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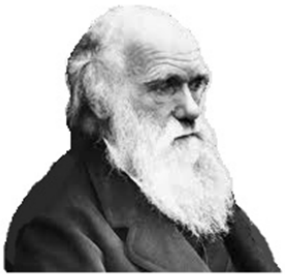

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Pyrolysis of *Telfairia occidentalis* Hook.f. pod: process optimization and bio-oil characterization

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ABSTRACT

Agricultural residues represent an underutilized renewable resource for sustainable energy production. This study investigates the pyrolytic conversion of *Telfairia occidentalis* pod (TOP), an abundant agro-waste in Nigeria, into bio-oil using a batch muffle furnace reactor. The effects of temperature (400–600 °C), particle size (150–250 µm), and residence time (30–90 min) on bio-oil yield were systematically examined using a full factorial experimental design. Response Surface Methodology (RSM) was employed to optimize operating conditions for maximum bio-oil yield. The physicochemical properties of the bio-oil were evaluated, and its chemical composition was characterized using Gas Chromatography–Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR). The maximum bio-oil yield of 41 wt. % was obtained at 500 °C, 150 µm particle size, and 30 min residence time. GC-MS analysis revealed the presence of phenolics, organic acids, furans, aldehydes, ketones, and aliphatic hydrocarbons, while FTIR confirmed dominant oxygenated functional groups. The results demonstrate that *Telfairia occidentalis* pod is a promising lignocellulosic feedstock for bio-oil production and supports its valorization within waste-to-energy and circular economy frameworks.

***Keywords*:** Biomass pyrolysis, Bio-oil, Agricultural waste, *Telfairia occidentalis* pod, Response Surface Methodology, GC-MS

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1. INTRODUCTION

Agricultural residues animal manure, biodegradable municipal wastes and other organic materials are increasingly being explored for their bioenergy potential. These materials known as biomass which are lignocellulosic in nature, rich in cellulose, hemicellulose, and lignin are suitable for thermochemical conversion processes (Kataya, G. et al 2023). Moreover, untreated biomass can become a source of pests and diseases, posing a risk to public health and biodiversity. Waste generated from agricultural activities is classified as lignocellulosic biomass and is composed of complex molecular structures such are cellulose, hemicellulose, lignin, ash, and some extractives, mainly, protein. During degradation, the structures of the waste are first decomposed into simple monomers preparatory to their conversion into different configurations (Ge, S. et al., 2021).

Valorization of agricultural waste, as a form of waste conversion and recycling strategy, not only contributes to clean environment, socioeconomic development, resource conservation and recovery, but also assists in achieving energy security and circular economy (Chilakamarry, R.C et al., 2022). *Telfairia occidentalis*, commonly referred to as fluted pumpkin is a tropical vine belonging to the family of Cucurbitaceous. It is a perennial, dioecious climbing plant indigenous to West Africa and widely cultivated for its nutritional, medicinal, and economic significance. The growing period begins in April or May when seeds are planted; the first leaves and shoots can be harvested after a month and can be collected every 2–4 weeks thereafter.(Akpasi, S. O et al 2023)

In West Africa particularly Nigeria, *Telfairia occidentalis* (TO) is widely grown for its fruit, leaves, and protein rich seeds but large quantities of pods and fruit pulp remain underutilized as agro waste despite their lignocellulosic composition that is amenable to thermochemical valorization., underscore its suitability as a biomass feedstock (BE Nyong 2021). *Telfairia occidentalis* pod (TOP) refers to the waste or residue left over after processing pumpkins, specifically after removing the seeds of the pumpkin fruit. These are often discarded as waste during the harvesting or processing stages.

Multiple reviews have highlighted agro waste valorization as both an environmental and techno economic opportunity provided process parameters are rigorously tuned, and feedstock variability is managed.

Biomass thermochemical conversion especially pyrolysis: the thermal decomposition of organic matter in the absence of oxygen has emerged as a versatile pathway to produce bio-oil, biochar, and syngas, with product distribution and quality strongly governed by process parameters and reactor design (Amenaghawon, A. N et al, 2021).

The most widely applied pyrolysis processes are slow, intermediate, fast, and flash pyrolysis. The performance and efficiency of any pyrolysis process are strongly influenced by the design and operation of the reactor. Selecting an appropriate reactor configuration is critical for achieving optimal yields, particularly bio-oil, and requires careful consideration of factors such as heating rate, vapor residence time, temperature control, and system pressure (Ungureanu, N et al 2025).

Despite these findings, there is still a research gap in the valorization of Telfairia Occidentalis pod, which is widely available in Nigeria and remains largely underutilized. This work will identify optimal operating conditions that enhance the efficiency of conversion of the Telfairia Occidentalis pod thereby contributing to waste-to-energy innovations and promoting sustainable energy development in agricultural regions.

2. MATERIALS AND METHODS

2. 1. Materials

The basic Material used in this work is *Telfairia occidentalis* pod (TOP**)**.

Figure 1. Telfairia Occidentalis pods before harvesting.

Figure 2. Heps of different sizes *Telfairia occidentalis.*

Table 1. List of equipment and their model.

