R.; Balagurumurthy, B.; Prakash, A.; Bhaskar, T. Catalytic hydrothermal liquefaction of water hyacinth. *Bioresour. Technol.* **2015**, *178*, 157−165.

(6) Fawad, M.; Khan, H.; Gul, B.; Khan, A.; Marwat, K. B. Comparative effect of herbicidal and non-chemical control methods against water hyacinth. *Pak. J. Weed Sci. Res.* **2015**, *21* (4), 593−605.

(7) Zheng, L.; Wu, R.; Guo, W.; You, W.; Ling, Y.; Fan, X. Design, synthesis and herbicidal activities of novel self-dispreading phenoxy carboxylic acid derivatives for the control of water hyacinth floating on the water surface. *Chin. Chem. Lett.* **2015**, *26*, 1008−1010.

(8) Nesslage, G. M.; Wainger, L. A.; Harms, N. E.; Cofrancesco, A. F. Quantifying the population response of invasive water hyacinth, *Eichhornia crassipes,* to biological control and winter weather in Louisana, USA. *Biol. Invasions* **2016**, *18*, 2107−2115.

(9) Tipping, P. W.; Martin, M. R.; Pokorny, E. N.; Nimmo, K. R.; Fitzgerald, D. L.; Dray, F. A.; Center, T. D. Current levels of suppression of water hyacinth in Florida USA by classical biological control agents. *Biol. Control* **2014**, *71*, 65−69.

(10) Fraser, G. C. G.; Hill, M. P.; Martin, J. A. Economic evaluation of water loss saving due to the ecological control of water hyacinth at New Year's Dam, Eastern Cape Province, South Africa. *Afr. J. Aquat. Sci.* **2016**, *41* (2), 227−234.

(11) Guerena, D.; Neufeldt, H.; Berazneva, J.; Duby, S. Water hyacinth control in Lake Victoria: Transforming an ecological catastrophe into economic, social and environmental benefits. *Sust. Prod. Consumpt.* **2015**, *3*, 59−69.

(12) Sindhu, R.; Binod, P.; Pandey, A.; Madhavan, A.; Alphonsa, J. A.; Vivek, N.; Gnansounou, E.; Castro, E.; Faraco, V. Water hyacinth a potential source for value addition: An overview. *Bioresour. Technol.* **2017**, *230*, 152−162.

(13) Sundari, M. T.; Ramesh, A. Isolation and characterization of cellulose nanofibers from the aquatic weed water hyacinth-Eichhornia crassipes. *Carbohydr. Polym.* **2012**, *87*, 1701−1705.

(14) Fileto-Perez, H. A.; Rutiaga-Quinones, O. M.; Sytsma, M. D.; Lorne, I. M.; Luo, W.; Pankow, J. F.; Rutiaga-Quinones, J. G. GC/MS analysis of some extractives from Eichhornia crassipes. *BioResources* **2015**, *10* (4), 7353−7360.

(15) Rezania, S.; Ponraj, M.; Din, M. F.; Songip, A. R.; Sairan, F.; Chelliapan, S. The diverse applications of water hyacinth with main focus on sustainable energy and production for new ear: An overview. *Renewable Sustainable Energy Rev.* **2015**, *41*, 943−954.

(16) Silva, R. P.; de Melo, M. M. R.; Silvestre, A. J. D.; Silva, C. M. Polar and lipophilic extracts characterization of roots, stalks, leaves and flowers of water hyacinth (Eichhornia crassipes) and insights for its future valorization. *Ind. Crops Prod.* **2015**, *76*, 1033−1038.

(17) Martins, P. F.; de Melo, M. M. R.; Sarmento, P.; Silva, C. M. Supercritical fluid extraction of sterols from Eichhornia crassipes biomass using pure and modified carbon dioxide. Enhancement of stigmasterol yield and extract concentration. *J. Supercrit. Fluids* **2016**, *107*, 441−449.

