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Boosted Bio-Oil Production and Sustainable Energy Resource Recovery Through Optimizing Oxidative Pyrolysis of Banana Waste

Rohit K. Singh [1,*], Bhavin Soni [1], Urvish Patel [1], Asim K. Joshi [1] and Sanjay K. S. Patel [2,*]

[1] Thermochemical Conversion Technology Division, Sardar Patel Renewable Energy Research Institute, Vallabh Vidyanagar, Anand 388120, Gujarat, India; thermo2@spreri.org (B.S.); patelurvish311@gmail.com (U.P.); solar1@speri.org (A.K.J.)
[2] Department of Biotechnology, Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar 246174, Uttarakhand, India
* Correspondence: thermo1@spreri.org (R.K.S.); sanjaykspatel@hnbgu.ac.in (S.K.S.P.)

Abstract: The increasing need for sustainable waste management and abundant availability of banana tree waste, a byproduct of widespread banana cultivation, have driven interest in biomass conversion through clean fuels. This study investigates the oxidative pyrolysis of banana tree waste to optimize process parameters and enhance bio-oil production. Experiments were conducted using a fluidized bed reactor at temperatures ranging from 450 °C to 550 °C, with oxygen to biomass (O/B) ratios varying from 0.05 to 0.30. The process efficiently converts this low-cost, renewable biomass into valuable products and aims to reduce energy intake during pyrolysis while maximizing the yield of useful products. The optimal conditions were identified at an O/B ratio of 0.1 and a temperature of 500 °C, resulting in a product distribution of 26.4 wt% for bio-oil, 20.5 wt% for bio-char, and remaining pyro-gas. The bio-oil was rich in oxygenated compounds, while the bio-char demonstrated a high surface area and nutrient content, making it suitable for various applications. The pyro-gas primarily consisted of carbon monoxide and carbon dioxide, with moderate amounts of hydrogen and methane. This study supports the benefits of oxidative pyrolysis for waste utilization through a self-heat generation approach by partial feed combustion providing the internal heat required for the process initiation that can be aligned with the principles of a circular economy to achieve environmental responsibility.

Keywords: banana waste; biomass; bio-oil; thermal process; oxidative pyrolysis; pyro-gas

Academic Editor: Nikolaos Kokkinos

Received: 3 December 2024
Revised: 27 December 2024
Accepted: 3 January 2025
Published: 7 January 2025

Citation: Singh, R.K.; Soni, B.; Patel, U.; Joshi, A.K.; Patel, S.K.S. Boosted Bio-Oil Production and Sustainable Energy Resource Recovery Through Optimizing Oxidative Pyrolysis of Banana Waste. *Fuels* **2025**, *6*, 3. https://doi.org/10.3390/fuels6010003

1. Introduction

The rising global demand for sustainable energy has spurred significant research into converting biomass into biofuels and bio-based chemicals. Biomass pyrolysis, a thermochemical technique, has garnered considerable interest in transforming diverse organic materials into valuable products such as bio-oil, bio-char, and pyro-gas. While first-generation biofuels have faced criticism for their adverse environmental and social effects, including rising food prices [1], second-generation biofuels have shown promise through studies demonstrating the energy potential of lignocellulosic feedstocks like agricultural and forest residues [2,3]. Third- and fourth-generation biofuels, which utilize microorganisms as feedstocks, offer benefits such as high energy content, low emissions, and eco-friendliness [4]. Despite these advantages, their economic viability is limited due to low yields and high production costs, necessitating further research to improve efficiency [5]. In contrast, second-generation biofuels are considered ideal because they leverage waste from the food industry, contributing to a circular economy with environmental and socioeconomic benefits [6]. Among various biomass sources, agricultural residues like banana tree waste are an abundant yet underutilized resource with significant potential for bioenergy production. Second-generation biomass is advantageous due to its minimal impact on food prices, waste reduction, and no need for additional land [1,5,7]. Banana production, which uses only 20 to 30% of the plant mass, leaves 70 to 80% as waste and for each tonne of bananas harvested, there are typically four tonnes of lignocellulosic waste generation [8]. Banana trees, cultivated predominantly in tropical and subtropical regions, produce over 150 million tons of bananas annually, with India leading global production. India contributed 30.8 million tonnes, representing 26.83% of the worldwide output [9]. However, the banana industry generates substantial waste, including leaves, pseudo-stems, and fruit peels.

