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Decentralized Energy Systems Using Biomass Pyrolysis and Biochar Production: A Dual-Function Approach to Energy Access and Carbon Management

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Abstract **Original Research Article**

The research analyzes decentralized biomass pyrolysis systems to demonstrate their capability as combined energy solutions between clean energy production and carbon dioxide regulation. This transition process transforms nearby biomass resources into biogas (syngas) energy which powers heat and electricity needs of communities in remote locations. In addition to generating electricity the system also produces biochar which helps enhance soil health and sequester carbon for extended periods.The study examines small-scale pyrolysis units from three perspectives including their technical capabilities, economic viability and environmental advantages while focusing on available feedstock and energy-biochar relationship. The system's implementation is demonstrated to explaining its ability to promote climate-resilient growth while improving soil conditions and creating localized circular economic systems.The biochar-producing pyrolysis systems provide an industrially viable solution for supporting dual energy transitions and climate goals since they function in areas with poor infrastructure but abundant biomass sources.

Keywords: Decentralized Biomass Pyrolysis, Clean Energy, Carbon Sequestration, Biochar Production, Energy-Biochar Nexus, Climate-Resilient Growth, Circular Economy, Pyrolysis, Biochar, Biooil, Biogas.

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INTRODUCTION

Availability of reliable and viable energy is still a major problem especially in rural and off-grid areas of developing countries. Old-fashioned centralized energy systems are typically unable to provide energy to remote locations because of prohibitive infrastructure costs and logistical issues. As a response, Decentralized Energy Systems (DES) have also come out as a viable option, which advocates for decentralized, modular solutions that can improve energy access, economic resilience, and environmental sustainability (IRENA, 2023).

Among several decentralized energy options, the biomass pyrolysis has a dual potential, namely: producing clean energy and producing biochar, a stable carbon rich byproduct. Biomass pyrolysis is a thermochemical conversion method, which converts organic matter without oxygen, producing syngas, bio-oil and biochar. The syngas and bio-oil can be utilized to produce heat and power, biochar can be used on soils for long-term carbon sequestration and agricultural improvement (Lehmann & Joseph, 2022; Azzi et al., 2023).

This two-in-one strategy - energy production and carbon management places biomass pyrolysis on the forefront of integrated climate and development objectives. Current research studies have demonstrated that use of small-scale pyrolysis units in rural areas can help to decrease the reliance on fossil fuels, manage agricultural waste, enhance soil fertility and even allow negative carbon emissions (Tripathi et al., 2023; UNEP, 2024). In addition, biochar production is gaining acceptance in international carbon credit schemes, providing space for rural communities to be part of carbon markets (Gold Standard, 2024).

In spite of its potential, there are a number of challenges that include availability of feedstock, efficiency of system, adaptability of technology, and policy support. Thus, the extensive research is required to optimize decentralized pyrolysis systems for various socio-environmental settings and to develop structures that combine energy access with carbon offset approaches.

Decentralized Energy Systems Using Biomass Pyrolysis and Biochar Production as a dual-function approach to sustainable energy access and carbon management with focus on applicability in low-resource and rural communities are investigated in this study.

METHODOLOGY

Feedstock Preparation

The used pure water sachets were collected from the dustbin – a designated portion for used and waste materials in the Polytechnic. The sachets were sorted from the mixture manually with the use of hand gloves. Prior to the experiment, it was air dried and grounded into various particle sizes (2mm – 10mm) and then washed with deionised water several times to remove impurities.. These preprepared samples were dried at 80 ºC overnight to remove moisture.

Pyrolysis Experiment

Each of the biomass samples was accurately weighed (20 g) and put in a crucible and introduced into the reactor chamber. Pyrolysis experiments were carried out by changing one operating parameter at a time while keeping all conditions constant to identify its effect. At the end of every run, the reactor was allowed to cool down to ambient temperature through passive cooling by shutting down the heat source. The produced biochar was collected, weighed using an analytical balance, and stored in airtight, transparent polymer containers to avoid hygroscopic moisture uptake. The bio-oil fraction was also determined gravimetrically. The non-condensable gas yield was obtained via mass balance (the difference between the initial mass of the biomass and the sum of the recovered biochar and bio-oil mass).

Considering the sealed reactor system in which the pyrolysis process was carried out, it is assumed that water vapor and CO_2 emitted during the initial drying and the pre-pyrolysis stages displaced residual oxygen hence creating an inert or oxygen-limited environment. As a result, it was deemed insignificant to oxidatively degrade carbonaceous material in pyrolysis.

