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Renewable energy potential of bio-oil from pyrolysis of *Gmelina arborea* seeds cultivated in Nigeria

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ABSTRACT

The increasing demand for renewable energy sources has intensified the search for sustainable alternatives to fossil fuels. Gmelina arborea (Teak) seeds, an underutilized biomass abundant in Nigeria, hold potential for bio-oil production. This study explored the feasibility of utilizing Gmelina arborea seeds for energy generation through pyrolysis, contributing to cleaner energy production and environmental conservation. Gmelina arborea seeds were collected within LAUTECH, Ogbomoso, and subjected to air and oven drying to reduce moisture content before grinding into powder. Pyrolysis of seed was performed in a bench-scale screw reactor at temperatures ranging from 485 to 596 °C. The bio-oil produced was analysed using standard ASTM methods, including proximate and ultimate analyses, Fourier Transform Infrared Spectroscopy (FTIR), and Gas Chromatography-Mass Spectrometry (GC-MS), to determine its chemical composition and energy potential. The bio-oil yield ranged from 21.3 to 25.3 wt.%, with the highest yield of 25.3 wt.% achieved at 596 °C. Characterization revealed favorable energy properties, including a Higher Heating Value (HHV) of 40.13 MJ/kg, kinematic viscosity, density, and flash point within practical application ranges. FTIR analysis identified functional groups such as alkenes, carboxylic acids, alcohols, ethers, and ketones, while GC-MS detected hydrocarbons like alkanes, alkenes, phenols, and naphthalene. The low nitrogen content (2.58-2.80 wt.%) indicates minimal environmental impact. This study highlights the viability of Gmelina arborea seeds as a renewable bioenergy feedstock, offering a cleaner, sustainable alternative to conventional fuels.

INTRODUCTION

The increasing global population, urbanization, and industrialization have intensified energy demands, creating significant environmental and sustainability challenges. Traditional energy sources such as petroleum, natural gas, coal, and nuclear power dominate global consumption but are fraught with concerns including rising costs, diminishing reserves, and severe environmental impacts (Kannahi and Arulmozhi, 2013; Gani, 2021). Fossil fuel combustion contributes substantially to greenhouse gas (GHG) emissions, driving global warming and climate change. These environmental repercussions, coupled with socioeconomic challenges, highlight the urgency of transitioning to renewable and sustainable energy alternatives aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Biomass has emerged as a promising renewable energy resource due to its abundance, eco-friendliness, and capacity to be converted into biofuels through various processes such as thermal, biological, and physical methods.

Among these, pyrolysis stands out as a thermochemical process that decomposes organic materials in the absence of oxygen to produce bio-oil, biochar, and biogas. Bio-oil serves as a potential substitute for fossil fuels, biochar enhances soil fertility, and biogas provides a clean energy source, making pyrolysis a versatile solution for energy and environmental challenges (Bridgwater, 2012; Demirbas, 2004; Lehmann *et al*., 2011). *Gmelina arborea*, a fast-growing tropical biomass from the Lamiaceae family, represents an underutilized resource with significant bioenergy potential. Commonly used in the wood and agronomy industries, its seeds, which are non-edible and considered waste, offer a sustainable feedstock for bio-oil production. Despite its wide availability in Nigeria, the potential of *Gmelina arborea* seeds for renewable energy production remains largely unexplored (Basumatary *et al*., 2012). This study investigates the pyrolysis of *Gmelina arborea* seeds sourced from Nigeria, focusing on bio-oil production and characterization. By leveraging this underutilized biomass, the research aims to provide a sustainable alternative to fossil fuels, reduce environmental degradation, and contribute to the development of renewable energy solutions. The study's findings are expected to advance the understanding of *Gmelina arborea*'s bioenergy potential while addressing critical energy and environmental challenges.

MATERIALS AND METHODS

Sampling and sample preparation

The fruits of *Gmelina arborea* were collected during the peak season in February from the Gmelina trees grown on the premises of Ladoke Akintola University of Technology, Ogbomoso and were taken to the Herbarium of the Department of Pure and Applied Biology for authentication and were given the voucher number (LHO 621). The fruits were de-capped, washed and air-dried, before being pounded into a powder that could be used in the pyrolysis process using a mechanical grinder.

Pyrolysis process

The pulverized sample of *Gmelina arborea* seed was pyrolyzed using a bench scale screw reactor at 400 ℃, 485 ℃, 560 ℃, 571 ℃, and 596 ℃. The pyrolysis process was carried out by optimizing parameters such as residence time, temperature and heating rate. The sample (100 g) was weighed into the reaction chambers externally heated by different pairs of band heaters at 400 to 600 ℃ (Okekunle *et al*., 2019). The fixed bed reactor was electrically powered and used to heat the sample-loaded retort. Nitrogen gas was used as a carrier gas to sweep the volatiles from the retort as they were formed. A rubber hose was channeled through the heated biomass in the form of volatile steam from the retort to a bio-oil trap which was immersed in an ice bath.

