Eichhornia Crassipes Transformation from Problems to Wide Unique Source of Sustainable Materials in Engineering Application

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Abstract. Eichhornia crassipes (EC) is an aquatic plant with a massive growth rate. The massive growth nature made it a threat because of its negative effect to the aquatic organisms, economic activities and others. However, with the help of researchers and technology, the negative effect would be turned into economic potential, whereby the EC was being transformed from a problematic concept to huge benefit towards sustainability of mankind. The EC was observed to be similar to fossil feedstock in terms of industrial usage but of less or no emission effect, thus considered eco-friendly. The present paper gives the insight of vital hidden opportunities from EC towards economy expansion. The EDX characterization apart from cellulose, hemicellulose and lignin indicate great potential of EC useful element, polymer, surfactant and carbonaceous strength. The EDX analysis indicated percentage values of carbon as 70.4\% and 64.8\% for carbon nanotubes and CMC polymer respectively. It shows good engineering properties both in mechanical strength and high young’s modulus due to the flexible hexagonal structure of the dominated carbon content. This makes it suitable in many engineering application including production of additives, electrical/electronic parts and development of microchips for telecommunication industry. With the help of nanotechnology, EC would be of high potential and predominant in the global market thereby reducing the dependent on the non-renewable material and the effect of fossil pollution will be reduced. Thus, the aqua-environment issue would be solved through steady utilization of the EC material.

1. Introduction

Eichhornia Crassipes (EC) is an aquatic and hydroponics plant, originated from Amazon river base of South America and currently found all over the globe. The plant, if matured, appears pleasant because its flower, with high proliferation growth. As a result of this fast growth development, it causes great challenges on the water bodies. The negative effect of eichhornia crassipes on water activities cannot be overemphasized, ranging from transportation, fishing, pollution and recreational activities [1], [2]. The total coverage of water bodies by EC, prevents direct sunlight penetration and other nutrients development thereby negatively affect aquatic
This contribute to some economics losses to the affected regions or countries. For example, in Nigeria as at early year 2000, the region of south- south was totally clamped down by this giant EC. In addition, body of water covered by this plant serves as surviving zone for mosquitos and some other dangerous amphibians. However, with the help of researcher, discovered that EC could be of huge benefit towards sustainability of mankind [3]–[5] This plant, apart from its flower, consist of three main parts, namely; root, shoot and leaf. Due to high potential of cellulose, hemicellulose, lignin and carbonaceous nature of the plant, has drawn researcher’s awareness towards production of useful materials, thus found adequate due to its affordability, availability and quality products for many years now [6]–[8]. More so, the root section of the plant is known with abundant of chelating agent which are useful in many engineering field [1]. According to [9], EC could serve as alternative fuel resources to solve the high consumption of fossil fuel. Since biomass possesses the properties of fossil feedstock, also a good renewable material and eco-friendly due to no or less release of sulphur content and carbon dioxide that causes greenhouse effect. This plant is known with high potential biomass materials, which are important in the field of research and innovation [6], [10], [11].

Many research presentations have been made using EC in order to ascertain its physiochemical characterisation [10]. It is obvious that service of forestry in providing material for cellulose and wood- based biomaterials are not sufficient owing to the ecological challenges [12]. In order to satisfy the industry, the idea of using every agricultural biomass that possess the needful criteria for cellulose and fossil came to the mind of researcher for utilization purposes [13]–[15] . The research towards utilizing these biomass of fossil feedstock properties provides a reliable, diversification and effective technology [16], [17]. Therefore, the objectives of these work is to unveil those industrial achievements from the use of EC that considered problematic in some regions of the world and to give some insight on some hidden potentials of EC for recent and advanced technology. Currently, series of serious research on EC are going on adopting nanotechnology approach. Generally, the possibility and achievement of these ideas are greatly dependents on utilization of sophisticated modern biomass conversion techniques [18]–[20]. In accordance with the global sustainability strive of patronizing biomass materials, owing to their features in mitigating pollutions greenhouse gas emission [21], [22]. Also, because of various constituents rich of EC material, its application in the industries varies based on their component, function group as to suit the purpose of the application as illustrated in Figure 1.

