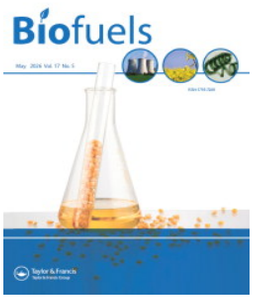
Taylor & Francis
Taylor & Francis Group



Biofuels

ISSN: 1759-7269 (Print) 1759-7277 (Online) Journal homepage: www.tandfonline.com/journals/tbfu20

Banana plant wastes for biofuels: indicators from characterization for thermochemical conversion

Emmanuel Menya, Joel Wakatuntu, Medard Turyasingura, Christopher Okot, Henning Storz, Isa Kabenge, Simon Savio Kizito, Allan John Komakech, Peter Wilberforce Olupot & Collins Okello

To cite this article: Emmanuel Menya, Joel Wakatuntu, Medard Turyasingura, Christopher Okot, Henning Storz, Isa Kabenge, Simon Savio Kizito, Allan John Komakech, Peter Wilberforce Olupot & Collins Okello (19 Mar 2026): Banana plant wastes for biofuels: indicators from characterization for thermochemical conversion, Biofuels, DOI: 10.1080/17597269.2026.2640661

To link to this article: https://doi.org/10.1080/17597269.2026.2640661

Published online: 19 Mar 2026.

Submit your article to this journal

Article views: 77

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=tbfu20

BIOFUELS
https://doi.org/10.1080/17597269.2026.2640661

Taylor & Francis
Taylor & Francis Group

Check for updates

Banana plant wastes for biofuels: indicators from characterization for thermochemical conversion

Emmanuel Menya[a], Joel Wakatuntu[b], Medard Turyasingura[b], Christopher Okot[a], Henning Storz[c], Isa Kabenge[d], Simon Savio Kizito[e], Allan John Komakech[d], Peter Wilberforce Olupot[b] and Collins Okello[a]

[a]Department of Biosystems Engineering, Gulu University, Gulu, Uganda; [b]Department of Mechanical Engineering, College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda; [c]Thuenen Institute of Agricultural Technology, Braunschweig, Germany; [d]Department of Agricultural and Biosystems Engineering, Makerere University, Kampala, Uganda; [e]Department of Forestry and Biodiversity Conservation, Makerere University, Kampala, Uganda

ABSTRACT

The banana value chain in Uganda generates a wide range of waste biomass, yet its suitability for thermochemical conversion remains largely unstudied. This study aimed to characterise banana rhizome, pseudostem, peduncle and inflorescences from *Mbwazirume* and *Mpologoma* cultivars in Uganda for potential use in thermochemical conversion processes. These wastes were characterised for lignocellulosic, proximate, elemental, and mineral composition, and higher heating value (HHV). Moisture content ranged from 9 to 14wt%, volatile matter 74-82%db, fixed carbon 12–17%db, and ash content 3-13%db. Inflorescences exhibited the highest lignin content (15.23–17.23%daf) and HHV (14.55–15.85 $MJkg^{-1}$) across cultivars, suggesting higher suitability for biochar production compared to its counterparts. However, inflorescences exhibited the highest nitrogen content (2.47–2.56%daf), suggesting higher NOx emissions potential. Inflorescences, rhizomes and peduncle exhibited higher ash content (6–13%db) than pseudostem (3.35–3.85%db), suggesting increased risk of slagging and fouling of heat transfer surfaces. Predominant mineral elements were found to be K (15888–28363 ppm), Ca (2000–9000 ppm), Si (2000–9000 ppm), and Mg (1120–4928 ppm), which can have catalytic functions during thermal decomposition. The low fuel ratio (0.16–0.22) of the wastes suggested poor fuel properties. These properties could be enhanced through torrefaction, making the wastes more suitable as sustainable feedstocks for biofuel production.

HIGHLIGHTS

- Banana plant wastes across banana cultivars were characterized.
- High volatile matter (74-82%db) suggested suitability for bio-oil and gas production.
- Low lignin content (7-18%daf) suggested low biochar yields from the plant wastes.
- Low fuel ratio (0.16–0.22), high O/C ratio (0.69–0.71) and ash content (6.76–12.08%db) suggested poor fuel properties.
- Torrefaction could enhance the fuel properties of the banana plant wastes.