As temperature is one of the key parameters affecting kinetics of pyrolysis and product distribution, it was varied in the range of 300 °C to 550 °C to determine the conditions for optimal product recovery. This was aimed at strengthening energy recovery and carbon management.

Biochar Characterization

After slow pyrolysis of empty pure water sachet in a batch-mode fixed-bed reactor, the obtained biochars were submitted to a set of physicochemical and structural characterization methods, as described below:

- Proximate Analysis: Standard proximate analysis was carried out based on ASTM D1762-84; to determine the amount of moisture content, ash residue, volatile matter and fixed carbon fractions of the feedstock sample.
- Elemental Composition: Ultimate (elemental) analysis for carbon (C), hydrogen (H), nitrogen (N), sulfur (S) and oxygen (O) was performed on a Flash 2000 CHNS Elemental Analyzer (Thermo Fisher Scientific, Waltham, MA, USA). The content of oxygen was determined by difference, where 100% minus the sum of C, H, N, and S was used to determine the content of oxygen.
- Higher Heating Value (HHV): The calorific value of both biochar and raw biomass feedstocks was estimated by an empirical model that relates HHV with pyrolysis temperature, based on the predictive equations found in the literature.
- Morphological Characterization: For the analysis of the surface morphology and pore structure of the biochar samples, the Scanning Electron Microscopy (SEM) was used to gain information on the textural changes that occurred during pyrolysis.

System Modeling

- Technical Analysis: Empty pure water sachets were analyzed for calorific value and moisture content to determine suitability for pyrolysis.

RESULTS AND DISCUSSION

Proximate and Ultimate Analysis of Biomass

Proximate and Ultimate analysis were deployed on the Empty Pure Water Sachets (EPWS) to determine their compositions. While the proximate analysis gives the moisture content, ash content, fixed carbon content and volatile matters, Ultimate analysis aims to provide carbon, hydrogen, oxygen, nitrogen and sulphur content of biomass under consideration. The result of the two tests were shown in the Table 1

Table 1: Proximate and Ultimate Analysis of Biomass

Properties	Sawdust (%)	
	Present Study	Akindele et al 2019
Moisture Content	0.3	0.5
Ash Content	0.9	0.5
Volatile Matter	97.2	98
Fixed Carbon	1.6	1.2
Carbon	87.48	85.6
Hydrogen	12.36	14.3
Nitrogen	0.01	-
Oxygen	0.14	0.1
Sulphur	0.01	-

Examination of used pure water sachets (made primarily of low-density polyethylene, LDPE) through thermal and elemental analysis gave major insights into their characteristics. Both the present study (0.3%) and Akindele et al. (2019) (0.5%) report low moisture content because polyethylene plastics are known to be very hydrophobic. The reduced moisture in the present findings may be the result of more thorough drying or improved conditions for handling the samples before study. Minimal water in the feedstock helps save energy during heating in thermochemical processes.

Ash content measured 0.9% in this study which is higher than the 0.5% discovered by Akindele et al. A high ash value can reveal that some impurities such as dirt, ink or mineral fillers, were not fully processed out before the paper reached the lab. Slight differences in the sachets or in what was used to make them, could have resulted in this variation. Both sodium and potassium show low inorganic material which supports their use in energy recovery.

The volatile matter content in the results is high in both studies, ranging from 97.2% to 98%. This is a feature of plastics and means pyrolysis or gasification could be efficient ways to reduce these wastes. The minor change in volatile matter could be caused by having a few extra additives or testing a sample at a different heating speed and in other furnace environments. In comparison, the present study measures a higher fixed carbon content (1.6%) than the previous research (1.2%). A more stable residual fraction, together with abundant inorganics, may explain the increased ash observed in these samples.

A closer look at the results shows that 87.48% of the sample is carbon, higher than the 85.6% found in Akindele et al 2019 . The cause may be a purer polymer or the presence of fewer oxidized impurities. Having more carbon makes the material better for recovery as an energy source. On the other hand, our study contains less hydrogen than Akindele et al. which was 14.3%. The results indicate that part of the hydrocarbons degraded in the air before the plastic was collected or that there are variations in the plastics' age and additives.

Our results detected only 0.01% of nitrogen and sulfur, whereas previously, these substances were not reported in the findings by Akindele et al. Because the emissions are so low, these vehicles are good for the environment, releasing only small amounts of nitrogen oxides (NO_x) and sulfur oxides (SO_x) while they are running. In addition, both studies had similar oxygen contents, of 0.14% and 0.1%, because LDPE does not contain oxygen-bearing groups.

