eNergetics 2024
DOI: https://doi.org/10.5281/zenodo.14735556

Original Scientific Article

Valorizing the Invasive Macrophyte *Eichhornia crassipes* as a Potential Bionergy Feedstock: Preliminary Assessment from Thermochemical Characterization

Maxwell de Arandas Pimentel[1], Fernado Mateus de Oliveira Santos[2], Gabriela Aurora Alexandre de Vasconcellos[3], Jhonatas Wagner Barbosa de Costa Gouveia[4], José Luiz Francisco Alves[5], Silvia Layara Floriani Andersen[6]

[1,2,3,4,5,6]Federal University of Paraíba, Laboratory of Materials and Environmental Chemistry, João Pessoa – PB, Brazil

[1]maxwell.pimentel@estudante.cear.ufpb.br, [6]silvia@cear.ufpb.br

Abstract—**The explosion in demand for energy resources since the Industrial Revolution has led us to seek more renewable energy sources. Although the evolution of renewable energies in the energy matrix represents significant advances, non-renewable energies are still more predominant. Biomass, particularly water hyacinth (*Eichhornia crassipes*), offers an alternative from the Amazon Basin. This aquatic plant grows at an astonishing rate, but its overabundance can cause disturbances in the ecological balance. Knowledge about the fundamental physicochemical characteristics of water hyacinth is essential for its potential as a renewable biomass towards relevant management strategies in line with the UN Sustainable Development Goals (SDGs), as provided in this work. With a volatile matter content of 67 wt.%, 37.5 wt.% carbon, a calorific value of 17.2 MJ/kg, and low sulfur content, water hyacinth shows potential as a raw material for thermochemical biomass conversion processes into value-added products. Experiments were conducted using a thermogravimetric analyzer in an inert atmosphere at four heating rates (5, 10, 20, and 30 °C.min^{-1}) to obtain the pyrolysis behavior of water hyacinth. The thermal degradation showed three stages of mass loss: (1) less than 7.1 ± 1.1 wt.% from 50 to 200 °C due to water evaporation and organic decomposition; (2) 48.1 ± 1.5 wt.% from 200 to 400 °C due to the decomposition of hemicellulose, cellulose, and lignin; and (3) 12.3 ± 0.6 wt.% above 400 °C, mainly due to lignin decomposition and biochar formation.**

Keywords - biomass, water hyacinth, bioenergy, bioproducts

I. INTRODUCTION

This increasing demand due to technological development and population growth over the years has caused severe environmental impacts by aggravating climate change. To overcome these challenges, renewable energy sources are well-known solutions to reduce Greenhouse Gases and mitigate environmental destruction [1-3].

The significant growth of renewable energy - still a relatively small part of total used fossil fuel as energy sources in many developing nations across the globe for recent few decades in most developed countries on up started - In this context, it is worth noting the significant shift that will be needed to finance technologies using renewable energy (solar radiation, biomass, geothermal, wind) that play an important role in decarbonization and sustainable development [4].

It is biomass one of the most important sustainable resources and it has a relevant impact

ISBN: 978-86-82602-05-7

Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-Non Commercial 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission.

on carbon neutrality as an efficient conversion process. It also decreases greenhouse gas emissions and promotes environmental sustainability through the utilization of renewable energy sources and the recycling of organic waste [5].

Aquatic phytoresources have been widely explored for bioenergy via a number of promising conversion methods like pyrolysis, gasification, liquefaction, fermentation or anaerobic digestion and enzymatic hydrolysis. At least 60% of the conversion from macrophytes However, these processes should be developed in a cost-effective manner [6-8].

Biomass is essentially organic material produced from plants, animals and microorganisms that is created either directly or indirectly via living organisms Biomass stores solar energy as chemical energy through photosynthesis, making it one of the most potent sources available for fulfilling global energy demands. Biomass is a bioenergy stored as energy in form of heat and gas for future use through combustion or repeated vegetation process, being usable in heat, electricity, cooking gas and transportation fuels as well. Mostly made of carbon, hydrogen, oxygen and nitrogen it also has traces of chlorine and sulfur [9,10].

One of biomass raw materials that can be renewed is Water hyacinth (*Eichhornia crassipes*). Indigenous to Brazil, in the Amazon Basin. As it is beautiful, the plant was disseminated as an ornamental across various regions of the globe since 1850s. By the late 1960s, there was proof that water hyacinth had already established internationally through tropical and subtropical ecosystems [11].

