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Coconut Fiber Pyrolysis: Bio-Oil Characterization for Potential Application as an Alternative Energy Source and Production of Bio-Degradable Plastics

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Abstract

The current energy crisis could be alleviated by enhancing energy generation using the abundant biomass waste resources. Agricultural and forest wastes are the leading organic waste streams that can be transformed into useful alternative energy resources. Pyrolysis is one of the technologies for converting biomass into more valuable products, such as bio-oil, bio-char, and syngas. This work investigated the production of bio-oil through batch pyrolysis technology. A fixed bed pyrolyzer was designed and fabricated for bio-oil production. The major components of the system include a fixed bed reactor, a condenser, and a bio-oil collector. The reactor was heated using a cylindrical biomass external heater. The pyrolysis process was carried out in a reactor at a pressure of 1atm and a varying operating temperature of 150˚C, 250˚C, 350˚C to 450˚C for 120 minutes. The mass of 1kg of coconut fiber was used with particle sizes between 2.36 mm - 4.75 mm. The results show that the higher the temperature, the more volume of bio-oil produced, with the highest yield being 39.2%, at 450˚C with a heating rate of 10˚C/min. The Fourier transformation Infrared (FTIR) Spectroscopy analysis was used to analyze the bio-oil components. The obtained bio-oil has a pH of 2.4, a density of 1019.385 kg/m^3, and a calorific value of 17.5 MJ/kg. The analysis also showed the presence of high-oxygenated compounds; carboxylic acids, phenols, alcohols, and branched oxygenated hydrocarbons as the main compounds present in the bio-oil. The results inferred that the liquid product could be bestowed as an alternative resource for polycarbonate material production.

Keywords

Batch Pyrolysis Technology, Coconut Fiber, Bio-Oil, Fourier Transformation Infrared Analysis

1. Introduction

Fossil fuels, while dominant in the energy sector, contribute to climate change, prompting the search for renewable energy sources [1]. Pyrolysis, a thermo-chemical technique used to recover energy from organic waste (biomass), heats the biomass material to approximately 500˚C in an oxygen-free environment [2]. The process generates bio-char, bio-oil, and light gases like Carbon Monoxide (CO), Hydrogen (H_2), Carbon Dioxide (CO_2), Methane (CH_4), and Water Vapor (H_2O) [3]. Biomass, derived from agricultural waste, industries, households, and forestry waste, is abundant in Sub-Saharan Africa. For instance, Kenya has significant resources, including coffee husks, stalks, cobs, sugarcane bagasse, and coconut waste [4]. While some residues are utilized for nutrient recycling or electricity generation, coconut waste remains underutilized, with more than 20,000 tons produced annually from approximately 10.2 million trees [5]. The coconut's mesocarp, comprising fibers and cork-like cells, is rich in hemicellulose, lignin, and cellulose, essential for bio-oil production [6]. Pyrolysis stands out as a promising biomass utilization route, converting biomass into fuel gases, solids, and liquids [7]. Fast pyrolysis aims to maximize liquid product yield by using finely ground biomass, high heating rates (>100˚C/min), controlled temperatures (around 500˚C), and rapid cooling of pyrolysis vapors [8]. Bio-oil, produced through syngas condensation, contains hydrogen, oxygen, and carbon, with negligible sulfur and nitrogen levels [9]. Its organic compounds include aldehydes, acids, alcohols, esters, sugars, ketones, phenols, phenol derivatives, and lignin-derived oligomers, finding uses in thermal plants, gas turbines, and as chemical feedstock [10]. Phenolic compounds, a major component, serve various applications, including as preservatives for raw leather and as environmentally friendly substitutes for chemical agents [11]. A fixed-bed pyrolyzer was chosen for its high carbon conversion efficiency, biomass ash content processing capability, ash melting ability, and low production cost compared to fluidized bed reactor types [12]. This research aims to convert waste coconut fiber biomass into economically valuable products like bio-oil, potentially serving as an alternative energy source for power generation and contributing to environmental conservation.

2. Materials and Methods

2.1. Feed Stock

The biomass sample used in this study was coconut fiber, supplied by the Coco Grow Company, located in Kwale County, Kenya. The coconut fiber underwent

sun-drying for four weeks, followed by oven-drying at 105˚C for 24 hours to achieve a moisture content below 10% [13], specifically 8.89%. After drying, the coconut fibers were ground using a large hammer mill at a rotating speed of 50 rpm. The ground products were then sieved with a BSS 52 size sieve shaker to obtain a particle size range of 2.36 - 4.75 mm [14]. The resulting sample was utilized in the subsequent pyrolysis process.

