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Bio-Oil Derived from Teff Husk via Slow Pyrolysis Process in Fixed Bed Reactor and Its Characterization

Marcin Landrat ¹, Mamo T. Abawalo ^{1,2,*}, Krzysztof Pikoń ¹ and Roman Turczyn ³

¹ Department of Technologies and Installations for Waste Management, Faculty of Energy and Environmental Engineering, Silesian University of Technology, 44-100 Gliwice, Poland

² Faculty of Mechanical Engineering, Jimma Institute of Technology, Jimma University, Jimma P.O. Box 378, Ethiopia

³ Department of Physical Chemistry and Technology of Polymers, Faculty Chemistry, Silesian University of Technology, 44-100 Gliwice, Poland

* Correspondence: mamo.tesemma2022@gmail.com

Abstract: Due to the depletion of fossil fuels and the destruction wrought by global warming caused by the combustion of fossil fuels, the search for renewable energy sources has become a major global concern. This study aimed to assess the bio-oil production from teff husk via slow pyrolysis process. The pyrolysis of teff husk took place in a batch reactor at a temperature between 400 °C and 500 °C with a 120 min retention time. At 450 °C, the pyrolysis process produced 32.96 wt.% of optimum bio-oil yield and had a HHV of 25.32 MJ/kg. TGA, FTIR, and SEM-EDX were used to analyze the produced bio-oil to investigate its thermal decomposition, functional groups, and surface morphology with its elemental composition, respectively. Alcohols, aromatic, phenols, alkanes, esters, and ethers were the primary compounds of the bio-oil produced by the slow pyrolysis of teff husk. The HHV of the biochar ranged from 21.22 to 22.85 MJ/kg. As a result, teff husk can be used to make biofuel; however, further bio-oil upgrading is needed for the produced teff husk bio-oil to be used effectively and commercially. Overall, the slow pyrolysis of teff husk offers a chance to produce biofuels with enhanced value that can be used for additional purposes.

Keywords: biomass; teff husk; pyrolysis; biofuel; bio-oil; biochar; TGA; FTIR; SEM; EDX



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1. Introduction

The world is currently on the verge of an energy crisis as a result of the rapid and ongoing depletion of fossil fuels, rising fuel consumption, and environmental pollution brought on by high fuel prices and greenhouse gas emissions. Due to human exploitation of resources such as fossil fuels brought on by industrialization and population growth, these resources are becoming increasingly scarce [1]. As a result of the rise in crude oil prices on the global market, developing countries are suffering. These countries' situations are getting worse as the energy supply and demand gap continues to increase over time. Due to this, researchers are motivated to minimize their reliance on restricted non-renewable energy sources and to look into alternate methods of energy generation which are eco-friendly and renewable in contrast with conventional fossil fuels. These issues stem from the use of energy derived from fossil fuels in several sectors, including electricity production, agricultural, transportation, industry, and others [2,3]. The largest source of exhaust emissions into the atmosphere, including carbon dioxide (CO₂), carbon monoxide (CO), and sulfur dioxide (SO₂), is the use of energy derived from fossil fuels [3–5]. One of the most promising resources for producing heat, power, alternative transportation fuels, high-valued biochemicals, etc., is biomass; because of its vast availability and carbon neutrality, 14% of the world's energy demands are fulfilled by biomass [6].

Over the last few decades, a number of methods for converting biomass into liquid, solid, and gaseous fuels have been discovered. Through a variety of processes, biomass

can be converted into biochemicals, biofuels, or other biobased products [7]. The only renewable resource that can be used to produce solid, liquid, and gaseous biofuels is biomass [6]. In terms of high energy density, transport and storage, liquid biofuels are superior to solid and gaseous fuels [8]. They can be incorporated into existing boilers, turbines, or engines, which is another benefit [9]. The most common techniques can be divided into two categories: thermochemical and biochemical, depending on the features of the processes involved [10,11].

Thermochemical pathways, in contrast to biochemical conversion, can deal with a large amount of feedstock in a comparatively shorter amount of time to create predicted products and energy. Pyrolysis, one of the most common thermochemical conversion processes for biomass, has drawn more attention since it is frequently used to create high-energy-density bio-oil for convenient transportation or biochar [12]. The complete pyrolysis of biomass can be thought of as the decomposition of polymer chains in biomass macromolecules into solid rich in carbon (biochar), condensable liquids (bio-oil), and non-condensable volatiles (gases) via the external application of heat in an inert atmosphere [13–15]. Pyrolysis consists of several spontaneous reactions influenced by numerous operating parameters such as reactor temperature, pyrolysis heating rate, time of reaction, particle size, biomass composition, and moisture content [8].