The water hyacinth is a floating aquatic plant with flexible stems, erect leaves, lilac flowers, and submerged roots, recognized for its effective nutrient absorption from water. Recognized as an invasive aquatic species, water hyacinth demonstrates an exceptionally high growth rate, with the potential to reach 220 kg ha^{-1} d^{-1}. The uncontrolled spread in freshwater ecosystems disturbs the ecological balance by reducing oxygen content and solar radiation access. Such situations are not appropriate for the native fauna and leads to problems like bad water quality for the fish, hindered waterways, challenges in extracting any water and higher chances of disease transmission [5,10-14].

However, this is the reason why the uncontrolled expansion of water hyacinth causes environmental problems. However, other research related to these plants indicates some advantageous characteristics that attract interest, provided they are applied under correct control. Water hyacinth can be used in phytoremediation and contribute to the treatment of wastewater. In addition, water hyacinth and its bioproducts have the potential to be used as adsorbents for the treatment of textile effluents and phosphate removal. It is also considered an attractive raw material for biofuels [15].

The literature reports various studies on the conversion of water hyacinth into valuable products through pyrolysis, including energetic biochar, bio-oil, and non-condensable gases, each with several energy and material applications. The pyrolytic gases, such as H_2 , CO, CH_4 , and C_2 H_2 , can be reformed to generate syngas with energy properties. The bio-oil, which contains a variety of compounds such as carboxylic acids, alcohols, esters, furans, phenols, aldehydes, and ketones, can be used in the production of liquid biofuels, contributing to the renewable energy matrix. On the other hand, the biochar, rich in carbon, has a wide range of applications, including soil remediation, functioning as a catalyst, serving as a precursor in the production of activated carbon, and being used as an adsorbent [11,14-16].

The objective of this work is to characterize water hyacinth (*Eichhornia crassipes*) and investigate its potential as a source of renewable biomass, focusing on its application as a raw material for energy bioproducts. Through a detailed analysis of its physicochemical properties and the behavior of mass loss under pyrolysis conditions, this study aims to highlight the potential of water hyacinth to sustainably contribute to the energy matrix while also helping to mitigate the environmental impacts arising from its uncontrolled growth.

Several Sustainable Development Goals (SDGs) are upheld by this initiative, such as SDG 7, which focuses on clean and affordable energy; SDG 12, which promotes the responsible utilization of renewable resources like biomass; SDG 13, which emphasizes climate action and the adoption of low-carbon technologies; and SDG 15, which addresses the management of invasive species, including water hyacinth, as well as the preservation of terrestrial ecosystems.

II. MATERIALS AND METHODS

A. Collection and Preparation

Water hyacinth biomass was collected in January 2024 from the Canhoto River in Canhotinho, Pernambuco, Brazil, where aquatic vegetation indicated eutrophication and the presence of invasive macrophytes. After collection, only the stems and leaves were retained, with roots discarded. The biomass underwent pre-drying outdoors for eight days at approximately 25 °C, followed by drying in a forced-air oven at 105 °C for 3 hours. It was then processed in a knife mill and manually sieved to achieve uniform particles smaller than 0.149 mm.

B. Physicochemical Characterization

The proximate analysis is a set of tests designed to quantify the contents of moisture (M), volatile matter (VM), ash (A), and fixed carbon (FC).

The moisture content was determined using the oven-drying method, in accordance with the ASTM E1756-08 [17]. An air-circulating oven, model MA035, at 105 ºC, was used.

The Volatile Matter (VM) content was determined according to the ASTM E872-82R18 [18], while the Ash (Z) content was evaluated in accordance with the ASTM E1755-01R20 [19].

The elemental composition of the water hyacinth sample, including the mass percentages of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S), was determined using an elemental analyzer model CE 1108 (Carlo Erba Instruments, Wigan, UK), following the standard procedures outlined in ASTM D3176-15 (ASTM, 2015). As shown in Eq. (1), the oxygen mass percentage was calculated by difference [8]:

$$O(\%) = 100 - \mathrm{C} - \mathrm{H} - \mathrm{N} - S - Z\,. \qquad (1)$$

To determine the higher heating value (HHV) of the biomass, an IKA C200 calorimeter was used, following the ASTM D5865M-19 [20]. The lower heating value (LHV) can be calculated from the value obtained for the HHV and the mass content of hydrogen, using Eq. (2) [21].

$$LHV(MJ/kg) = HHV - 0.2183 \times H\,. \qquad (2)$$

The bulk density (BD), also known as bulk specific weight, of water hyacinth was determined following the ASTM E873-82 [22].