ARTICLE HISTORY
Received 23 October 2025
Accepted 1 March 2026

KEYWORDS
Banana rhizome; pseudostem; peduncle; inflorescence; characterization; biofuels

Introduction

The banana plant is a non-woody plant belonging to the genus *Musa*. The plant usually grows to a height ranging from 0.8 m to more than 7.5 m [1]. It produces fruit only once a lifetime, requiring 10–12 months from planting to harvest [2]. The main component of the banana plant is its pseudostem, which is cylindrical in nature, and composed of long fibres that strongly overlap leaf-petiole sheaths [1]. After bearing the fruit, the pseudostem dies and is replaced by another pseudostem [2]. The portion of the plant that generates the new pseudostem is referred to as the rhizome. About 30 large leaves, 30–60 cm wide and up to 2 m long, are produced in each plant [1]. Essentially, for every tonne of banana fruits

CONTACT Emmanuel Menya E.Menya@gu.ac.ug Department of Biosystems Engineering, Gulu University, P.O. Box 166, Gulu, Uganda.
© 2026 Informa UK Limited, trading as Taylor & Francis Group

harvested, over 4 tonnes of banana biomass are produced, with banana leaves accounting for 0.48 tonnes [3], pseudostems 3 tonnes [3], stalks 0.16 tonnes [3], peduncle 0.13 tonnes [4], banana peels 0.25 tonnes [5] and rejected fruits 0.1 tonnes [3]. Based on the residue-to-product ratio, Uganda generates about 44.8 million tonnes of waste biomass, placing the banana value chain topmost in the country in terms of biomass potential. While cultivators harvest banana fruits for food, other parts of the plant have diverse applications. Fresh leaves, for example, are used for food packaging [6], composting [7] and mulching [8], while pseudostems are used for plantation mulching [2,9], starch production [10], and for the manufacture of ropes, textiles and paper [11]. On the other hand, peels and rejected fruits are used as animal feed [8] and as a compost material [7]. However, the scale of these applications remains limited, exacerbated by concerns over the spread of pests and diseases, such as bacterial wilt [8]. Consequently, a huge surplus of the waste biomass poses disposal challenges, prompting farmers to openly dump and/or burn the waste, posing health and environmental concerns [12].

Thermochemical conversion processes such as torrefaction, pyrolysis, gasification and combustion offer promising prospects for managing the surplus banana plant wastes sustainably. Compared to biochemical conversion processes, thermochemical conversion processes offer greater efficiency and flexibility [13]. Thermochemical conversion processes involve decomposition of the organic waste fraction at moderate to high temperatures with or without oxygen, producing solid, liquid and/or gaseous biofuels [14]. Various banana plant wastes have been explored for thermochemical conversion into biofuels, including banana peels [15–17]–[18], leaves [2,18–21], pseudostems [11,18, 22–24], rachis [25,26] and fruit bunch waste [7,27]. While thermochemical processing offers better prospects, they require feedstocks with the requisite properties for successful conversion. For instance, the torrefaction process requires biomass with a moisture content of $\leq$10wt% [28,29], while pyrolysis or gasification requires biomass with a moisture content of 20-30wt% [30]. This helps to avoid several operational challenges, such as high tar yields during pyrolysis [31], and the tar entrainment problem in gasifier-engine systems [32]. Moreover, a low moisture content avoids wastage of useful heat energy for drying of biomass [33]. Generally, in thermochemical conversion processes, biomass with a high fixed carbon content is preferred due to its higher energy density, which can lead to a higher energy throughput of a given conversion system [34]. In pyrolysis, biomass with high lignin and carbon contents is desired for biochar production due to higher biochar and carbon yields [18,35,36], while in gasification, biomass with a higher volatile matter content is desired for syngas production due to higher gas yields [37,38]. Furthermore, in gasification, biomass with a higher fixed carbon content is required for replenishing the char needed for thermal cracking of tar [39]. A low ash content $\leq$5-6%db is desired to avoid lowering the heating value [32], alongside preventing operational problems like slagging, fouling, corrosion, excessive tar formation, and blockage of the reactor [34,40]. These, and several other properties of banana plant wastes need to be carefully evaluated prior to deployment of the wastes as feedstocks in thermochemical conversion processes. However, the properties of banana plant wastes can vary widely with banana cultivar, plant part, level of maturity, soil conditions, agronomic practices, and geographical origin [41].