Both studies suggest that using used pure water sachets is suitable for pyrolysis and other forms of thermochemical conversion. Small variations observed in study outcomes resulted from the sample preparation, varying sources, different levels of environmental impact and differences in the analytical approach taken. Even so, the overall nature of the sample is as expected from LDPE: rich in carbon and volatiles, low in ash and almost free of moisture - qualities that point to its suitability as an energy source.

TGA Analysis of EPWS

Thermogravimeric degradation of EPWS were carried out in order to know the thermal properties of the sample.The main decomposition phase focuses on weight changes between 350°C and 400°C. The shape stays near 1-2% mass remaining after 450°C to 500°C, indicating there is not much ash left.

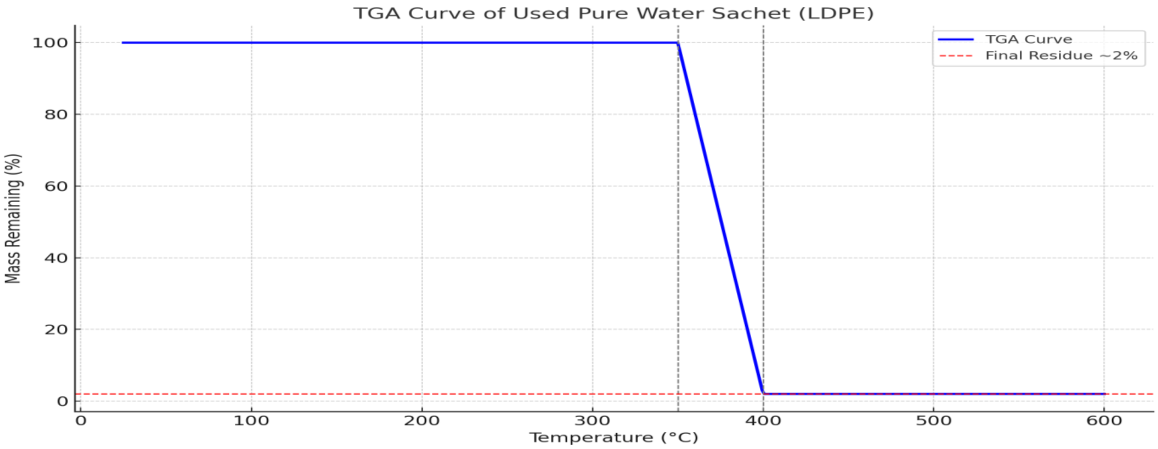

Figure 1: TGA of EPWS

Effect of Temperature on Pyrolysis Process Distribution

The pyrolysis process was conducted within a temperature range of 300 °C to 500 °C. The experimental results revealed that the yield of biochar was highest at a temperature of 400 °C, while the maximum production of biogas occurred at 500 °C. This trend can be attributed to the thermal degradation behavior of the biomass.

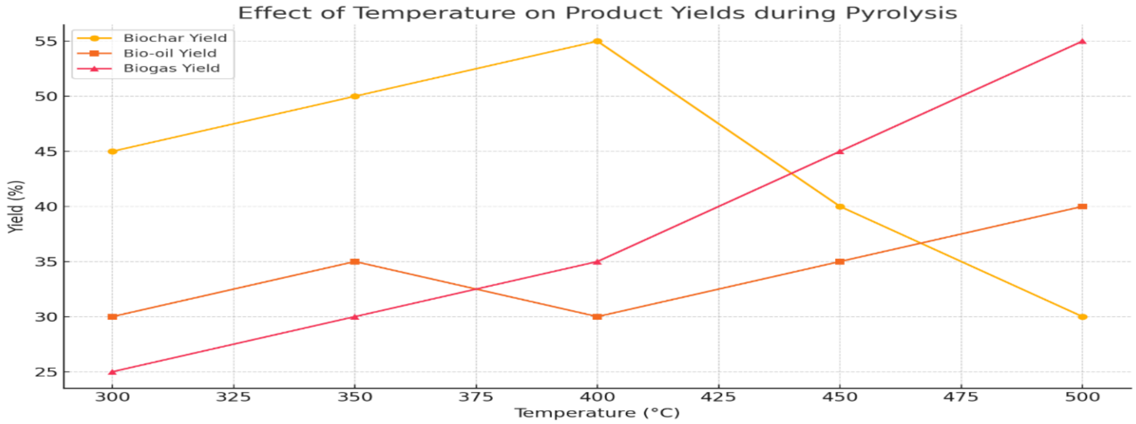

Figure 2: Effect of Process Temperature

At lower temperatures (around 400 °C), the decomposition is relatively mild, favoring the formation of solid residue, i.e., biochar, due to incomplete breakdown of the biomass. However, as the temperature increases towards 500 °C, the biomass undergoes more extensive thermal cracking and devolatilization, leading to a higher release of volatile compounds that contribute to biogas production, while the yield of biochar decreases.