The collector trap immersed in the ice bath is required to condense the incoming volatile steam. A second bio-oil trap collector was employed to trap the condensable vapour that escaped from the first oil trap without condensing (Okekunle *et al*., 2019). The pyrolyzed biochar was withdrawn from the furnace and weighed to evaluate the biochar yield using Equation 1 (Selvarajoo *et al*., 2022) and the obtained biochar samples at different temperatures labeled GS3 (560 ℃), GS6 (571 ℃), GS8 (596 ℃), GS10 (525℃), and GS11(485 ℃). Similarly, the bio-oil was collected in a filtering flask placed at the opposite end of the tubular furnace and weighed to determine the bio-oil yield using the mathematical relationship in Equation 2 (Peng *et al*., 2021). On the other hand, the biogas yield was evaluated as the difference between biochar and bio-oil yield using Equation 3 (Li *et al*., 2022).

$$\text{Yield of Biochar (\%)} = \frac{weight\ of\ solid\ product}{weight\ of\ sample} \times 100\% \quad (1)$$

$$\text{Yield of Bio-oil (\%)} = \frac{weight\ of\ liquid\ product}{weight\ of\ the\ sample} \times 100\% \quad (2)$$

$$\text{Yield of Biogas (\%)} = \frac{100\% - Yield\ of\ Biochar\ (\%)}{Yield\ of\ Biochar\ (\%)} \quad (3)$$

Characterization of pyrolytic product

The bio-oil obtained was characterized. The density, moisture content, ash content, pH, elemental composition, viscosity, and heating values as suggested were measured (Chukwuneke *et al*., 2016). The chemical constituents of the bio-oil were determined by GC-MS analysis while the organic functional groups in the oil were characterized via FTIR techniques. The Chemical composition of bio-oil was tested by GC-MS with a quadruple detector and a DB-1MS capillary column (30mm × 0.25mm inner diameter × 0.25µm thickness). Helium was used as the carrier gas with a constant flow of 1.2mL/min. The initial temperature of the oven temperature program was set at 40 ℃ and continued for 4 minutes, rising by 5 ℃/min to 250 ℃, which continued for 10min.

The computer matching of the mass spectra was performed using the NIST98 and WILEY 7.0 library and the retention times of known species injected in the chromatographic column were used for identification. The density of the bio-oil was obtained using a density measurement bottle (pycnometer). Viscosity measurement of the bio-oil was performed using a U-tube viscosity from which the kinematic viscosity at 25℃ mm^2/s was determined. The pH measurement was carried out with a digital pH meter (Hanna model-HI 8424). Moisture content in the oil was measured by the Karl-Fischer titration method under D3173-03 standards. The solid content in the pyrolyzed bio-oil was measured as an ethanol-insoluble portion (Suchithra *et al*., 2014). The acid value of the oil was determined by direct titration with a standard potassium hydroxide solution according to Anyanwu and Adefila, (2014). The ash content was determined according to ASTM D3174-07. The refractive index was measured using a digital tabletop refractometer (Hanna model-HI96800).

The elemental analysis is necessary to ascertain the Carbon, Hydrogen, Oxygen, Nitrogen and Sulfur contents of the oil sample. Carbon, Hydrogen and Nitrogen contents of the feedstock were determined using LECO CHN 2000 Elemental Analyzer according to the test methods of ASTM D5291-02 while the Oxygen content was determined by difference. The heating value of the oil was obtained according to the ASTM D5865 standard test method for the Gross calorific value of Coal and Coke on a dry basis for sun-dried samples. The PAAR 1341 oxygen bomb calorimeter with Benzoic acid pellets was used to determine the Gross calorific value (HHV).

The GC-MS of the oil obtained from the feedstock was analyzed with an Agilent 7890 GC/5975MS using a DB-1701 column for identification and quantification of their chemical compositions while the FTIR spectra of the bio-oil were obtained using JASCO4100 FTIR spectrometer. The bio-oil obtained at the maximum oil yield condition was tested for its fuel properties using the ASTM standard method for petroleum products (Ilknur and Emine, 2011). These include flash points, fire points, pour points, cloud points, cetane indexes, etc.