2.2. Raw Biomass Characterization

The sieved coconut sample underwent characterization to evaluate its structural, chemical, and textural characteristics. Both proximate and ultimate analyses were conducted following the ASTM standard methods (ASTM E870-829) [15].

2.2.1. Proximate Analysis

This analysis aimed to determine the ash content, fixed carbon, volatile matter, and moisture content of the biomass. The moisture was measured on an air-dry basis, while volatile matter and fixed carbon were calculated on a dry basis, excluding total and inherent moisture. The volatile matter, ash content, and moisture content were determined following the ASTM 1762-84 test method [16].

2.2.2. Ultimate Analysis

The ultimate analysis provided information on the biomass composition in terms of hydrogen, carbon, nitrogen, oxygen, and sulfur contents. An elemental analyzer (manufacturer: ELTRA, Germany) was used to analyze the elemental composition, including carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) [16]. The oxygen content was calculated with the equation:

$$\mathrm{O}(\%) = 100 - (\mathrm{C} + \mathrm{H} + \mathrm{N} + \mathrm{S}) \quad (1)$$

2.3. Fixed Bed Pyrolyzer Setup

The pyrolysis of coconut fiber samples was carried out in a 5 kg capacity multi-purpose small-scale, fixed bed pyrolyzer. The setup consisted of a reactor, a condensing unit, and an oil collector. The reactor, made of 304 stainless-steel, featured a conical feeder header at the top and an exit pipe for syngas removal to the condenser. The reactor and its conical header were sealed using bolts and a steel gasket to ensure air tightness. A cylindrical heater was used to heat the reactor externally, with temperature regulation facilitated by a PID temperature controller. Two K-type thermocouples were positioned to measure the temperature of the biomass and syngas immediately as it exited from the reactor. The reactor was insulated with a combination of fire bricks, refractory cement, fondu cement, and castable material, all contained within a low alloy mild steel holder. Pyrolysis experiments were conducted at temperatures ranging from 250˚C to 450˚C under atmospheric pressure. The reaction effluent, comprising volatile compounds and syngas, was cooled through a counter-flow shell and tube heat exchanger. The condenser and shell were constructed from 304 stainless steel, with copper tube pipes internally for efficient cooling. A steel gasket fully sealed

the condenser, and the liquid products were collected in a PET plastic bottle attached to the condenser. Non-condensable gases were absorbed in water. The fixed bed pyrolyzer set up is as shown in Figure 1.

The conversion of the coconut fiber sample to bio-oil based on the weight ratio was calculated using Equations (2), (3) and (4) [17].

$$\text{Liquid yield } \% = \frac{\text{total liquid product weight}}{\text{feed weight}} \times 100 \tag{2}$$

$$\text{Char yield } \% = \frac{\text{char weight}}{\text{feed weight}} \times 100 \tag{3}$$

$$\text{Gas yield } \% = 100 - \left[\text{liquid yield } \% + \text{char yield } \%\right] \tag{4}$$

2.4. Experimental Procedure

The investigational parameter selected was the pyrolysis temperature, with a constant biomass particle size and heating rate. To identify the best process conditions for maximum bio-oil production, we first investigated the effect of temperature on the pyrolysis distribution. This involved varying the temperature from 250˚C to 450˚C, while maintaining the particle size and heating rate constants at values of 2.36 - 4.75 mm and 10˚C/min, respectively. The temperature was initially set at 250˚C, from which other temperature variances were explored. Subsequent experiments were conducted with the temperature ranging from 250˚C to 450˚C, with the particle size and heating rate remaining unchanged.

