The Production of Eco-Friendly and High-Quality Paper, and an Alternative to Coal from Eichhornia Plant and Testing Their Physical and Chemical Properties Respectively

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Abstract

Eichhornia, a rapidly regenerating aquatic plant from the Nile River. Its leaves contain 53.45% cellulose, 24.43% lignin, and 22.12% hemicellulose (Smith et al., 2020) — values comparable to those found in wood fibers: 25%lignin and 25%-35% hemicellulose*(General compositions of softwoods and hardwoods and their lignin linkages, n.d.)* both Eichhornia plant and wood share similar composition. Due to its high cellulose content it is suggested that the plant could be a viable alternative raw material for wood in the paper industry in Egypt. In this study, stalks were processed via a 10% KOH pulping method at 100–120°C to extract cellulose, followed by a 10% NaOCl bleaching step to obtain white pulp. Paper sheets (1 cm × 5 cm) produced from this pulp showed a high rigidity and a high ductility such as commercial paper and exhibited a maximum stress of 0.37500 MPa, strain of 0.28000%, force of 1.87500 N, displacement of 0.11200 mm, and a gauge length of 40.0000 mm. Additionally, mixing the remaining roots with dark liquor produced as a by-product in the pulping process in a 6:1 ratio yielded mixture. This mixture is used to make tablets which can be an alternative source of energy instead of coal in low-temperature heating applications such as space heating in well-insulated buildings. In addition, the benefit from these by-products and wastes contributes to sustainability and preserving the environment from harmful wastes. The tablets' heat of combustion was measured by Oxygen bomb calorimeter and was approximately 9.18 MJ/Kg.These results indicate that using Eichhornia not only produces paper with competitive mechanical properties relative to commercial wood-based paper in tensile strength, strain and deformation, provide an alternative source of energy but also offers a sustainable approach by making an advantage of this environmentally and economically harmful plant.

Keywords: Eichhornia, cellulose fibers, dark liquor, paper and heat of combustion

Introduction

Eichhornia crassipes, commonly known as water hyacinth, is one of the world's most invasive aquatic plants. Numerous studies have documented its detrimental impact on freshwater ecosystems. Its rapid growth and tendency to form dense mats on the water's surface have been shown to significantly reduce light penetration and deplete dissolved oxygen, leading to fish kills and loss of biodiversity. For example, research conducted in regions along the Nile has reported that these mats block sunlight essential for submerged vegetation and create hypoxic conditions detrimental to aquatic life (Gopal, 1987). Moreover, water hyacinth's high water uptake—exceeding three billion cubic meters annually in some places (Shabana, 2005)—additional stress on water resources and increases the economic burden on water management authorities, as repeated removal efforts prove both challenging and costly due to the plant's rapid vegetative reproduction within 7–10 days (Gopal, 1987). Despite these ecological challenges, Eichhornia crassipes exhibits a promising chemical composition for industrial applications. Its leaves contain approximately 53.45% cellulose, 24.43% lignin, and 22.12% hemicellulose (Smith et al., 2020)—values that are remarkably similar to the composition of conventional wood fibers which generally contain around 25% lignin and 25–35% hemicellulose (General compositions of softwoods and hardwoods and their lignin linkages, n.d.).

Prior research into non-wood fibers for paper production has highlighted water hyacinth's potential as a sustainable alternative, especially in regions facing deforestation and high imports of paper pulp. Building on these findings, the present study hypothesizes that the plant can be utilized not only to produce paper pulp with competitive mechanical properties but also to generate an energy source from its residual biomass through tablet formation, thus addressing both environmental and economic concerns

Materials and Methods

Eichhornia plants were collected from the Nile River water. After removing the leaves and roots, the stalk portions were separated and washed with freshwater to remove impurities. The washed stalks were air dried at ambient temperature of 30-45 ◦C on the oven for 6 hours to be able to grind it and cut it into small pieces. Pulping was done using *potassium hydroxide (KOH)* at about 10% percentage for around 3 hours to dissolve lignin in order to extract the cellulous from the wood fibers. The process was carried out at a high temperature of (100◦C:120◦C) to increase the efficiency of the pulping process. Then the temperature was decreased to 20◦C and *NaOCl* solution at concentration 10% was added for around 24 hours to produce a white paper:bleaching process. *NaOCL* was chosen for the pulping process to decrease the overall process cost. In addition, *NaOCl* offers several distinct advantages over hydrogen peroxide H_2O_2 which is that it is a more powerful oxidizer than the *H2O2*, which enables it to break down lignin and other non-cellulosic components more efficiently. After the pulp was produced the paper sheets were formed and dried on a specimen of porous, hydrophilic textile for around 24 hours and then they were cut at size 1cm length and 5cm width to test their mechanical properties then by tensile testing. All chemicals used in the experiments were procured from the laboratory's internal inventory.