![Figure 1. Eichhornia crassipes and its key potential constituents](image_url)
Following the building blocks (functional groups) of biomaterial and the upgrading reactions for more products [23]–[25], it is necessary to understand the morphology of the material as show in Figure 1. Since cellulose, hemicellulose and lignin behaves differently during industrial usage. The selection of EC component for application depends on the elemental constituents and the behaviour of such constituted elements/compound during operation.

2. Methodology
2.1 Materials
Eichhornia crassipes plant were obtained from Onuko River, Atani, Anambra state, Eastern part of Nigeria. Other needed materials were electric dry blender, planetary ball mill machine (PM100) (Retsch Germany), electric furnace drying oven, ethanol, EDX and FESEM machine.

2.2 Preparation of Eichhornia Crassipes Nanoparticles of carbon nanotubes (EC-CNTs)
The plant was exposed to direct sunlight for about 24 days prior to preparation. The process used was cyclic heating approach adopted by [26]. Before the cyclic heating, the plant stem and root components were selected, reduced their sizes using dry blender and subjected into 210 °C in an oven for about four (4) hours for optimum dry. At this point, the materials turn to brown-black. For nanoparticles generation, the grinding was done in two phase. The first was direct grind as to reduce parts of EC using planetary ball mill machine (250mL tungsten carbide (WC) grinding jar was carefully loaded with about 70% by volume WC mill balls of 3 mm in diameter together with 33.3% by volume of dry grinded EC (approximately 78 mL). The grinding took about 3 hours at a programmed speed of 300 rpm. The sample were further pass through cyclic heating in electric furnace of about 240° C. The sample was washed with diluted hydrochloric acid solution of 15 %, washed again with deionized distilled water. Further dried and regrind again using ball mill with addition of little ethanol to avoid agglomeration [27].

2.3 Carboxymethyl polymer from Eichhornia crassipes (EC)
The grinded EC-NPs (powder form) (the more the sample tiny the quicker the extraction process proceeds), sieved to obtain desired size of 60 mesh. Next step is use of soxhlet apparatus and solvent mixture of toluene and ethanol with volume of 2:1 to heat water hyacinth powder which is already wrapped with filter paper for dewaxing, adopted from bio-polymer work by [16]. The lignin removal process was done by mixing 1 wt% solution of NaCL2 with water hyacinth powder resulted from dewaxing process, further laid in water bath at 80°C for 3 hrs. removal of remain hemicellulose content was conducted by using a solution of 170g of NaOH for 3hrs at room temperature. After that, the treated water hyacinth cellulose was washed and neutralized by using distilled water and CH3COOH. Drying process was carried out in an Oven (heat) at temperature of 110°C for 4-5 hrs to get the final result of cellulose isolation. Synthesis of carboxymethyl cellulose (CMC) started with alkalization process. This is done by mixing 5 grams of obtained cellulose with various composition of reaction medium (isobutyl and isopropyl alcohol). Then the solution was put in 3 neck flask with stirrer for 10 minutes and added with 20 ml of 5% of NaOH. The whole process of alkalization was spent 1 hour at room temperature. The next step was carboxymethylation process which conducted by adding NaMCA (Sodium monochloacetic) as much as 6 grams and stirred it for 3.5 hours at 55°C. Then CMC was obtained by neutralising and purifying it with CH3COOH was ethanol, then rinse thoroughly to remove undesirable by-products, finally, the cellulose derivative is generated.

2.4 FESEM and EDX characterization of the samples
The final samples were taking to laboratory for nanoscale characterization using FESEM as in Figure 2. Also the application of EDX for elemental compositions and compound structure were
conducted respectively as in Figure 3.