Thermogravimetric analyses were conducted using the SDT650 thermogravimetric analyzer (TA Instruments). The experiments were carried out under an inert nitrogen (N_2) atmosphere with 99.99% purity, at a constant flow rate of 100 $mL.min^{-1}$ and with a sample mass of approximately 10 mg. The temperature range used for the analyses varied from ambient temperature to 1000 °C, with heating rates of 5, 10, 20, and 30 $°C.min^{-1}$.

III. RESULTS AND DISCUSSION

A. Physicalchemical Characterizations

Table I highlights the physicochemical properties of water hyacinth.

When comparing the values of volatile matter and fixed carbon from Table I with the results presented by [5] for the same species, a notable similarity emerges. The authors reported a higher volatile matter content of 70.5 wt.%, along with a lower fixed carbon content of 13.7 wt.%.

According to [8], the significant result for the volatile matter in this biomass suggests that the pyrolysis process of water hyacinth can yield a high amount of condensable gases (bio-oil) and non-condensable gases.

TABLE I. PHYSICOCHEMICAL CHARACTERIZATION OF WATER HIACINTH.

Sample: Water Hyacinth (*Eichhornia crassipes*)	
Properties	**Values**
Proximate Analysis	*Mass percentage (%)*
Moisture[a] (M)	16.5
Ash[b] (Z)	18.9 ± 0.2
Volatile Matter[b] (VM)	67.0 ± 0.4
Fixed Carbon[b] (FC)	14.1 ± 0.2
Elemental Analysis	*Mass percentage (%)*
Carbon[b] (C)	37.5
Hydrogen[b] (H)	3.2
Nitrogen[b] (N)	4.9
Sulfur[b] (S)	0.3
Oxygen[b] (O)	35.2
Heating value	($MJ.kg^{-1}$)
Higher heating value (HHV)	17.2 ± 0.1
Lower heating value (LHV)	16.1
Bulk density (BD)	($kg.m^{-3}$) 145.3 ± 4.9

Legend: (a) Air dried basis; (b) dry basis.

In the proximate analysis, [23] found a moisture content of 13.6 wt.%, a value close to the 16.5 wt.% obtained in this study. Regarding ash content, the cited study reported 15.1 wt.% while this work found 18.9 wt.%, indicating a good agreement between the data.

The proximate analysis of sugarcane bagasse conducted by [24] revealed a volatile matter content of 76.5 wt.% and fixed carbon content of 16.8 wt.%, results comparable to those observed in studies on water hyacinth.

Another biomass that exhibits values similar to those found in the analysis of water hyacinth is the wood from the species *Ficus nítida*, which has a fixed carbon content of approximately 16.9 wt.%, volatile matter of 68.8 wt.%, and ash content of 14.4 wt.%, as reported by [25]. Additionally, rice straw, according to the analysis by [26], also shows comparable results, with 65.2 wt.% volatile matter, 16.6 wt.% fixed carbon, and 12.6 wt.% ash. Several researchers emphasize that biomass with high volatile matter content and low ash content is particularly suitable for the pyrolytic conversion process [27,28].

The elemental analysis of water hyacinth showed carbon as the main component, with 37.5 wt.% by, followed by oxygen (39.8 wt.%), nitrogen (4.5 wt.%), hydrogen (3.2 wt.%), and sulfur (0.3 wt.%). The levels of carbon, oxygen, and hydrogen are comparable to other lignocellulosic biomasses used for energy purposes. However, the nitrogen content is higher than that found in other biomasses, which range from 0.14 wt.% to 1.8 wt.% [29,30] potentially requiring additional methods to treat NOx emissions during the thermochemical process. The low sulfur content indicates great potential for clean bioenergy production, without the need for extra treatment for sulfur oxides [30]. Thus, the elemental composition of water hyacinth reinforces its potential as a sustainable alternative for bioenergy production.