The lignin content of banana plant wastes varies from 5 to 38%db, hemicellulose 10-42%db, and cellulose 10-70%db [11,18, 42–44], while volatile matter, fixed carbon and ash contents vary from 41 to 90%db [42,45], 0.2-47%db [42,43] and 6-25%db [3,25], respectively. The carbon content varies from 35.65 to 41.30%daf in banana peels [18,46], 33.98-37.12%daf in fruit bunch waste [7], and 15.9-44.85%daf in banana leaves [3,19–21, 42,45]. The hydrogen content varies from 4.90 to 6.19%daf in banana peels [18,46], 4.02-5.65%daf in fruit bunch waste [7], 5.4-9.2%daf in banana leaves [3,19,20,42,45], 4.36–5.93%daf in pseudostem [3,43,45]. Nitrogen content is low in pseudostems (0.38%daf) [3,45], leaves (0.58-0.98%daf) [3,19, 21,45] and bunch waste (0.90%daf) [7], but relatively higher in fruit bunch waste (3.11%daf) [7], fruit bunch stem (2.19%daf) [43], and banana peels (1.94%daf) [18]. Oxygen content varies from 45.94 to 53.80%daf in banana peels [18,46], 57.16%daf in fruit bunch stem [43], 41.4-73.4%daf in banana leaves [3,19–21,42], and 46.80-55.37%daf in pseudostems [3,43].

Although a few studies have characterized banana plant wastes across cultivars [47,48], no study has characterized multiple plant parts, including the rhizome, pseudostem, peduncle and inflorescences from *Mbwazirume* and *Mpologoma* cultivars in Uganda for their suitability in thermochemical conversion processes. Therefore, this study set out to characterize these banana plant wastes for potential utilization in

thermochemical conversion processes such as torrefaction, hydrothermal carbonization (HTC), pyrolysis, gasification and combustion. These plant wastes were analyzed for lignocellulosic, proximate, elemental, and mineral composition, as well as fuel ratio, heating value, oxygen functional groups, and thermal behaviour. Although the thermochemical processes and pretreatment strategies were not experimentally investigated, the results from this study provide a basis for future studies to experimentally validate the banana plant wastes as sustainable biofuel feedstocks.

Materials and methods

Sample collection and preparation

Banana plant wastes from *Mpologoma* and *Mbwazirume* cultivars were sourced from Mukono Zonal Agricultural Research and Development Institute (MuZARDI) located in central Uganda. MuZARDI is the second largest ZARDI in terms of total annual banana production in the country [12]. The collected waste samples from each banana cultivar included the rhizome, pseudostem, peduncle and inflorescence. Each of these samples was open sun-dried to a moisture content of 10–12wt%, milled to a particle size $\leq$250 μm and then stored in plastic containers until the time for analyses.

Characterization

The collected banana rhizomes, pseudostems, inflorescences and peduncles were characterised for lignocellulosic composition, proximate composition, fuel ratio, elemental composition, mineral composition, heating value, oxygen functional groups and thermal behavior (see Figure 1). The methods for each of the analyses are described below.

Lignocellulosic composition

Lignin, hemicellulose and cellulose contents for each of the collected banana plant wastes were analyzed *via* neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) according to methods described by Van Soest et al. [49]. Hemicellulose content was obtained by subtracting ADF from the NDF value, while the cellulose content was obtained by subtracting the ADL value from the ADF value. The holocellulose content was then obtained as the summation of cellulose and hemicellulose.

Proximate composition and fuel ratio

The banana plant wastes were analyzed for proximate composition, including moisture content, volatile matter, fixed carbon and ash contents. This was achieved by using the thermogravimetric analyzer (TGA) 4000 Perkin Elmer. This involved heating about 2 g of the milled sample in the furnace of the thermogravimetric analyzer from ambient temperature to 600 °C at a ramping rate of 20 °C min^{-1} under a nitrogen flow of 60 mL min^{-1}. At the same ramping rate, heating was continued up to 900 °C, but under an airflow. This temperature was held constant for 3 min until there was no further change in mass of the