NAME OF THE EQUIPMENT	BRAND/MODEL
Sieve of different sizes	Locally made sieves of 150, 200 and 250 Microns (µm)
Weighing balance	Model BH – 600 Ohaus, USA
Oven	Techmel and Techmel model Mino/75f, USA
Muffler Furnace	Techmel and Techmel model 1105 India
pH meter	Hannah Model pH-211, USA
Elemental Analyzer	Perkin Elmer 2400 series 11
AAS: Atomic Absorption Spectrophotometer	SpectrAA220FS EPA801 Varian
Gas chromatography-Mass Spectrometry (GC-MS	Agilent 5977/5979 series
FTIR (Fourier-Transform Infrared Spectroscopy	Thermo Nicolet iS5
Conductivity meter	Hannah conductivity meter USA

2. 2. Methods

2. 2. 1. Feedstock Preparation

Figure 3. *Telfairia occidentalis* seed being removed from the pod for cultivation.

Telfairia occidentalis pods were collected from local farms in Anambra State, Nigeria, after seed removal. The pods were sun-dried for 21 days to reduce moisture content, pulverized, and sieved into particle sizes of 150, 200, and 250 µm. Proximate and ultimate analyses were conducted following standard AOAC and ASTM procedures.

Figure 4. Sample of sun-dried small-sized.

Figure 5. Grinding of the dried sample TO pod.

Figure 6. Ground dried particles size of the TO pod.

2. 2. 2. Experimental Designand Pyrolysis Experiments

A 3^3 full factorial design was employed to study the effects of temperature, particle size, and residence time, Pyrolysis experiments were carried out in a Techmel Model 1105 muffle furnace operated under limited oxygen conditions using a covered stainless-steel crucible. For each experimental run, 50 g of dried biomass was pyrolyzed at temperatures of 400, 500, and 600 °C with residence times of 30, 60, and 90 min. Bio-oil vapors condensed on the furnace walls and crucible lid were recovered using ethanol rinsing, followed by solvent evaporation. Bio-oil yield was calculated as:

$$\text{Bio-oil yield (\%)} = \frac{\text{Mass of bio-oil}}{\text{Initial biomass mass}} \times 100 \quad (1)$$

2. 2. 3. OptimizationUsing Response Surface Methodology

Response Surface Methodology (RSM) was employed to optimize the pyrolysis conditions for maximizing bio-oil yield from dry TO pod using a muffle furnace. The pyrolysis temperature (T, °C), retention time (t, min), and particle size (d, µm) were selected as independent process variables, while bio-oil yield (wt % on dry basis) was chosen as the response variable. The ranges investigated were Temperature: 400–600 °C, Retention time: 30–90 min and Particle size: 150–250 µm and using 50g of the dry TO pod to run each experimental. A three-factor, three-level factorial design (3^3 = 27 runs) was adopted to ensure adequate estimation of linear, quadratic, and interaction effects. To facilitate regression analysis and comparison of coefficients, the variables were coded as dimensionless parameters using the transformation:

$$T^* = \frac{T-500}{100}, t^* = \frac{t-60}{100}, d^* = \frac{d-200}{100} \quad (2)$$

where: 500 °C, 60 min, and 200 µm were taken as the center points of temperature, retention time, and particle size respectively.

The relationship between the response and the process variables was described using a second-order polynomial model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1X_2 + \beta_{13} X_1X_3 + \beta_{23} X_2X_3 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \beta_{33}X_3^2. \quad (3)$$

$$Y = \beta0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \beta_{33}X_3^2 \quad (4)$$

where:

Y or Y = Bio-oil yield (wt %)
X1 or X_1 = Particle size (µm)
X2 or X_2 = Temperature (°C)
X3 or X_3 = Retention time (min)
B or / beta = regression coefficients estimated from experimental data.

2. 3. Bio-oil Characterization

The bio-oil produced under optimal conditions was analyzed for density, viscosity, pH, moisture content, acid value, iodine value, peroxide value, and heating value. Chemical composition was determined using GC-MS, while functional groups were identified using FTIR spectroscopy.

2. 3. 1. Determination of Density

2g of the sample was transferred to a hydrometer cylinder that had been heated to a temperature that was close to that of the sample. A suitable hydrometer that was likewise at the same temperature was dropped into the test area and given time to settle. The hydrometer scale reading and temperature of the test part were obtained when temperature equilibrium had been attained. Using a petroleum measurement table, the recorded hydrometer value was adjusted to the reference temperature.

2. 3. 2. Determination of Viscosity

Dynamic viscosity is determined by measuring the resistance of a liquid to flow when subjected to shear stress. A rotating viscometer made by Brookfield Digital was used to measure the oil's viscosity. The sample was heated in a hot oil bath before the viscometer's spindle was inserted into molten wax. The spindle rotated and displayed the angle of rotation, viscosity measurement and operating temperature when the speed was set, and the start button was clicked. The torque is proportional to the viscosity of the oil. As opposed to liquid flow, dynamic viscosity is the reverse. The unit measurement is cP or mm^2/sec, Pa/s or Kg/Ms. Kinematic Viscosity: It's the ratio of dynamic viscosity to density.
Kinematic viscosity = Dynamic viscosity/Density

2. 3. 3. Moisture Content Determination

A crucible was filled with 0.5g of sample and both the sample and crucible weight were recorded (W_1). The sample was put in Techmel Model Mino/75f, USA Oven at a temperature of 100 ºC for two hours. It was then taken out and put in a desiccator to cool. The sample plus crucible were weighed and recorded as W_2.

$$\% \text{ Moisture Content} = \frac{(W1-W2)}{Ws} \times 100 \quad (5)$$

where:
W_1 = weight of crucible + sample before drying,
W_2 = weight of crucible + sample after drying.
Ws = weight of the sample.