![Figure 2. FESEM image of EC-CNTs, EC-CMCmer and EC-Silica extract of E polyC nanoparticle](image)

**Figure 2.** FESEM image of EC-CNTs, EC-CMCmer and EC-Silica extract of E polyC nanoparticle

![Figure 3. EDX image of EC-CNTs and EC-CMC polymer sample indicating their strength.](image)

**Figure 3.** EDX image of EC-CNTs and EC-CMC polymer sample indicating their strength.

3. Materials Applications
The outcome of the analysis will guide the users for adequate utilization both in preparation and selection of machine owing to the working condition of the system thus classified possible areas to use engineering application. With good understanding of the components and appropriate use of modern biomass conversion and treatment techniques, satisfactory products certainly obtained from EC materials.

4. Mechanical Applications
For different engineering application, the choice and nominating of materials depends mostly on the properties of the material as to meet the design task. In mechanical usage which comprises of tribological and combustion operations. The products ought to possess similar characteristic with fossil feedstock and ability give desirable functions and optimum performance.
4.1 Tribological Materials

Bio-oil of EC was produced through pyrolysis process in a fixed bed reactor [29]. Characterization of bio-oil of EC shows presents of alcohols, alkanes, carboxylic acid, phenols, ketones, alkenes, aromatics, quinines and aldehydes, but of high percentage of benzyl-alcohol and phenethyl alcohol [30][31]. According to [29], the high heating value of EC oil was observed to be 28.35MJ/kg compared to that of fossil with 29.865MJ/kg. The viscosity and pour point were of suitable values of 19.8 Cts + 15°C and 2.93 respectively [29]. Furthermore, for excellent properties of EC oil for lubrication applications, it possesses good insolubility in water but miscible in ethanol, acetone and ether. It shows optimum performance when use for paints, inks and epoxy resin coating [29], with no sulphur content and insignificant nitrogen percentage makes it eco-friendly in usage. In addition, the content of benzyl-alcohol present in bio-oil of EC, if react with carboxylic acids form esters which enhances tribological properties of lubricants during operations. According to [27], materials with high percentage of carbon (carbonaceous), is good for nanotube production for anti-wear operation during lubrication. The root section of the EC plant contains special constituent called chelating capable of bring tiny ions together for the film formation during lubrication. In the analysis of products from carbonaceous materials shows good thermal strength to withstand the working conditions [32], [33]. Also, materials yield more strength with multi-wall nanotubes (MWCNTs) production from carbonaceous nanotube materials [27], [32]. Recent research proves that appropriate pre-treatment of biomaterial activated its properties for mechanical use like; strength and biodegradability [35]. The nanotubes of multi-wall and single-wall of biomaterials for additives and other production application, indicates high young’s modulus (~1 TPa) owing to their hexagonal flexible and crosslinking structure of carbon atoms thus made their thermal properties excellent [34], [36]. In supporting the additive opportunity from EC material, it was discovered to be of hydrophobic potential [37] thereby found very effective in sorbent application in oil spill treatment [38]. The investigatory study on surfactant strength of EC in oil lubricant yield a successful result [39], [40]. Further reduction in the size of EC into nanoscale metamorphous from hydrophobic to amphiphilic (hydrophobic tail and hydrophilic head) nature [41] as a result of increase in surface area for blending in oil lubricant, illustrated in Figure 4(b).
Figure 4. Image of carbon nanotubes (a) [34] and arrangement of bio-amphiphilic material in oil [42][43].