2.5. Characterization

Fourier Transform Infrared spectroscopy (FTIR) serves as a crucial analytical technique for identifying the chemical bonds within a bio-oil molecule sample. The FTIR analysis was conducted using an IR Tracer-100 Shimadzu model (Shimadzu Corporation, Kyoto, Japan). The FTIR spectra of the bio-oil were

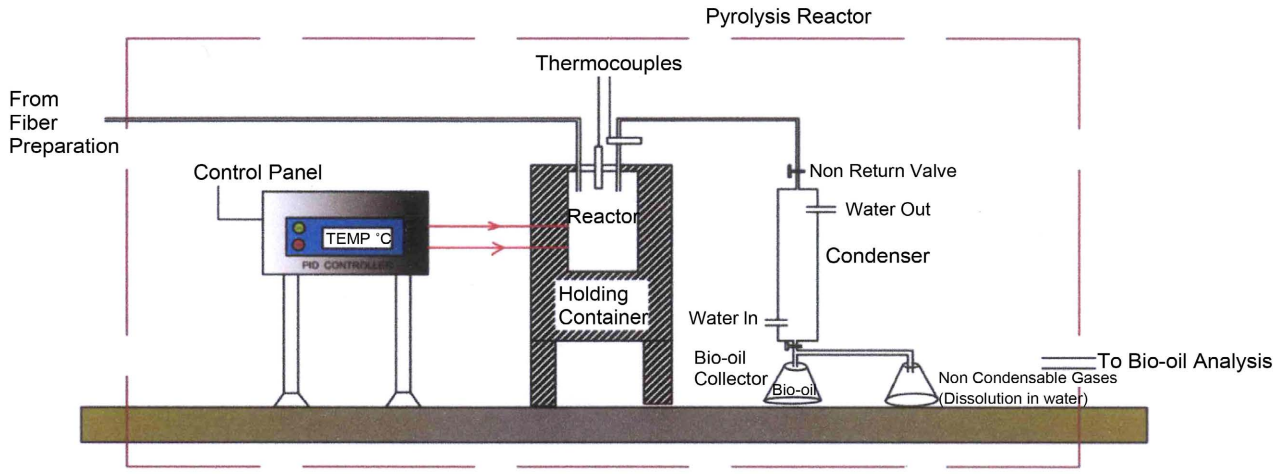

Figure 1. A schematic diagram for bio-oil production from coconut fiber.

recorded via a Perkin Elmer synthesis monitoring system. For characterization, the dried sample was combined with Potassium Bromide (KBr) powder, which has 100% transmittance in the wavelength range of 4000 - 400 cm^{-1}, to avoid absorbance interference. This powder was then pressed into a pellet form. The FTIR spectra were acquired using a Nicolet 6700 spectrometer (Thermo Scientific, USA) operating in the wavelength range of 400 - 4000 cm^{-1} with a resolution of 8 cm^{-1}.

3. Results and Discussion

3.1. Proximate Analysis of the Coconut Fiber

The physicochemical characteristics and proximate analysis values of coconut fiber biomass are presented in Table 1. The analysis followed standard methods for volatile material content (ASTM E872-82, 2019), higher heating value (ASTM D240-2017), ash content (ASTM E1755, 2015), moisture content (AOAC 934.01, 2000), and fixed carbon content (calculated by difference). The results revealed volatile matter, moisture content, ash content, calorific value, and carbon content of 79.84%, 8.89%, 9.7%, 18.7 MJ/kg, and 30.91%, respectively. These values are consistent with those found in other coconut fibers [18] [19].

The moisture content of less than 10 wt% facilitates rapid heat transfer in the pyrolysis reactor, making the used coconut fiber suitable for thermal conversion [13]. The high volatile matter content indicates a strong potential for liquid oil production during thermochemical conversion, while the slightly higher ash content compared to other coconut fibers suggests a potential reduction in bio-oil yield due to sludge formation [20]. The high carbon content and heating value underscore the suitability of coconut fiber for both biochar and bio-oil production via thermochemical conversion routes [21].

3.2. Ultimate Analysis of the Coconut Fiber

The ultimate analysis, which assesses the elemental composition of the coconut fiber biomass on a dry basis, is crucial for determining its quality as a feedstock for thermal conversion processes [22]. The analysis, conducted on a Carbon, Hydrogen, Nitrogen, and Sulfur elemental analyzer (ELTRA, Germany), revealed carbon, hydrogen, nitrogen, and sulfur contents, with oxygen content determined via subtraction from the total mass fraction considering the ash content

Table 1. Proximate analysis of coconut fiber.

Parameters	Value (wt)
Volatile matter	79.84
Moisture content	8.89
Ash content	9.7
HHV (MJ/kg)	18.7
Carbon content	30.91

from proximate analysis (Table 2).