At temperature conditions of 350–550 °C, the biomass components start to decompose, and this process continues to a temperature of about 800 °C. As a result, the biomass's linkages between hydrogen, carbon, and oxygen break down, producing solid, liquid, and gaseous pyrolysis products. These might be classified as primary or secondary reactions. The primary reaction pathway involves dehydration and charring reactions. This process produces both primary products and intermediates. The intermediates attained during the primary reactions are subjected to secondary reactions, which breakdown the intermediates. The pathway for the secondary reaction consists of volatilization and degradation reactions [10]. The biomass's primary constituents do not degrade at the same rate during pyrolysis.

The pyrolysis process conditions will determine the rate and extent of their degradation. Hemicellulose typically decomposes first, followed by cellulose, then lignin, which decomposes under a wider temperature range [14]. Bio-oil produced by the pyrolysis of biomass is sometimes referred to as pyrolytic oil, bio-fuel oil, and pyrolysis oil [16,17]. It generally occurs as a dark brown organic liquid [17–19]. Numerous aromatic hydrocarbons, alkanes, phenol derivatives, as well as small amounts of alcohol, ketones, amines, esters, ethers, and sugars with H/C molar ratios higher than 1.5 are among the hundreds of organic compounds found in bio-oil [20,21]. It is produced by pyrolysis at high temperatures in the absence of air or oxygen. The produced bio-oils can be used as fuels in boilers or upgraded subsequently to produce fuels and bulk chemicals using various techniques such as hydrogenation [22,23], zeolite cracking [24–28], and aqueous phase processing [29,30].

Pyrolysis temperature is recognized to significantly impact product distribution based on earlier investigations and literature reviews [31–35]. While low heating rates encourage char development [16,36], faster heating rates at a temperature of about 500 °C maximize bio-oil yield [37,38]. According to Nigrinad and Williams [39], when rice husks were pyrolyzed in a fluidized bed reactor, the amount of carbon monoxide produced in the gas byproducts increased as the pyrolysis temperature increased.

In another study by Abnisa et al. [40], the bio-oil yield increased from 36.8 wt.% to 46.1 wt.% at pyrolysis temperatures between 400 and 500 °C for palm tree empty fruit bunches; however, at temperatures between 600 and 800 °C, the bio-oil yields fell from 42.9 to 35.6 wt.%. The decrease in organic and particular product yields and secondary cracking of volatiles at temperatures above 500 °C can explain the decline in bio-oil yields [41]. More gaseous products have been produced due to the cracking, which has also been seen at other biomass wastes in the literature [42,43].

According to the studies, Ethiopia has a total annual bio-energy availability of 750 PJ (46.5% forest residue, 34% crop residue, 18.8% livestock waste, and 0.05% MSW) [44]. Teff

(*Eragrostis teff*) is an annual cereal crop that self-pollinates. It represents the majority of cereal crops grown in Ethiopia. Teff grain has reportedly been produced at a rate of 3.7 million tons annually in recent years [44].

The properties of bio-oil are significantly affected by the type of feedstock and pyrolysis conditions. Previous findings had reported on the bio-oil production derived from different types of biomass feedstock such as oil palm wastes [6], rapeseed [9], rice husk [39], and sunflower-pressed bagasse [32].

Teff husk is a renewable energy source and an attractive fuel for generating transportation fuels. The consumption and production of teff increased day by day, resulting in increased teff husk generation due to the highly increasing population rate in the country. In Ethiopia, it has been estimated that teff husk produces more than 1.75 million tons of trash annually, most of which is burned on the field [45] (Figure 1), which causes severe environmental pollution. However, if these agricultural residues are converted into fuel, it will solve many problems in Ethiopia. Pyrolysis of biomass is a very cost-effective and green technology [15]. Pyrolysis of teff husk can be an alternate fuel oil production method. The country imports petroleum by investing millions of dollars and is facing a transportation fuel crisis. For the scattered distribution of teff husk in Ethiopia and the relatively low cost, the small- and medium-sized pyrolysis plants have a significant competitive advantage in producing bio-oil from teff husk. Through teff husk-derived bio-oil, this problem can also be solved, which helps improve the country's economy. However, the potential of teff husk for biofuel production by thermochemical conversion has not been the subject of a single study.