With these properties, the hydrophilic head been polar in nature, stick to the polar surface of the working machine while the hydrophobic tail of non-polar and oil affinity, dissolves in oil lubricant, and with its antioxidant property, help in protecting the fluid against degradation. Since the EC contain benzyl-alcohol, and when react with carboxylic acids during operation form esters which is excellent in film formation for lubrication enhancement [29][44]. The cellulose component of EC is good for the production of carboxymethyl polymer for viscosity improver towards rheological performance of lubricant in service

4.2 Combustion Materials
For a material to be selected for combustible (fuel) application, it must meet the desirable requirement like having its flash point higher than 37.8°C and below 93.3°C. It must be capable to generate vapour if exposed to temperature above its flash point and ignite in contact with ignition source [22], [45]. The EC composite briquette shows adequate physical requirement for solid fuel ranging from densities, durability index and possess good strength as well as optimum calorific value similar to other agricultural solid fuel [10], [46]. In addition, gasification of biofuel of EC, certainly more components of gas fuel will be generated with higher calorific value and a significant reduction of CO2 emission in the environment [47]. Anaerobic co-digestion for biogas production was successfully carried out using EC together with pig dung and poultry dropping’s [48].

5. Electrical Application
The high percentage of carbon in EC analysis in Figure 3, makes it suitable for the electric al capacitors production. Investigations and excellent performance of activated carbon made it widely applied in the production of super-capacitors. However, the strength and the behaviour of these materials depends on adequate preparation and treatment processes for proper functioning in operation. In the synthesis study of carbon microsphere from EC [49] using water hydrolysis and carbonization approach, revealed the potential of EC biomass in the production. It shows good properties during testing including electrochemical stability and high yield of carbon microspheres for the capacitors production [49]. On the study analysis of EC ability to function as thermal insulator was conducted [5] together with natural rubber latex (NRL). The result was found suitable for applications especial with thermal conductivity and density with values of 0.0246-0.0305 W/mK and 465-646 kg/m², respectively [5], and can yield good materials for production of microchips in the field of telecommunication technology.

6. Chemicals
Eichhornia crassipes has been reported by the previous researchers of having huge opportunity for production of good number of bio-chemicals [3][29]. Apart from the characterized chemicalconstituents and pigments in EC oil [29], it still possesses more of bio-chemical strength
Many enzymes have been formulated from EC biomass both from modified and unmodified form [3], [52]. However, with the assistance of biomass modern conversion technology, more of biochemicals of quality grades certainly will be generated from EC biomass [60]. Some of the interesting bio-chemicals of EC used in the engineering industries are listed in Table 1.

Table 1. Special Biochemicals and Enzymes of Eichhornia crassipes

| Bio-chemical     | Production                        | Application                                                                 | Ref.   |
|------------------|-----------------------------------|-----------------------------------------------------------------------------|--------|
| Levulinic acid   | Degradation of cellulose          | Production of biopolymer, epoxy resins and polycarbonates. For synthesis of organic compounds. | [53]   |
| Shikimic acid    | Extraction from EC leaves of about 3.25% | production of drugs and Tamiflu.                                             | [54]   |
| Biogas           | Anaerobic fermentation of EC-biomass by methanogenic bacteria | Quality Bio-fuel                                                             | [48]   |
| Bioethanol       | From pre-treatment to hydrolysis to fermentation | Bio-fuel, additive for gasoline in motor fuel                               | [55]   |
| Biobutanol       | From clostridium beijerinckii approach | Bio-fuel, solvent, hydraulic fluid, detergent formulation and use as chemical intermediate | [56]   |
| Biopolymer       | Hydrolysis of EC as main carbon source | Packaging material, additives                                                | [3][57]|
| Cellulase        | Aspergillus niger and Trichoderma viride fermentation | Pharmaceutical use, laundry detergent and food processing                    | [57]   |
| Glucosidase      | Rhizopus oryzae fermentation       | Pharmaceutical use as antidiabetic drugs                                      | [58]   |
| Xylanase         | From Trichoderma reesi NRRL 3652   | Additives, ingredient in detergent, biofuel production                       | [59]   |

7. Conclusion
The idea of utilizing the products of eichhornia crassipes in the industrial production significantly help in mitigating the occurrences of pollution through the steady use of fossil feedstock products. Constant harvest of EC from the water bodies for the purpose of industrial application massively control the social-economic challenges from the proliferation growth of this plant in the aqua-environment. The characterization results and elemental constituents of EC biomaterial gives the researchers a promising trend towards more valuable products and makes EC more economically sustainable. It exhibits excellent engineering properties including good mechanical strength in order to withstand various forces and other working conditions. Again, with the help of modern technology for fast and easy conversion of these products evidently will escalate the commercialization of EC biomaterials. This could promote it to be the world leading sustainable biomass thereby mute its problematic impact.