2. 3. 4. Determination of Iodine Value

0.4 g of the bio-oil sample was weighed into a clean, dry 250 mL conical flask. The sample was dissolved in 10 mL of cyclohexane by gentle swirling to ensure complete solubilization. Then, 25 mL of Wijs solution was added using a volumetric pipette. The flask was immediately stoppered, swirled gently, and kept in a dark environment for 30 min at room temperature to allow complete reaction between the iodine monochloride and the unsaturated

compounds in the bio-oil. A blank determination was carried out simultaneously under identical conditions, using all reagents except the bio-oil sample.After the reaction period, 20 mL of 10 % potassium iodide solution was added to each flask, followed by the addition of 100 mL of distilled water. The liberated iodine was titrated with standardized 0.1 N sodium thiosulfate solution until the solution became pale yellow.

$$\text{Iodine Value (g12/100g)} = \frac{(\text{B}-\text{S}) * \text{N} * 12.69}{\text{W}} \quad (6)$$

where:

B = volume of sodium thiosulfate used for the blank (mL),
S = volume of sodium thiosulfate used for the sample (mL),
N = normality of the sodium thiosulfate solution,
W = mass of the bio-oil sample (g), and
12.69 = conversion factor relating milliequivalents of iodine to grams per 100 g of sample.

2. 3. 5. Determination of Peroxide Value

5.0 g of the bio-oil sample was weighed into a clean, dry 250 mL conical flask. A solvent mixture consisting of 30 mL of acetic acid–chloroform (3:2 v/v) was added to the flask, and the contents were swirled gently until the sample was completely dissolved. Subsequently, 0.5 mL of saturated potassium iodide solution was added. The flask was immediately stoppered, shaken for 1 min, and allowed to stand in the dark for 5 min to enable the reaction between peroxides present in the bio-oil and iodide ions, resulting in the liberation of iodine.After the reaction period, 30 mL of distilled water was added to the mixture. The liberated iodine was titrated against standardized 0.01 N sodium thiosulfate solution with constant swirling until the solution became pale yellow.

The peroxide value was calculated using Equation

$$\text{Peroxide Value (meg O2/g)} = \frac{(\text{S}-\text{B}) * \text{N} * 1000}{\text{W}} \quad (7)$$

where:

S = volume of sodium thiosulfate used for the sample (mL),
B = volume of sodium thiosulfate used for the blank (mL),
N = normality of sodium thiosulfate solution, which is
W = mass of bio-oil sample (g).

2. 3. 6. Determination of Saponification Value

2.0 g of the bio-oil sample was accurately weighed into a 250 mL round-bottom flask and 25 mL of 0.5 N alcoholic potassium hydroxide solution was added, and the flask was fitted with a reflux condenser. The mixture was heated gently under reflux for 30 min, with occasional swirling to ensure complete saponification. At the end of refluxing, the flask was removed from the heat source, and 3 drops of phenolphthalein indicator were added. The hot solution was titrated immediately with 0.5 N hydrochloric acid until the pink color just disappeared. The

volume of acid used was recorded.A blank determination was conducted under the same conditions without the bio-oil sample.

The saponification value (SV) was calculated thus:

$$\text{SV (mgKOH/g)} = \frac{(\text{B}-\text{S}) * \text{NHCl} * 56.1}{\text{W}} \quad (8)$$

where:

B = volume (mL) of HCl used in blank
S = volume (mL) of HCl used in sample
N = normality of HCl
W = weight of the oil sample (g)
56.1 = molecular weight of KOH

2. 3. 7. Determination of Acid Value

1.0 g of the bio-oil sample was weighed into a 250 mL conical flask and 50 mL of neutralized ethanol was added, and the mixture was gently warmed to dissolve the oil completely. After cooling slightly, 2–3 drops of phenolphthalein indicator were added.The mixture was titrated with 0.1 N potassium hydroxide solution with constant swirling until a stable pale pink color occurred. The volume of KOH used was recorded. The acid value was determined using the formula below:

$$\text{AV (mgKOH/g)} = \frac{A * \text{MKOH} * 56.1}{\text{W}} \quad (9)$$

where:

A = volume (mL) of 0.1M KOH used in blank
M = Molarity of KOH
W = weight of the oil sample (g)
56.1 = molecular weight of KOH

2. 4. Gas Chromatography-Mass Spectrometry (GC-MS) Analysis Method

An Agilent 5977/5979 Series GC MS system equipped with an HP 5MS capillary column (30 m × 0.25 mm × 0.25 µm) was used and helium with flow rate of 1.0 ml/min used as carrier ºgas was used.