Two major byproducts resulted from the process. The first byproduct is the residual roots of the Eichhornia plant. The second byproduct is the dark liquor generated during the KOH-based lignin isolation process; this liquor primarily contains solubilized lignin fragments, carbohydrate derivatives, and residual alkaline chemicals—mainly unreacted potassium hydroxide and its derived salts. The Eichhornia plant's remaining roots and the dark liquor were subsequently blended at a ratio of 6:1 (roots to liquor) to produce tablets exhibiting a high heat of combustion, thereby presenting a potential alternative to coal in low-temperature heating applications such as space heating in well-insulated buildings. This mixture was then subjected to an oven-drying process at temperatures between 60 and 80 °C for approximately 4 hours after shaping them into circular molds until completely dried. Finally, the heat of combustion of the dried tablets was measured using an oxygen bomb calorimeter to assess the potential of this mixture as an alternative energy source to coal.

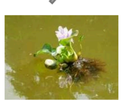

FIGURE 1. Eichhornia plant

FIGURE 2. Drying leaves to be grind

FIGURE 3. Lignin isolation process.

FIGURE 4. Cellulose fibers separation from dark

FIGURE 5. Paper pulp

FIGURE 6. Produced paper.

FIGURE 7. Tablets of high heat of combustion

FIGURE 8. Drying the root powder and dark liquor mixture

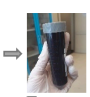

FIGURE 9. Dark liquor process

FIGURE 10. Powder of Eichhornia roots

Results

Following the chemical treatment of the plant fibers and their subsequent formation into paper, a series of experiments was conducted to evaluate the quality and elucidate the mechanical properties of the material—specifically its maximum stress, strain, force, displacement, and gauge length. To achieve this, tensile testing was performed using a universal testing machine configured as a tensile tester. Two sheets were chosen for the experiment. These two paper specimens, each measuring 1 cm by 5 cm, were secured such that a gauge length of 40 mm was defined. The samples were then subjected to a controlled uniaxial tensile load until they deformed and ultimately failed. Throughout the test, the device continuously measured and recorded the applied force, the corresponding displacement, and calculated both the stress and strain experienced by the paper.

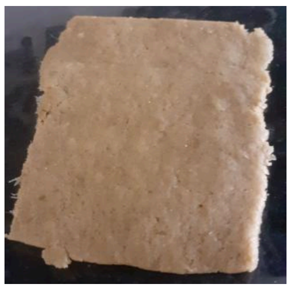

FIGURE 11. Paper samples before drying.

A uniaxial tensile test was performed on a rectangular paper sheet with the following dimensions: 0.50 mm thickness, 10.00 mm width, and a 40.00 mm gauge length. The cross-sectional area of the specimen is therefore 5.00 mm². Strain was calculated from the testing machine's crosshead displacement over the 40 mm gauge length, and stress was obtained by dividing the recorded load by the cross-sectional area.

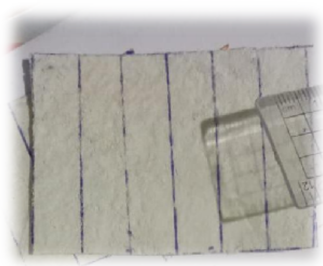

FIGURE 12. Paper samples after drying marked to be 1 cm x 5 cm sheets.