Acknowledgement
The authors hereby acknowledge the research grants provided by Universiti Tecknologi Malaysia, under GUP project no. Q. J130000.2524.20H29 and FRGS project no. R. J130000.7951.5F057

References
[1] S. Rezania, M. Ponraj, M. F. M. Din, A. R. Songip, F. M. Sairan, and S. Chelliapan, “The diverse applications of water hyacinth with main focus on sustainable energy and production for new era: An overview,” Renew. Sustain. Energy Rev., vol. 41, pp. 943–954, 2015.
[2] A. Malik, “Environmental challenge vis a vis opportunity,” Case Water Hyacinth, vol. 33, pp. 122–138, 2007.
[3] R. Sindhu et al., Water hyacinth a potential source for value addition: An overview, vol. 230. 2017.
[4] M. Ibrahim, H. S., Amimar, N. S., Sovlack, M. and Ibrahim, “Removal of Cd (11) and Pb (11) from aqueous solution using dried water hyacinth as a bio-sorbert,” Environ. Manage., vol. 7, no. 11, pp. 3–15, 2012.
[5] C. Jaktorn and S. Jiajitsawat, “Production of Thermal Insulator from Water Hyacinth Fiber and Natural Rubber LatexEnergy Research & Promotion Center, Faculty of Sciences, Research Network & Innovation Development of Smart Materials for Energy, Sensors and Bio-resources,
Faculty of,” *Int. J. Sci.*, vol. 11, no. 2, pp. 31–41, 2014.

[6] D. Mishima, M. Kuniki, K. Sei, S. Soda, M. Ike, and M. Fujita, “Ethanol production from candidate energy crops: Water hyacinth (Eichhornia crassipes) and water lettuce (Pistia stratiotes L.),” *Bioresource Technol.*, vol. 99, no. 7, pp. 2495–2500, 2008.

[7] H. Abral, H. Putra, S. M. Sapuan, and M. R. Ishak, “Effect of Alkalization on Mechanical Properties of Water Hyacinth Fibers-Unsaturated Polyester Composites,” *Polym. - Plast. Technol. Eng.*, vol. 52, no. 5, pp. 446–451, 2013.

[8] N. Jafari, “Ecological and socio-economic utilization of water hyacinth (Eichhornia crassipes Mart Solms) N JAFARI,” *J. Appl. Sci. Environ. Manag.*, vol. 14, no. 2, pp. 43–49, 2010.

[9] R. W. Ziehe, “The composition of the water hyacinth Eichhornia crassipes (Mart Solms),” pp. 1–18, 2019.

[10] D. O. Okia, C. K. Ndiema, and M. S. Ahmed, “Physical and Chemical Properties of Water Hyacinth Based Composite Briquettes,” *Sci. Res. J.*, vol. IV, no. Xi, pp. 28–36, 2016.

[11] A. Bhattacharya and P. Kumar, “Water hyacinth as a potential biofuel crop,” *Electron. J. Environ. Agric. Food Chem.*, vol. 9, no. 1, pp. 112–122, 2010.

[12] T. Bridgewater, “Biomass for energy,” *J. Sci. Food Agric.*, vol. 86, no. 12, pp. 1755–1768, 2006.