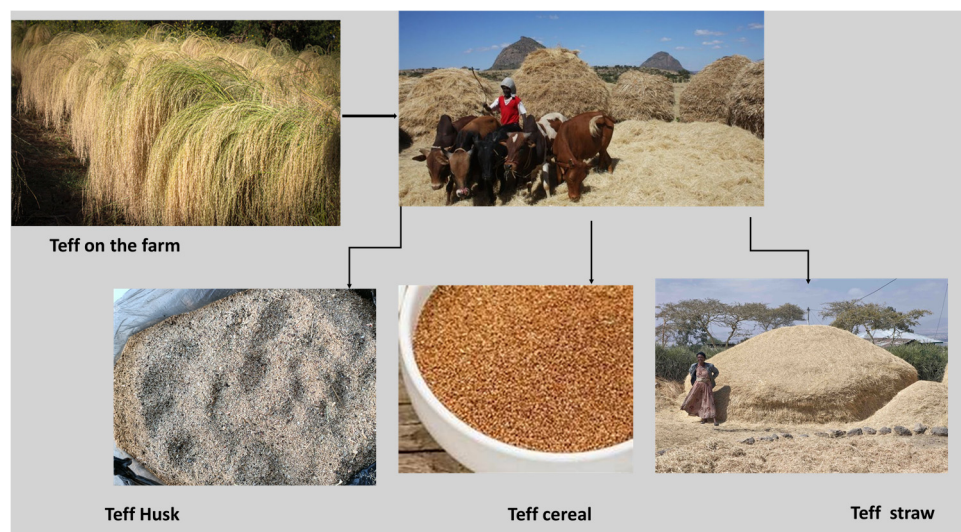


Figure 1. Teff with its residues.

With all this in mind, this study aims to assess bio-oil production from teff husk (TH) via a slow pyrolysis process. The potential of TH to produce the highest yield of bio-oil was evaluated. In this work, teff husk was pyrolyzed in a fixed bed reactor to determine the optimum values of reaction temperature and residence time for getting the highest bio-oil yields. The properties of teff husk-derived bio-oil yield at optimum conditions were studied and compared with the properties of bio-oil derived from other types of biomass.

2. Materials and Methods

2.1. Feedstock Collection and Preparation

In this study, the feedstock used was *eragrostis teff* husk. Because of Ethiopia's strong demand for this specific crop relative to other crops, this particular type of agricultural crop was selected. This feedstock were collected from a teff flour mill factory in the Ethiopian cities of Adama and Jimma. Samples were separated from the teff grain, washed, and

air-dried. The air-dried samples were ground in a blender. The samples were milled to particle size: <0.5 mm.

2.2. Feedstock Characterization

The sample's proximate analysis was performed to determine its moisture, volatile, and ash content, according to the ASTM International E1756-01, E872-82, and E1755-01, respectively. Additionally, utilizing combustion equipment and an electric furnace, the final analyses of the carbon (C), hydrogen (H), sulfur (S), chlorine (Cl), and nitrogen (N) were determined. The fixed carbon was determined through the difference of the sum of the others in relation to the total sample:

$$FC \text{ (wt.\%)} = 100 - (\text{VM wt.\%} + \text{MC wt.\%} + \text{AC wt.\%}) \quad (1)$$

where FC is the fixed carbon content, MC is moisture content, VM is the volatile matter and AC is the ash content.

An elemental analyzer (Perkin Elmer 2400) was used to directly determine the wt.% of elemental analysis of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) contents of the feedstock. Meanwhile, the oxygen (O) content was determined by using Equation (2):

$$O \text{ (\%)} = 100 - (\%C + \%H + \%N + \%S + \%Cl). \quad (2)$$

To determine the ground teff husk samples', weighing about 0.5–0.6 g, higher heating values, a commercial Parr 6200 Isoperibol bomb calorimeter made by Parr Instrument Company in Moline, Illinois, the United States of America, was used (HHV). The procedure was carried out according to the ASTM D 2015 standard test method. All the analyses were conducted at least three times to obtain the reproducible data. The properties of teff husk are summarized in Table 1.

Table 1. Physicochemical characteristics of teff husk.

Analysis	Results
Proximate Analysis (wt.% as dry bases)	
Moisture	8.57
Volatiles	76.85
Ash	6.13
Fixed carbon	8.45
Ultimate Analysis (wt.% as dry bases)	
Carbon	41.39
Hydrogen	7.77
Nitrogen	2.323
Sulphur	0.055
Chlorine	0.0063
Oxygen ^a	48.46
Calorific value	
HHV (MJ/kg)	15.41

^a by difference.

2.3. Pyrolysis Experimental Procedure

The teff husk was pyrolyzed in a batch fixed bed reactor and the reaction pathway of pyrolysis shown in Figure 2. The apparatus consisted of an electric furnace, a condenser, a thermocouple, and a temperature controller. A K-type thermocouple was installed to measure the reactor's actual temperature. A proportional integral derivative (PID) temperature controller managed the maximum working temperature of this reactor up to 500 °C. One kilogram of the dried teff husk with particle sizes of <0.5 mm was charged into the reactor to start the pyrolysis process. Within three different reaction times (120 min, 107 min, and 120 min, respectively), the temperature of the pyrolysis experiment was

raised by 4.2 °C/min from ambient temperature to the required temperatures (400, 450, and 500 °C).