When comparing the ash content of water hyacinth, which is 18.9 wt.%, with other lignocellulosic biomasses, as shown in studies by [31], it is noted that this value is similar to or lower than several analyzed residues, such as eucalyptus bark (19.0 wt.%), mint stems (18.2 wt.%), moringa oleifera leaves (21.5 wt.%), and bamboo cane residues (39.6 wt.%).

Ash, as an inorganic residue, increases transportation, handling, and processing costs, influencing dust emissions, ash management, and combustion technology selection. High ash content lowers the heating value, promotes slag formation, reduces heat transfer efficiency, and raises maintenance frequency and costs for equipment [31].

TABLE II. COMPARATIVE RESULTS OF ELEMENTAL ANALYSIS OF WATER HYACINTH.

Sample: Water Hyacinth (*Eichhornia crassipes*)				
C(%)	**H(%)**	**N(%)**	**O(%)**	**Reference**
39.9	5.3	3.5	35.2	[32]
40.0	5.3	1.2	34.5	[33]
37.9	5.2	2.5	25.5	[34]
37.5	4.8	3.2	35.1	Authors

The results presented in Table I, related to the elemental analysis, are consistent with the values reported in the literature. This compatibility is also evident in Table II, which presents data from studies related to the elemental analysis of water hyacinth.

Some biomass types show similar chemical compositions to water hyacinth. For example, in the studies by [26] on rice straw, the following values were recorded for the commonly analyzed chemical elements: carbon (38.6 wt.%), hydrogen (4.2 wt.%), nitrogen (1.1 wt.%), and sulfur (0.6 wt.%).

When compared to other biomass sources, this property of water hyacinth stands out, making it an attractive option for use as a biofuel in potential applications in thermochemical processes. The higher heating value of water hyacinth, as identified in this study (17.2 $MJ.kg^{-1}$), is comparable to or even exceeds that of various biomass sources described by [31], such as lemon peel (17.2 $MJ.kg^{-1}$), rice husk (15.9 $MJ.kg^{-1}$), tomato waste (14.2 $MJ.kg^{-1}$), pomegranate peel (15.2 $MJ.kg^{-1}$), and eucalyptus bark (16.2 $MJ.kg^{-1}$).

Bulk density is a crucial factor for logistical planning in the handling and transportation of biomass, as higher values typically lead to lower storage and handling costs [16]. Water hyacinth, with a bulk density of 145.3 $kg.m^{-3}$, is comparable to *Gmelina arborea* wood (151.5 $kg.m^{-3}$) [35] and surpasses sugarcane bagasse (119.1 $kg.m^{-3}$) [35] and rice husk (129.0 $kg.m^{-3}$) [36]. The use of this biomass in the bioenergy sector can be optimized through pelleting or briquetting processes [37].

B. Thermogravimetric Analysis

Thermogravimetric analysis is crucial for evaluating biomass mass loss during pyrolysis.

Energy product yields vary with temperature: lower temperatures favor bio-oil and biochar production, while higher temperatures increase pyrolytic gas production. Identifying the optimal temperature range is key, as the diverse biomass composition, including cellulose, hemicellulose, lignin, and extractives, decomposes at different temperatures, influencing pyrolysis efficiency [14].

Fig. 1 shows the thermogravimetric curves (TG) of water hyacinth, depicting pyrolysis mass loss behavior as a function of temperature at heating rates of 5, 10, 20 and 30ºC.min^{-1}.

Fig. 2 presents the corresponding first-order derivative of the mass loss curve (DTG) for each heating rate.

The pyrolysis behavior of water hyacinth indicates that an initial mass loss of less than 7,1 ± 1,1 wt.% occurs in the temperature range of 50 to 200°C. In the 50 to 150°C range, the mass loss is mainly due to the evaporation of adsorbed water and the release of hydration water from the cellular structures.

The mass loss observed between 150 and 200°C is due to the thermal decomposition of light organic extractives in water hyacinth.

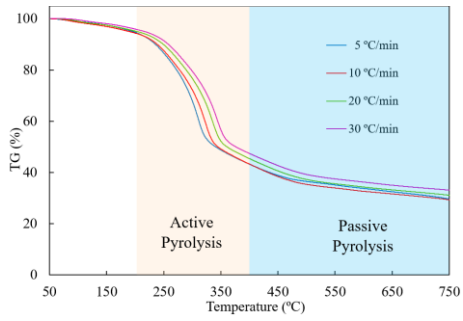


Figure 1. Thermogravimetric Curves (TG) of Water Hyacinth.