RESULTS AND DISCUSSION

Product yield

Table 1 presents the product yields from the pyrolysis of *Gmelina arborea* seeds at various temperatures. The bio-oil yield increased with rising pyrolysis temperatures. At 485°C, the yield was 21.3 wt.%, while at 525°C, it increased to 22.6 wt.%. The highest yield of 25.3 wt.% was achieved at 596°C after 60 minutes of pyrolysis. This trend aligns with previous studies, such as that of Selvarajoo and Ohit (2020), which reported similar increases in bio-oil yield as the pyrolysis temperature rose to 650°C, followed by a decrease when temperatures exceeded this range. Alongside the increase in bio-oil yield, there was a noticeable decrease in the biochar yield. The biochar yield dropped from 24.4 wt.% at 485°C to 23.3 wt.% at 596°C, indicating a higher conversion of biomass into liquid products at elevated temperatures. This behavior is typical of pyrolysis, where higher temperatures lead to more thermal degradation of the organic matter, favoring the production of bio-oil and gas at the expense of solid biochar. Correspondingly, the gas yield decreased from 54 wt.% at 525°C to 51.2 wt.% at 596°C, suggesting that, as the temperature increased, the process favored the production of bio-oil over gaseous products.

The temperature-dependent product distribution observed in Table 1 highlights the relationship between pyrolysis conditions and the yields of bio-oil, biochar, and biogas. At 485°C, the bio-oil yield was 21.3 wt.%, but with an increase in temperature to 596°C, the bio-oil yield rose to 25.3 wt.%, while biochar and biogas yields decreased. These results are consistent with other studies on pyrolysis, which have shown an increase in bio-oil yield with temperature up to an optimum point, after which yields can plateau or decline (Bridgwater, 2012).

The increased bio-oil yield observed at higher temperatures can be attributed to the more complete decomposition of *Gmelina arborea* seeds. As temperature rises, the thermal degradation of complex organic polymers within the biomass is enhanced, leading to a greater production of liquid hydrocarbons that condense into bio-oil. The decrease in biochar yield with increasing temperature further supports this, as more of the biomass is converted into volatile gases and bio-oil instead of solid residues.

Table 1: Product yield by pyrolysis process by temperature

Run	Sample	Temperature (℃)	Resident Time (mins)	Bio-oil (wt.%)	Biochar (wt.%)	Bio-gas (wt.%)
1	GS3	560	50	23.2	24.3	52.5
2	GS6	571	45	24.1	23.8	52.1
3	GS 8	596	60	25.3	23.5	51.2
4	GS10	525	60	22.6	23.3	54.1
5	GS11	485	45	21.3	24.4	53.9

The reduction in biogas yield at higher temperatures suggests that the pyrolysis process shifts towards producing more bio-oil, a trend that is beneficial for renewable energy production but reduces the potential for biogas as a by-product. From the pyrolysis yields, it is clear that the maximum temperature for producing bio-oil from *Gmelina arborea* seeds is 596°C. This temperature produces the most bio-oil yield, while still allowing a moderate yield of biochar and biogas. However, the decreasing trends in both biochar and biogas production at this temperature suggest that while bio-oil production is maximized, the potential for other valuable by-products such as biochar and biogas may be limited. These findings are similar to those reported by Demibras (2004), who found that the best bio-oil yields were obtained at temperatures between 500°C and 600°C for various biomass feedstocks.

Overall, these results indicate that pyrolysis at elevated temperatures, particularly around 596°C, is an efficient process for producing bio-oil from *Gmelina arborea* seeds. The bio-oil produced could serve as a renewable energy source, offering a promising alternative to traditional fossil fuels.

Proximate and ultimate analysis of bio-oil

The bio-oil produced from *Gmelina arborea* seeds exhibited a pale brown color. The results for elemental composition, moisture content, density, viscosity, ash content, pH, higher heating value (HHV), and acid value are summarized in Tables 2 and 3. The heating values of the bio-oil ranged from 25.25 to 40.13 mg/kg, indicating a high energy content suitable for bio-oil production. These values were higher than those reported by Okoroigwe *et al.* (2015) and Hossain *et al.* (2014) but aligned with those reported by Oyebanji *et al.* (2017). The HHV of the bio-oil, as shown in Table 2, increased with higher pyrolysis temperatures and heating rates, ranging from 25.25 to 40.13 mg/kg. The observed values fall within the conventional fuel range (15-40mj/kg), making the bio-oil suitable for use in combustion processes, such as boiler applications. The bio-oil exhibited a low pH, indicating its corrosive nature. The pH increased with rising pyrolysis temperatures, reaching a peak of 4.40 at 571°C, before decreasing again at 525°C. The pH values ranged between 3.40 and 4.40, which is consistent with the findings for bio-oils from other feedstocks like corn stover (Muthukumarappan *et al.*, 2011). Such low pH values are typical for bio-oils, which contain substantial amounts of organic acids such as acetic and formic acids, contributing to their corrosiveness, especially at elevated temperatures (Antonakou *et al.*, 2006; Konur, 2021). The moisture content of the bio-oil decreased as the pyrolysis temperature increased. Bio-oil produced at 560°C had the highest moisture content of 7.29%, while the bio-oil produced at 571°C had the lowest moisture content of 4.39%. These findings are consistent with other reports, such as Oasmaa *et al.* (2020), and are comparable to those for bio-oils derived from palm shells (Abnisa *et al.*, 2013). The moisture content affects the heating value of the bio-oil, with higher moisture content leading to lower heating values, while reduced moisture content can improve fuel conversion efficiency (Setter *et al.*, 2020). The density of the bio-oil produced from *Gmelina arborea* seeds ranged from 0.81 to 0.84 g/cm³, meeting the density specifications required for engine use (Renato *et al.*, 2016; Valente *et al.*, 2011). The observed range is in line with the density of biodiesel fuels, indicating that the bio-oil is suitable for fuel applications. Higher-density fuels tend to be harder to burn, while lower-density fuels facilitate better combustion (Bergthorson and Thomson, 2015). Viscosity measurements at 25°C indicated that the bio-oil viscosity decreased with increasing pyrolysis temperatures, with bio-oil produced at 571°C showing the lowest viscosity. This property is advantageous in reducing friction in engine parts and facilitating smoother flow, thereby improving combustion efficiency. Bio-oil viscosity from *Gmelina arborea* seeds is comparable to that reported by Suchithra *et al.* (2010) and Okoroigwe *et al.* (2012).