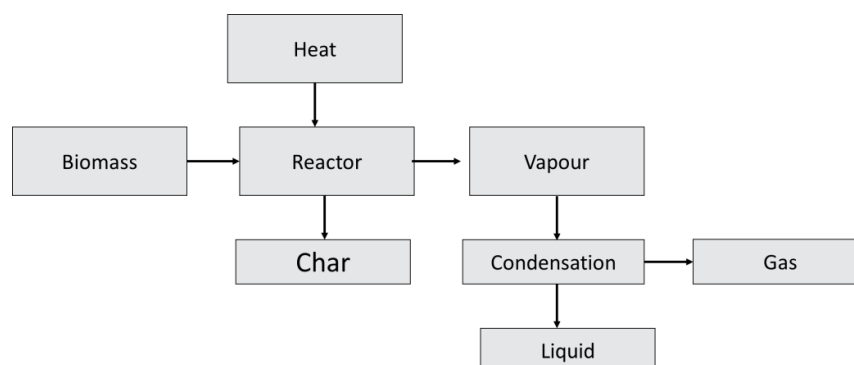


Figure 2. Reaction pathway of pyrolysis process.

The bio-oils that could be condensed during the pyrolysis process were collected in a liquid sample port at room temperature after being condensed in a series of condensers. The bio-oil was then gravimetrically weighed to determine its weight and stored in a closed glass jar for later investigation. Within the reactor, on top of the sand, and in the char pot, char was collected. It did not result in a significant rise in bio-oils because the amount of char in the liquid was less than 2% based on pyrolysis liquid.

The following equations were used for the determination of the yields of the products:

$$\text{Bio - oil yield (\%)} = \frac{\text{mass of bio - oil (g)}}{\text{initial mass of feedstock (g)}} \times 100; \quad (3)$$

$$\text{Biochar yield (\%)} = \frac{\text{mass of bio - oil (g)}}{\text{initial mass of feedstock (g)}} \times 100; \quad (4)$$

$$\text{Gas yield (\%)} = 100 - (\text{Bio oil yield} + \text{biochar yield}). \quad (5)$$

The optimum yield of bio-oil which is obtained under conditions of 450 °C were used for all of the experiments. To validate the data, each experiment was repeated in 3 replicates, and the average result was taken as the final yield.

2.4. Product Analysis

Since this study aimed to assess the potential of the feedstock, the analysis of bio-oil derived from optimum conditions of 450 °C and 4.2 °C/min, which produced the highest bio-oil yield, was carried out for the ultimate analysis and higher heating value (HHV). Thermogravimetric analysis (TGA) was employed to investigate the feedstock and bio-oils thermal decomposition. The collected thermal data was then used to analyze the thermal behavior of the raw teff husk sample and produced bio-oil. The temperature at which the maximum decomposition rate occurs was investigated from the DTG curve (wt.%/min vs. temperature). As a result, the extracted bio-oil and raw teff husk sample's thermal stability and the percentage of volatile materials was observed. To achieve the required operating conditions, the atmosphere of operation and the desired heating program can be adjusted. For each sample, a 3.0 ± 0.1 mg was pyrolyzed at a heating rate of 5, 10, or 25 °C/min to a maximum temperature of 900 °C, followed by a nitrogen purge at a flow rate of 30 mL/min.

The basic functional groups of bio-oil were analyzed using FTIR Spectrum Two with diamond UATR accessory from PerkinElmer, resolution 2 cm⁻¹, 16 scans. Chemical bonds will contract, stretch, and absorb infrared radiation in a specific wavelength range upon the interaction of an infrared light with samples, regardless of the structure of the other molecules. This concept resulted in the identification of the functional groups found in the bio-oil. The FTIR spectra were obtained with an 8 cm⁻¹ resolution in the 400–4000 cm⁻¹

area. To validate the data, each experiment was repeated in 3 replicates, and the average result was taken as the final yield.

3. Results and Discussion

3.1. Characteristics of Feedstock

Table 1 summarizes the results of the proximate and elemental analyses of the teff husk. It was discovered that teff husk had the following moisture, ash, and volatile matter contents: 8.57 wt.%, 6.13 wt.%, and 76.85 wt.%, respectively. Because of its high volatile content in teff husk, it is indicated that teff husk is a suitable feedstock for bio-oil production via slow pyrolysis process [9]. The elemental analysis reveals that raw teff husk contained a percentage of carbon (41.39 wt.%) and hydrogen (7.77 wt.%) similar to the value reported in the literature, and the percentage of sulfur and chlorine is only (0.055 wt.%) and (0.0063 wt.%) respectively. The fixed carbon content of teff husk is 11.19 wt.% and was determined using the formula in Equation (1). Low levels of sulfur and nitrogen oxides will be released by the teff husk during the synthesis of bio-oil (Table 1). Teff husk is an environmentally friendly feedstock for the slow pyrolysis process since it has a low concentration of nitrogen, chlorine, and sulfur in its elemental composition, as shown by elemental analysis.

