Optimization of Bio-Oil Production from Coconut Shell Biomass Using Continuous Slow Pyrolysis

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Abstract

Over the past two decades, the global interest in using biomass as a renewable energy source has significantly increased, especially in agriculturally rich countries. A pilot plant with a continuous operation mode was designed, built, and evaluated for producing bio-char and its derivatives, such as bio-oil and synthesis gas. The system comprises a rotary pyrolysis reactor, a cyclone separator, and a condenser unit. An LPG stove provides external heat to the retort, featuring adjustable heat control. The production of bio-oil utilizes a water condensation method for direct condensation. Trials were performed using various biomass types, altering residence times and pyrolysis temperatures. This study presents the yields of bio-oil obtained under various conditions and provides a detailed characterization of these products.

Keywords: pyrolysis reactor, bio-oil,biochar;

1. Introduction

The global energy landscape is increasingly pivoting towards renewable sources due to escalating environmental concerns and the finite nature of fossil fuels. Among renewables, biomass plays a crucial role, particularly in regions with robust agricultural outputs. It offers a promising solution for energy production while simultaneously addressing waste management issues [1]. Recent advances in biomass technology have facilitated more efficient conversion processes, primarily through enhanced pyrolysis techniques. These advancements not only improve energy yield but also contribute to the broader application of biomass in both industrial and residential settings [2]. Sustainability in biomass energy production is critical, considering its impact on carbon emissions and potential contributions to climate change mitigation. Studies highlight the dual benefits of biomass: reducing reliance on fossil fuels and minimizing carbon footprints [3]. The design of efficient pyrolysis systems is fundamental to optimizing biomass conversion. The continuous type pilot plant discussed herein represents a significant step forward, incorporating a rotary pyrolysis reactor, cyclone separator, and condenser assembly for optimal energy recovery [4]. Heating efficiency and control are paramount in pyrolysis processes. The use of an LPG stove with adjustable heat settings in the pilot plant allows for precise management of the pyrolysis temperature, critical for maximizing bio-oil yield [5]. The method of condensing bio-oil directly influences its quality and yield. Employing a water condenser method, as utilized in this study, ensures direct condensation, which is essential for preserving the integrity and energy content of the bio-oil [6]. A range of biomass types, residence times, and pyrolysis temperatures were experimented with to establish optimal conditions for bio-oil production. These experiments are vital for understanding the variable impacts on bio-oil yield and characteristics [7]. Looking forward, integrating IoT and AI technologies into biomass pyrolysis processes could further enhance efficiency and control, paving the way for smarter renewable energy systems [8]

2. Materials and Methods

2.1 Experimental Procedure

Each experiment begins by setting predefined conditions including the initial biomass sample's weight, the temperature of the reactor, the flow rate of nitrogen, and the screw's velocity. Initially, the biomass undergoes milling and thorough drying. A predetermined weight of the sample is then measured and placed in a sealed glass flask, separate from the main reactor. The reactor's temperature is controlled by igniting the burner, which utilizes LPG as fuel. As the reactor warms up, the rising temperature is continuously monitored and displayed via a temperature sensor. The pyrolysis reaction is initiated at the set conditions, during which both the temperature and duration are recorded at the moment bio-char is collected. Concurrently, gases that can be condensed are directed through iron pipes towards the condenser. Here, specific gases are cooled and condensed to form pyrolytic oil, commonly referred to as bio-oil. The process concludes with the production of three main byproducts: bio-char, bio-oil, and synthesis gas, all resulting from the pyrolysis of the biomass.

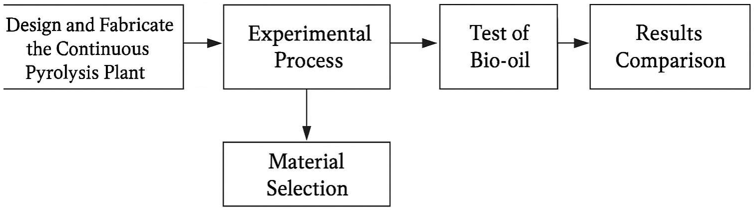


Fig 1: Flow chart of the proposed work.