Table 1: Proximate Analysis of Bio-oil produced from *Gmelina arborea seeds*

Temperature Range (°C)	**pH**	**Refractive index**	**Density g/cm^3**	**Ash content %**	**Moisture content %**	**Viscosity gcm^{-1}s^{-1}**	**Acid value g/100g**	**Heating value mj/kg**
485	4.11±0.014	0.39±0.000	0.83±0.000	0.05±0.007	6.48±0.049	3.08±0.014	173.38±0.657	40.13±0.014
525	3.4±0.014	0.39±0.000	0.84±0.001	0.06±0.000	5.83±0.014	2.28±0.035	72.92±0.021	35.84±0.028
560	3.73±0.021	0.39±0.000	0.82±0.000	0.06±0.000	7.29±0.021	2.49±0.035	280.95±0.636	25.25±0.777
571	4.40±0.000	0.39±0.000	0.83±0.001	0.08±0.000	4.39±0.014	3.16±0.021	78.57±0.042	37.68±0.106
596	3.94±0.049	0.39±0.000	0.81±0.001	0.1±0.000	4.55±0.021	2.75±0.014	62.3±0.569	28.42±0.028
ASTM G Ren *et al* .,(2016)	2.00-4.000	1.45-1.490	0.80-1.300	≤0.25	≤30	2.5-6.0	≤70	≥15

Table 2: Elemental components of bio-oil yield from *Gmelina arborea* seeds

Parameter (%)	485 °C	525 °C	560 °C	571 °C	596 °C
Carbon	24.75±0.007	26.71±0.007	16.95±0.777	20.45±2.397	24.5±0.141
Hydrogen	42.81±0.007	34.80±0.000	30.95±0.636	36.5±0.141	41.11±0.070
Oxygen	31.5±0.141	28.65±0.070	18.68±0.106	21.3±0.707	25.55±0.084
Nitrogen	2.93±0.021	2.60±0.014	2.73±0.021	2.82±0.021	2.76±0.014

Low viscosity reduces problems such as incomplete combustion, nozzle clogging, and lubricant contamination (Hassan *et al*., 2006). Ash content, which is an important indicator of fuel quality, varied significantly with pyrolysis temperature. The ash content was lowest at 485°C (0.05%) and highest at 596°C (0.10%). Excessive ash content can negatively impact combustion efficiency, increasing handling costs, and causing fouling in combustion equipment (Ogunsanwo *et al*., 2011). In this study, the ash content of bio-oils from *Gmelina arborea* was comparable to those from other biomass sources, such as those reported by Okoroigwe *et al*. (2012) and Kato *et al*. (2016), and within the typical range for bio-oils. The acid values ranged from 72.92 to 280.75, indicating that the bio-oil's acidic constituents, particularly at higher pyrolysis temperatures, could affect lubrication properties and stability. Higher acid values typically correspond to increased corrosion risks in storage and engine components (Liu *et al*., 2022). The ultimate analysis of the bio-oil (Table 3) revealed significant variation in the elemental composition. Carbon content ranged from 16.95% to 26.71%, hydrogen ranged from 18.08% to 31.50%, and oxygen ranged from 28.65% to 42.81%. As pyrolysis temperature increased, the carbon and hydrogen content generally decreased, while the oxygen content also decreased, suggesting that reducing oxygen enhances oil stability and hydrocarbon upgrading potential (Shah *et al*., 2012). The low nitrogen content further supports the potential of *Gmelina arborea* bio-oil for bioenergy production with reduced environmental impact.

In summary, the bio-oil derived from *Gmelina arborea* seeds has high energy content, suitable viscosity, and density for fuel use, but its low pH and moisture content may pose challenges for storage and combustion. The elemental composition indicates potential for bioenergy applications with appropriate treatment to mitigate corrosion and other operational issues.

