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Extraction of bio-oil from the pyrolysis of banana tree waste using a fixed-bed reactor

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The rapid and ongoing depletion of fossil fuel reserves is driving up energy costs and harming the environment due to greenhouse gas emissions, leading to a global energy crisis. This situation highlights the urgent need to produce renewable fuel from biomass. This research focuses on extracting bio-oil from banana tree waste under different operating conditions. In this study, the pyrolysis process of banana tree waste was carried out in a fixed-bed reactor to maintain controlled conditions and prevent unwanted cracking. To optimize the process, the effects of temperature, particle size, and nitrogen flow rate on bio-oil yield were investigated. Experiments were conducted at temperatures ranging from 400 to 600 ℃, with feedstock particle sizes of 0.5 – 2.0 mm and nitrogen flow rates between 0.5 and 2 liters per minute. The optimal conditions for maximizing bio-oil yield were determined. Under these conditions, the maximum bio-oil yield of 32.13% was obtained at a temperature of 500 ℃, with a particle size of 1.2 – 2.0 mm and a nitrogen flow rate of 1 liter per minute. The results also demonstrate how temperature, particle size, and nitrogen flow affect the bio-oil yield during pyrolysis. The study concludes that banana tree waste can be efficiently converted into bio-oil through proper processing, contributing to sustainable energy production while minimizing environmental impact. The chemical composition of the bio-oil was analyzed using the GC-MS technique, which identified various compounds, including phenols, acids, and other chemical components.

Keywords: Biomass; Renewable Energy; Banana Tree Waste; Pyrolysis; Bio-oil.

Introduction:

The rapid depletion of fossil fuel reserves, rising fuel prices, increased fuel consumption, greenhouse gas emissions, and environmental degradation have all contributed to the current energy crisis [1]. Agricultural waste, such as crop husks, leaves, stems, and shells, is often underutilized and poorly managed. Instead of converting this waste into bioenergy, compost, or animal feed, it is commonly burned in open fields, which releases greenhouse gases like carbon dioxide and methane, further exacerbating global warming [2]. This practice lowers air quality, contributes to acid rain, and affects nearby water bodies. Through atmospheric deposition, these pollutants can enter aquatic ecosystems, reducing water pH and harming aquatic life [3]. Banana trees, with their abundant cultivation and high biomass yield, especially in Asia, Africa, and Latin America, are an attractive source of biomass for producing biofuels and other chemicals [4]. According to the Food and Agriculture Organization of the United Nations (FAO), global trade in tropical fruits reached 7.7 million tons in 2019, reflecting a 6.4% (465,000 tons) increase from previous years [5]. Biomass from banana trees has various uses: pseudo-stems can serve as mulch, a starch source, or raw material for ropes, fabrics, or paper, while peels can be used as compost or animal feed. Discarded fruits are also suitable for animal consumption [4]. Despite these potential uses, about 60% of banana biomass is wasted through open burning and dumping, which poses significant risks to human and environmental health [5].

Pyrolysis is one of the most effective methods for converting biomass into biofuel. This process involves heating biomass at high temperatures in an inert atmosphere, typically using argon or nitrogen gas [6]. Nitrogen acts as a carrier gas, preventing oxidation and ensuring controlled thermal decomposition [7]. Due to its high energy content, banana waste can yield biofuels and other valuable products through pyrolysis. A typical ton of banana waste consists of 750 kg (75%) pseudo-stems, 100 kg (10%) leaves, 40 kg (4%) rachis, and 110 kg (11%) peels. These byproducts are ideal raw materials for bio-refineries, which can produce biofuels and bio-based chemicals [8]. During pyrolysis, biomass decomposes in the absence of oxygen, yielding bio-char and bio-oil rich in carbon. The primary components of lignocellulosic biomass—cellulose, lignin, and hemicellulose—degrade when heated between 300 and 500 ℃ [9].

Some researchers prefer pyrolysis due to its optimal operating conditions, including moderate temperatures (300-500 ℃) and medium heating rates [10]. Compared to slow pyrolysis, it provides higher bio-oil yields and avoids the excessive formation of bio-char and bio-gas associated with fast pyrolysis [11]. Fixed-bed reactors are often favored over fluidized-bed reactors because they produce higher bio-oil yields. The slower heating rate in fixed-bed reactors allows more thorough pyrolysis of the feedstock, resulting in valuable liquid products with minimal gas and char. Although fluidized-bed reactors operate quickly, their high gas production reduces their efficiency for maximizing bio-oil yield [12]. Several factors influence banana waste pyrolysis in fixed-bed reactors, including temperature, heating rate, particle size, and residence time. Temperature plays a critical role in product distribution, with lower temperatures favoring bio-char and gas formation and higher temperatures promoting bio-oil production [13]. Typically, temperatures between 350 and 650 ℃ are used to maximize bio-oil yield, while residence times of 2 to 10 minutes help achieve a balanced output [10].