A comprehensive pyrolysis unit will be constructed, which includes a reactor, a cyclone separator, a condenser, and the necessary piping for downstream processing. The detailed steps of this process are illustrated in Figure 1. A continuous screw-type reactor will be engineered with a specialized heating system utilizing LPG for intensive heat application. Additionally, the cyclone separator within the unit is meticulously designed to efficiently separate bio-char from the pyrolysis vapors. The unit will feature a coiled-type water coolant condenser, which is crucial for separating bio-oil from synthesis gases. Furthermore, a hopper will be integrated to regulate the amount of biomass fed into the reactor. A preprocessing unit is planned to manage the size reduction of various biomass materials to an optimal particle size of approximately 8mm. This step is essential for ensuring the uniformity and efficiency of the feed material entering the reactor.

2.2 Pyrolysis Process: Experiments on pyrolysis were carried out using a rotating drum reactor, which features a sweep gas system utilizing nitrogen. This reactor is heated externally with LPG. The investigation focused on several critical parameters: the reaction temperature, nitrogen flow rate, and biomass particle size, all of which are integral to the pyrolysis process.

2.3 Raw Material Preparation: As depicted in Figure 2, the preparation process involves using 15 kg each of coconut shells and coconut husks, along with 8 kg of dried coconut munch, achieving a moisture content of 8-9%. Post-drying, the larger samples are cut into smaller pieces, approximately 1 inch in length, to enhance the efficiency of the combustion process. These prepared samples are then placed into the pyrolysis reactor for further processing.

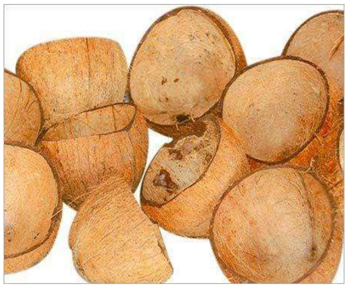


Fig 2: Coconut shell

3. Results and Discussion

3.1 Producing bio- oil

The yield of bio-oil during the pyrolysis process is influenced by temperature variations, which can be regulated through a gas flow controller using a valve mechanism. When the combustion chamber operates within the temperature range of 220°C to 260°C, there is a higher production of char. However, temperatures exceeding 250°C tend to enhance the generation of bio-oil and syngas. The percentage yield of bio-oil is determined using the following equation:

Yield (%) = (Weight of bio-oil produced [kg] / Weight of biomass fed [kg]) × 100%

(Equation 1)

In this study, coconut shell was selected as the biomass feedstock. The shells were cut into 1-inch segments, and an initial mass of 2.5 kg was prepared and introduced into the pyrolysis chamber, which was maintained at 280°C. After 15 minutes of processing, approximately 1.7 kg of char was recovered, while the collected bio-oil amounted to 4.88 kg. This observation reflects the effectiveness of high-temperature pyrolysis in maximizing liquid product yield from coconut shell biomass.

Fig 3: Bio-oil

3.2 Characteristics of bio-oil

The characteristics of raw coconut shell bio-oil, its diesel blend, and pure diesel were evaluated following ASTM standards, revealing notable differences among the fuels as summarized in the table 1. The physicochemical properties of coconut shell bio-oil, its diesel additive blend, and pure diesel fuel demonstrate notable differences essential for evaluating their suitability in combustion applications. The **flash point** and **fire point** of coconut shell bio-oil are significantly higher, recorded at 260°C and 320°C respectively, which implies enhanced safety in storage and handling compared to diesel, which exhibits lower values of 45°C and 60°C. The **bio-oil blend**, combining bio-oil with diesel additives, shows intermediate values (flash point of 120°C and fire point of 125°C), making it a safer alternative than diesel while offering better combustion support.