[13] L. Ma, T. Wang, Q. Liu, X. Zhang, W. Ma, and Q. Zhang, “A review of thermal-chemical conversion of lignocellulosic biomass in China,” *Biotechnology Advances*, vol. 30, no. 4, pp. 859–873, 2012.

[14] P. Kumar Gupta *et al.*, “An Update on Overview of Cellulose, Its Structure and Applications,” *Cellul. [Working Title]*, pp. 1–22, 2019.

[15] U. S. E. I. Administration, “Biomass renewable energy from plants and animals (Converting biomass),” 2016.

[16] C. R. B. Furkan H. Isikgora, “Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers,” *Polym. Chem.*, vol. 6, pp. 4497–4559, 2015.

[17] S. Irnmark, “Biomass as Raw Material for Production of High-Value Products,” *Biomass Vol. Estim. Valorization Energy*, pp. 1–19, 2017.

[18] D. G. Olson, J. E. McBride, A. Joe Shaw, and L. R. Lynd, “Recent progress in consolidated bioprocessing,” *Curr. Opin. Biotechnol.*, vol. 23, no. 3, pp. 396–405, 2012.

[19] N. Canabarbo, J. F. Soares, C. G. Ancheta, C. S. Kelling, and M. A. Mazutti, “Thermochemical processes for biofuels production from biomass,” *Sustain. Chem. Process.*, vol. 1, no. 1, p. 22, 2013.

[20] K. S. Rawat, “Biomass to fuel: Conversion Techniques,” *Uttarakhand Sci. Educ. Cent.*, pp. 155–194, 2016.

[21] M. Murtala, N. Shawal, and D. Usman, “Biomass as a Renewable Source of Chemicals for Industrial Applications,” *Int. J. Eng. Sci. Technol. BIOMASS*, vol. 4, no. 02, pp. 721–730, 2012.

[22] D. O. Okia, MS Ahmed, and CK Ndiema, “Combustion and Emission Characteristics of Water Hyacinth Based Composite Briquettes,” *Sci. Res. J.*, vol. V, no. Xi, pp. 9–17, 2017.

[23] Q. Zhang, J. Chang, T. Wang, and Y. Xu, “Review of biomass pyrolysis oil properties and upgrading research,” *Energy Convers. Manag.*, vol. 48, no. 1, pp. 87–92, 2007.

[24] M. Anwar, M. Iqbal, N. M. Julkapli, P. S. Kong, J. J. Ching, and H. V. Lee, “Development of catalyst complexes for upgrading biomass into ester-based biolubricants for automotive applications: a review,” *RSC Adv.*, no. 10, 2018.

[25] L. Wu, T. Moteki, A. A. Gokhale, D. W. Flaherty, and F. D. Toste, “Production of Fuels and Chemicals From Biomass: Condensation Reactions and Beyond,” *Chem*, vol. 1, no. 1, pp. 32–58, 2016.

[26] Zaytseva and G. Neumann, “Carbon nanomaterials: Production, impact on plant development, agricultural and environmental applications,” *Chem. Biol. Technol. Agric.*, vol. 3, no. 1, pp. 1–85, 2016.

[27] N. Salah, M. S. Abdel-wahab, S. S. Habib, and Z. H. Khan, “Lubricant Additives Based on Carbon Nanotubes Produced from Carbon-Rich Fly Ash,” *Tribol. Trans.*, vol. 60, no. 1, pp. 166–175, 2017.

[28] E. A. Okoronkwo, P. E. Imoisili, S. A. Olubayode, and S. O. O. Olusunle, “Development of Silica Nanoparticle from Corn Cob Ash,” *Adv. Nanoparticles*, vol. 05, no. 02, pp. 135–139, 2016.