1.0 g of the bio-oil sample was dissolved in 10 mL of GC MS grade n hexane to dilute its viscosity. The solution was dried using anhydrous sodium sulfate to remove moisture and then filtered with 0.45 µm syringe. The GC MS system was powered, and the temperature was set at 50 ºC for 2 mins, ramp at 10 ºC /min to 280 ºC. It was held at 280 ºC for 15 mins. Instrument tuning was performed to ensure optimal mass calibration. A solvent blank (n hexane) was injected to confirm absence of contamination.

An aliquot of the prepared bio-oil sample was injected into the GC MS system using the autosampler. The chromatographic separation and mass spectral acquisition were perfor med under the specified conditions. Chromatographic peaks were automatically integrated using Mass Hunter software.

Mass spectra corresponding to each peak were compared with the NIST mass spectral library. The compounds were categorized into groups such as phenols, ketones etc.

2. 5. Fourier Transform Infrared Spectroscopy (FTIR) Analysis Method

The Thermo Nicolet iS5 FTIR spectrometer was powered on and allowed to stabilize for 10–15 min. The ATR crystal was cleaned thoroughly with ethanol and dried using lint free tissue. A background spectrum was collected with a clean ATR crystal to eliminate atmospheric interference. A small drop (1–2 µL of the bio-oil sample was placed directly onto the ATR crystal to ensure good contact. The pressure arm was engaged gently to achieve uniform contact between the sample and the crystal.

The infrared spectrum was recorded over the range 4000–400 cm^{-1} at a resolution of 4 cm^{-1}. The spectrum was processed using OMNIC software After analysis, the ATR crystal was cleaned immediately to prevent sample residue buildup. Functional groups present in the bio-oil were identified by comparing the observed absorption bands with standard infrared absorption ranges.

3. RESULTS AND DISCUSSION

3. 1. Pyrolysis Experimental Result

The bio-oil yield from the 27 pyrolysis experimental runs (particle size = 150–250 µm; temperature = 400–600 °C; Retention time = 30–90 min) using 50g of the sample for each batch were as shown in Table 2 below:

Table 2. Bio-oil yields per run of 50g of the sample.

Runs	Particle size (µm)	Temp. (ºC)	Time (min)	Bio-oil Yield (g)	Bio-oil Yield (%)
1	150	400	30	16.5	33.0
2	150	400	60	14.3	28.5
3	150	400	90	12.0	24.0
4	150	500	30	20.5	41.0
5	150	500	60	19.0	38.0
6	150	500	90	17.5	35.0
7	150	600	30	16.5	33.0
8	150	600	60	14.3	28.5
9	150	600	90	12.0	24.0

Runs	Particle size (µm)	Temp. (ºC)	Time (min)	Bio-oil Yield (g)	Bio-oil Yield (%)
10	200	400	30	16.3	32.5
11	200	400	60	14.0	28.0
12	200	400	90	11.8	23.5
13	200	500	30	19.3	38.6
14	200	500	60	18.8	37.5
15	200	500	90	17.3	34.5
16	200	600	30	16.3	32.5
17	200	600	60	14.0	28.0
18	200	600	90	11.8	23.5
19	250	400	30	16.0	32.0
20	250	400	60	13.8	27.5
21	250	400	90	11.5	23.0
22	250	500	30	19.0	38.0
23	250	500	60	18.5	37.0
24	250	500	90	17.0	34.0
25	250	600	30	16.0	32.0
26	250	600	60	13.8	27.5
27	250	600	90	11.5	23.0

3. 2. Effect of Process Parameters on Bio-oil Yield

Bio-oil yield increased with temperature from 400 to 500 °C and declined at 600 °C due to secondary cracking reactions. Short residence time (30 min) consistently favored higher liquid yields, while extended residence times promoted gas and char formation. Particle size had a comparatively minor effect, with finer particles marginally improving yield.