Each ton of banana harvest results in about 100 kg of fruit being rejected and approximately four tons of lignocellulosic waste, including three tons of pseudo-stems, 160 kg of stalks, 480 kg of leaves, and 440 kg of peels [8,9]. These wastes are often left in the fields, where they decompose and produce greenhouse gases like methane (CH_4) and carbon dioxide (CO_2). Alternatively, they may be discarded or burned, leading to environmental pollution and the loss of potential energy resources. Utilizing this waste for production purposes not only helps reduce environmental pollution but also adds value to banana cultivation, which has faced market fluctuations in recent years. Banana waste can be repurposed as biomass for renewable energy generation or for producing chemical inputs [10]. Methods for valorising this waste include compacting it into briquettes [11,12], converting it to CH_4 gas through anaerobic digestion [13], or fermenting it to produce ethanol [14,15]. Direct combustion of pseudo-stems and leaves is another method to generate power [13]. Pyrolysis of banana tree waste solves waste management issues and provides a renewable energy source and valuable by-products. Fast pyrolysis is particularly effective for maximizing liquid product yield, such as bio-oil, by using moderate temperatures around 500 °C, high heating rates (>100 °C/s), and short vapor residence times (0.5 to 10 s). This process generally requires finely ground biomass with particle sizes less than 1 mm and careful control of reaction temperatures. The pyrolysis vapours and aerosols must be rapidly cooled to produce bio-oil [16]. Studies have explored fast pyrolysis in fluidized bed reactors for various biomass types. For instance, Heidari et al. [17] conducted fast pyrolysis of Eucalyptus grandis wood in a continuous-feed fluidized bed reactor, finding that bio-oil yield peaked at 50.8% with the lowest water content at 450 °C. Gas yield increased from 29.4% to 48.4% as the temperature rose from 450 °C to 600 °C, while bio-char yield decreased from 19.7% to 14.2%. Fernandes [18] performed slow pyrolysis of banana cultivation wastes (leaves and pseudo-stems) in a fixed bed reactor, achieving high bio-char yields (56.8% for leaves and 58.4% for pseudo-stems) but lower bio-oil yields (9.4% for leaves and 11.8% for pseudo-stems), typical of slow pyrolysis. This study demonstrated the technical viability of slow pyrolysis for these wastes. Other research has assessed the fast pyrolysis of banana waste, reporting gas yields ranging from 32.5% to 49.6%, liquid yields from 27.0% to 29.6%, and solid yields from 23.3% to 39.5% [19,20]. Yield variations depend on feedstock, reactor type, heating rate, and pyrolysis temperature [10,16]. These studies indicate that the pyrolysis products are promising for use as fuels after further refinement and that the liquids produced can generate valuable chemical products with significant commercial potential [8,21,22].

Fernandes [18] utilized oxidative fast pyrolysis in an auto-thermal pilot-scale plant, akin to the system used by Mesa-Perez et al. [23], under similar operating conditions, to produce bio-oil and bio-char. Both studies assessed the biomass and the characteristics of the resulting products through chemical and thermal analyses, and they determined mass and energy yields. Traditional pyrolysis typically occurs without oxygen, relying on external heat sources to sustain the endothermic reaction. In contrast, oxidative pyrolysis introduces a controlled amount of oxygen, partially oxidizing the biomass. This process generates internal heat, enhancing the overall energy efficiency and improving heat distribution within the reactor. It also affects product distribution, potentially resulting in a more balanced output of bio-oil, bio-char, and pyro-gas. Mesa-Perez et al. [23] explored oxidative fast pyrolysis of sugar cane straw in an auto-thermal fluidized bed reactor at temperatures ranging from 470 °C to 600 °C. They noted that the pyrolysis plant configuration required burning 10 to 15 wt% of the biomass with air to produce the necessary heat for the reactor bed, reaching temperatures of 450 to 470 °C to initiate the pyrolysis reaction. This auto-thermal approach facilitates energy integration and reduces operational costs, enhancing process feasibility. The optimal bio-oil yield was achieved at 470 °C, with product yields of bio-oil and bio-char reaching 35.5 wt% and 48.2 wt%, respectively. Although bio-oil yield is lower compared to inert atmosphere pyrolysis due to biomass combustion for heat generation, the bio-char yield is significantly higher [23]. Research specifically targeting bio-oil production from banana wastes is limited [22]. Few studies have investigated using banana peels for bio-oil production [21], with some estimating optimal pyrolysis parameters through thermogravimetric and kinetic studies [24]. Ozbay et al. [20] used banana peels as feedstock, determining that 550 °C is the optimal temperature, resulting in a bio-oil yield of 28.0%. However, there is a notable lack of research on the properties and potential of bio-oil derived from other banana waste materials, such as banana leaves, pseudo-stems, peduncles, and rhizome knots. Therefore, waste biomass utilization in producing biofuels and value-added products can benefit energy applications in the transportation sector [25,26]. Further, the biofuel production economy can be improved by unitizing byproducts of another process, such as biodiesel production from fatty acid ethyl esters originating from the corn oil-based bioethanol production process [27].

This study aims to explore the oxidative pyrolysis of banana tree mix waste using a fluidized bed reactor, focusing on optimizing process parameters and analysing the resulting product yields and compositions via clean technologies. The specific objectives are to identify the optimal pyrolysis temperature for maximum bio-oil recovery, later experimentation on oxidative conditions with different oxygen-to-biomass ratios (O/B ratio) for maximum bio-oil recovery with minimal effect of oxidation process on the derived products followed by the product characterization. Understanding the oxidative pyrolysis process and its impact on product distribution is essential for advancing efficient and sustainable biomass conversion technologies. This auto-thermal approach of oxidative pyrolysis facilitates energy integration and reduces operational costs, enhancing process feasibility. By optimizing conditions for banana tree waste, this study aims to strengthen the use of agricultural residues for renewable energy production and highlight the advantages of oxidative pyrolysis over traditional methods by reducing energy input for the process. The results are anticipated to provide valuable insights for designing and operating industrial-scale pyrolysis systems and supporting sustainable agricultural waste management and energy generation.

2. Materials and Methods

2.1. Feedstock Preparation

Banana plant residues, including leaves, pseudo-stems, and peduncles, were collected from agricultural fields in Anand district, Gujarat. The collected biomass was chopped along the radial axis and sun-dried for 5–7 days. Following the drying process, the material was processed using a hammer mill to achieve a particle size of $\leq$5 mm. The cellulose, hemicellulose, and lignin contents were quantified using established analytical techniques.

Additionally, the biomass was characterized according to ASTM standards to evaluate its properties during experimentation.