This study's higher heating value (HHV) of raw teff husk is 15.41 MJ/kg. In comparison to the literature value published by Leitea et al. [46], this value is slightly higher. Teff husk, however, had a lower HHV than other biomasses, including the coconut, rhizomes of cassava, and oil palm, which contained, respectively, 17.77 MJ/kg, 23.67 MJ/kg, and 19.35 MJ/kg of HHV [2,20,24]. According to Jung et al. [42], higher fixed carbon contents increase the amount of heat produced during combustion and a higher heating value. The raw teff husk sample's TG and DTG profiles for the temperature range of 40–800 °C, with a heating rate of 10 C/min, are shown in Figure 3. According to the TG plot in Figure 3, heat propagated into the raw teff husk at a temperature of about 110 °C and drove out the inherent moisture, which is about 8% of the sample weight. The main degrading processes, such as depolymerization, cracking, and decarboxylation, occurred over a temperature range of 155–650 °C. Raw teff husk began to degrade thermally at around 155 °C, and the rate reached its peak between 270 °C and 425 °C. This result agrees with recent studies on lignocellulosic feedstocks with high ash and potassium [26,27]. It is thought that this is due to the ash's catalytic effect. The devolatilization of the sample was almost completed at a temperature of about 650 °C. The TGA results also demonstrated two main weight loss regimes for teff husk. The decomposition of hemicellulose and the early stages of cellulose decomposition might be correlated with the lower temperature regime (155–350 °C), whereas the later stages of cellulose decomposition were primarily correlated with the upper-temperature regime (350–455 °C). Lignin thermal degradation occurred throughout the pyrolysis temperature range (170–560 °C).

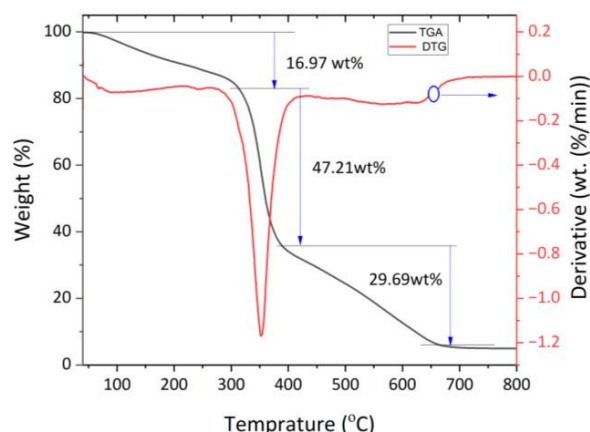


Figure 3. Thermogravimetric (TG) and derivative thermogravimetric (DTG) of teff husk.

3.2. Product Yield

The influence of temperature on the pyrolysis product yields of teff husk (biochar, bio-oil, and gas) was examined and plotted in Figure 4. Teff husk was subjected to pyrolysis in the temperature range of 400 °C to 500 °C to examine the effect of temperature on the product distribution. It is remarkable that the bio-oil yield increased from about 30.5 to 32.96 wt.% as the temperature rose from 400 °C to 450 °C, respectively, but that yield reduced once the temperature went up to 500 °C. An increase in the primary decomposition reactions of the teff husk, such as from thermal cracking and dehydration, could cause an increase in bio-oil yield as the pyrolysis temperature raised from 400 °C to 450 °C. In contrast, the continued cracking of the products at a temperature beyond 450 °C, resulting in non-condensable gases such as CH₄, CO, and CO₂ as described in the prior research [41,46], was the cause of the drop in bio-oil production as the pyrolysis temperature increased further to 500 °C. As the pyrolysis continued, the char yield decreased from about 43 wt.% to 36.5 wt.% with the increase in pyrolysis temperature. The fact that the gas yield dramatically increased as the temperature increased from 400 °C to 500 °C served as evidence (Figure 4).

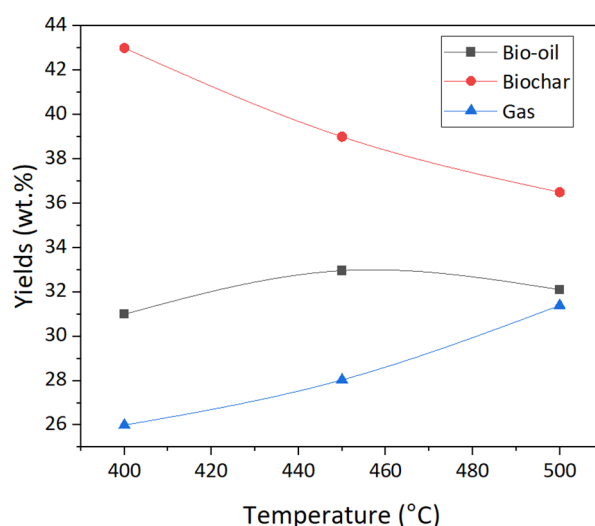


Figure 4. Effect of temperature on the product distributions of teff husk pyrolysis.