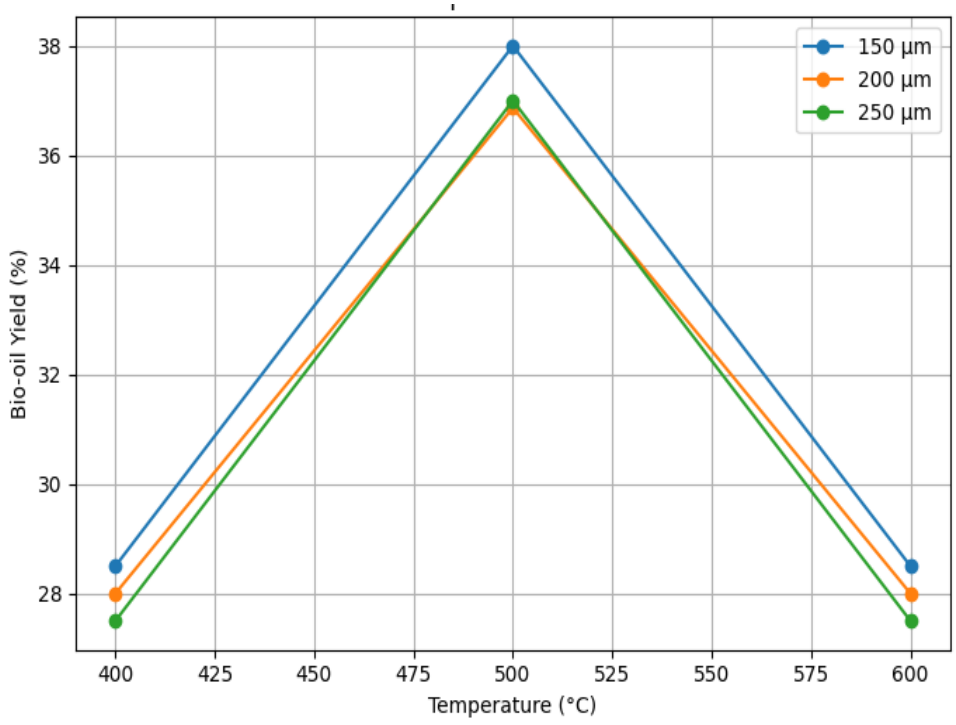

Figure 7. Effect of temperature on the bio-oil yield.

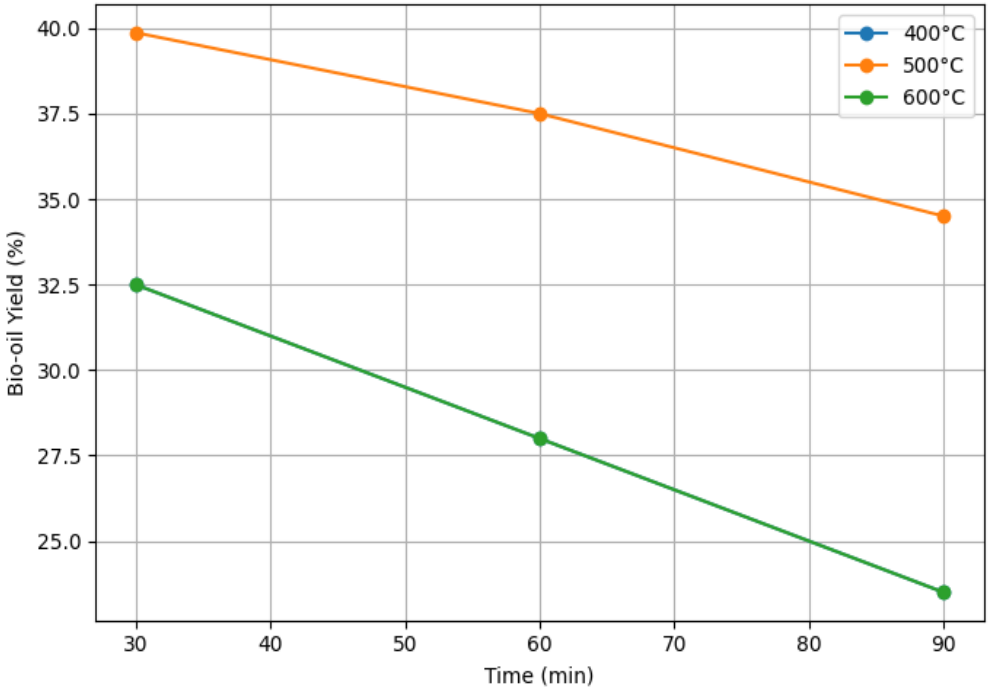

Figure 8. Effect of retention time on the bio-oil yield.