2.2. Experimental Setup and Procedure

The illustration of the experimental setup is presented in Figure 1. During the experimentation, a fluidized bed pyrolyzer with a reactor diameter of 102 mm and a length of 1200 mm was utilized. The fluidization was achieved using sand with a particle size ranging from 0.5 mm to 2 mm, creating a sand bed height of 150 mm just below the feed entry point. A comprehensive description of the experimental setup is provided elsewhere [28]. The experiments were conducted over a temperature range of 440 °C to 560 °C. The oxygen-to-biomass (O/B) ratios were varied between 0.05 and 0.3, and residence times were adjusted accordingly. Before biomass introduction, the reactor was preheated to the desired temperature using electrical heating coils. The biomass, specifically banana tree waste, was fed into the reactor at an initial rate of 5 kg/h using a screw feeder. Oxygen was introduced at controlled rates to achieve the target O/B ratios, which influenced the yields and quality of the products. During pyrolysis, the reactor was maintained in a specific mode to ensure optimal conditions. The bio-oil was condensed and collected in traps, while the bio-char was collected from the bottom of the cyclone separator chamber. Pyro-gas were continuously sampled from the gas outlet for component analysis. The pyro-gas samples were collected in gas sampling bags and analyzed using gas chromatography to determine their composition. The product yield was calculated as follows: (i) bio-oil yield (%) as a mass of liquid/mass of feedstock × 100, (ii) bio-char yield (%) as a mass of residue/mass of feedstock × 100, and (iii) pyro-gas yield (%) as 100 − (bio-char yield and bio-oil yield). The optimal process conditions were determined based on the products' yield and quality (volume). The composition analysis of bio-oil was evaluated by gas-chromatography-mass spectroscopy (GC-MS ISQ Series Trace^{TM} 1300, Thermo Scientific, Waltham, MA, USA) [29].

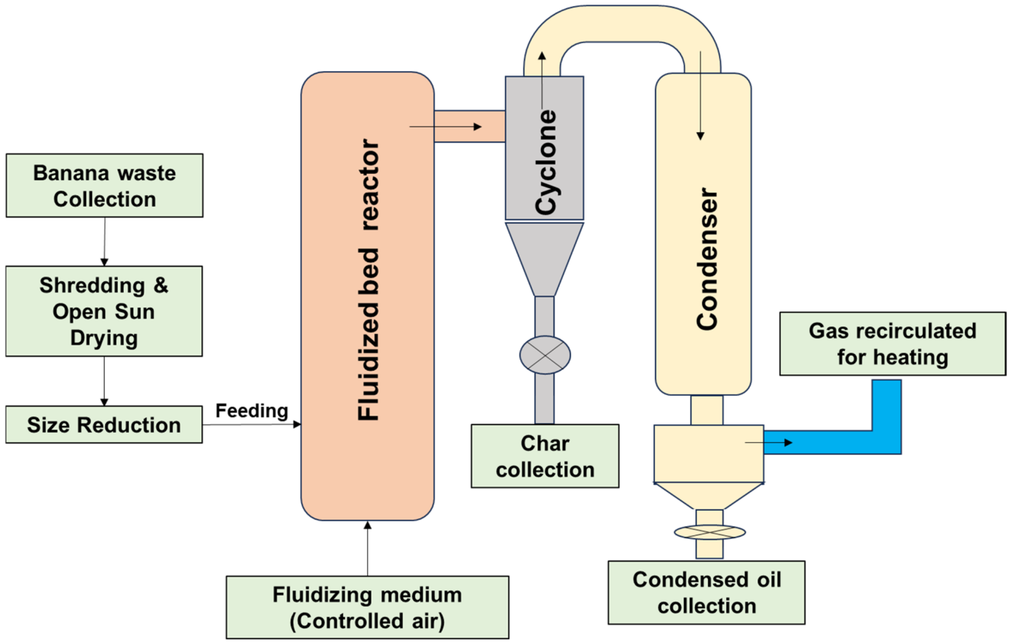

Figure 1. Illustration of the experimental set-up as a self-heat generation by partial feed combustion provides the internal heat required for the process initiation.

3. Results and Discussion

3.1. Raw Material Characterization

Characterizing raw banana tree waste is crucial for assessing its viability and potential applications, as outlined in Table 1. The elemental analysis reveals that the waste comprises 35.2% carbon, 4.3% hydrogen (H_2), and 59.0% oxygen. This significant oxygen content, characteristic of lignocellulosic biomass, influences the product distribution during pyrolysis, particularly affecting the yield and composition of bio-oil [8,22]. The minimal sulfur and nitrogen levels make banana tree waste an advantageous feedstock for energy production [8,30]. The moisture content of the raw banana tree waste, measured at 10.08% after sun drying, can facilitate heat transfer in the pyrolyzer. However, excessive moisture may impair process efficiency by requiring additional energy for evaporation. The waste also exhibits a high ash content of 14.8% and a fixed carbon content of 4.5%, attributed to its substantial cellulose and lignin content [22]. The higher heating value (HHV) of the banana tree waste is 14.2 MJ/kg, reflecting moderate energy content and indicating its potential as a viable feedstock for pyrolysis [22,28]. The HHV is influenced by the biomass's composition, with lignin contributing a higher calorific value compared to cellulose and hemicellulose [8]. Analysis indicates that the high cellulose content (33.1%) may enhance the production of levoglucosan and other anhydrous sugars during pyrolysis [16,22,31]. In contrast, the lignin content (31.8%) contributes to the formation of phenolic compounds and hydrocarbons with elevated calorific values. Additionally, lignin's presence leads to a higher proportion of solid residues due to its carbon content and the formation of aromatic compounds [8,32]. In addition, high lignin present in biomass is inhibitory for developing biowaste-based microbial fermentation to produce energy and value-added products [33–36]. The hemicellulose and moisture content contribute to a more substantial aqueous fraction of acetic acid and various gas-phase compounds [16,30].