The characteristics of bio-oil are heavily influenced by feedstock type and pyrolysis conditions [14]. Key factors affecting the pyrolysis yield and efficiency of banana tree waste include its lignocellulose composition, moisture content, and ash concentration. Without proper drying, the high moisture content in banana waste can lower pyrolysis efficiency. The concentrations of cellulose, hemicellulose, and lignin also significantly impact bio-oil yields, with higher cellulose content generally leading to greater bio-oil output. Additionally, ash content affects the thermal stability of the feedstock, further influencing process efficiency [15].

Objectives:

This study aims to explore how different pyrolysis parameters affect the production of bio-oil from banana tree waste. It evaluates the efficiency of extracting high-quality bio-oil from this waste. Additionally, it seeks to determine the optimal temperature, particle size, and nitrogen flow required to maximize bio-oil yields during the pyrolysis process in a fixed-bed reactor with a capacity of 30 grams. The study also examines how varying operating conditions influence both bio-oil yield and its characteristics. Finally, the research assesses the properties of the obtained bio-oil.

Materials and Methods:

Collection and Preparation of Feedstock:

Banana tree waste was chosen as the feedstock due to the widespread cultivation and high demand for this banana variety in Pakistan. The banana leaves used in the experiments were collected from a farmer in Nawabshah, Khairpur, Sindh, Pakistan. Only mature banana trees, over 10 months old, were selected to ensure high-quality leaves. The leaves were carefully cut from the stem, measuring between 30 to 50 cm, and placed on a sterile canvas to avoid soil contamination. The fresh, moist leaves were then divided into 4 to 8 sections and manually chopped into smaller pieces before drying. Initially, the chopped leaves were air-dried outdoors in the Sukkur region for 5 to 6 days. To further reduce moisture content, the leaves were oven-dried at 105 °C for 8 hours, ensuring they were sufficiently desiccated for subsequent analysis.

Feed Characterization:

The banana tree waste was chopped to reduce particle size, and sieve analysis was conducted using screens with mesh sizes of 200, 400, 600, 800, and 1000. Two particle size ranges were selected: 0.5–1.2 mm and 1.2–2.0 mm. Proximate analysis was performed to measure moisture content, volatile matter, ash content, and fixed carbon in the banana waste samples. Moisture content was determined using ASTM E871-82 [16], which specifies that dried materials should have a moisture level below 10%. Volatile matter was assessed according to ASTM E872 [16], and ash content was measured following ASTM E1102-84 [17]. Fixed carbon content was calculated by subtracting the moisture, volatile matter, and ash percentages from 100. Each analysis was repeated three times to ensure accuracy and reliability. The Perkin-Elmer Series II CHNS/O 2400 Analyzer was used for ultimate analysis, measuring the carbon, hydrogen, nitrogen, sulfur, and oxygen content in the feed samples. The fixed carbon and oxygen contents were calculated using the following formulas:

- **Fixed Carbon (%)** = 100 - (volatile matter + moisture content + ash content)
- **Oxygen (%)** = 100 - (Carbon + Hydrogen + Nitrogen + Sulfur)

Lignocellulosic analysis was conducted to quantify the biomass's hemicellulose, lignin, cellulose, and extractive content, using standard methods ASTM D1106 [18], ASTM D1103 [19], ASTM D1104 [20], and ASTM D1105 [21]. The samples' higher heating value (HHV) was measured using an Adiabatic Bomb Calorimeter (IKA C-200). The lower heating value (LHV) was then calculated using the following formula:

$$\textbf{LHV (dry, MJ/kg)} = \text{HHV (dry)} - 2.442\,(8.936 \times H / 100)$$

Experimental Methodology:

The pyrolysis of banana tree waste was performed in a fixed-bed reactor under atmospheric nitrogen pressure. The reactor had a length of 10 cm and an inner diameter of 5 cm. This reactor type was selected due to its ease of operation, controlled heating conditions, and ability to facilitate gradual pyrolysis, which enhances bio-oil yield. Unlike fluidized-bed reactors, the fixed-bed reactor minimizes secondary cracking by maintaining a stable reaction environment with better residence time control. Nitrogen gas (N_2) was used as an inert medium to prevent combustion and oxidation, thereby ensuring that thermal decomposition of the biomass produced volatile compounds. Nitrogen flow also influenced vapor residence time, which in turn affected the yield and composition of bio-oil by reducing excess char or gas formation.