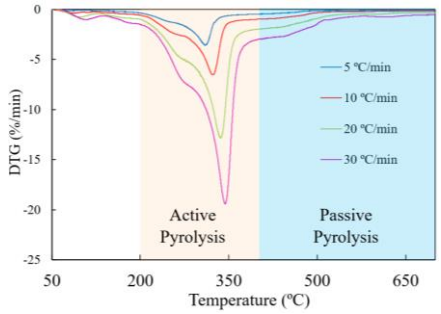


Figure 2. DTG Curves of Water Hyacinth.

Literature on the pyrolysis of invasive macrophytes provides support for this mass loss occurring in the temperature range of 50 to 200°C. [10,21].

The active pyrolysis zone, the average mass loss is 48.1 ± 1.5 wt.%, occurring between 200 and 400°C. This zone is characterized by the conversion of volatile matter into condensable vapors and non-condensable gases, resulting from the devolatilization of hemicellulose, cellulose, and part of the lignin. This zone exhibits the most significant mass loss. Passive pyrolysis, beginning at 400°C and characterized by an average mass loss of 12.3 ± 0.6 wt.%, is marked by the gradual decomposition of lignin and the subsequent formation of biochar [38].

Since the experiments for each heating rate were conducted in an inert atmosphere, Table III summarizes the most relevant weight losses as a percentage for the pyrolysis of water hyacinth.

The average total mass loss of water hyacinth across the three stages is 67.5 ± 1.2 wt.%. In invasive aquatic macrophytes, stages 1 and 2 are more closely related to the decomposition of carbohydrates, such as hemicellulose and cellulose. Stage 3, in turn, is predominantly associated with the decomposition of lipids and lignin [8]. The structural differences in lignocellulosic biomass determine its decomposition order. Hemicellulose, with an amorphous and random structure, degrades most easily. Cellulose, with a crystalline structure of

TABLE III. THERMAL PYROLYSIS OF WATER HYACINTH: VARIATION OF MASS LOSS.

Sample: Water Hyacinth* (*Eichhornia crassipes*)				
Stage 1	*Heating rate (ºC.min^{-1})*	*T_i (ºC)*	*T_f (ºC)*	*Percent mass loss (%)*
	5	50	200	6.8
	10	50	200	8.5
	20	50	200	7.2
	30	50	200	5.8
Stage 2	*Heating rate (ºC.min^{-1})*	*T_i*	*T_f*	*Percent mass loss (%)*
	5	200	400	50.3
	10	200	400	47.7
	20	200	400	47.3
	30	200	400	47.2
Stage 3	*Heating rate (ºC.min^{-1})*	*T_i*	*T_f*	*Percent mass loss (%)*
	5	400	700	11.7
	10	400	700	11.9
	20	400	700	12.53
	30	400	700	13.03

Legend: (*) on a dry basis; ti: initial temperature; tf: final temperature.

glucose monomers, is more resistant. Lignin, a complex three-dimensional polymer, has the highest thermal stability [38].

In the temperature range of 200 to 350°C, the initial decomposition of light organic components, such as hemicelluloses and extractives, is observed, leading to a more pronounced reduction in mass. This trend aligns with the findings de [38]. Thermal decomposition of hemicellulose occurs between 201 and 325°C. Cellulose and part of the lignin decompose between 350 and 500°C, with cellulose mainly decomposing between 350 and 400°C, causing significant mass loss due to accelerated thermal degradation [39]. It is expected that lignin will continue to decompose over a wide temperature range, approximately from 180°C to 700°C [39]. Above 500°C, mass loss tends to slow down and stabilize, indicating the formation of carbonaceous compounds that are more resistant to thermal decomposition and the creation of pyrolytic charcoal [40]. The mass loss reduction indicates that most organic components have decomposed, and carbonaceous compounds are beginning to stabilize [33].

Devolatilization temperatures of the biomass were noted at 313°C, 324°C, 338°C, and 345°C for heating rates of 5, 10, 20, and 30°C/min, respectively. The pyrolysis solid product consists of fixed carbon and ash, with the residual mass of water hyacinth indicating the biochar yield, reflecting the proportion of fixed carbon and ash content [30]. As heating rates increased, DTG peaks shifted to higher temperatures, indicating more intense decomposition. The mass loss percentage varied with temperature, reflecting low heat transfer efficiency due to the biomass particle's thermal resistance. Volatile constituent release and their secondary reactions absorb heat in endothermic processes, hindering effective heat transfer to the particle core and reducing thermal degradation efficiency [10].