Table 1. Component analysis of mixed banana waste used in experiments.

Component	Value	Component	Value
Elemental analysis		Proximate analysis	
Carbon (%)	35.2	Moisture (%)	10.1
Hydrogen (%)	4.3	Ash (%)	14.8
Nitrogen (%)	1.4	Volatile (%)	70.6
Sulfur (%)	0.04	Fixed carbon (%)	4.5
Oxygen	59.0		
Lignocellulosic analysis			
Cellulose (%)	33.1		
Hemicellulose (%)	12.9		
Lignin (%)	31.8		
Extractives (%)	8.8		
Calorific value (MJ/kg)	14.2		

3.2. Thermogravimetric Analysis

The primary degradation process begins around 180 °C, with the decomposition of lipids and the release of a small quantity of residual bound moisture (Figure 2). As the temperature continues to rise, hemicellulose begins to degrade, followed by the decomposition of cellulose. Most of the mass loss, approximately 65%, is observed between 180 and 350 °C, corresponding to the breakdown of these two significant components [16,37]. At higher temperatures, lignin decomposition occurs, contributing to a substantial weight loss of around 25% in the temperature range of 420–550 °C. Beyond this, a minor mass loss may be observed, potentially due to the catalytic effects of ash interacting with fixed carbon, leading to the formation of carbonates. The DTG curve further highlights the temperature ranges in which maximum decomposition occurs. The first peak is observed at around 310 °C, corresponding to the maximum reaction rate primarily associated with the degradation of hemicellulose and cellulose [16]. The second phase, corresponding to lignin degradation, occurs within the 420–550 °C temperature range, with the highest conversion rate at 451 °C. Hemicellulose and cellulose are primarily responsible for the significant mass loss in the 180–350 °C range, while lignin degradation dominates the 420–550 °C range. These findings agree with established literature, which reports similar degradation patterns for various biomasses [1,32,37–40]. The moisture content of banana tree waste, slightly higher than that of other biomass types, contributes to an increased energy requirement for pyrolysis due to the need to evaporate excess water before the onset of the main decomposition processes [37]. The TG and DTG curves provide a clear understanding of the pyrolysis behavior of banana waste, offering insights into the temperature-dependent behavior of its components and the resulting product distribution during thermal conversion [16,37].

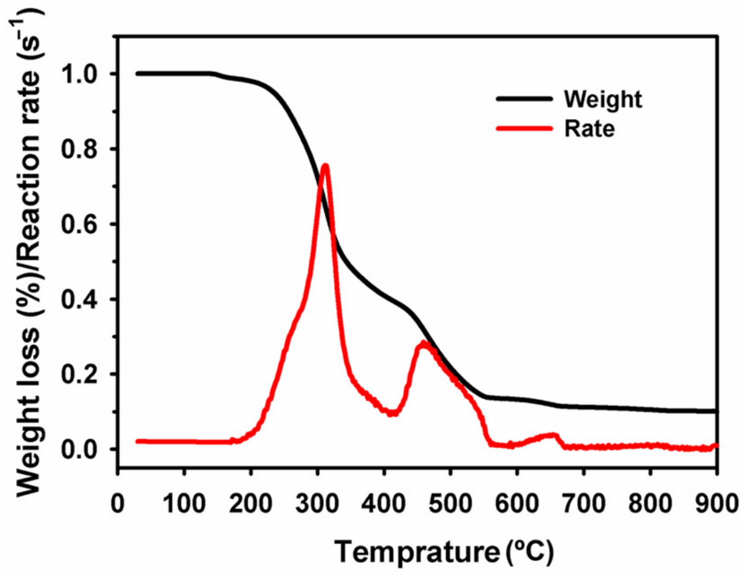

Figure 2. TG and DTG curve of banana waste pyrolysis.

3.3. Effect of Temperature on Product Yield

Thermogravimetric analysis (TGA) was employed to determine the optimal temperature range of 440–560 °C for studying the effect of temperature on product yields during the pyrolysis of banana waste in a fluidized bed system. The pyrolysis experiments were carried out with a fixed volatile retention time of 2 s. The fluidized bed pyrolyzer was preheated to the target temperature, with sand (<2 mm particle size) used as the fluidizing medium. The sand was preheated before introducing the banana waste to minimize temperature fluctuations. Before each experiment, the system was stabilized for at least 20 min to ensure steady-state conditions, after which measurements were taken. The accompanying Figure 3 illustrates the effect of operating temperature on bio-oil, char, and gas yields during banana waste pyrolysis. The observed trends reflect the thermal decomposition behavior of the main biomass constituents. At the lower temperature of approximately 440 °C, the oil yield starts at around 30.0%, while char and gas yields are about 40.0% and 30.0%, respectively.

As the temperature increases, the oil yield initially rises, peaking near 500 °C, before gradually declining with further temperature increases. This initial rise in oil yield can be attributed to the thermal decomposition of hemicellulose and cellulose, which release volatile compounds such as acids, ketones, and anhydrous sugars, essential precursors in bio-oil formation [31,38]. However, the oil yield declines at higher temperatures due to the increased production of non-condensable gases and reduced char content [41]. The char yield steadily decreases with increasing temperature, dropping from around 40.0% at 440 °C to below 30.0% at 560 °C. This reduction aligns with typical pyrolysis behavior, where higher temperatures promote biomass volatilization, leaving less solid residue behind [16,37]. Although lignin contributes to some char formation, the yield diminishes as more biomass is converted into volatile compounds and gases [10,32]. Conversely, the gas yield significantly increases as the temperature rises, going from approximately 30% at 440 °C to over 50% at 560 °C [40,41]. This trend is primarily driven by the degradation of lignin and other biomass components, which produce larger volumes of non-condensable gases at elevated temperatures [21,32,37]. The graph (Figure 3) underscores the influence of temperature on product distribution during banana waste pyrolysis. As the temperature rises, there is a consistent increase in gas production, a continuous reduction in char yield, and an initial increase in bio-oil yield followed by a decline at higher temperatures, which was in line with the published literature [30,31,37,38]. For further studies, the optimal temperature of 500 °C was selected based on the high conversion of biomass into bio-oil without any detrimental effects.