A schematic diagram of the pyrolysis setup is shown in Figure 1. Briefly, 30 grams of banana tree residues were loaded into the reactor, and nitrogen gas was purged at a flow rate of 0.5 liters per minute. The initial temperature of the reactor was set to 25 °C, and a thermocouple was used to monitor the internal temperature. The vapors generated during the pyrolysis process were condensed using a spiral condenser, with cooling water maintained at 4 °C. The condensed bio-oil was then collected in a collection chamber.

Pyrolysis experiments were conducted in three series using a fixed-bed reactor. Before each experiment, the reactor's temperature was stabilized and controlled using a thermocouple connected to a control panel to ensure uniform heating.

In the **first series**, the focus was on studying the effect of reaction temperature on the yield distribution. Banana leaves were pyrolyzed at temperatures of 400, 450, 500, 550, and 600 °C to determine the optimal temperature for maximizing bio-oil yield. All other operating parameters were kept constant. The **second series** aimed to examine the impact of particle size on bio-oil yields. Banana residue particles were divided into two size ranges: 0.5–1.2 mm and 1.2–2.0 mm. These particle sizes were tested under varying temperatures to observe their effect on bio-oil production. In the **third series**, nitrogen gas was used as an inert medium to create an oxygen-free environment, preventing combustion. Since pyrolysis is a thermal degradation process that requires the absence of oxygen, nitrogen ensured that the system remained oxygen-free, preserving the controlled conditions necessary for pyrolysis. The nitrogen flow rate was regulated using a flow meter connected to the gas cylinder, helping maintain a stable inert atmosphere.

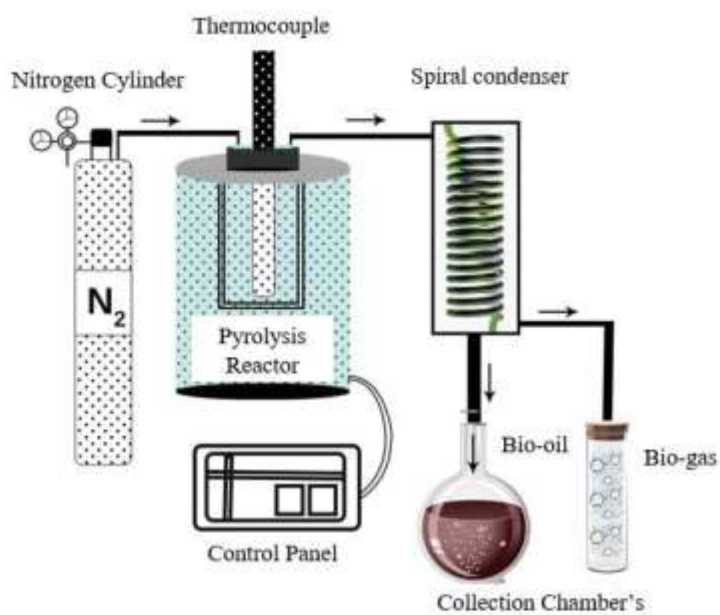

Figure 1. Experimental diagram of Pyrolysis process

Before each run, thermal equilibrium was reached, and key parameters like temperature and nitrogen flow were kept constant. This setup allowed the controlled release of volatile compounds, minimized combustion risks, and maintained the desired inert environment. By adjusting the nitrogen flow rate, the pyrolysis process was optimized, product distribution improved, and temperature fluctuations controlled, thereby enhancing overall efficiency. The methodology's flow diagram is shown in Figure 2.

The bio-oil yield was calculated using the following formula:

% Yield of bio-oil (wt. %) = (Bio-oil mass (g) / Dry feedstock mass (g)) × 100%

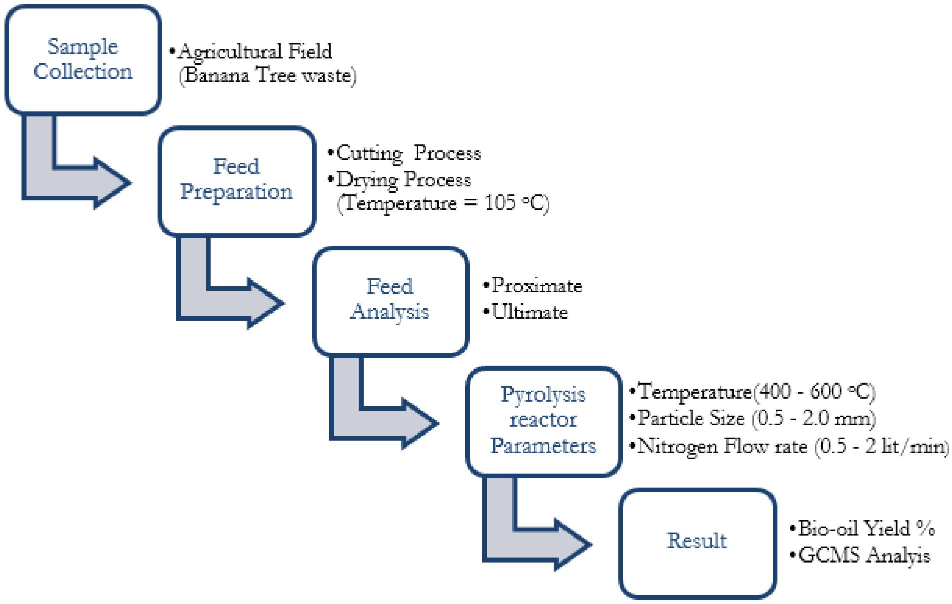

Figure 2. Flow diagram of Pyrolysis process

Product Analysis:

The extraction of bio-oil under optimal pyrolysis conditions, which yielded the highest liquid output, was thoroughly analyzed. To determine the chemical composition of the collected bio-oil, Gas Chromatography-Mass Spectrometry (GC-MS) was employed. The analysis focused on the bio-oil produced at a pyrolysis temperature of 500 °C, where chemical constituents were carefully evaluated. To prepare the samples for GC-MS analysis, a Liquid-Liquid Extraction (LLE) technique was used to remove water content. This step is essential in isolating and purifying the liquid products, particularly for separating organic compounds from the aqueous phase generated during pyrolysis. Since pyrolysis produces a complex mixture of gases, solids, and liquids—including water, organic compounds, oils, acids, alcohols, and phenols—the presence of water can hinder the analysis and application of the liquid products.

In the LLE process, dichloromethane was mixed with the liquid sample in a 1:1 volumetric ratio. Specifically, 5 mL of the liquid bio-oil and 5 mL of dichloromethane were combined and stirred thoroughly. The mixture was then centrifuged at 4000 rpm for 10 minutes, causing it to separate into two distinct phases: the organic phase (settling at the bottom) and the aqueous phase (accumulating at the top). The aqueous phase was discarded, and the lower organic fraction was collected for further preparation. To optimize chromatographic performance, 1 µL of the organic fraction was diluted with 990 µL of hexane. The solution was then filtered using a syringe filter to remove any remaining particles and transferred to a GC vial. Finally, the prepared sample was injected into the GC-MS system, where the chemical compounds in the bio-oil were identified and quantified with high sensitivity and precision.

Results:

Impact of Operating Parameters on Bio-Oil Yield (%):

The study aimed to evaluate how different operating conditions influence product yield. The following section discusses the key findings based on various parameters.

Temperature's Impact on Bio-Oil Yield (%):

The maximum bio-oil yield from banana tree waste was observed at a pyrolysis temperature of 500 °C, with a recorded yield of 32.13 wt. %. As the temperature increased from 400 °C to 500 °C, the bio-oil yield rose from 26.60 wt. % to 32.13 wt. %. However, when the temperature was further increased from 500 °C to 600 °C, the bio-oil yield decreased to 28.20 wt. %. This trend indicates that increasing the temperature up to 500 °C enhances bio-oil production while reducing bio-char yield. However, beyond 500 °C, the yield of bio-oil declines due to secondary cracking. At excessively high temperatures, pyrolysis vapors undergo secondary cracking, which increases gas production while reducing the yields of both bio-oil and bio-char. This explains the drop in bio-oil yield when the temperature rises from 500 °C to 600 °C.