(18) del Melo, M. M. R.; Silva, R. P.; Silvestre, A. J. D.; Silva, C. M. Valorization of water hyacinth through supercritical CO2 extraction of stigmasterol. *Ind. Crops Prod.* **2016**, *80*, 177−185.

(19) Mohanty, K.; Jha, M.; Meikap, B. C.; Biswas, M. N. Biosorption of Cr (VI) from aqueous solutions by Eichhornia crassipes. *Chem. Eng. J.* **2006**, *117* (1), 71−77.

(20) Li, Q.; Chen, B.; Lin, P.; Zhou, J.; Zhan, J.; Shen, Q.; Pan, X. Adsorption of heavy metal from aqueous solution by dehydrated root powder of long-root Eichhornia Crassipes. *Int. J. Phytorem.* **2016**, *18* (2), 103−109.

(21) Low, K. S.; Lee, C. K.; Tan, K. K. Biosorption of basic dyes by water hyacinth roots. *Bioresour. Technol.* **1995**, *52*, 79−83.

(22) Sarkar, M.; Rahman, A. K. M. L.; Bhoumik, N. C. Remediation of chromium and copper on water hyacinth (E. crassipes) shoot powder, Water Res. *Technol.* **2017**, *17*, 1−6.

(23) Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Huang, X.; Zeng, G.; Zhou, Y.; Zheng, B.; Cai, X. Competitive removal of Cd(ii) and Pb(ii) by biochars produced from water hyacinths: performance and mechanism. *RSC Adv.* **2016**, *6*, 5223−5232.

(24) Zhang, F.; Wang, X.; Yin, D.; Peng, Bo.; Tan, C.; Liu, Y.; Tan, X.; Wu, S. Efficiency and mechanisms of Cd removal from aqueous solution by biochar derived from water hyacinth (Eichornia crassipes). *J. Environ. Manage.* **2015**, *153*, 68−73.

(25) Doumer, M. E.; Rigol, A.; Vidal, M.; Mangrich, A. S. Removal of Cd, Cu, Pb and Zn from aqueous solutions by biochars. *Environ. Sci. Pollut. Res.* **2016**, *23*, 2684−2692.

(26) Zhang, F.; Wang, X.; Xionghui, J.; Ma, L. Efficient arsenate removal by magnetite modified water hyacinth biochar. *Environ. Pollut.* **2016**, *216*, 575−583.

(27) Sadeek, S. A.; Negm, N. A.; Hefni, H. H. H.; Wahab, M. M. A. Metal adsorption by agricultural biosorbents:Adsorption isotherm, kinetic and biosorbents chemical structures. *Int. J. Biol. Macromol.* **2015**, *81*, 400−409.

(28) Zheng, J. C.; Liu, H. Q.; Feng, H. M.; Li, W. W.; Lam, M. H. W.; Lam, P. K. S.; Yu, H. Q. Competitive sorption of heavy metals by water hyacinth roots. *Environ. Pollut.* **2016**, *219*, 837.

(29) Hasan, S. H.; Talat, M.; Rai, S. Sorption of cadmium and zinc from aqueous solutions by water hyacinth (Eichchornia crassipes). *Bioresour. Technol.* **2007**, *98*, 918−928.

(30) Gupta, A.; Balomajumder, C. Removal of Cr(VI) and phenol using water hyacinth from single and binary solution in the artificial photosynthesis chamber. *J. Water Proc. Engg.* **2015**, *7*, 74−82.

(31) Zheng, J.; Feng, H.; Lam, M.; Lam, P.; Ding, Y.; Yu, H. Removal of Cu(II) in aqueous media by biosorption using water hyacinth roots as a biosorbent material. *J. Hazard. Mater.* **2009**, *171*, 780−785.

(32) Yi, Z.; Yao, J.; Chen, H.; Wang, F.; Yuan, Z.; Liu, X. Uranium biosorption from aqueous solution onto Eichhornia crassipes. *J. Environ. Radioact.* **2016**, *154*, 43−51.