[29] I. Wauton and S. E. Ogbeide, “Characterization of pyrolytic bio-oil from water hyacinth (Eichhornia crassipes) in a fixed bed reactor using pyrolysis process,” *Biofuels*, vol. 0, no. 0, pp. 2–
6, 2019.
[30] K. Promdee, T. Vitidsant, and S. Vanpetch, “Comparative Study of Some Physical and Chemical Properties of Bio-Oil from Manila Grass and Water Hyacinth Transformed by Pyrolysis Process,” Int. J. Chem. Eng. Appl., vol. 3, no. 1, pp. 72–75, 2013.
[31] M. Bertero, G. De La Puente, and U. Sedran, “Fuels from bio-oils: Bio-oil production from different residual sources, characterization and thermal conditioning,” Fuel, vol. 95, pp. 263–271, 2012.
[32] M. Kalin, J. Kogovšek, and M. Remškar, “Mechanisms and improvements in the friction and wear behavior using MoS2 nanotubes as potential oil additives,” Wear, vol. 280–281, no. 127, pp. 36–45, 2012.
[33] G. Griffin, D. Batten, and T. Beer, “A Review of Physical Properties of Biomass Pyrolysis Oil,” Int. J. Renew. Energy Dev., vol. 5, no. 1, pp. 2004–2007, 2015.
[34] S. Lijima and C. Bradec, “Structural Flexibility of Carbon Nanotubes,” J. Chem. Phys., vol. 104, no. 5, pp. 2089–2092, 2014.
[35] M. S. Sacks and C. J. Chuong, “Orthotropic mechanical properties of chemically treated bovine pericardium,” Ann. Biomed. Eng., vol. 26, no. 5, pp. 892–902, 1998.
[36] R. Leander, S. Suárez, A. Rosenkranz, “Tribo-Mechanisms of Carbon Nanotubes: Friction and Wear Behavior of CNT-Reinforced Nickel Matrix Composites and CNT-Coated Bulk Nickel,” J. Lubr., vol. 4, no. 2, pp. 4–11, 2016.
[37] M. J. Rani, M. Murugan, P. Subramaniam, and E. Subramanian, “A study on water hyacinth Eichhornia crassipes as oil sorbent,” J. Appl. Nat. Sci., vol. 6, no. 1, pp. 134–138, 2018.
[38] Gulf Sea Grant, E. Maung-douglass, L. Graham, C. Hale, and S. Sempier, “Emerging Surfactants, Sorbents, and Additives for Use in Oil Spill Clean-Up.”
[39] M. J. Rani, M. Murugan, P. Subramaniam, and E. Subramanian, “A study on water hyacinth Eichhornia crassipes as oil sorbent,” J. Appl. Nat. Sci., vol. 6, no. 1, pp. 134–138, 2014.
[40] T. Zhang and R. E. Marchant, “Novel polysaccharide surfactants: The effect of hydrophobic and hydrophilic chain length on surface active properties,” J. Colloid Interface Sci., vol. 177, no. 2, pp. 419–426, 1996.
[41] Z. Soulguir, S. Roudesli, E. About-Jaudet, L. Picton, and D. Le Cerf, “Novel cationic and amphiphilic pullulan derivatives II: pH dependant physicochemical properties,” Carbohydr. Polym., vol. 80, no. 1, pp. 123–129, 2010.
[42] L. A. Quinchia, M. A. Delgado, T. Reddyhoff, C. Gallegos, and H. A. Spikes, “Tribological studies of potential vegetable oil-based lubricants containing environmentally friendly viscosity modifiers,” Tribol. Int., vol. 69, no. 10, pp. 110–117, 2014.
[43] I. M. Banat, S. K. Satpute, S. S. Cameotra, R. Patil, and N. V. Nyayanit, “Cost effective technologies and renewable substrates for biosurfactants production,” Front. Microbiol., vol. 5, 2014.
[44] M. Koyama et al., “Tribro chemical reaction dynamics of phosphoric ester lubricant additive by using a hybrid tight-binding quantum chemical molecular dynamics method,” J. Phys. Chem. B, vol. 110, no. 35, pp. 17507–17511, 2006.
[45] A. G. Wang, D. Austin, and H. Song, “Catalytic Biomass Valorization,” Biomass Vol. Estim. Valorization Energy, pp. 1–23, 2017.
[46] A. Demirbas, Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues, vol. 31, no. 2. 2005.
[47] E. J. Sikarwar, Vineet Singh et al., “Progress in biofuel production from gasification,” Sci. Journals, vol. 61, pp. 187–248, 2017.
[48] A. Okewale and O. Adesina, “Evaluation of biogas production from co-digestion of pig dung, water hyacinth and poultry droppings,” Waste Dispos. Sustain. Energy, vol. 1, no. 4, pp. 271–277, 2019.
[49] F. Kurniawan, M. Wongso et al., “carbon microsphere fromwater hyacinth for super-capacitor electrode,” J. Taïwan Inst. Chem. Eng., vol. 8, no. 47, pp. 198–204, 2014.
[50] M. J. Biddy, C. J. Scarlata, and C. Kinchin, “Chemicals from biomass: A market assessment of bioproducts with near-termpotential,” 2016.
[51] X. S. Zhang, G. X. Yang, H. Jiang, W. J. Liu, and H. S. Ding, “Mass production of chemicals frombiomass- derived oil by directly atmospheric distillation coupled with co-pyrolysis,” Sci. Rep., vol. 3, pp. 1–12, 2013.
[52] N. E. A. El-Naggar, S. Deraz, and A. Khalil, “Bioethanol production from lignocellulosic feedstocks based on enzymatic hydrolysis: Current status and recent developments,” *Biotechnology*, vol. 13, no. 1, pp. 1–21, 2014.