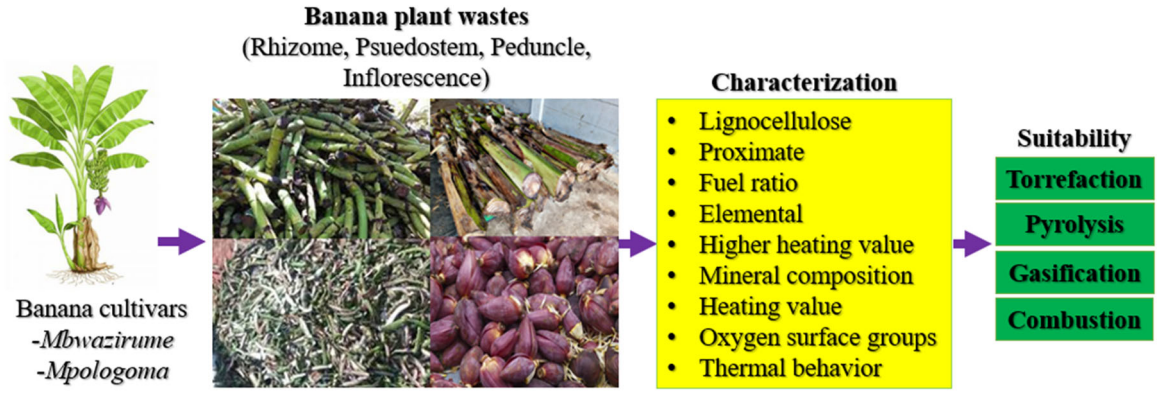


Figure 1. Schematic diagram showing steps followed throughout the study.

remaining residue. The different components in the biomass were determined as percentage weight losses carefully determined from thermogravimetric curves of percent weight loss *versus* temperature. The moisture content was obtained as weight loss due to dehydration of the waste biomass from room temperature to temperatures ranging from 105 to 120 °C. Volatile matter content was obtained as weight loss due to thermal degradation of the biomass at temperatures ranging from 120 and 600 °C. Fixed carbon content was obtained as the weight loss due to combustion of the remaining organic material at temperatures ranging from 600 to 900 °C. Ash content was obtained as the amount of residue left after combustion of the organic material expressed as a percentage of the oven-dry biomass sample.

The fuel ratio (FR) of each banana plant waste was determined according to Equation (1) [40].

$$\mathrm{FR} = \frac{\text{Fixed carbon content}}{\text{Volatile matter content}} \tag{1}$$

Elemental composition

The elemental components (C, H and O) for each of the banana plant wastes were determined from their proximate compositions according to correlations given in Equation (2)-(4) [50].

$$C = 0.637FC + 0.455VM(wt\%) \tag{2}$$

$$H = 0.052FC + 0.062VM(wt\%) \tag{3}$$

$$O = 0.304FC + 0.476VM(wt\%) \tag{4}$$

where, *FC* and *VM* are fixed carbon and volatile matter contents, respectively, in wt%.

Nitrogen (N) content was determined separately using the Kjeldahl method [51]. This method is based on the conversion of the fuel-bound nitrogen to ammonia (NH_3), which is subsequently separated by distillation and determined by titration using HCl solution and methyl red as an indicator. The sulphur (S) content was then determined by difference.

Higher heating values

The higher heating values of the banana plant wastes were determined using a bomb calorimeter (Model: C2000 basic, IKA Co., Germany) (see Figure 2). About 1 g of each sample was burnt in the presence of oxygen inside a sealed container and the heat released from combustion was measured by the calorimeter.