In terms of **calorific value**, diesel has the highest energy content at 43,500 KJ/Kg, closely followed by the bio-oil blend with 40,170 KJ/Kg. In contrast, coconut shell bio-oil has a comparatively lower calorific value of 18,450 KJ/Kg. When analyzing low-temperature flow properties, **pour point** and **cloud point** show that diesel performs better in cold environments with values of -18°C and -3°C respectively. The bio-oil blend exhibits moderate cold flow performance (pour point -10°C, cloud point 1°C), whereas coconut shell bio-oil performs the least favorably with a pour point of 4°C and a cloud point of 18°C.

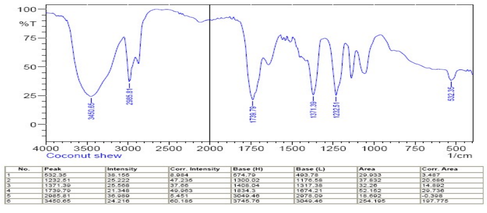
Looking at **density at 40°C**, coconut shell bio-oil has the highest value at 926 kg/m³, followed by diesel at 820 kg/m³, and the blend at 764 kg/m³. Regarding **viscosity at 40°C**, diesel shows the highest viscosity of 4.2 cSt, the bio-oil blend has a moderate viscosity of 3.42 cSt, and coconut shell bio-oil has the lowest at 1.42 cSt, indicating smoother flow characteristics. Finally, the **ash content** is minimal in diesel (0.01%), slightly higher in the blend (0.25%), and highest in coconut shell bio-oil (0.36%), indicating a greater likelihood of residue or deposits when using the bio-based fuel. Overall, blending coconut shell bio-oil with diesel improves energy content and handling safety while mitigating some limitations of using raw bio-oil alone.

Table 1: Properties of coconut shell vs blended bio-oil

Properties	Coconut shell Bio-oil	Bio-oil Blended (Bio-oil diesel additive)	Diesel
Flash Point	260ºC	120 ºC	45 ºC
Fire Point	320ºC	125 ºC	60 ºC
Calorific Value KJ/Kg	18450	40170	43500
Pour Point	4	-10	-18
Cloud Point	18	1	-3
Density at 40°C (kg/m3)	926	764	820
Viscosity 40°C (cSt)	1.42	3.42	4.2
Ash Content	0.36%	0.25%	0.01%

3.3 FTIR of Coconut shell:

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical method employed to acquire the infrared spectral profile of a material, whether in solid, liquid, or gaseous form. It is commonly used to examine absorption, emission, photoconductivity, or even Raman scattering properties of substances. Unlike conventional techniques that scan individual wavelengths, FTIR spectrometers capture a full range of infrared frequencies simultaneously, enabling the rapid collection of high-resolution spectral data across a broad spectrum. This makes FTIR particularly efficient for identifying chemical bonds, functional groups, and molecular structures in various sample as shown in Fig 4.



No.	Peak	Intensity	Corr. Intensity	Base (H)	Base (L)	Area	Corr. Area
1	532.35	38.155	8.984	574.79	493.78	29.933	3.487
2	1232.51	25.222	47.235	1300.02	1176.58	37.832	20.686
3	1371.39	25.568	37.66	1408.04	1317.38	32.26	14.892
4	1739.79	21.348	49.963	1834.3	1674.21	52.152	29.736
5	2985.81	36.989	5.451	3049.46	2978.09	18.692	-0.398
6	3450.65	24.216	60.185	3745.76	3049.46	254.195	197.775

Fig 4 : FTIR analysis

Conclusion

The continuous pyrolysis of coconut shell and coconut frond under oxygen-free conditions effectively facilitated the production of bio-oil. By maintaining the chamber temperature above 250°C and employing LPG as the heating source, the process ensured efficient thermal decomposition of the biomass. The systematic monitoring of biomass input and output weights enabled accurate quantification of the bio-oil yield. This method demonstrates the potential of utilizing agricultural residues for sustainable bio-oil generation, offering a viable approach for renewable energy production.

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