Sample #1	Thickness	Width	Gauge Length
Units	mm	mm	mm
1 - 1	0.5000	10.0000	40.0000

Table (1)

Name	Max_Force	Max_Disp	Max_Stress	Max_Strain
Units	N	mm	MPa	%
1 - 1	1.87500	0.11200	0.37500	0.28000

Table (2)

Sample #2	Thickness	Width	Gauge Length
Units	mm	mm	mm
1 - 1	0.5000	10.0000	40.0000

Table (3)

Name	Max_Force	Max_Disp	Max_Stress	Max_Strain
Units	N	mm	MPa	%
1 - 1	3.12500	0.21000	0.62500	0.52500

Table (4)

For the dark liquor resulting from the lignin isolation process and roots remaining, which are rich in organic compounds such as carbon and phosphorous, that makes them capable to produce heat energy from combustion process, for that reason a mixture of Eichhornia roots and dark liquor was used to produce alternative source of coal as shown in fig (15). After producing the samples, the heat of combustion of it was measured to be compared with heat of combustion produced by thermal coal by using Oxygen bomb calorimeter as shown in table (5).

FIGURE 13. Dark Liquor

FIGURE 14. Powder of Eichhornia roots.

FIGURE 15. Resulting Samples.

Eichhornia roots and dark liquor	9.18 MJ/ Kg
Coal	29.3 MJ/ Kg

Table (5) heat of combustion of coal compared with Eichhornia roots and dark liquir mixture

Discussion

The use of waste materials and their investment for the benefit of humanity is one of the most important strategies that will achieve sustainability on the surface of the earth. In this research paper, it was able to produce high quality paper from cellulose fibers in Eichhornia plant and an effective source of energy from Eichhornia roots and the dark liquor, thereby presenting a potential alternative to coal in low-temperature heating applications such as space heating in well-insulated buildings. After doing multiple trials to increase the effectiveness of the produced paper, The Eichhornia paper was compared to commercial paper: from stress/strain curve as shown in fig (17) and fig (16) the produced paper has high rigidity and high ductility such as commercial paper. The Paper could be produced from the fibers of Eichhornia plant, NaOCl was inexpensive and effective in bleaching the paper. The KOH was affordable, and suitable for the plant fibers.

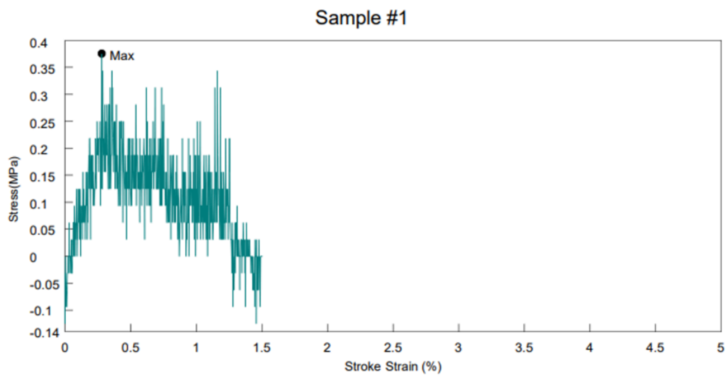

FIGURE 16. Stress/Strain for Sample 1.

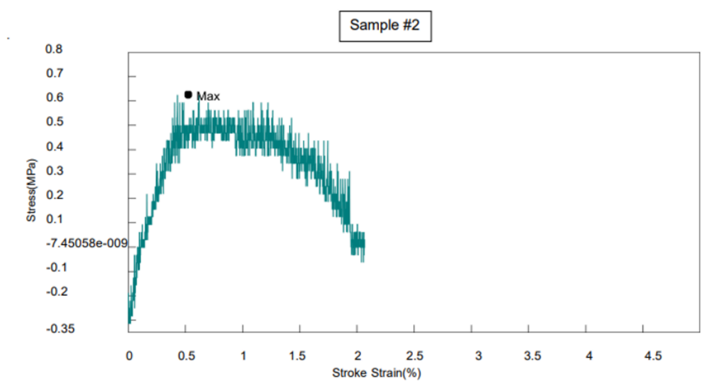

FIGURE 17. Stress/Strain for Sample 2.