C. Challenges and Future Research

The main challenge with water hyacinth is developing effective control strategies, as methods like mechanical, chemical, and biological treatments are often costly and ineffective. However, the increasing value of its biomass has shifted focus toward sustainable use rather than eradication. A circular economy approach is needed to balance controlled reproduction for industrial applications while preventing environmental imbalances. Harvesting methods should be tailored to local resources to ensure both economic and environmental sustainability, providing socio-economic benefits [41].

Interest is growing in optimizing biochar production from water hyacinth, primarily for use as fertilizer. Valorizing this invasive plant boosts local economies by creating jobs, supporting markets, and reframing it as a valuable resource. This approach also clears water bodies for activities like fishing, irrigation, and navigation. Biochar offers environmental benefits, including soil remediation, increased agricultural productivity, reduced dependence on mineral fertilizers, and mitigation of nitrate and phosphate pollution, gas emissions, and leaching [42,43].

Other challenges include high operational costs for industrial-scale processes, mainly due to water hyacinth's high moisture content and low material density, which require advanced drying and transportation. In addition, the plant's ability to absorb nutrients can make biochar more prone to heavy metal contamination, potentially compromising its safety for use [41].

Given the technical challenges, complementary techniques like TG-FTIR and Py-GC/MS are crucial for understanding biomass thermal degradation. TG-FTIR monitors mass loss and gas release, helping analyze degradation stages and optimize processes. Py-GC/MS detects specific volatile compounds like phenols and furans, offering molecular insights, despite its limitations with non-volatile compounds. Combining these methods enhances the understanding of biomass behavior, such as water hyacinth, and improves its conversion into bioenergy and value-added products [33].

IV. CONCLUSION

This study characterized water hyacinth by its moisture, ash, volatile matter, fixed carbon, and elemental composition. Its high volatile content makes it ideal for pyrolysis, enabling efficient biofuel conversion. Water hyacinth's superior calorific value surpasses other biomasses, emphasizing its potential for sustainable bioenergy production. Thermogravimetric analysis revealed its suitability for pyrolysis and transformation into bioproducts like biochar. Responsible reuse of water hyacinth not only supports the local economy but also mitigates the environmental impacts of its uncontrolled spread.

V. ACKNOWLEDGMENT

The authors would like to acknowledge National Concil for Scientific and Technological Development - CNPq for financial support (Process: 407977/2023-6).

REFERENCES

[1] Abi Bianasari, A., Khaled, M. S., Hoang, T. D., Reza, M. S., Bakar, M. S. A., & Azad, A. K. (2024). Influence of combined catalysts on the catalytic pyrolysis process of biomass: A systematic literature review. *Energy Conversion and Management*, *309*, 118437.

[2] Ahmad, W., Nisar, J., Anwar, F., & Muhammad, F. (2023). Future prospects of biomass waste as renewable source of energy in Pakistan: A mini review. *Bioresource Technology Reports*, 101658.

[3] Chen, X., Zhang, H., Zhao, X. X., Gong, Q., & Chang, C. P. (2024). Do renewable energy investment and financial development mitigate climate change?. *Journal of Asian Economics*, *93*, 101749.

[4] Opoku, E. E. O., Acheampong, A. O., Dogah, K. E., & Koomson, I. (2024). Energy innovation investment and renewable energy in OECD countries. *Energy Strategy Reviews*, *54*, 101462.

[5] Mallick, D., et al. (2023). Mechanistic investigation of pyrolysis kinetics of water hyacinth for biofuel employing isoconversional method. *Sustainable Energy Technologies and Assessments*, *57*, 103175.

[6] Pal, D. B., et al. (2023). Sustainable valorization of water hyacinth waste pollutant via pyrolysis for advance microbial fuel investigation. *Chemosphere*, *314*, 137602.

[7] Ugya, A. Y., Okoh, O. O., Okoh, A. I., & Hossain, M. I. (2024). Aquatic phytoresources: An environmentally sustainable alternative biomaterial for bioenergy production. *Renewable and Sustainable Energy Reviews*, *205*, 114877.