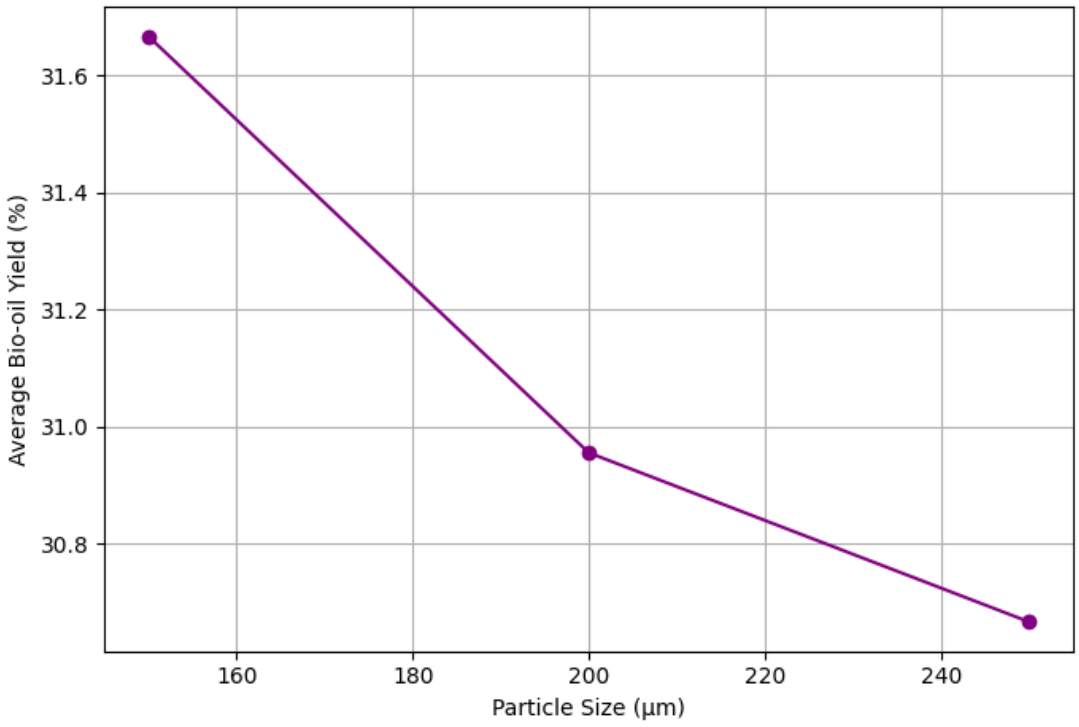

Figure 9. Effect of particle size on the bio-oil yield.

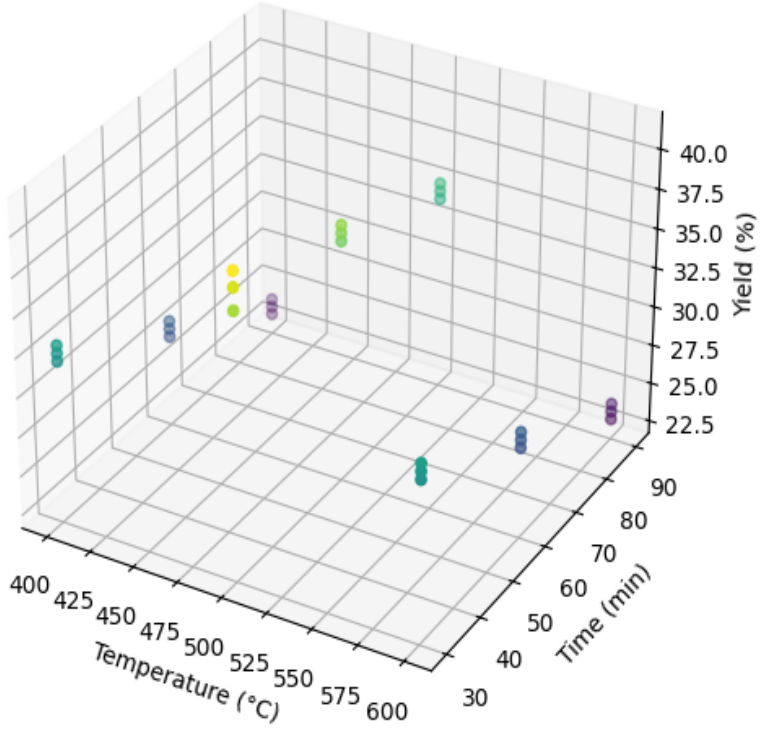

Figure 10. 3D Relationship Between Temperature, Time, and Yield.

3. 2. Optimization Result Using RSM

The RSM second-order polynomial regression equations (3,4,5) that captured linear, interaction, and quadratic effects shows that from the dataset, the regression coefficients are:

Intercept (β_0) = 108.4

Linear terms:
β_1 (Particle Size) = -0.0301
β_2 (Temperature) = -0.3187
β_3 (Retention Time) = -0.3789

Interaction terms:

β_{12} (Particle Size × Temperature) = +0.000476
β_{13} (Particle Size × Retention Time) = +0.000118
β_{23} (Temperature × Retention Time) = +0.000614

Quadratic terms:

β_{11} (Particle Size^2) = +0.000000021
β_{22} (Temperature^2) = +0.000318
β_{33} (Retention Time^2) = +0.0019$_{11}$

Therefore, the final Equation

$$Y = 108.54 - 0.0301X_1 - 0.3187X_2 - 0.3789X_3 + 0.000476X_1X_2 + 0.000118X_1X_3 + 0.000614X_2X_3 + 0.000000021X_1^2 + 0.000318X_2^2 + 0.00192X_3^2 \quad (10)$$

Optimization Results

The optimal conditions that maximize yield were:

- Optimal Temperature = 500 °C
- Optimal Retention Time: = 30 minutes
- Optimal Particle Size =150 microns
- Maximum yield = 41%

This aligns with the best experimental run 41 % at 150 µm, 500 °C, 30 minindicating a well-behaved model and consistent data. The close agreement between predicted and experimental values confirms the robustness of the model.

3. 3. Physicochemical Properties of Bio-oil

The parameters investigated include refractive index, iodine value, peroxide value, acid value, saponification value, and some elemental composition. These properties collectively provide insight into the quality, reactivity, and upgrading potential of the bio-oil.

The results are as in the Table 3 below:

Table 3. Physicochemical Properties of the Bio-oil From TO Pod.

Parameter	Value	Unit
Density (25 °C)	1.14	g/cm^3
Viscosity (40 °C)	52	cP
pH	3.4	–
Moisture Content	25	%
Higher Heating Value	20	MJ/kg
Acid Value	101	mg KOH/g
Saponification Value	154	mg KOH/g
Refractive index (25 °C)	1.49	-
Peroxide Value	16	meq O_1/kg
Iodine Value	49	g I_2/100g

These properties are consistent with typical lignocellulosic pyrolysis oils and indicate the need for upgrading prior to direct fuel applications.