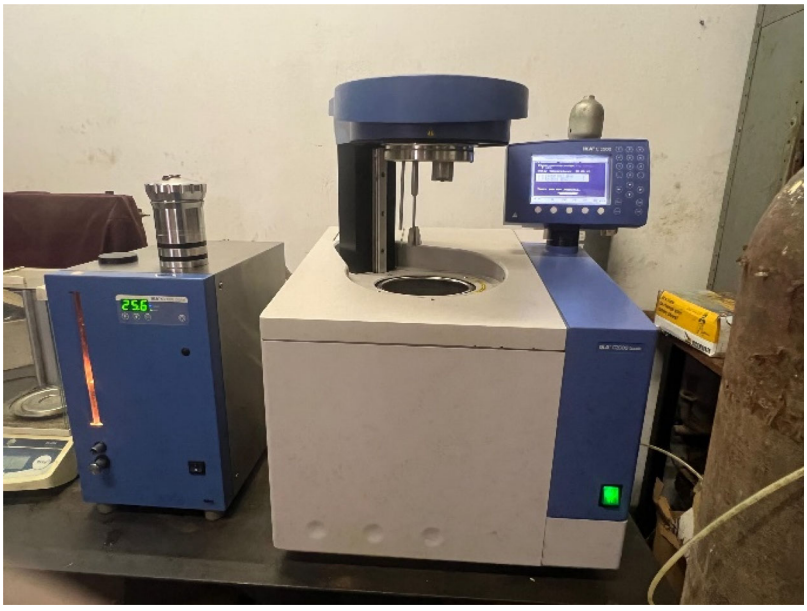


Figure 2. The bomb calorimeter (Model: C2000 basic, IKA Co., Germany) used to determine the higher heating value of the banana plant wastes.

Mineral composition

The banana plant wastes were analyzed for mineral elements using the atomic absorption spectroscopy technique. This involved digesting the samples with concentrated nitric acid and hydrogen peroxide (30 wt%), followed by aspiration of the resultant solutions directly on the atomic absorption spectrometer (Agilent 240FS) for the determination of Na, Mg, Al, P, K, Ca and Fe. The powdered plant material was also scanned using an X-ray fluorescence (XRF) spectrometer (Epsilon 1) for the determination of silicon.

FTIR spectroscopy

Oxygen functional groups present on the surface of banana plant wastes were determined using a Fourier transform infra-red spectrometer (model: TENSOR27, Bruker, Germany). The spectra were obtained by scanning in the range of 4000-400 cm^{-1} at a resolution of 4 cm^{-1}.

Thermal behaviour

Banana plant wastes from selected cultivars were further assessed for thermal behaviour following procedures by Menya et al. (2020). This involved heating about 10–15 mg sample of each selected banana plant waste in a thermal analyzer (4000 Perkin Elmer) from 25 to 800 °C at a heating rate of 25 °C min^{-1}, under N_2 gas flow (50 $mLmin^{-1}$), which provided an inert atmosphere. Thermogravimetric (TG) and differential thermogravimetric (DTG) curves of percent weight loss (mass%) versus temperature (°C) and percent rate of weight loss (mass%min^{-1}) versus temperature (°C), respectively, were generated. From the TG/DTG curves, important information about each sample was carefully obtained, including mass losses that occurred in the different temperature zones, onset and offset temperatures, maximum thermal degradation rates, as well as information about the lower and higher peak temperatures.

Results and discussion

Table 1 presents the lignocellulosic composition, proximate composition, elemental composition, and higher heating values of banana rhizome, pseudostem, peduncle and inflorescence from *Mpologoma* and *Mbwazirume* cultivars sourced from MuZARDI in Uganda. The discussion of results for each of these parameters is presented in the subsequent sub-sections.

Lignocellulosic composition

Lignin

The inflorescence exhibited the highest lignin content among banana plant wastes within and across cultivars (Table 1), followed by the rhizome, while the pseudostem and peduncle exhibited the lowest. The *Mbwazirume* cultivar exhibited slightly lower lignin content across all plant wastes compared to *Mpologoma*, suggesting potential varietal differences in composition. The lignin contents obtained in this study are comparable to those reported in the literature, including 7.86%daf for pseudostem [52], 5–12%daf for pseudostem fibre [44], and 11.48%daf for inflorescence [52]. However, they are lower than other reported values, such as 37.3%daf for pseudostem [43] and 14.25%daf for peduncle [53]. These variations may be attributed to differences in banana variety, soil conditions, agronomic practices, season, and geographical origins [41]. Given the recalcitrance of lignin to thermochemical decomposition and consequently its significant contribution to char formation, processes like torrefaction, HTC and pyrolysis would lead to higher char yields from inflorescence than from rhizome, pseudostem and peduncle, which have lower lignin contents. Additionally, the higher lignin content of the inflorescence also suggests a higher heating value compared to the other banana plant wastes (Table 1). However, the variations in heating value among plant wastes within and across cultivars were relatively small. According to Jenkins et al. [54], lignin has a much higher heating value than other lignocellulosic components due to its lower degree of oxidation.