Fuel properties of bio-oil produced from *Gmelina arborea* seeds

The fuel qualities of the bio-oil produced from *Gmelina arborea* seeds were determined under maximum oil yield conditions. The properties evaluated include flash point, pour point, cloud point, heating value, and cetane index, as shown in Table 4. The results demonstrate that *Gmelina arborea* seeds have a high energy content, ranging from 25.25–40.13 mg/kg, indicating their potential suitability for bio-oil production. The heating values of the bio-oil exceed those reported in studies by Okoroigwe *et al*. (2015) and Hossain *et al*. (2014), but are comparable to those reported by Oyebanji *et al*. (2017). The higher heating values (HHV) of the bio-oil, as shown in Table 6, increased with increasing temperatures and heating rates, ranging from 25.25–40.13 mg/kg. These values fall within the conventional fuel range, suggesting that the bio-oil is suitable for use as fuel oil and in boiler combustion applications. The pour point of the bio-oil ranged from 2.54°C to 3.81°C, while the cloud point varied from 4.8°C to 7.61°C. These values show some variability depending on the temperature at which the oil was produced. In comparison, Ochi *et al*. (2019) reported a pour point of 4°C and a cloud point of 5°C for bio-oil extracted, characterized, and transesterified from *Gmelina arborea* seeds using methanol and a heterogeneous catalyst. The observed differences in results may be attributed to variations in the method of oil extraction, which could influence the chemical composition and physical properties of the bio-oil.

Table 4 presents the fuel properties of bio-oil produced from *Gmelina arborea* seeds at different temperatures.

Table 4: Fuel properties of bio-oil produced from *Gmelina arborea* seeds

Temperature range (°C)	Flash point (°C)	Pour point (°C)	Cloud point (°C)	Cetane Index	Heating value mg/kg
485	55.83±0.042	3.63±0.014	7.61±0.014	7.59±0.021	40.13±0.014
525	55.45±0.07	2.85±0.014	6.91 ±0.007	6.85±0.042	35.84±0.028
560	56.31±0.091	2.54±0.049	4.8±0.000	6.73±0.035	25.25±0.777
571	60.95±0.636	3.81±0.014	6.68±0.035	7.81±0.014	37.68±0.106
596	54.81±0.014	3.56±0.014	7.12±0.028	6.94±0.028	28.42±0.028
ASTM D	≥45	-15	>49	47	≥15

The flash point of the bio-oil was determined using the Cleveland open cup method, and the results in Table 4 indicate an increasing trend in flash point with rising temperature. This trend is consistent with findings from Egbosiuba (2022), who reported similar flash point values (54.81–60.95°C) for bio-oils derived from other feedstocks. While the fuel properties of the *Gmelina arborea* bio-oil indicate its potential as an alternative to diesel fuel, further analysis is needed to evaluate its performance in practical applications. For example, a more detailed comparison with conventional diesel fuel would help to assess combustion efficiency, emissions, and storage stability. Additionally, evaluating the impact of the bio-oil's fuel properties on engine performance and long-term usability would provide a clearer understanding of its viability as a replacement for traditional fuels.

Moreover, while the cetane index is reported in Table 4, its significance in terms of ignition quality and combustion characteristics is not discussed. A higher cetane index generally indicates better ignition properties, which would be useful for understanding how *Gmelina arborea* bio-oil performs in internal combustion engines. In conclusion, the fuel properties of *Gmelina arborea* bio-oil are promising, but further research, including performance testing and environmental impact assessment, is needed to fully assess its potential as a sustainable alternative to conventional diesel fuel.

Fourier Transform Infrared Spectroscopy (FTIR) of Bio-oil

The functional group composition of bio-oil derived from *Gmelina arborea* seeds was analyzed using FTIR spectroscopy in the wavelength range of 3550 – 459 cm^{-1}, as shown in Figure 1. The identified functional groups and their corresponding compounds are summarized in Table 5.A broad absorption band observed between 3550 – 3150 cm^{-1} is attributed to the O–H stretching vibrations of hydroxyl groups from phenols, alcohols, and carboxylic groups bonded to aromatic rings. This is consistent with the presence of oxygenated compounds, which are common in biomass pyrolysis oils. The peak between 3150 – 3000 cm^{-1} corresponds to the C–H stretching of alkenes, indicating the presence of unsaturated hydrocarbons.