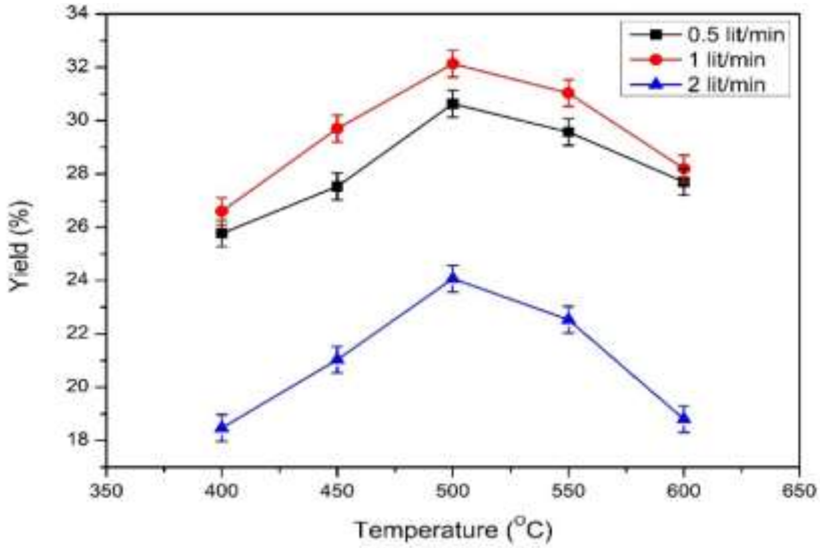

Figure 3. Temperature's impact on Bio-Oil Yield %

Figure 3 illustrates the relationship between temperature, nitrogen flow rates, and bio-oil yield percentage, showcasing the combined impact of these parameters on pyrolysis efficiency. The graph demonstrates that the highest bio-oil yield is achieved at a pyrolysis temperature of 500 °C and a nitrogen flow rate of 1 liter per minute (L/min). This optimal combination enhances the thermal breakdown of organic compounds while maintaining the inert conditions necessary for preventing combustion and ensuring efficient product distribution.

As shown in the figure, increasing the temperature to 500 °C improves bio-oil yield due to enhanced volatilization of the feedstock, while excessively high temperatures lead to a decline in yield due to secondary cracking. Additionally, the nitrogen flow rate plays a crucial role in maintaining a uniform temperature profile and facilitating the escape of volatile compounds, contributing to an optimized pyrolysis environment.

Particle Size's Impact on Bio-Oil Yield (%):

The study revealed that bio-oil yield (%) increased with larger particle sizes, irrespective of the temperature. At lower pyrolysis temperatures, such as 400 °C and 450 °C, smaller particle sizes (0.5 – 1.2 mm) resulted in reduced bio-oil yields. However, as particle size increased to the range of 1.2 – 2.0 mm, a significant improvement in yield was observed, particularly at temperatures between 500 °C and 600 °C. Figure 4 shows the particle size's impact on bio-oil yield percentage.

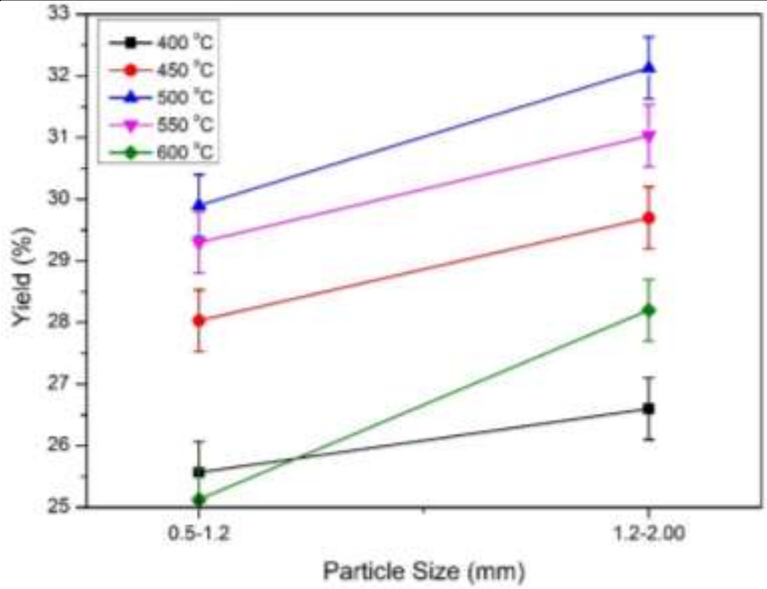

Figure 4. Particle Size's impact on Bio-oil Yield %

Nitrogen flow's impact on the Bio-oil Yield %:

As described and evident in the graph, the flow rate significantly affects the pyrolysis process. The carrier gas flows through the condenser with less contact time, it produces less vapor condensation at higher flow rates, which leads to lower yields. At lower flow rates, the pyrolysis reaction is incomplete, and an undesirable product is formed. In contrast, a higher yield is obtained with a flow rate of 1 liter/min because the vapors in the condenser have more time to interact with the walls, allowing them to condense from gas to liquid. In this study, the yield percentage was found to be higher at a 1 liter/min flow rate compared to 0.5 and 2 liters/min. The nitrogen flow rate was observed to significantly affect the yield percentage, as shown in Figure 5.