[8] Alves, J. L. F., et al. (2019). Kinetics and thermodynamics parameters evaluation of pyrolysis of invasive aquatic macrophytes to determine their bioenergy potentials. *Biomass and Bioenergy*, *121*, 28-40

[9] Cai, J., Zhou, W., Zhu, X., Dong, Y., Zhao, S., & Tian, L. (2024). Research on the application of catalytic materials in biomass pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *177*, 106321.

[10] Mishra, R. K., Singh, B., & Acharya, B. (2024). A comprehensive review on activated carbon from pyrolysis of lignocellulosic biomass: An application for energy and the environment. *Carbon Resources Conversion*, *7*(4), 100228.

[11] Djihouessi, M. B., Olokotum, M., Chabi, L. C., Mouftaou, F., & Aina, M. P. (2023). Paradigm shifts for sustainable management of water hyacinth in tropical ecosystems: A review and overview of current challenges. *Environmental Challenges*, *11*, 100705.

[12] Bronzato, G. R. F., Ziegler, S. M., Silva, R. C., Cesarino, I., & Leão, A. L. (2017). Characterization of the pre-treated biomass of *Eichhornia crassipes* (water hyacinth) for the second generation ethanol production. *Molecular Crystals and Liquid Crystals*, *655*(1), 224-235.

[13] Midhun, V. C., Jayaprasad, G., Anto, A., & Anish, R. (2023). Preparation and characterisation study of water hyacinth briquettes. *Materials Today: Proceedings.*

[14] Pal, D. B., Singh, R. K., Gautam, S., Sharma, T., & Kundu, P. (2023). Sustainable valorization of water hyacinth waste pollutant via pyrolysis for advance microbial fuel investigation. *Chemosphere*, *314*, 137602.

[15] Allam, F., Elnouby, M., El-Khatib, K. M., El-Badan, D. E., & Sabry, S. A. (2020). Water hyacinth (*Eichhornia crassipes*) biochar as an alternative cathode electrocatalyst in an air-cathode single chamber microbial fuel cell. *International Journal of Hydrogen Energy*, *45*(10), 5911-5927.

[16] Rahman, M. A. (2018). Pyrolysis of water hyacinth in a fixed bed reactor: Parametric effects on product distribution, characterization and syngas evolutionary behavior. *Waste Management*, *80*, 310-318.

[17] *ASTM E1756-08, Standard Test Method for Determination of Total Solids in Biomass*. West Conshohocken, PA, 2015.

[18] *ASTM E872 - R18, Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels*. West Conshohocken, PA, 2020.

[19] ASTM *E1755-01R20, Standard Test Method for Ash in Biomass*. West Conshohocken, PA, 2020.

[20] *ASTM D5865M-19, Standard Test Method forGross Calorific Value of Coal and Coke*. West Conshohocken, PA, 2019.

[21] Alves, J. L., et al. (2020). Lignocellulosic residues from the Brazilian juice processing industry as novel sustainable sources for bioenergy production: preliminary assessment using physicochemical characteristics. *Journal of the Brazilian Chemical Society*, *31*, 1939-1948.

[22] *ASTM E873-82, Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels*. West Conshohocken, PA, 2019.

[23] Liu, Z., Hu, Y., Wang, J., Meng, J., Zhang, Y., & Chen, R. (2023). Study on the combustion characteristics and kinetics of water hyacinth co-combustion with anthracite. *Chemical Engineering Research and Design*, *200*, 637-645.

[24] Ramirez, J. A., & Rainey, T. J. (2019). Comparative techno-economic analysis of biofuel production through gasification, thermal liquefaction, and pyrolysis of sugarcane bagasse. *Journal of Cleaner Production*, *229*, 513-527.

[25] Tabal, A., Barakat, A., Aboulkas, A., & El Harfi, K. (2021). Pyrolysis of ficus nitida wood: Determination of kinetic and thermodynamic parameters. *Fuel*, *283*, 119253.

[26] Pan, Z., Li, X., Fu, L., Li, Q., & Li, X. (2023). Environmental sustainability by a comprehensive environmental and energy comparison analysis in a wood chip and rice straw biomass-fueled multi-generation energy system. *Process Safety and Environmental Protection*, *177*, 868–879.