The bio-oil yields were relatively low at the lowest temperature of 400 °C. Due to the incomplete pyrolysis of teff husk at this temperature, the bio-oil yield was only 7.2% after 55 min. The significant occurrence of dehydration reactions and thermal cracking caused the bio-oil yields to rise to about 25.8% and 30.6%, respectively, when the residence time was prolonged to 91 and 120 min. These led to an increase in the yield of the bio-oil product.

3.3. Properties of Produced Bio-Oil

We conducted a proximate and ultimate analysis on bio-oil that was produced at optimal conditions (450 °C and 165 min). Calorific value is a crucial factor in examining bio-oil as a fuel. The calorific value for this study is shown in Table 2 as higher heating value (HHV). At 450 °C, the bio-oil produced had an HHV of about 25.32 MJ/kg.

Table 2. Properties of optimum bio-oil.

Characteristic	Temperature Results at 450 °C
Ultimate analysis (wt.% as dry bases)	
Carbon	49.87
Hydrogen	9.69
Sulfur	0.025
Oxygen ^a	37.0
Calorific value	
HHV (MJ/kg)	25.32

^a by difference.

Thermogravimetric analysis was used to analyze the thermal properties of the optimum yield bio-oil. The volatilization of the three bio-oil yields occurred in a low temperature range between 40 and 250 °C with a small shoulder at 150–220 °C (Figure 5). The maximum peak temperatures of BT-400 °C and BT-500 °C bio-oils were 125 °C, and 130 °C, respectively. Nevertheless, bio-oil from BT-450 °C showed another volatilization stage at a temperature > 150 °C.

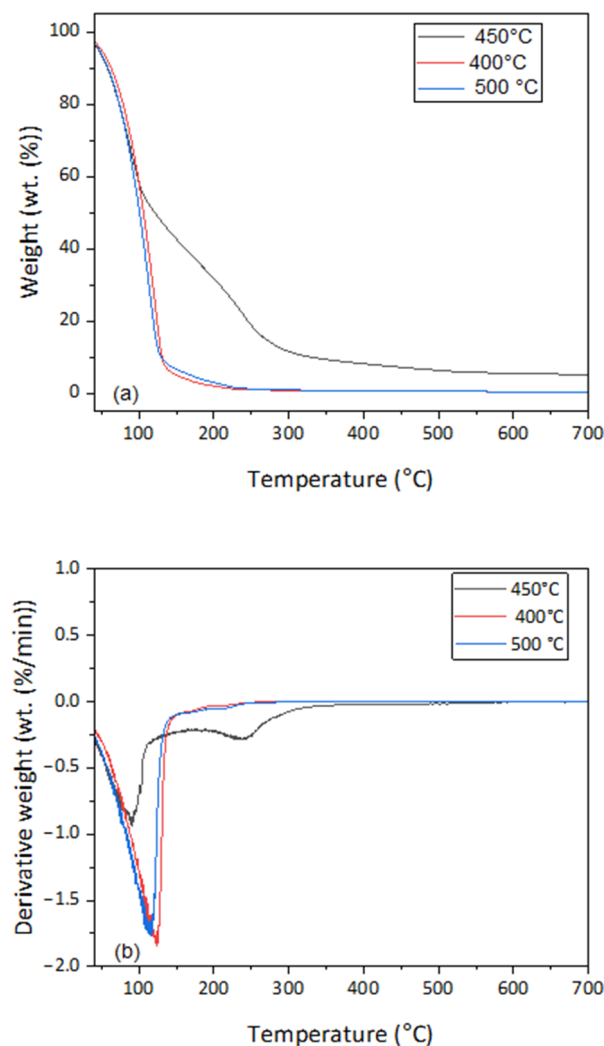


Figure 5. Thermal behavior of bio-oil produced from teff husk pyrolysis: (a) thermogravimetric curves (TG) and (b) derivative thermogravimetric (DTG).

Both their thermal cracking and evaporation may represent the weight loss of bio-oil as a function of temperature [47–49]. These thermograms indicated the evaporation of water and light volatiles and the predicted bio-oil boiling point distribution at temperatures up to 150 °C. The low boiling point (C14–30) compounds detected by GC/MS [50] and secondary products from chemicals in bio-oil reacting with one another after thermal activation are both responsible for the majority of weight loss of bio-oil (40–70%) between 100 and 300 °C. These teff husk bio-oils were full of low boiling compounds. These results complemented the mass loss data from the TGA/DTG outcomes (Figure 5). About 5 wt.% of the residual carbon from 400 and 500 °C was still present at 700 °C, but bio-oil from 450 °C had about 8 wt.%. According to Haarlemmer and colleagues, wood-derived pyrolysis oil had a residual carbon content between 11 and 13%, lower than hydrothermal oils (17–24%) [51]. Table 2 lists the characteristics of the bio-oils produced by the pyrolysis of teff husk.