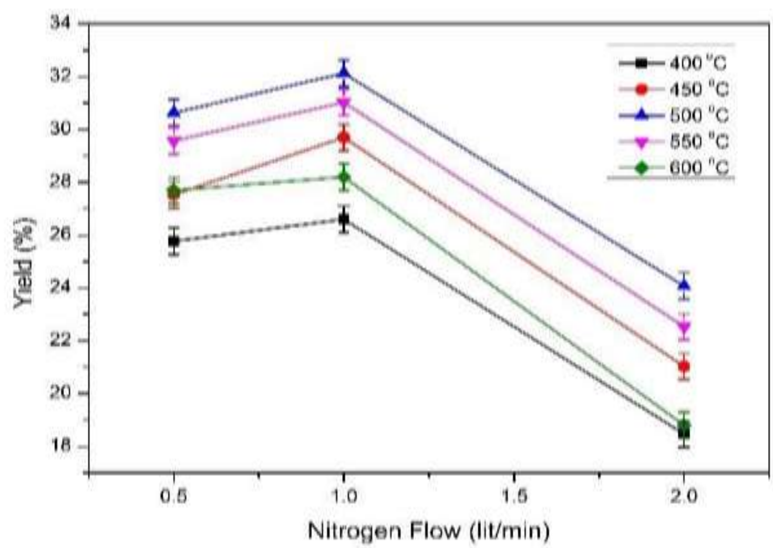

Figure 5. Nitrogen Flow's impact on Bio-oil Yield %

Characterization and Composition of Bio-oil:

The chemical compounds in the bio-oil produced from the pyrolysis of banana tree waste were identified using the GC–MS technique. The results, listed in Table 1, were analyzed at the University of Gurat's Department of Chemistry. GC-MS analysis was performed to investigate the chemical composition of the pyrolysis liquid under optimal conditions. The findings, illustrated in Figure 6, provide a detailed overview of the chemical makeup of the pyrolysis liquid.

Table 1. Chemical compounds in bio-oil

Sr No.	Chemical products identified in bio-oil
1	Acetic acid
2	Propionic acid
3	Phenol
4	Phenol, 3-methyl-
5	Benzene carboxylic acid
6	1,2-Benzenediol
7	D-Allose
8	9,12- Octadecadienoic acid (Z,Z)-
9	Octadecenoic acid
10	10-Octadecenoic acid
11	Tetradecanoic acid
12	Dodecanoic acid

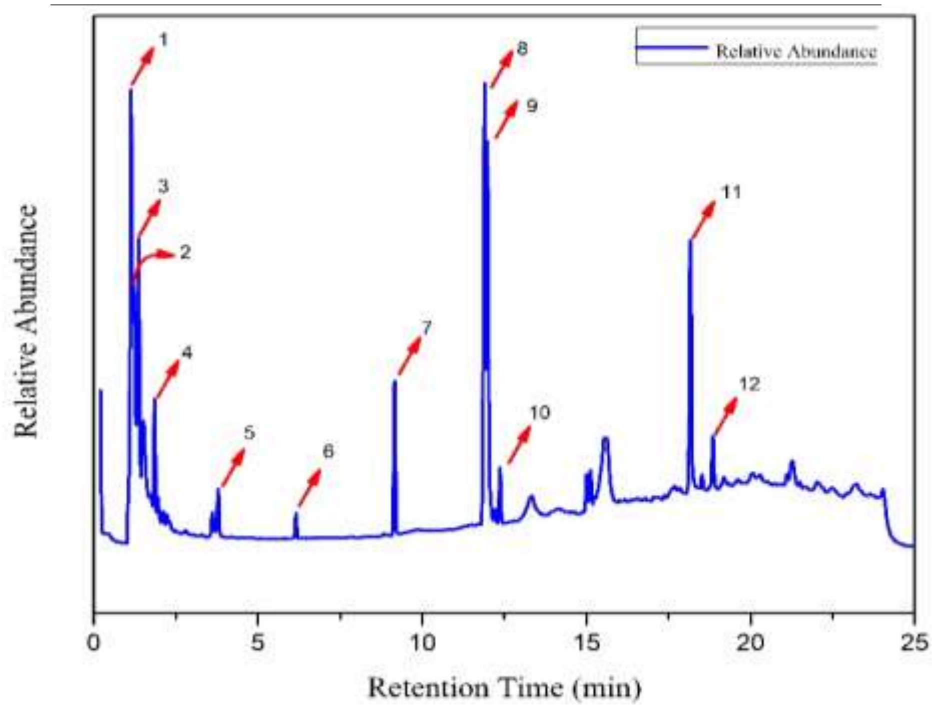

Figure 6. Spectrum of GC-MS analysis

Discussion:

Characterization of Banana tree waste:

The physical and chemical properties of banana tree waste are shown in Table 2, along with relevant research findings on other biomass samples. Understanding the potential for bioenergy production from banana waste requires analyzing its pyrolysis behavior in a fixed-bed reactor. The banana tree waste had a moisture content of 8.21 wt. %, which falls within the acceptable range of 7% to 15% for the pyrolysis process [22]. Higher moisture levels reduce the biomass's heating value, leading to less energy production and bio-oil with higher moisture content, which decreases fuel efficiency [22]. The volatile matter content in banana tree waste was 78.36 wt. %, which is high when compared with other biomass sources like rice husk and wheat straw [8]. Its ash content was 6.43 wt. %, consistent with typical vegetable biomasses, which usually contain between 0.4 wt. % and 22.6 wt. % ash [20]. A higher ash content can impact the yields and quality of the char and bio-oil produced during pyrolysis [20]. The fixed carbon content was 7.02 wt. %, also within the typical range of 7% to 20% for vegetable biomasses [20]. The biomass had a high carbon content (43.10 wt. %) and hydrogen content

(7.19 wt. %), along with low nitrogen (0.15 wt. %) and sulfur (0.24 wt. %). Low sulfur and nitrogen levels are beneficial because they reduce the emission of corrosive and toxic nitrogen and sulfur oxides.

According to Table 2, the higher heating value (HHV) of banana tree waste was 17.728 MJ/kg, comparable to other agricultural biomass sources. A higher HHV means more energy can be generated during pyrolysis [7]. Banana tree waste, like other biomass feedstocks, contains lignocellulosic components that undergo thermal breakdown, releasing vapors and gases during pyrolysis. This process yields liquid and gaseous bio-products [22]. The average cellulose, hemicellulose, and lignin contents in banana tree waste were 30.91%, 25.17%, and 17.53%, respectively, aligning with values reported in earlier studies [22]. The heating rate is a critical parameter in the pyrolysis process, significantly influencing both the yield and quality of bio-oil. Studies have shown that slower heating rates, typically used in fixed-bed reactors, allow for more thorough thermal degradation of biomass, leading to higher bio-oil yields with fewer non-condensable gases and less char production. This is because slower heating provides sufficient time for volatiles to be released and condensed into liquid form, as observed in pyrolysis studies on rice husk and wheat straw, which reported optimized bio-oil yields at moderate heating rates. In contrast, fast pyrolysis methods, often conducted in fluidized-bed reactors, tend to prioritize higher heating rates, which favor the production of lighter hydrocarbons and reduce bio-oil viscosity but can lead to lower overall yields due to secondary cracking of vapors. Additionally, the chemical composition of bio-oil is influenced by heating rates, with higher rates producing bio-oil with greater water content and more unstable oxygenated compounds, while slower rates enhance the formation of phenolic compounds and acids, which improve bio-oil stability. This study, conducted at moderate heating conditions, aligns with existing research that emphasizes the benefits of controlled heating for optimizing bio-oil output and enhancing its chemical characteristics for potential biofuel applications. Future work could explore the synergistic impact of heating rates with catalysts to further improve bio-oil yield and reduce oxygen content.

Products Yield:

The mass yields of pyrolysis products from various biomasses, including date palm waste, rice husk, and banana tree waste, are summarized in Table 3 based on findings from different authors. The bio-oil yield from banana tree waste was found to be 32.13 wt. %. The differences in bio-oil yields between banana tree waste and other biomasses can be attributed to variations in reactor design, experimental setup, processing capacity, and feedstock type. Based on thermal analysis, pyrolysis of banana tree waste was conducted at 500 °C in a fixed-bed reactor. In a separate study, researchers reported that at 525 °C, fast pyrolysis of date palm waste produced 27.4 wt. % bio-oil. However, as the pyrolysis reaction accelerated, bio-oil production decreased [23]. Similarly, another study using rice husk in a fixed-bed reactor produced 30.18 wt. % bio-oil at approximately 500 °C [24].