The elemental composition closely matches the findings by Liu *et al.* [18] and indicates a significant energy value for the biomass. The low levels of nitrogen and sulfur contribute to the environmental friendliness of coconut fiber biomass, reducing the emissions of NO_x and SO_x [23]. The high percentages of carbon (30.91%) and oxygen (46.54%) highlight the biomass's suitability for biochar production.

3.3. Pyrolysis Yield at Different Experimental Temperatures

Pyrolysis experiments conducted on coconut fiber with a particle size range of 2.36 - 4.75 mm at temperatures between 250˚C - 450˚C and a heating rate of 10˚C/min revealed differential yields of syn-gas, bio-char, and bio-oil.

Figure 2 shows an increase in process temperature correlated with an increased yield of bio-oil and syn-gas and a decreased yield of char. Specifically, bio-oil yield increased from 30.3% at 250˚C to a peak of 39.2% at 450˚C, while char yield decreased from 50.6% to 39.6% within the same temperature range.

The increase in gas yield from 19.1 to 21.2 wt% can be attributed to enhanced secondary cracking reactions of the coconut fiber [24]. These findings are consistent with the pyrolysis of other biomasses and indicate that a heating rate below 15˚C/min facilitates the breakdown and reformation of chemical bonds in the feedstock, leading to increased biochar production [24] [25] [26].

Table 2. Elemental composition of coconut fiber.

Parameters	Value (wt)
Carbon	30.91
Hydrogen	6.77
Nitrogen	0.20
Oxygen	46.54
Sulfur	0.11

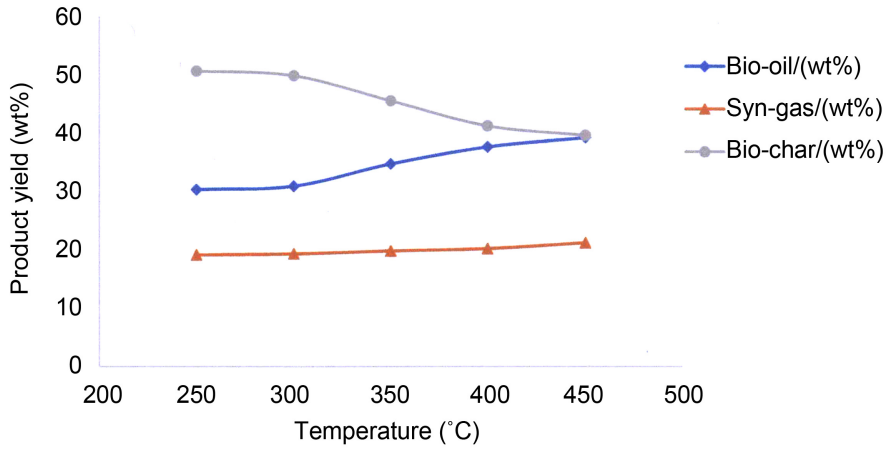

Figure 2. Effect of operating temperature on product yield.