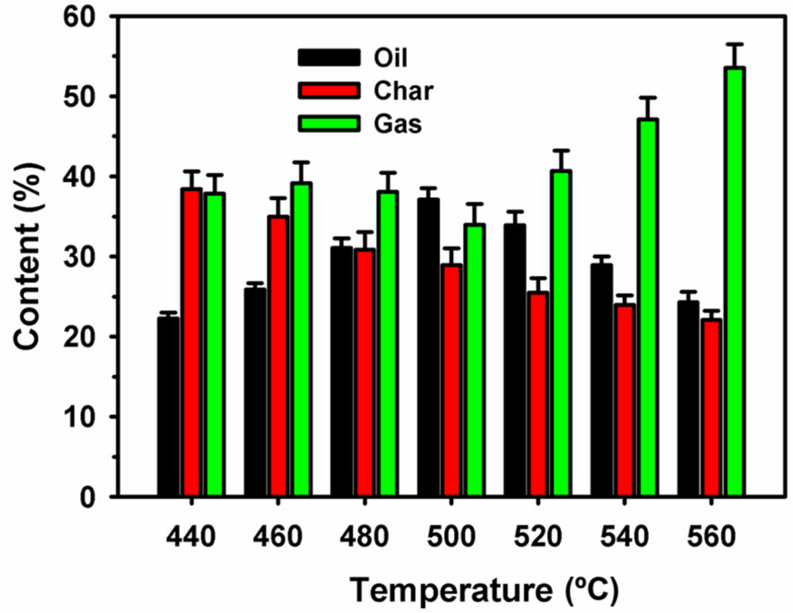

Figure 3. Banana mix waste fluidized bed pyrolysis product yield distribution with varying processing temperatures.

3.4. Effect of O/B Ratio on Product Yield

The oxygen-to-biomass ratio (O/B ratio) is a crucial parameter in oxidative pyrolysis, as it directly influences the yield and composition of the pyrolysis products [42]. This ratio controls the degree of oxidation within the reactor, affecting the resulting products' energy balance and distribution. In experiments conducted at a lower equivalence ratio (ER), minimal oxidation was observed, leading to a higher bio-char yield and gases. The heat input required was comparatively lower than that in traditional pyrolysis processes [43,44]. However, as the ER ratio increased from 0.05 to 0.1 (Figure 4), there was a gradual reduction in char yield, indicating its utilization in oxidation reactions for heat generation [43]. Simultaneously, bio-oil production showed a slight increase in weight percentage, with a significant increase in volume due to the formation of low-density bio-oil containing higher concentrations of oxygenated compounds [44–46].

Further ER ratio increases negatively impacted bio-oil production, while gas yields, especially carbon monoxide (CO) and CO_2, increased [42]. The heightened char oxidation resulted in lower char yield with a higher ash content and high gas phase conversion [8,16]. The optimum ER ratio for oxidative pyrolysis was in the range of 0.1–0.12. At this range, the char generated during the process produced sufficient heat for self-sustained operation while maximizing the bio-oil yield [43]. Beyond this range, additional oxidation reactions led to the conversion of more products into gas phases, predominantly CO and CO_2, with small amounts of H_2. The increase in ER also resulted in higher water content and more acidic components in the bio-oil [43,44]. The increased bio-oil yield within this ER range can be attributed to the highly porous nature of the char, which acts as a catalyst, facilitating interactions among volatiles and leading to the formation of longer-chain hydrocarbons. However, further increases in the ER led to diminished bio-oil yields.

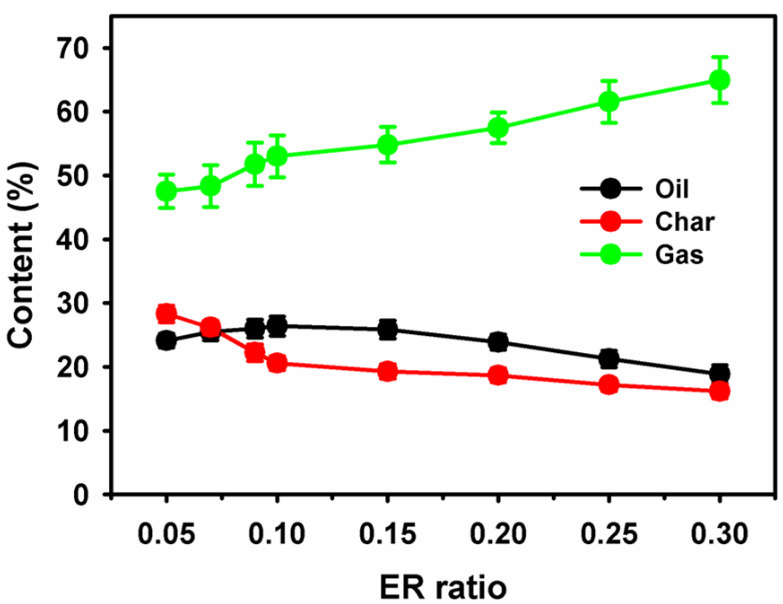

Figure 4. Effect of ER ratio on banana mix waste pyrolysis products in a fluidised bed reactor at a temperature of 500 °C.