In a large-scale process, 100 g of paper pulp was produced using 5 g of potassium hydroxide (KOH) and 5 g of sodium hypochlorite (NaOCl). According to current supplier pricing data, the cost of KOH is approximately $0.10 per kilogram and that of NaOCl is about $1.41 per kilogram (Sigma-Aldrich, 2021). Moreover, these chemicals are widely used in wastewater treatment applications for processes such as oxidation and disinfection, where their cost-effectiveness has been documented (United States Environmental Protection Agency [EPA], 2020). The estimated production cost for one kilogram of paper pulp is approximately $0.062 (ICIS, 2022). In contrast, market surveys indicate that the current commercial price for paper pulp is about £20.18 per kilogram (Statista, 2022).

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Pulp Yield of Eichhornia and Comparison to Other Sources

Cost Analysis and Economic Viability

Fixed Costs

According to Walls (2023), the initial establishment cost for a dedicated paper factory is estimated at \$4.9 million, which covers expenses such as land acquisition, factory setup, and machinery procurement. Additional fixed costs include a solar energy installation at \$13,000 (Samani, 2022) and transport carts priced at \$14,700 (World Paper Mill, 2023).

To minimize these expenses, an alternative strategy involves repurposing the existing Rakata factory in Alexandria—previously used for rice straw–based paper production. By utilizing pre-existing infrastructure and making only minor modifications to adapt machinery for processing Eichhornia pulp, fixed costs could be reduced substantially (World Paper Mill, 2023).

Variable Costs

For Eichhornia pulp production, the costs of raw materials and chemicals are as follows:
KOH (Potassium Hydroxide): \$1.41 per kg;
NaOCl (Sodium Hypochlorite): \$0.10 per kg;
Eichhornia pulp processing: \$0.062 per kg.

These figures are reported by Poomsawat et al. (2023) and result in a total production cost of approximately \$61.05 per ton of Eichhornia–based paper. This cost is significantly lower than the prevailing market price of paper, which stands at about \$1,632.45 per ton (Poomsawat et al., 2023).

Profitability and Investment Recovery

With a market price for paper at roughly \$1,632.45 per ton and production costs of \$61.05 per ton, the net revenue per ton is calculated as follows:
Net Revenue per Ton = \$1,632.45 − \$61.05 = \$1,571.40 per ton.

Assuming a daily production capacity of one ton, Walls (2023) estimates that a small factory could generate annual revenue of approximately \$574,561. Under stable production and market conditions, the fixed investment of \$5 billion is projected to be recovered in about 8 years (Walls, 2023).

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References

Abral, H., Dalimunthe, M. H., Hartono, J., Efendi, R. P., Asrofi, M., Sugiarti, E., Sapuan, S. M., Park, J.-W., & Kim, H.-J. (2018). Characterization of tapioca starch biopolymer composites reinforced with micro scale water hyacinth fibers (pp. 7-8). Starch/Stärke, 70, 1700287. https://doi.org/10.1002/star.201700287

Kriticos, D. J., & Brunel, S. (2015). Assessing and managing the current and future pest risk from water hyacinth (Eichhornia crassipes), an invasive aquatic plant threatening the environment and water security. PLOS ONE, 10(10), e0120054. https://doi.org/10.1371/journal.pone.0120054

Hidayah, N., & Wusko, I. (2020). Isolation of cellulose fiber from water hyacinth (Eichhornia crassipes) by bleaching-alkalination method. In Proceedings of the First National Seminar Universitas Sari Mulia. https://doi.org/10.4108/eai.23-11-2019.2298330

Islam, M., Rahman, F., Papri, S., Faruk, M., Das, A., Adhikary, N., Debrot, A., & Ahsan, M. (2021). Water hyacinth (Eichhornia crassipes (Mart.) Solms.) as an alternative raw material for the production of bio-compost and handmade paper. Journal of Environmental Management, 294, 113036. https://doi.org/10.1016/j.jenvman.2021.113036

Novaes, E., Kirst, M., Chiang, V., Winter-Sederoff, H., & Sederoff, R. (2010, October). Lignin and biomass: A negative correlation for wood formation and lignin content in trees (pp. 555-561). Plant Physiology, 154(2). https://doi.org/10.1104/pp.110.161281

Ho, C. Y., Powell, R. W., & LiLEY, P. E. (2009). Selected values of heats of combustion and heats of formation of organic compounds containing the elements C, H, N, O, P, and S (pp. 1221-1277). Journal of Physical and Chemical Reference Data, 38(4), https://doi.org/10.1063/1.3253099