This work determined the types of chemical bonds (functional groups) of the produced bio-oil using FTIR spectra. Figure 6 displays the FTIR spectra of the produced bio-oil by the pyrolysis of teff husk. The light's wavelengths showed that the three separate bio-oils have chemical bonds with similar characteristics. The bio-oil fractions contained several peaks with weak, medium, broad, and strong intensities that represented several bond types, including C–H, C–O, O–H, C=O, and C–C. The C=O stretching vibrations between 1706 and 1720 cm^{-1} show that the bio-oil contains aldehydes, carboxylic acids, and ketones, whereas the strong absorption bands between 2850 and 3000 cm^{-1} that are characteristic of O–H stretching in all of the bio-oils indicate the presence of phenols and alcohols [52].

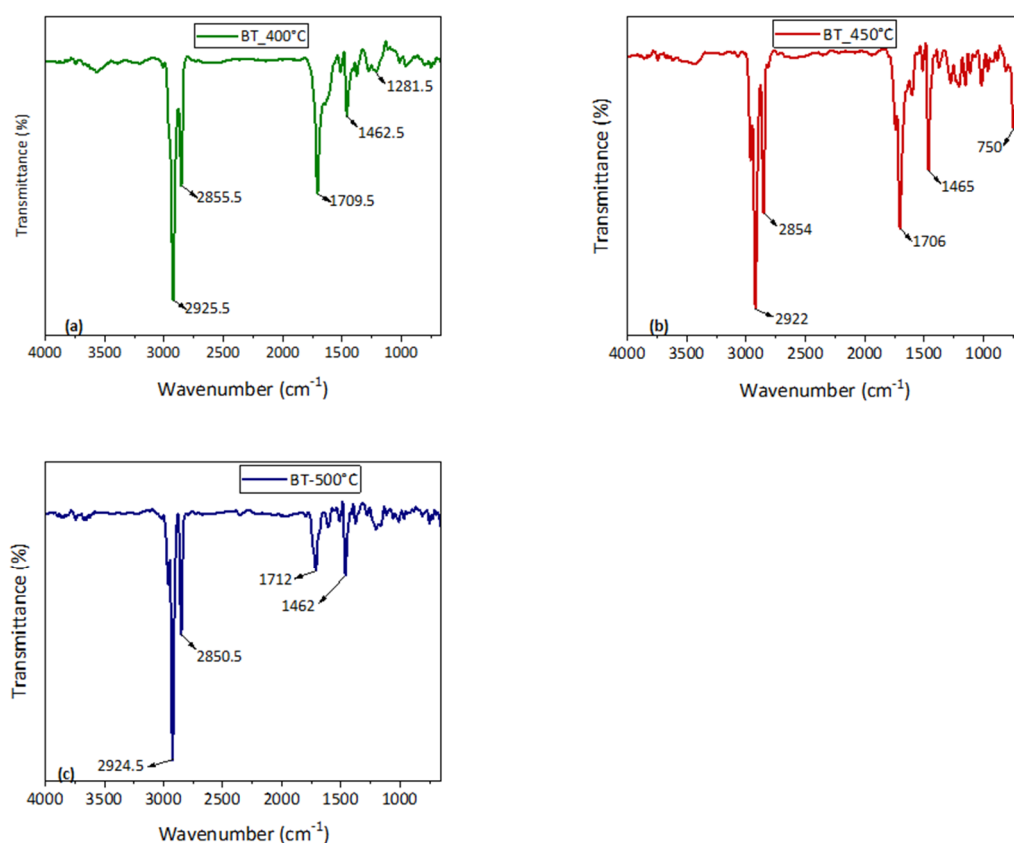


Figure 6. FTIR spectra of the bio-oils from teff husk slow pyrolysis at (a) at 400 °C (b) 450 °C, (c) 500 °C.

Likewise, the bands between 1400 and 1600 cm^{-1} represented C–C stretching vibrations due to aromatics and alkenes. The weak bands at 3200 cm^{-1} indicated the presence of hydrocarbon groups bound to aromatic rings. The C–H stretching vibrations between 650 and 900 cm^{-1} and deformation vibrations between 1350 and 1480 cm^{-1} indicated the

presence of aromatics and alkanes, respectively. On the other hand, the detection of C–O stretching absorptions within the range of 1210 to 1320 cm^{-1} indicated the presence of acid compounds. According to Table 3 FTIR study results, the bio-oil derived from teff husk has a common functional group.