The region between 2980 and 2850 cm^{-1} is associated with the C–H stretching of saturated aliphatic bonds, suggesting the presence of alkanes in the bio-oil. The absorption band between 1800 and 1744.4 cm^{-1} is likely due to C=O stretching vibrations, possibly originating from aldehydes and esters. Additionally, the observed peak at 1600 – 1500 cm^{-1} corresponds to C=C stretching vibrations, characteristic of aromatic compounds. The band between 1490 and 1325 cm^{-1} is attributed to O–H bending vibrations, confirming the presence of alcohols and phenols. The peak at 1375.4 cm^{-1} corresponds to the deformation vibration of aliphatic CH_3 groups, further supporting the presence of aliphatic compounds. The region from 1300 – 1230 cm^{-1} displays C–O stretching vibrations, which may indicate the presence of esters. The absorbance peak at 1237.5 cm^{-1} is associated with aromatic C–O and phenolic–OH stretching, while the peak at 1141 cm^{-1} corresponds to the stretching of aliphatic ether C–O or alcohol C–O groups. The peak at 1118.2 cm^{-1} is indicative of C–N stretching, suggesting the presence of nitrogen-containing compounds, such as amines. The peak at 713 cm^{-1} corresponds to C–H stretching vibrations, associated with aromatic compounds.

Additionally, the band between 785 – 540 cm^{-1} further confirms the presence of C–H stretches, which are indicative of additional aromatic components. The identified functional groups in the bio-oil such as alkanes, aliphatic hydrocarbons, aromatic compounds, aldehydes, ketones, alcohols, carboxylic acids, and phenols, indicate a complex mixture. Most of these groups contain oxygen, which is consistent with the oxygenated nature of bio-oils. Oxygenated compounds are known to influence bio-oil properties, including stability, viscosity, and combustion behavior, as reported by Abnisa *et al*. (2013).

Furthermore, a comparison with studies on other biomass pyrolysis oils (Chukwuneke *et al*., 2019; Pinto *et al*., 2018; Ogunsanwo *et al*., 2014) reveals similar functional group profiles, suggesting that *Gmelina arborea* bio-oil shares key characteristics with other biomass-derived oils. Abnisa *et al*. (2013) noted that the presence of high levels of oxygenated compounds in biomass pyrolysis oils contributes to their unique properties, such as lower heating values and higher acidity, which can affect their use in energy production. Armynah *et al*. (2018) also reported a peak at 3452 cm^{-1}, attributed to organic O–H stretching, likely related to water retention or other hydroxyl groups in the bio-oil.

Table 5: Fourier Transform Infrared Spectroscopy of bio-oil from *Gmelina arborea* seeds

Frequency cm^{-1}	Functional groups	Actual cm^{-1}	Class of compounds
3550-3150	O-Hstr	3398,3170	Alcohol, phenol
3150-3000	C-Hstr	3020	Alkenes
2980-2850	C-Hstr	-	Alkanes
2500-2000	C ≡Cstr, C≡Nst	2360	Alkynes
2000-1500	C=Ostr	1998	Acid halides
2000-1500	C=Ostr	1859	Aldehyde and ketone.
	C=Cstr	1697	Alkenes, aromatics
1600-1500	C=Cstr	1558	Alkenes, aromatics
1490-1325	O-Hbend	1404, 1342	Alcohol, phenol
1300-950	=C-H, C-Ostr	1253,1138,1053,1022,937	Carboxylic acid, Anhydride.
900-650	=C-H$_{bend}$	875,798	Aromatic