[27] Mumbach, G. D., et al. (2022). Investigation on prospective bioenergy from pyrolysis of butia seed waste using TGA-FTIR: Assessment of kinetic triplet,

thermodynamic parameters, and evolved volatiles. *Renewable Energy*, *191*, 238-250.

[28] Alves, J. L. F., et al. (2022). Prospection of catole coconut (*Syagrus cearensis*) as a new bioenergy feedstock: Insights from physicochemical characterization, pyrolysis kinetics, and thermodynamic parameters. *Renewable Energy*, *181*, 207-218.

[29] Mumbach, G. D., et al. (2024). Unlocking the potential of pequi (*Caryocar brasiliense*) residues for bioenergy and renewable chemicals: Multicomponent kinetic modeling, thermodynamic parameter estimation, and characterization of volatile products through TGA and Py-GC/MS experiments. *Industrial Crops and Products*, *209*, 117928.

[30] García, R., Pizarro, C., Lavín, A. G., & Bueno, J. L. (2014). Spanish biofuels heating value estimation. Part II: Proximate analysis data. *Fuel*, *117* (Part B), 1139-1147.

[31] Parikh, J., Channiwala, S. A., & Ghosal, G. K. (2005). A correlation for calculating HHV from proximate analysis of solid fuels. *Fuel*, *84*(5), 487-494.

[32] Huang, L., et al. (2016). Thermodynamics and kinetics parameters of co-combustion between sewage sludge and water hyacinth in CO_2 /O_2 atmosphere as biomass to solid biofuel. *Bioresource Technology*, *218*, 631-642.

[33] Huang, H., Liu, J., Liu, H., Evrendilek, F., & Buyukada, M. (2020). Pyrolysis of water hyacinth biomass parts: Bioenergy, gas emissions, and by-products using TG-FTIR and Py-GC/MS analyses. *Energy Conversion and Management*, *207*, 112552.

[34] Gao, J., et al. (2023). In-situ catalytic bio-oil production from hydrothermal liquefaction of Cu-impregnated water hyacinth: Screening of reaction parameters. *Journal of the Energy Institute*, *109*, 101308.

[35] Kumar, M., Upadhyay, S. N., & Mishra, P. K. (2019). A comparative study of thermochemical characteristics of lignocellulosic biomasses. *Bioresource Technology Reports*, *8*, 100186.

[36] Abdullah, M. Z., Husain, Z., & Pong, S. L. Y. (2003). Analysis of cold dow fluidization test results for various biomass fuels. *Biomass and Bioenergy*, *24*, 487-494.

[37] Almeida, M. C. P. dos S., et al. (2024). Valorization of wood residues from vegetation suppression during wind energy plant implementation and its potential for renewable phenolic compounds through flash pyrolysis: A case study in northeast Brazil's semi-arid region. *Forests*, *15*(4), 621.

[38] de Paiva, E. M., et al. (2024). Pyrolysis of cashew nutshell residues for bioenergy and renewable chemicals: Kinetics, thermodynamics, and volatile products. *Journal of Analytical and Applied Pyrolysis*, *177*, 106303.

[39] Hu, Z., Ma, X., & Li, L. (2015). Optimal conditions for the catalytic and non-catalytic pyrolysis of water hyacinth. *Energy Conversion and Management*, *94*, 337-344.

[40] Harun, M. Y., Dayang Radiah, A. B., Zainal Abidin, Z., & Yunus, R. (2011). Effect of physical pretreatment on dilute acid hydrolysis of water hyacinth (*Eichhornia crassipes*). *Bioresource Technology*, *102*(8), 5193-5199.

[41] Irewale, A. T., Dimkpa, C. O., Elemike, E. E., & Oguzie, E. E. (2024). Water hyacinth: Prospects for biochar-based, nano-enabled biofertilizer development. *Heliyon*, *10*(17), e36966.

[42] Akter, A., Nadim, Md. K. A., Mitu, M., Reza, Md. S., Alim, S. M. A., & Islam, Md. M. (2023). Water hyacinth: Potential applications for environmental sustainability and socio-economic development. *Journal of Agroforestry and Environment*, *16*(1), 31-39.

[43] Maulidyna, A., et al. (2021). Review: Economic impacts of the invasive species water hyacinth (*Eichhornia crassipes*): Case study of Rawapening Lake, Central Java, Indonesia. *International Journal of Bonorowo Wetlands*, *11*(1).