The ER ratio directly impacts product distribution and the quality of the resulting products [42]. The bio-oil yield from oxidative pyrolysis is generally lower than conventional pyrolysis, but partial oxidation facilitates the formation of acids, alcohols, ketones, and aldehydes [45]. Although these oxygenated compounds improve bio-oil stability, they also increase their acidity and corrosiveness, necessitating further fuel application upgrades [14]. In the case of bio-char, the char produced at optimal ER ratio tends to be of higher quality, exhibiting enhanced porosity, a larger surface area, and more excellent fixed carbon content. However, increased ER leads to lower-quality char production with reduced carbon and higher ash content [41]. The inorganic components in the char can be beneficial for soil health, particularly when used as a soil amendment. The pyro-gas or gas yield is generally higher due to partial combustion during oxidative pyrolysis, producing significant amounts of CO and CO_2, along with small quantities of H_2 and CH_4. While the calorific value of this pyro-gas is lower, it can still be utilized in other chemical synthesis processes [39,42].

3.5. Product Characterization

3.5.1. Bio-Oil

During oxidative pyrolysis with an ER ratio of 0.1 to 0.12, the process promotes partial oxidation, which enhances the yield of certain valuable compounds, such as acids and aldehydes, while reducing the overall tar content in the bio-oil [16,31]. This controlled oxidation minimizes the presence of highly reactive oxygenated species, leading to improved bio-oil stability [42,44]. It has also been reported that longer residence times during pyrolysis favor secondary reactions, which promote the cracking of larger molecules into more minor, more volatile compounds. This molecular breakdown contributes to a higher quality bio-oil, with reduced tar and increased fractions of lighter compounds [16,31,44]. The bio-oil produced from banana tree waste is a complex mixture of organic compounds, including oxygenated hydrocarbons, phenolics, acids, aldehydes, and ketones, which are heavily influenced by feedstock characteristics and pyrolysis conditions. Oxygen during oxidative pyrolysis significantly impacts the composition of the bio-oil, steering the reactions towards the formation of oxygenates such as carboxylic acids and ketones, which are crucial for improving the fuel properties of bio-oil [45].

Physical analysis of the bio-oil revealed several important properties (Table 2). The density of the bio-oil was measured at 1280 kg/m^3, which is higher than conventional fossil-based fuels like furnace oil [8,30,44]. Additionally, the viscosity of the bio-oil was reported to be comparatively higher than furnace oil, indicating that it may require further processing for use in engines. The water content of the bio-oil was 2.3%, which is typical for biomass-derived oils, as water is a significant byproduct of pyrolysis reactions [8]. The solid content in the bio-oil was 6.4%, mainly due to the carryover of char and other solid residues (Table 2) from the pyrolysis process. A calorimetric analysis revealed that the heating value of the bio-oil's organic fraction was 24.8 MJ/kg, which is comparable to other biomass-derived fuels and makes it a promising alternative energy source [35,45].

Table 2. Physical bio-oil (organic fraction) characterization obtained during oxidative pyrolysis at 500 °C.

Properties	Unit	Values
Water content	wt%	2.3
Ash content	wt%	0.24
Total solid	wt%	6.40
Heating value	MJ/kg	24.88
Density (@40 °C)	kg/m^3	1280
Viscosity (@40 °C)	cP	30.3
Flash point	°C	87
Acidity	pH	4.8

The bio-oil's composition is also strongly influenced by the breakdown of significant biopolymers in the banana waste feedstock. Phenolic compounds, including phenol, guaiacol, and syringol, are primarily derived from the degradation of lignin [45]. These compounds are of significant interest due to their potential use as chemical feedstocks. In contrast, aromatic hydrocarbons like benzene, toluene, and xylene are produced in smaller concentrations [8,44]. The degradation of hemicellulose and cellulose during pyrolysis results in carboxylic acids, mainly acetic acid and formic acid, which can lower the pH of the bio-oil. Intermediate compounds, such as sugars, are also formed during cellulose breakdown, leading to furfural generation, which has potential industrial applications (Figure 5) [42]. In summary, oxidative pyrolysis of banana tree waste at controlled ER levels offers a viable method for producing bio-oil with enhanced chemical stability, reduced tar content, and favorable physical properties. The diverse composition of the bio-oil, rich in valuable phenolics, acids, and aldehydes, highlights its potential for use as both a biofuel and a source of industrial chemicals [39]. Further refinement of pyrolysis conditions, including optimization of residence times and oxygen levels, could improve the quality and economic viability of bio-oil derived from banana waste, contributing to sustainable waste management and renewable energy production [1,16,42].