(33) Romanova, T. E.; Shuvaeva, O. V.; Belchenko, L. A. Phytoextraction of trace elements by water hyacinth in contaminated area of gold mine tailing. *Int. J. Phytorem.* **2016**, *18* (2), 190−194.

(34) Li, X.; Zhou, Y.; Yang, Y.; Yang, S.; Sun, X.; Yang, Y. Physiological and proteomics analyses reveal the mechanism of Eichhornia crassipes tolerance to high-concentration cadmium stress compared with Pistia stratiotes. *PLoS One* **2015**, *10*, 1−22.

(35) El-Khaiary, M. I. Kinetics and mechanism of adsorption of methylene blue from aqueous solution by nitric acid treated water hyacinth. *J. Hazard. Mater.* **2007**, *147*, 28−36.

(36) Guerrero-Coronilla, I.; Morales-Barrera, L.; Cristiani-Urbina, E. Kinetic, isotherm and thermodynamic studies of amaranth dye biosorpton from aqueous solution onto water hyacinth leaves. *J. Environ. Manage.* **2015**, *152*, 99−108.

(37) Mahamadi, C.; Mawere, E. High adsorption of dyes by water hyacinth fixed in alginate. *Environ. Chem. Lett.* **2014**, *12*, 313−320.

(38) Mahamadi, C.; Zambara, P. High Cu removal from water using water hyacinth fixed on alginate. *Environ. Chem. Lett.* **2013**, *11*, 377−383.

(39) Roy, T. K.; Mondal, N. K. Biosorption of Congo Red from aqueous solution onto burned root of Eichhornia crassipes biomass. *Appl. Water Sci.* **2015**, 1−14.

DOI: 10.1021/acssuschemeng.7b00051

(40) Rani, S.; Sumanjit, K.; Mahajan, R. K. Comparative study of surface modified carbonized Eichhornia crassipes for adsorption of dye safranin. *Sep. Sci. Technol.* **2015**, *50*, 2436−2477.

(41) Cai, R.; Wang, X.; Ji, X.; Peng, B.; Tan, C.; Huang, X. Phosphate reclaim from simulated and real eutrophic water by magnetic biochar derived from water hyacinth. *J. Environ. Manage.* **2017**, *187*, 212−219.

(42) Banu, S. U. N.; Maheswaran, G. Synthesis and characterization of nanocrystalline embedded activated carbon from Eichornia crassipes and its use in the removal of Malachite green. *Water Qual. Res. J. Can.* **2015**, *8* (5), 158−169.

(43) Kaur, S.; Rani, S.; Mahajan, R. K. Adsorption of dye crystal violet onto surface modified Eichhornia crassipes. *Desalin. Water Treat.* **2015**, *53*, 1957−1969.

(44) Bedekar, P. A.; Kshirsagar, S. D.; Gholave, A. R.; Govindwar, S. P. Degradation and detoxification of methylene blue dye absorbed on water hyacinth in semi continuous anaerobic-aerobic bioreactors by novel microbial consortium-SB. *RSC Adv.* **2015**, *5*, 99228−99236.

(45) Djaenudin; Wulan, D. R.; Hariyadi, H. R. Effect of electrodeposition reactor type on nickel recovery from electroplating wastewater. *Procedia Chem.* **2015**, *16*, 155−163.

(46) Raja, M. W.; Islam, Q. A.; Basu, R. N. Oxygen separation membrane derived from aquatic weed: A novel bioinspired approach to synthesize BaBi0.2Co0.35Fe0.45O3−6 perovskite from water hyacinth (Eichhornia crassipes). *J. Membr. Sci.* **2017**, *522*, 168−174.

(47) Uday, U. S. P.; Choudhury, P.; Bandyopadhyay, T. K.; Bhunia, B. Classification, mode of action and production of xylanase and its application from biofuel production from water hyacinth. *Int. J. Biol. Macromol.* **2016**, *82*, 1041−1054.

(48) Pattra, S.; Sittijunda, S. Optimization of factors affecting acid hydrolysis of water hyacinth stem (Eichhornia crassipes) for biohydrogen production. *Energy Procedia* **2015**, *79*, 833−837.