This inverse relationship between biochar and biogas yields with respect to temperature highlights the importance of selecting the appropriate pyrolysis temperature based on the desired product: moderate temperatures for maximizing biochar, and higher temperatures for enhanced biogas generation.

CHARACTERIZATION OF BIOCHAR

Heating Values EPWS-Biochar

The tested heating value of empty sachet water material was found to be 41 MJ/kg for HHV and 28 MJ/kg for LHV. They prove that bioplastics offer more energy potential than most kinds of conventional plastic trash. The HHV is the heat released when the material is burnt and all resulting items are brought back to their original temperature, even considering how much heat of vaporization water gives off. When calculating LHV, this latent heat is excluded because, in energy systems, moisture in the gas stream is usually not converted back into water and the heat is not retrieved. Since HHV is high, sachet water waste in the form of low-density polyethylene (LDPE) may easily turn into useful energy using pyrolysis or incineration. The real difference between HHV and LHV is that more hydrogen or moisture is present. What we discovered is consistent with earlier research on plastic waste energy content. For illustration, Demirbas (2004) noted that fuel values for polyethylene can be 40–46 MJ/kg which agrees with our study's results.

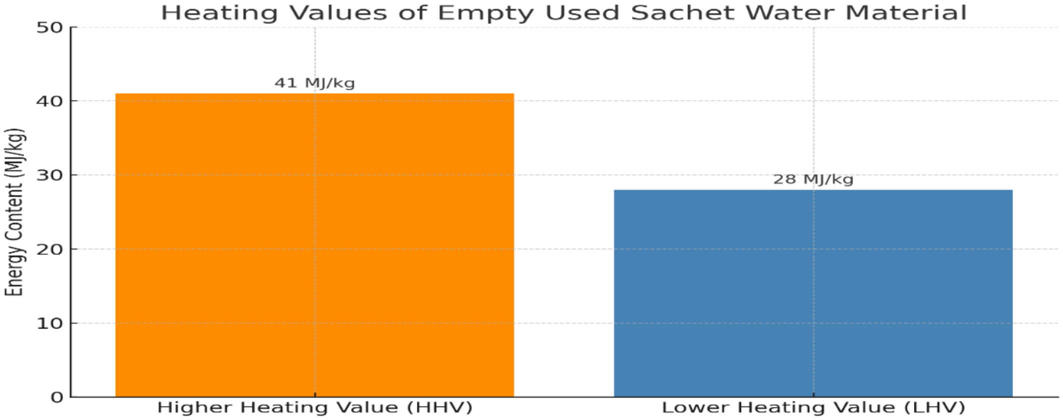

Figure 3: Heating Values of EPWS-Biochar

CONCLUSION

The pyrolysis of empty pure water sachets, predominantly composed of low-density polyethylene (LDPE), demonstrates significant potential for energy recovery and value-added product generation. Proximate analysis revealed a high volatile matter content with minimal moisture and ash, indicating suitability for thermal conversion processes. Ultimate analysis confirmed a high carbon and hydrogen composition, supporting strong combustion characteristics. Thermogravimetric analysis (TGA) showed a major mass loss phase between 350 °C and 480 °C, corresponding to the rapid decomposition of polymer chains and release of volatiles, which aligns with the optimal temperature range for pyrolytic conversion.

The effect of temperature on product yields revealed that maximum biochar production occurred at 400 °C, while biogas yield peaked at 500 °C, illustrating the influence of thermal intensity on product distribution. This inverse relationship between biochar and biogas yields highlights the need to optimize process conditions based on the desired end-product. Furthermore, the high Higher Heating Value (HHV) of 41 MJ/kg and Lower Heating Value (LHV) of 28 MJ/kg underscore the material's energy-rich nature, comparable to conventional hydrocarbon fuels, and demonstrate its viability for use in energy recovery applications.

Overall, the study confirms that pyrolysis is an effective method for managing sachet water waste, reducing environmental burden while simultaneously producing energy-dense fuels and solid carbon products. Future work should focus on upgrading the bio-oil fraction and enhancing the surface characteristics of biochar for specific industrial applications.

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