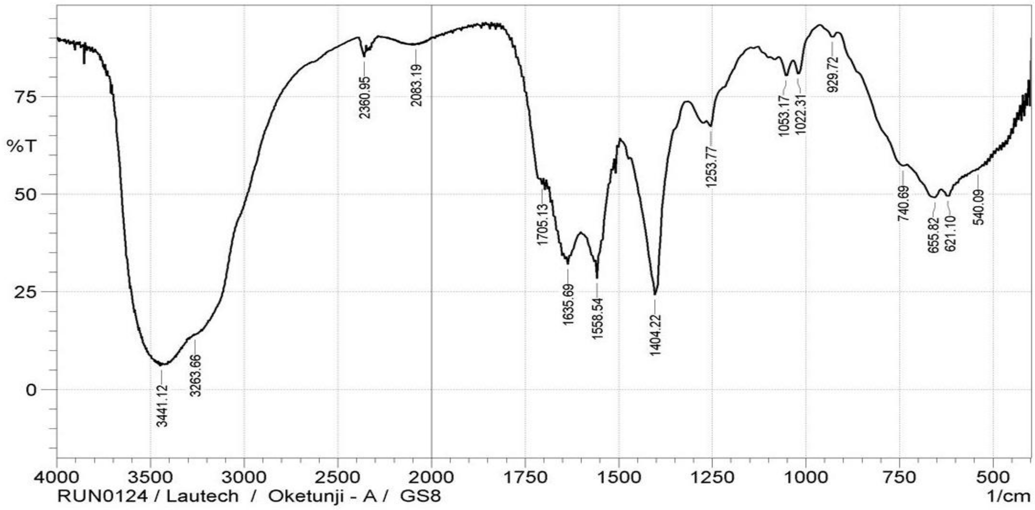

Figure 1: FTIR analysis of Bio-oil

GC-MS analysis of bio-oil yield

The GC-MS chromatograms for the bio-oil derived from *Gmelina arborea* seeds are shown in **Figure 2**, and the chemical composition of the bio-oil is detailed in **Table 6**. A total of thirty-six chemical compounds were identified, with the major constituents being 28-Nor-17. beta.(H)-hopane (8.75%) and Decahydro-1,1,4a,5,6-pentamethylnaphthalene (7.08%), followed by Naphthalene 2,3-dimethyl (6.20%), 1-Anthracenamine (5.56%), and 2,4-Di-tert-butylphenol (3.95%). These compounds are primarily hydrocarbons, fatty acids, alcohols, esters, ethers, phenols, and ketones. The presence of these compounds suggests that the bio-oil from *Gmelina arborea* seeds has diverse chemical components that could be valuable for a variety of industrial applications. The major compounds, such as hopane derivatives and pentamethylnaphthalene, highlight the potential of the bio-oil as a source of hydrocarbons, which are important in biofuel production. The presence of naphthalene and anthracenamine derivatives further indicates the potential for the bio-oil to serve as a feedstock for the pharmaceutical and chemical industries. Moreover, the identification of fatty acids, esters, and phenolic compounds adds to the bio-oil's versatility. Fatty acids, often found in biofuels, and esters, which are important for various chemical syntheses, support the idea of utilizing this bio-oil as a renewable energy source or for producing valuable chemicals. Additionally, bioactive compounds like phenols and aromatic compounds suggest potential uses in pharmaceutical applications, further broadening the bio-oil's range of possible industrial uses.

These results align with findings from similar studies on biomass-derived bio-oils, which have identified similar chemical profiles and confirmed their potential for energy production, chemical synthesis, and even pharmaceutical applications (Kim *et al*., 2017; Okoroigwe *et al*., 2012; Oyebanji *et al*., 2017). The presence of such a diverse range of compounds makes *Gmelina arborea* bio-oil a promising candidate for use as an industrial feedstock. Overall, the GC-MS analysis not only confirms the chemical complexity of *Gmelina arborea* bio-oil but also highlights its potential for various applications. These applications include biofuel production, chemical synthesis, and the pharmaceutical industry. As such, further studies focusing on optimizing the yield, improving the efficiency of the extraction process, and exploring the reactivity and stability of the bio-oil components in different industrial contexts are essential to maximize its potential.

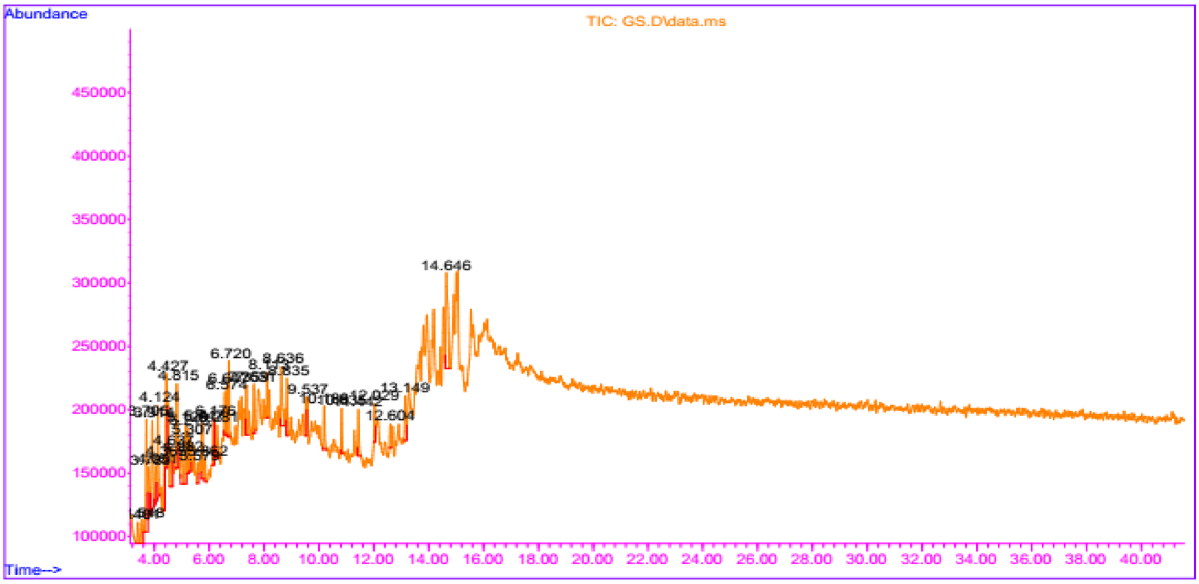

Figure 2: Abundant Components in the Sample

CONCLUSION

This study investigated the pyrolysis of *Gmelina arborea* seeds, conducted at temperatures ranging from 485°C to 596°C with a particle size of 0.075 mm in a bed reactor. The results demonstrated that the maximum oil yield of 25.5 wt.% was achieved at 596°C, which compares favorably with yields reported for other biomass materials. The bio-oil yield increased with higher temperatures and heating rates, indicating that temperature plays a crucial role in maximizing bio-oil production.