(49) Barua, V. B.; Kalamdhad, A. S. Effect of various types of thermal pretreatment techniques on the hydrolysis, compositional analysis and characterization of water hyacinth. *Bioresour. Technol.* **2017**, *227*, 147−154.

(50) Choudhary, A. K.; Chelladurai, H.; Kannan, C. Optimization of combustion performance of bioethanol (water hyacinth) diesel blends on diesel engine using response surface methodology. *Arab J. Sci. Eng.* **2015**, *40*, 3675−3695.

(51) Yan, J.; Wei, Z.; Wang, Q.; He, M.; Li, S.; Irbis, C. Bioethanol production from sodium hydroxide/hydrogen peroxide pretreated water hyacinth via simultaneous saccharification and fermentation with a newly isolated thermotolerant Kluyveromyces marxianu strain. *Bioresour. Technol.* **2015**, *193*, 103−109.

(52) Das, S.; Bhattacharya, A.; Haldar, S.; Ganguly, A.; Gu, S.; Ting, Y. P.; Chatterjee, P. K. Optimization of enzymatic saccharification of water hyacinth biomass for bio-ethanol: Comparison between artificial neural network and response surface methodology. *Sust. Mater. Technol.* **2015**, *3*, 17−28.

(53) Ma, F.; Yang, N.; Xu, C.; Yu, H.; Wu, J.; Zhang, X. Combination of biological pretreatment with mild acid pretreatment for enzymatic hydrolysis and ethanol production from water hyacinth. *Bioresour. Technol.* **2010**, *101*, 9600−9604.

(54) Jiu, B.; Li, B.; Yu, Q. Effects of Pb on pyrolysis behaviour of water hyacinth. *J. Anal. Appl. Pyrolysis* **2015**, *112*, 270−275.

(55) Cheng, Y.; Chen, K.; Chou, T. Concurrent calcium peroxide pretreatment and wet storage of water hyacinth for fermentable sugar production. *Bioresour. Technol.* **2015**, *176*, 267−272.

(56) Kumar, A.; Singh, L. K.; Ghosh, S. Bioconversion of lignocellulosic fraction of water hyacinth (Eicchornia crossipes) hemicellulose acid hydrolysate to ethanol by Pichia stipites. *Bioresour. Technol.* **2009**, *100*, 3293−3297.

(57) Munjeri, K.; Ziuku, S.; Maganga, H.; Siachingoma, R.; Ndlovu, S. On the potential of water hyacinth as a biomass briquette for heating applications. *Int. J. Energy Environ. Eng.* **2016**, *7*, 37−43.

(58) Rezania, S.; Md Din, M. F.; Kamaruddin, S. F.; Taib, S. M.; Singh, L.; Yong, E. L.; Dahalan, F. A. Evalution of water hyacinth (Eichhornia crassipes) as a potential raw material source for briquette production. *Energy* **2016**, *111*, 768−773.

(59) Huang, L.; Liu, J.; He, Y.; Sun, S.; Chen, J.; Sun, J.; Chang, K.; Kuo, J.; Ning, X. Thermodynamics and kinetics parameters of co-combustion between sewage sludge and water hyacinth in CO2/O2 atm as biomass to solid biofuel. *Bioresour. Technol.* **2016**, *218*, 631−642.

(60) Gao, J.; Chen, L.; Yan, Z.; Wang, L. Effect of ionic liquid pretreatment on the composition, structure and biogas production of water hyacinth (Eichhornia cassipes). *Bioresour. Technol.* **2013**, *132*, 361−364.

(61) Tan, S. J.; Supri, A. G. Properties of low density polyethylene/natural rubber/water hyacinth fiber composites: the effect of a2016, alkaline treatment. *Polym. Bull.* **2016**, *73*, 539−557.

(62) Abral, H.; Kadriadi, D.; Rodianus, A.; Mastariyanto, P.; Arief, I. S.; Sapuan, S. M.; Ishak, M. R.; Ilhamdi. Mechanical properties of water hyacinth fibers-polyester composites before and after immersion in water. *Mater. Eng.* **2014**, *58*, 125−129.