In related experiments, banana waste pseudo-stem was used to produce bio-oil through fast pyrolysis. The process was conducted at temperatures ranging from 470 °C to 540 °C, with the highest bio-oil yield of 29.4% obtained at 500 °C. The reduced liquid yield at higher temperatures was attributed to secondary cracking of pyrolysis vapors and liquid products, which led to increased gas production [22]. Oxidative fast pyrolysis further reduced bio-oil yields due to biomass volatilization and partial combustion within the reactor, resulting in higher production of water and non-condensable gases.

Table 2. Comparison of characteristics of banana tree waste with another biomass residue

Analysis / Elements	Banana tree waste (This study)	Corn Cob[25]	Sugarcane Bagasse[22]	Rice Husk[25]
Proximate Analysis (wt. %)				
Moisture content	8.21	12.77	10.4	10.89
Ash content	6.43	2.30	16.4	15.14
Volatile matter	78.36	91.16	74.0	73.41
Fixed Carbon	7.02	6.54	13.0	11.44
Ultimate Analysis (wt. %)				
Carbon	43.10	42.10	43.2	41.92
Hydrogen	7.19	5.90	6.70	6.34
Nitrogen	0.15	0.50	0.30	1.85
Sulphur	0.24	0.48	0.20	0.47
Lignocellulosic Analysis (wt. %)				
Cellulose	30.91	42.2	38	32.0
Hemicellulose	25.17	30.7	27	15.0
Lignin	17.53	12.2	19	23.5
Calorific Values (MJ/kg)				
HHV	17.287	16	18	12.87
LHV	15.637	14	17	12.20

Table 3. comparison of Bio-oil yield % of banana tree waste and with another biomass

Biomass residue	Temperature (℃)	Bio-oil yield (wt. %)	Reference
Banana tree waste	500	32.13	This study
Date Palm waste	525	27.4	[23]
Rice Husk	500	30.18	[24]

Another study investigated agricultural biomass, such as sugarcane bagasse, in the pyrolysis process. At an optimal temperature of 525 °C, a maximum bio-oil yield of 33.25 wt. % was obtained. However, as the temperature increased, bio-oil yield decreased, while bio-gas production increased [22]. Previous research also reported a bio-oil yield of 30.18 wt. % from rice husk pyrolysis at 500 °C [24]. Table 3 provides a comparison of bio-oil yields from banana tree waste and those obtained in studies on date palm waste and rice husk pyrolysis. This study aims to explore how factors such as temperature, particle size, and nitrogen flow influence bio-oil yield.

The chemical composition of the bio-oil produced through banana tree waste pyrolysis was identified and analyzed using GC-MS analysis. The chromatograms displayed prominent peaks corresponding to major compounds, while smaller peaks indicated unidentified compounds. The bio-oil from banana tree waste contained various chemical compounds, with phenols being the dominant constituents [26]. Key chemical components in the bio-oil included phenol, 3-methylphenol, and 1,2-benzenediol [27]. Acetic acid and propanoic acid were also detected during the bio-oil analysis [28][29]. Other identified compounds included tetradecanoic acid, 1,2-tetradecanoic acid, benzenedicarboxylic acid, and octadecanoic acid [30]. Additionally, D-allose, 1,2-benzenediol, and 9,12-octadecanoic acid (ZZ) were present in the bio-oil [31].

Conclusion:

This research investigated the pyrolysis of banana tree waste using a fixed-bed reactor. Several operating parameters were studied, including temperature, particle size, and nitrogen flow. Based on the experimental findings, the following conclusions were drawn:

a) Under optimal conditions in a fixed-bed reactor—specifically, a temperature of 500 °C, particle size of 1.2 to 2.0 mm, and nitrogen flow rate of 1 liter/min—the maximum bio-oil yield was achieved. These conditions resulted in a highest bio-oil yield of 32.13 wt. %.

b) Increasing the temperature from 400 to 500 °C raised bio-oil production from 26.60 wt. % to 32.13 wt. %. However, when the temperature increased beyond 500 °C (up to 600 °C), bio-oil production decreased.

c) Higher nitrogen flow rates during the pyrolysis process reduced the bio-oil yield.

d) GC-MS analysis revealed that the bio-oil produced from banana tree waste was rich in phenol groups, acids, alkyl benzene, and several other chemical compounds.

Ongoing research is currently focused on evaluating the impact of heating rates on the pyrolysis process. Future studies will explore the introduction of catalysts to enhance pyrolysis reactions and increase the yield of desired products. Additionally, we plan to integrate pyrolysis with other energy systems to improve overall energy recovery and utilization.

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