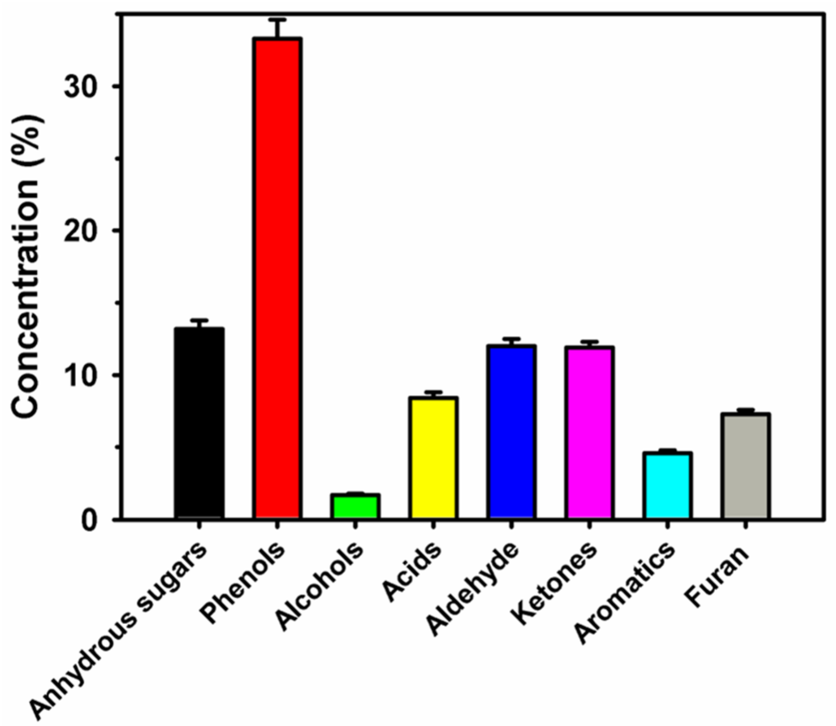

Figure 5. A relative percentage of the different component groups in bio-oil derived from banana mix waste obtained at 500 °C.

3.5.2. Bio-Char

The bio-char derived from the oxidative pyrolysis of banana tree waste was comprehensively characterized to evaluate its potential applications in energy production, agriculture, and carbon sequestration. The analysis included an assessment of its proximate composition, calorific value, and bulk density, providing insights into its structural and chemical properties. The bio-char exhibited a high ash content of 33.2%, indicative of substantial inorganic material in the banana tree waste feedstock. Previously, a lower ash content of 16.0–21.2% was noted for rice husk, corn cobs, and bagasse sugarcane-based bio-char [47]. In contrast, at a higher pyrolysis temperature of 550 °C for buckwheat husk, Mulberry wood, and peanut shell-derived bio-char, a low ash content of 5.8–9.1% was reported [48]. This high ash content is typical of bio-chars produced from agricultural residues and contributes significantly to its mineral composition [10]. These minerals, including potassium, calcium, and magnesium, benefit soil fertility, making bio-char valuable as a soil amendment. However, a high ash content may lower the bio-char's overall calorific value, reducing its effectiveness as a fuel. The volatile matter content was measured at 33.3%, indicating that the bio-char retains a portion of easily degradable compounds [43]. Previously, a lower volatile content of 22.4% was reported for bio-char originating from pine chips [49]. This moderate volatile content is suitable for agricultural applications, mainly where slow-release nutrients are advantageous. The bio-char's fixed carbon content was also determined to be 31.4%, a vital indicator of the carbon retained after pyrolysis. High fixed carbon is desirable for carbon sequestration, as it ensures the bio-char's long-term stability in soils, making it practical for carbon storage. Moreover, fixed carbon enhances bio-char's potential in activated carbon production due to its thermal stability and adsorptive capacity [50,51]. The calorific value of the bio-char was 20.3 MJ/kg, which, while lower than traditional fossil fuels, is sufficient for its use as a supplementary fuel in energy generation processes such as co-firing in biomass power plants or heating purposes. In contrast, a lower calorific value of 13.6 MJ/kg was recorded for bio-char of banana pseudo-stems derived by fast pyrolysis at 500 °C [50]. Its moderate energy content suggests that although bio-char may not be a primary fuel source, it can contribute to renewable energy systems, especially in decentralized or low-tech applications that utilize agricultural residues [41]. The bio-char's bulk density was relatively low, which is advantageous for soil applications, as it can improve soil aeration, water retention, and overall soil structure. However, this low density may present challenges for transportation and storage, as larger volumes would be required to reach the necessary mass, potentially increasing logistical costs, particularly in industrial-scale operations [51,52].

3.5.3. Pyro-Gas

The composition of the gas phase is a crucial factor in evaluating the efficiency of the pyrolysis process and the potential for pyro-gas utilization in energy production [8]. The primary components identified in the gas stream from oxidative pyrolysis of banana tree waste include CO (22.0%), CO_2 (16.2%), H_2 (8.8%, CH_4 (4.9%), and trace amounts of other light hydrocarbons at an operational condition of 20 min (Figure 6). During the initial reaction stage, the gas flow was kept at maximum, and biomass was fed into the system slowly, resulting in complete combustion, producing a large amount of CO_2. Further, the feeding was increased to maintain the air-to-biomass ratio and the reactor's temperature. Therefore, increased biomass feeding to the reactor results in incomplete combustion and produces a large amount of CO. In contrast, as the reaction happens, the air-to-biomass feeding ratio balances, the steady stage is achieved, and stable reaction heat (ER ratio) and a stable gas profile are observed for the defined ER ratio [29,51]. Therefore, the pyrolysis conditions significantly influence the gas composition, particularly the O/B ratio, and temperature [29]. The CO_2 content was also notably high, reflecting the breakdown of cellulose, hemicellulose, and lignin within the banana tree waste during pyrolysis in the presence of oxygen. Although CO_2 does not contribute to the heating value of pyro-gas, its production provides insight into the overall carbon balance and environmental impact of the process—the combustion reaction producing CO_2 results in providing the heat required for pyrolysis reaction [42]. Controlling CO_2 emissions is essential for optimizing the gas composition for energy applications. CO is typically present in an intermediate concentration, formed primarily through partially oxidizing carbon-rich biomass [8,30]. CO is critical in the pyro-gas energy content and can be further utilized in energy generation or chemical synthesis processes. The H_2 content in the pyrolysis gas was moderate (8.8%), resulting from the thermal decomposition of biomass and secondary cracking of hydrocarbons [32]. In contrast, the diverse biomass wastes pyrolysis yield analysis via proximate analysis and product composition through predictive modeling suggested a low H_2 content of 0.0–0.2% under temperature and heating range of 350–750 °C and 5.0–10.0 °C/min, respectively [29]. CH_4 was also present in mild concentrations, originating from biomass pyrolysis and secondary reactions of more significant hydrocarbons. The balance between maximizing gas yield and producing higher-value liquid or solid products is controlled by adjusting the oxygen supply [47]. The pyro-gas generated during oxidative pyrolysis of banana tree waste consists mainly of combustible gases such as CO, H_2, and CH_4, and non-combustible CO_2. The gas composition varies depending on the O/B ratio, pyrolysis temperature, and residence time [42–44]. The optimal conditions for maximizing combustible gas yield were found at a temperature of 500 °C and an O/B ratio of 0.1. Under these conditions, the pyro-gas exhibited higher concentrations of CO and H_2, contributing to a moderate heating value [16,50]. The heating value of pyro-gas is a crucial parameter for its energy applications. Based on the gas composition, the lower heating value (LHV) was estimated to range between 12 and 14 MJ/m^3, which aligns with typical biomass (rich in cellulose and hemicellulose)-derived pyro-gas with a range of 14.6–15.2 MJ/kg [16]. This heating value makes the pyro-gas suitable for various applications, including power generation, co-firing in boilers, and as a feedstock for chemical synthesis, offering a versatile energy source in renewable energy systems [28].