(63) Tan, S. J.; Supri, A. G.; Chong, K. M. Properties of recycled high density polyethylene/water hyacinth fiber composites: Effect of different concentration of compatibilizer. *Polym. Bull.* **2015**, *72*, 2019−2031.

(64) Ramirez, N. F.; Hernandez, Y. S.; Leon, J. C.; Garcia, S. R. V.; Lvova, L. D.; Gonzalez, L. G. Composites from water hyacinth (Eichhornea Crassipe) and polyester resin. *Fibers Polym.* **2015**, *16* (1), 196−200.

(65) Abral, H.; Putra, H.; Sapuan, S. M.; Ishak, M. R. Effect of alkalization on mechanical properties of water hyacinth fibers-unsaturated polyester composites. *Polym.-Plast. Technol. Eng.* **2013**, *52*, 446−451.

(66) Supri, A. G.; Tan, S. J.; Ismail, H.; Teh, P. L. Effect of poly(methyl methacrylate) modified water hyacinth fiber on properties of low density polyethylene/natural rubber/water hyacinth fiber composites. *Polym.-Plast. Technol. Eng.* **2011**, *50*, 898−906.

(67) Supri, A. G.; Tan, S. J.; Ismail, H.; Teh, P. L. Enhancing interfacial adhesion performance by using poly(vinyl alcohol) in (low density polyethylene)/(natural rubber)/(water hyacinth fiber) composites. *J. Vinyl Addit. Technol.* **2013**, *19*, 47−54.

(68) El-Zawahry, M.; Abdelghaffar, F.; Abdelghaffar, R. A.; Hassabo, A. G. Equilibrium and kinetic models on the adsorption of reactive black 5 from aqueous solution using Eichhornia crassipes/chitosan composite. *Carbohydr. Polym.* **2016**, *136*, 507−515.

(69) Kurniawan, F.; Wongso, M.; Ayucitra, A.; Soetaredjo, F. E.; Angkawijaya, A. E.; Ju, Y.; Ismadji, S. Carbon microsphere from water hyacinth for supercapacitor electrode. *J. Taiwan Inst. Chem. Eng.* **2015**, *47*, 197−201.

(70) Mochochoko, T.; Oluwafemi, O. S.; Jumbam, D. N.; Songca, S. P. Green synthesis of silver nanoparticles using cellulose extracted from an aquatic weed-water hyacinth. *Carbohydr. Polym.* **2013**, *98*, 290−294.

(71) Songsamoe, S.; Matan, N.; Matan, N. Effect of UV-C radiation and vapor released from a water hyacinth root absorbent containing bergamot oil to control mold on storage of brown rice. *J. Food Sci. Technol.* **2016**, *53*, 1445−1453.

(72) Fan, R.; Luo, J.; Yan, S.; Wang, T.; Liu, L.; Gao, Y.; Zhang, Z. Use of water hyacinth (Eichhornia crassipes) compost as a peat substitute in soilless growth media. *Compost Sci. Util.* **2015**, *23* (4), 237−247.

(73) Chang, C.; Cheng, W. Multiple dietary administrating strategies of water hyacinth (Eichhornia crassipes) on enhancing the immune response and disease resistance of giant freshwater prawn, Macrobrachium rosenbergii. *Aquacult. Res.* **2016**, *47*, 140−152.

(74) Istirokhatun, T.; Rokhati, N.; Rachmawaty, R.; Meriyani, M.; Priyanto, S.; Susanto, H. Cellulose isolation from tropical water hyacinth for membrane preparation. *Procedia Environ. Sci.* **2015**, *23*, 274−281.

(75) Soenjaya, S. A.; Handoyo, N.; Soetaredjo, F. E.; Angkawijaya, A. E.; Ju, Y.; Ismadji, S. Preparation of carbon fiber from water hyacinth liquid tar. *Int. J. Ind. Chem.* **2015**, *6*, 1−7.