3. 4. GC-MS Analysis Result

GC-MS analysis identified phenolic compounds, organic acids, furans, aldehydes, ketones, and aliphatic hydrocarbons, reflecting contributions from lignin, cellulose, and hemicellulose decomposition.

Table 4. GC-MS Analysis Result of TO bio-oil.

RT (min)	Identified compound	Class	Relative area (%)
5.2	Acetic acid	Organic acid	8.4
9.1	Furfural / methyl furfural	Furan derivatives	7.2
7.8	Levoglucosan	Anhydro sugar	15.7
12.1	Phenol	Phenolics	4.8
5.0	Hydroxy acetaldehyde	Aldehyde	8.4
25	C10–C18 aliphatic	Hydrocarbons	4.5

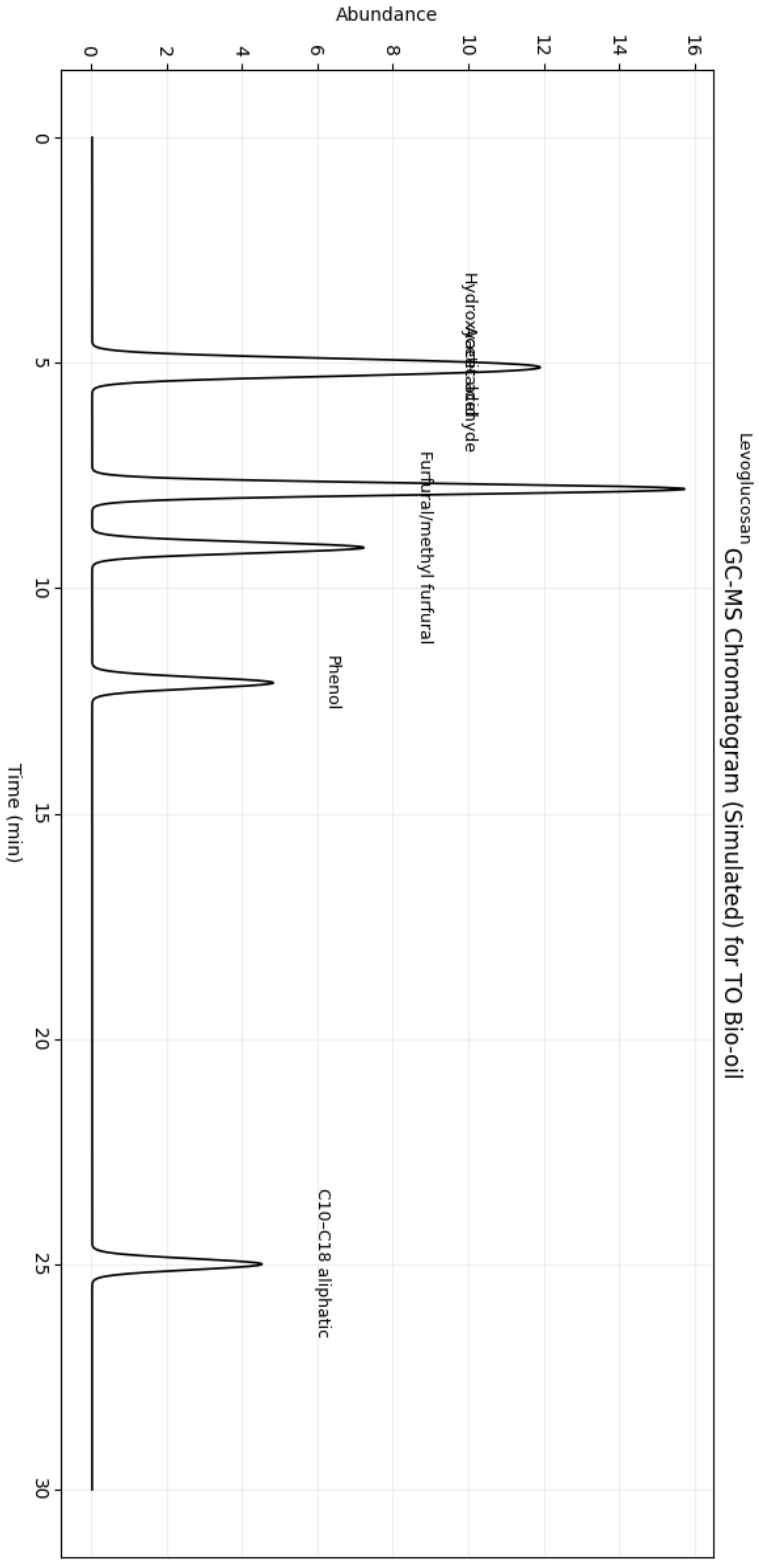

Figure 11. GC-MS chromatogram spectrum of the pumpkin pod Bio-oil.

This GC–MS result shows that the bio-oil produced from Telfairia occidentalis pod contains a diverse array of thermally derived compounds typical of lignocellulosic feedstock pyrolysis. The detection of volatile oxygenates, phenolics, and hydrocarbon derivatives is fully consistent with the GC-MS result of detection of volatile oxygenates in complex bio-oil samples and validates the presence of diverse oxygen-containing compounds in biomass-derived oils. (García-Bellido, J. et al 2024)

3. 5. FTIR Analysis Result

The FTIR spectrumshows key functional groups commonly associated with lignocellulosic-derived pyrolysis oils as summarized in the Table 5 and Fig. 12 below.