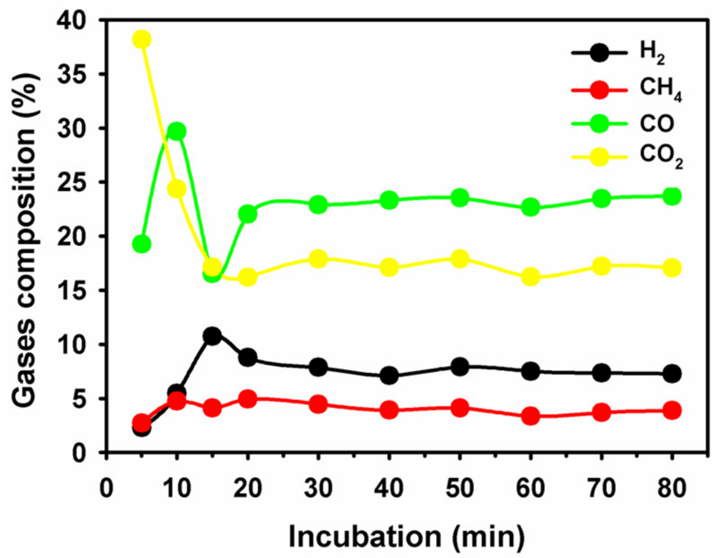

Figure 6. The concentration variation of pyrolytic gas components over 60 min after stable operation (20 min).

4. Conclusions

In conclusion, using banana biomass waste for pyrolysis presents significant potential for energy recovery by producing various pyrolysis products, including fuels. The moisture content in the biomass plays a crucial role in influencing product yield and distribution during the pyrolysis process. Oxidative pyrolysis, in particular, offers several advantages, including higher gas yields, improved energy efficiency, and reduced tar formation. It also provides greater flexibility in product distribution and simplifies reactor design, making it a promising approach for converting biomass into value-added products. Additionally, oxidative pyrolysis enhances carbon conversion efficiency and supports sustainability objectives by facilitating energy recovery, thereby contributing to cleaner waste management practices. While oxidative pyrolysis leads to a reduced overall product yield compared to conventional pyrolysis, it offers the benefit of lowering energy consumption during the process. A complex mixture of oxygenated hydrocarbons, phenolics, acids, aldehydes, ketones, furan derivatives, alcohols, and aromatic hydrocarbons characterizes the bio-oil derived from oxidative pyrolysis of banana tree waste. Oxygen during pyrolysis significantly affects both the bio-oil's yield and chemical composition, distinguishing it from that produced through non-oxidative methods. Moreover, oxidative pyrolysis with a low equivalence ratio (ER) of 0.1–0.12 has minimal impact on bio-oil quality, though a reduction in overall product yield is observed. A thorough understanding of the bio-oil's composition is crucial for optimizing the pyrolysis process and exploring its potential applications in biofuels and chemical production through clean technologies.

Author Contributions: Conceptualization, R.K.S. and S.K.S.P.; methodology: R.K.S. and B.S.; validation, B.S. and U.P.; formal analysis, B.S., U.P. and A.K.J.; investigation, R.K.S., B.S., U.P. and S.K.S.P.; resources, R.K.S. and A.K.J.; data curation, B.S. and U.P., writing—original draft preparation, R.K.S.; writing—review and editing, R.K.S., A.K.J. and S.K.S.P.; supervision, R.K.S., A.K.J. and S.K.S.P.; project administration, R.K.S., A.K.J. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This piece of research is financially supported by the Indian Council of Agricultural Research (ICAR), New Delhi, Govt. of India (GoI) under All India Coordinated Research Project (AICRP) on Energy in Agriculture and Agro-based Industries (EAAI) program (grant number: VVN/EAAI/DRET-LBT/2023/01).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank the Director, Sardar Patel Renewable Energy Research Institute (SPRERI), Vallabh Vidyanagar, Anand, Gujarat, India, for his support and encouragement. Also, the author would like to thank Vice Chancellor Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar, for providing necessary support.

Conflicts of Interest: The authors declare no conflicts of interest.

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