[53] B. Girisuta, B. Danon *et al.*, “Experimental and Kinetic Modelling Studies on the acid-catalysed hydrolysis of Water Hyacinth Plant to Levulinic acid,” *Biomaterials*, vol. 99, no. 5, pp. 8367–8375, 2008.

[54] LM Lenora, D. Suresh Babu *et al.*, “Eichhornia crassipes (Mart.) solms:- An alternate renewable source for Shikimic acid, a precursor for Tamiflu, a swine flu drug,” *J. Pharmacogn. Phytochem.*, vol. 5, no. 1, pp. 178–181, 2016.

[55] G. Gunja, V. Gupta, P. Jain and C. Sharma, “Production of bioethanol from Water Hyacinth by Isolated thermotolerant bacteria,” *Biofuels*, vol. 9, no. 3, pp. 1–9, 2016.

[56] B. Park, H. Park, and S. Yun, “Production of Biobutanol by Clostridium beijerinkii from Water Hyacinth,” *Biotechnology*, vol. 31, no. 1, pp. 79–84, 2016.

[57] A. Sindhn, R. Raveendrar *et al.*, “Production of Cellulase in Submerged Fermentation Using Water Hyacinth as Carbon Source and Reutilization of Spent Fungal Biomass for Dye Degradation,” *Int. J. Curr. Microbiology Appl. Sci.*, vol. 5, no. 10, pp. 99–108, 2016.

[58] R. Ray, M. Karmakar and R. Rain, “A Statistical Approach for Optimization of Simultaneous Production of B-Glucosidase and Endoglucanase by Rhizopus oryae from Solid-Stata of Water Hyacinth Using Central Composite Design,” *Bioresources*, vol. 12, no. 7, pp. 1–6, 2011.

[59] R. Narendhirakannan, and A. Manivannan, “Response surface optimization for co-production of cellulase and Xylanase enzymes by Trichoderma reesi NRRL-3652,” *Int. J. ChemTech Res.*, vol. 6, no. 7, pp. 3883–3888, 2014.

[60] C. V. Sagar and N. A. Kumari, “Sustainable Biofuel Production From Water Hyacinth (Eichhornia Crassipes),” *Int. J. Eng. Trends Technol.*, vol. 4, no. 10, pp. 4454–4458, 2013.