Table 3. FTIR functional group compositions of produced bio-oil.

Wave Number (cm^{-1})		Functional Group	Class of Compound
Range	Actual		
2850–3000	2850.5–2925	C–H stretching	Aliphatic/Alkane
1706–1720	1706, 1709, 1712	C=O stretching	Ketones, Carboxylic Acids, and Aldehydes
1350–1480	1462–1465	C–H bending	Alkanes
1400–1600	1403–1449	C–C stretching	Aromatic
1210–1320	1281	C–O stretching	Acid
650–900	750	C–H	Aromatic
1300–950	126, 1050	C–O stretching	Primary, secondary and tertiary alcohols, Phenols, esters and ethers

3.4. Comparison of Teff Husk Bio-Oil with Other Pyrolysis Bio-Oil and Fuel

Several properties of the bio-oil produced by the teff husk pyrolysis process are examined. Table 4 presents the findings. The characteristics of bio-oil produced from various biomasses and petroleum fuel were also discussed for comparison. According to Table 4, the high heating value of teff husk bio-oil produced at optimum conditions (25.32 MJ/kg) is less than petroleum fuel, more than bio-oil published by [1], and nearly similar to bio-oil produced from other feedstocks reported by Sellin et al. [53] and Rahmad Mohd et al. [54]. Additionally, the minimum HHV of pyrolysis liquid is 15 MJ/kg in accordance with ASTM D7544. When compared to the standard value, the HHV of the teff husk bio-oil discovered in this investigation is good. This might be because teff husk bio-oil has a low percentage of water content and an intermediate carbon composition.

Table 4. Properties of teff husk bio-oil and comparison with petroleum fuel and other bio-oils.

Type of Liquid	Teff Husk (450 °C)	BPS (500 °C)	Bio-Oil of BL	Mesocrap Fiber (Bottom Layer)	Petroleum Fuel
References		[52]	[54]	[2]	[55]
	Elemental analysis (wt.%)				
C	49.87	3.78	55.9	58.93	85.2
H	9.69	9.56	7.8	8.67	11.1
S	0.025	0.72	0.08	0.0	2.3
O	37.0	84.6	35.3	31.73	1.0
Calorific Value HHV (MJ/kg)	25.32	5.35	25.0	27.97	42.94

4. Conclusions

In this study, pyrolysis of teff husk was carried out at certain temperatures ranging from 400 °C to 500 °C with particle sizes of less than 0.5 mm in a fixed bed reactor with a nominal capacity of 1 kg/h, and the bio-oil produced was characterized. The maximum bio-oil yield of 32.96 wt.% was obtained at a temperature of 450 °C, which is relatively similar to the bio-oil yield from other agricultural residues. The physicochemical properties of the bio-oil produced from teff husk are comparable with those obtained from pyrolytic liquid products from other agricultural residues in the literature. The ultimate analysis of the product indicated that the contents of carbon, oxygen, hydrogen, nitrogen, sulfur and chlorine were 41.39 wt.%, 48.46 wt.%, 7.77 wt.%, 2.323 wt.%, 0.055 wt.%, and 0.0063 wt.% respectively. The bio-oil produced from teff husk also gave high carbon, hydrogen, and

oxygen contents. The HHV of 25.32 MJ/kg is close to the commercial biodiesel products requirement. These values were observed to be in the ranges of values stated in the literature for bio-oils produced from agricultural residues.

The bio-oil produced has a considerable range of functional groups of aliphatic, alkanes, aromatic, ketones, aldehydes, alcohols, phenols, and carboxylic acids, and the majority of the functional groups indicate the presence of oxygen. After upgrading, teff husk-derived bio-oil products can be a potential biofuel option for the future renewable energy demands of the country. Establishing bio-oil production by slow pyrolysis will significantly reduce greenhouse gas emissions and energy poverty, improve socioeconomic problems, and be economically sustainable in the country. Finally, the finding of this study is that teff husk is one of the agricultural residues that have the potential to produce bio-oil via a slow pyrolysis process in a fixed bed reactor

Author Contributions: Conceptualization, M.T.A. and M.L.; methodology, M.T.A.; formal analysis, M.T.A. and R.T.; investigation, M.T.A. and M.L.; resources, M.L.; writing—original draft preparation, M.T.A.; writing—review and editing, K.P. and M.L.; visualization, K.P. and M.L. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

BT	Bio-oil at a given temperature
DTG	Derivative thermogravimetric
EDX	Energy dispersive X-ray spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
GHG	Greenhouse gas
HHV	Higher heating value
PID	proportional integral derivative
TH	Teff husk
TGA	Thermogravimetric Analysis

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