The physicochemical properties of the bio-oil obtained from *Gmelina arborea* fall within acceptable ranges for biofuel production, showing potential for both energy generation and industrial applications. The oil produced had high carbon, hydrogen, and oxygen content, and the higher heating value (HHV) ranged from 25.25 to 40.13 MJ/kg, which is comparable to some conventional fossil fuels. This indicates that bio-oil could be a viable alternative for renewable energy production, especially in regions like Nigeria where *Gmelina arborea* is abundantly available.

Table 6: Chemical composition of bio-oil from *Gmelina arborea* seeds on chromatograms

Compounds	R_T	Area (%)
1,2-Benzenediol, 4-[2-(methylamino)ethyl]-	3.401	1.21
2-Amino-1-(o-hydroxyphenyl) propane	3.548	1.83
Decahydro-1,1,4a,5,6-pentamethylnaphthalene	3.705	7.08
Naphthalene, 2,7-dimethyl-	3.789	3.58
Naphthalene, 2,3-dimethyl-	3.914	6.20
Benzyl alcohol, 4-methoxy-6-fluoro	4.051	2.18
Decahydro-1,1,4a,5,6-pentamethylnapthalene	4.124	4.77
Bicyclo[2.2.1]heptane, 2,2,3-trimethyl-	4.365	2.74
1-Anthracenamine	4.427	5.56
Naphthalene, 1,6,7-trimethyl-	4.637	2.92
2,4-Di-tert-butylphenol	4.815	3.95
Naphthalene, 2,3,6-trimethyl-	4.982	2.36
Naphthalene, 1,6,7-trimethyl-	5.129	2.89
Decahydro-8a-ethyl-1,1,4a,6-tetramethylnaphthalene	5.213	2.04
l-Alanine, N-octanoyl-, heptyl ester	5.307	1.46
1,2-Benzenediol, 4-(2-amino-1-hydroxypropyl)-	5.579	1.21
Tetradecane	5.747	2.73
1,6-Dimethyl-4-ethylnaphthalene (Norcadalene)	5.862	0.99
Sarcosine, N-valeryl-, propyl ester	6.176	2.56
dl-Alanine-beta-naphthylamide	6.281	1.78
2- Chloropropionic acid, octadecylester	6.574	1.44
Eicosane, 9-cyclohexyl-	6.647	1.82
Phenanthrene	6.720	2.82
Pentadecane	7.359	1.94
Phenanthrene, 4-methyl-	7.631	2.54
Hexadecane	8.113	1.60
1-Methyl-3-phenyl-1H-indene	8.636	3.75
Eicosane	8.835	2.38
Octadecane, 1-chloro-	9.537	1.70
o-Veratramide	10.186	1.97
L-Aspartic acid, N-(2,4-dinitrophenyl)-	10.835	1.94
l-Alanine, N-valeryl-, decyl ester	11.442	2.17
3-(2-Aminoethyl)-7-methoxy-5-nitro	12.029	1.80
1,4-Benzenedicarboxamide, N,N'-bis	12.604	0.84
alpha. -Acetyl-N,N-dinormethadol	13.149	2.52
28-Nor-17.beta.(H)-hopane	14.646	8.75

GC-MS analysis revealed a wide variety of functional groups in the bio-oil, including alkanes, aliphatic and aromatic compounds, aldehydes, ketones, alcohols, carboxylic acids, and phenols, many of which are oxygenated. These findings suggest that *Gmelina arborea* seeds could be a source of valuable industrial chemicals, such as L-aspartic acid, in addition to serving as a potential energy source. Moreover, the fuel properties of the bio-oil, such as kinematic viscosity, density, pH, flash point, and HHV, met or exceeded conventional fossil fuel standards.

While the results are promising, the optimization of fast pyrolysis processes and equipment will be essential for scaling up production and improving efficiency. Future research should focus on refining the pyrolysis process to maximize yield, reduce energy consumption, and assess the economic feasibility of large-scale bio-oil production. Furthermore, the long-term stability and environmental impacts of using *Gmelina arborea* as a bioenergy source need to be explored to ensure its sustainable contribution to global renewable energy demands. In conclusion, *Gmelina arborea* presents significant potential as a bioenergy source with favorable fuel and chemical properties. With continued optimization of pyrolysis technology, it could play an important role in meeting future energy needs, particularly in areas with abundant *Gmelina* biomass. Additionally, the integration of *Gmelina* into renewable energy strategies could have positive environmental and economic impacts, especially in developing countries like Nigeria.

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