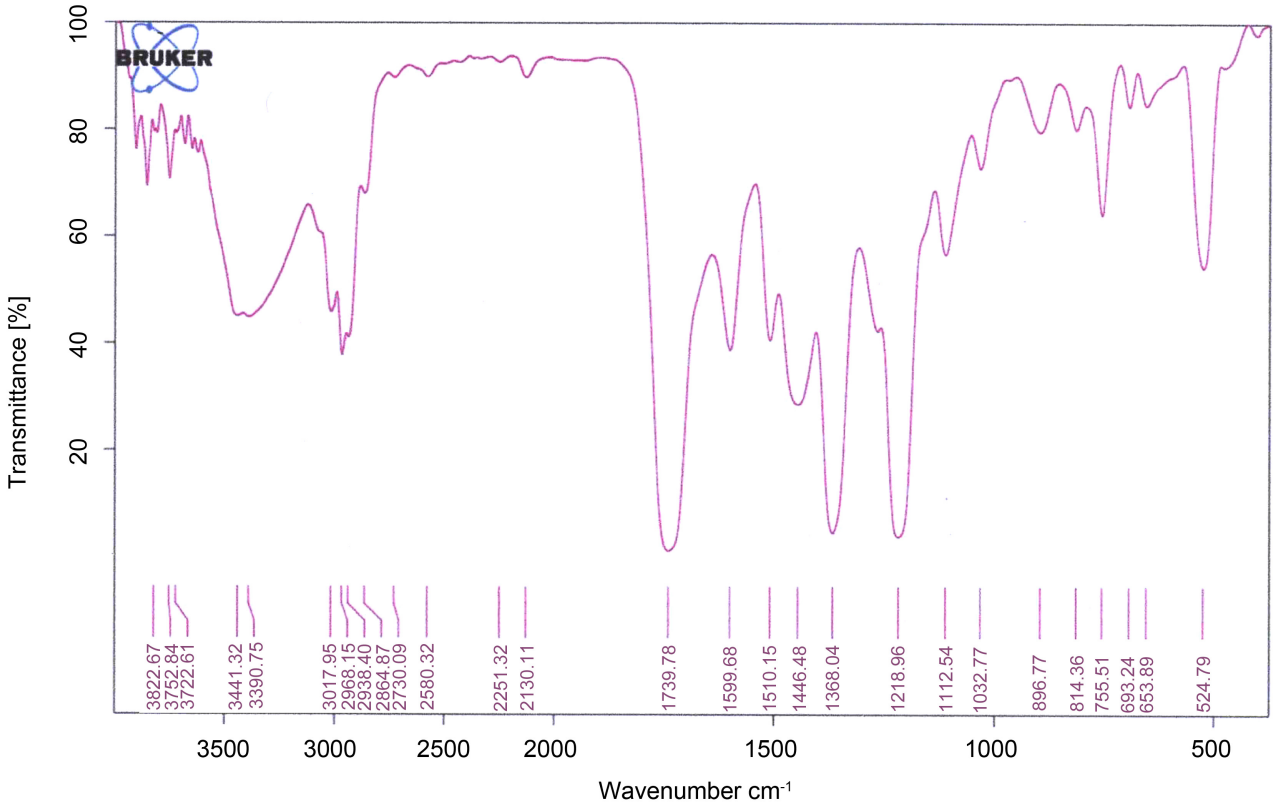

Figure 3. Fourier transform infrared spectroscopy spectra of coconut fiber oil at 450˚C.

Table 3. Different assignments of the FTIR spectra of coconut fiber oil.

Wave number (cm^{-1})	Type of vibration	Functional group
3441.32	H-bonded O-H stretch (Broad Strong Band)	Alcohol/Phenol
2968.15	Doublet	Carbon dioxide
2130.11	C ≡ C stretch (medium)	Terminal Alkyne
1739.78	C=O stretch (strong)	Ketone or Carboxylic acid
1599.68	C=C stretch (medium)	Alkene
1368.04	C=C stretch (medium)	Aromatic
1218.96	C–O stretch	Alcohol
1112.54	C–O stretch	Ether
1032.77	C–O stretch	Ether
896.77	C–H bend	Aromatic
814.36	C–H bend	Aromatic
755.51	C–H bend	Aromatic
693.24	C–H bend	Aromatic

3.4. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy is a fundamental technique for identifying characteristic functional groups in oil, thanks to the specific absorption and emission of infra-

red radiation by chemical bonds [27]. The FTIR spectrum of the coconut fiber oil, obtained at 450˚C, **Figure 3**, features strong and medium intensity peaks associated with various functional groups, indicative of the presence of alcohols, phenols, ketones, or carboxylic acids, alkenes, aromatics, and ethers, **Table 3**. This spectrum, alongside corroborating GC-MS analysis, points to the bio-oil's complex molecular composition derived from the pyrolysis of cellulose, hemicellulose, and lignin within the coconut fibers [28] [29] [30]. The high presence of oxygenated compounds in the bio-oil, as revealed by FTIR spectroscopy, underscores its potential for fractionation into valuable chemical classes and further application as a fuel.

4. Conclusion

The study on the thermochemical conversion of coconut fiber waste to bio-oil via fixed-bed pyrolysis has led to several noteworthy conclusions. Firstly, coconut fiber pyrolysis yields significant bio-oil, with the yield greatly influenced by the process temperature. An optimal yield of 39.2 wt% was achieved with a biomass particle size range of 2.36 - 4.75 mm at a final temperature of 450˚C and a heating rate of 10˚C/min. The heating value of the bio-oil is comparable to other biomass sources, indicating its potential as a fuel. Furthermore, FTIR spectroscopy has identified oxygenated compounds, including carboxylic acids, phenols, alcohols, and branched oxygenated hydrocarbons, as the main constituents of the bio-oil, highlighting its versatility and potential for sustainable energy solutions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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