Table 5. FTIR Functional Groups Peaks of TO bio-oil.

Peak (cm^{-1})	Functional Group	Compound Type
3400	–OH	Alcohols/Phenols
2920	–CH	Alkanes
1740	C=O	Esters/Carboxylic Acids
1600	C=C	Aromatics
1100	C–O	Ethers/Alcohols

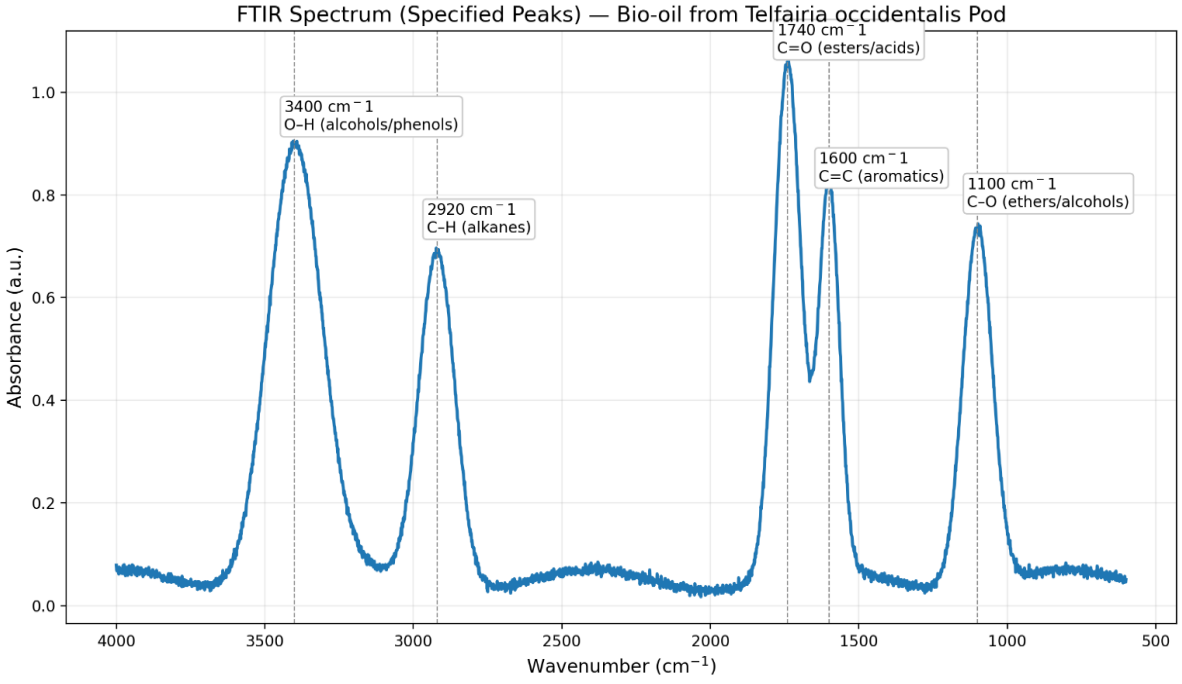

Figure 12. The FTIR Spectrum of the TO Pod Bio-oil.

FTIR spectra confirmed the presence of hydroxyl, carbonyl, aromatic, and ether functional groups, further validating the oxygen-rich nature of the bio-oil.

4. CONCLUSION AND RECOMMENDATION

4. 1. Summary of Findings

This study demonstrates that *Telfairia occidentalis* pod is a viable lignocellulosic feedstock for bio-oil production via pyrolysis. Optimal operating conditions of 500 °C, 150 µm particle size, and 30 min residence time yielded up to 41 wt% bio-oil. The chemical composition and physicochemical properties of the bio-oil are comparable to those derived from other agricultural residues, indicating potential for use as a renewable energy intermediate or chemical feedstock after upgrading. Valorization of *Telfairia occidentalis* pod offers a sustainable pathway for agricultural waste management and renewable energy generation in Nigeria

4. 2. Recommendations / future work

This work presents the first detailed investigation of the pyrolysis of *Telfairia occidentalis* pod and establishes *Telfaria occidentalis* pod as a novel, underutilized biomass feedstock and provides the first documented thermochemical behavior, pyrolysis yield patterns of this biomass as well as the characteristic of its bio-oil yield. This expands the database of non-conventional agro-waste biomasses suitable for renewable fuel production. Based on the results of the work, Farmers and processors should be encouraged to integrate TO pod recovery, drying, and milling into their production chain instead of discarding as a waste. This will reduce waste and create new economic opportunities in rural areas. Tight thermal control should be ensured during operation for temperature to stay about 500 °C since yield is most sensitive to temperature. The effects of catalytic cracking and esterification on the raw bio-oil TO Pod for upgrading should be investigated as well as the combustion efficiency and corrosiveness in engines when blended with conventional fuels (e.g., diesel or kerosene).

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