Table 1. Composition of banana plant wastes across *mpologoma* and *mbwazirume* cultivars obtained from MuZARDI in Uganda.

Banana variety/ waste type	Lignocellulosic composition (%dry-ash-free basis (daf))			Proximate composition					Elemental composition (%dry-ash-free basis (daf))					
	Lignin	Hemicellulose	Cellulose	MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	FR	C	H	S	N	O	Reference
Mpologoma														
Rhizome	14.12	29.06	18.21	11.57	75.58	15.71	8.71	0.21	48.63	6.03	0.70	0.79	44.64	This study
Pseudostem	8.61	17.13	18.15	10.99	80.84	15.32	3.85	0.19	48.40	6.04	0.69	0.77	44.86	This study
Peduncle	8.25	23.28	29.25	11.27	77.38	13.09	9.53	0.17	48.13	6.06	0.70	0.63	45.11	This study
Inflorescence	17.23	24.15	20.06	9.72	74.09	16.14	9.76	0.22	48.75	6.02	0.71	2.47	44.52	This study
Mbwazirume														
Rhizome	12.14	26.25	28.13	12.05	72.78	15.14	12.08	0.21	48.63	6.03	0.70	0.72	44.64	This study
Pseudostem	7.01	28.31	27.23	13.81	81.72	14.93	3.35	0.18	48.31	6.05	0.70	0.76	44.94	This study
Peduncle	7.19	16.26	42.16	12.71	79.45	13.79	6.76	0.17	48.19	6.05	0.70	0.21	45.06	This study
Inflorescence	15.23	23.15	22.08	11.85	77.71	12.43	9.86	0.16	48.01	6.06	0.70	2.56	45.23	This study
Other studies														
Banana stalk	20.0	28.0	47.0	–	76.0	5.0	19.0	0.07	33.00	4.3	0.30	1.90	60.50	[11]
Pseudostem	37.3	17.5	44.0	10.2	88.8	0.2	11.0	0.002	37.93	4.46	0.37	1.87	55.37	[43]
Inflorescence	11.48	16.83	47.30	8.33	–	–	6.51	–	47.19	3.21	0.17	1.96	43.08	[52]
Pseudostem	7.86	24.37	44.02	12.30	–	–	4.93	–	35.53	6.01	0.07	1.35	52.78	[52]
Banana leaves	15.4	28.5	53.5	74.7	41.3	46.5	12.2	1.13	15.90	9.2	0.05	1.4	73.40	[42]
Banana peels	8.90	41.36	9.9	11.56	88.02	2.70	9.28	0.04	35.65	6.19	0.0021	1.94	45.94	[18]
Pseudostem	5.77	25.36	38.48	7.98	89.43	1.21	9.36	0.01	33.46	6.44	0.04	0.80	49.94	[18]
Inflorescence	28.44	–	56.48	10.45	–	–	3.44	–	–	–	–	–	–	[59]
Peduncle	14.25	19.83	53.44	85.00	89.92	–	–	–	–	–	–	–	–	[53]
Peduncle	–	–	–	5.24	–	–	9.95	–	–	–	–	–	–	[61]
Pseudostem fibres	5-12	10-30	60–70	–	–	–	–	–	–	–	–	–	–	[44]
Pseudostem	3.32	45.69	43.52	–	–	–	6.76	–	–	–	–	–	–	[60]
Mbwazirume banana peel	–	–	–	10.61	78.30	15.19	6.52	0.19	46.94	5.79	0.30	0.23	46.74	[47]
Nakyinyika banana peel	–	–	–	12.37	79.85	14.70	5.45	0.18	46.22	5.60	0.36	0.41	47.41	[47]

Note: i) *FR* is fuel ratio, and ii) (^{m}) implies that analysis was based on wet basis.

Hemicellulose

The hemicellulose content varied among the banana plant wastes within and across the cultivars (Table 1). Within the *Mpologoma* cultivar, the rhizome exhibited the highest hemicellulose content (29.06%daf), followed by the inflorescence (24.15%daf) and peduncle (23.28%daf), while the pseudostem exhibited the lowest content (17.13%daf). In contrast, the *Mbwazirume* cultivar showed a different trend, with the pseudostem exhibiting the highest hemicellulose content (28.31%daf), followed by the rhizome (26.25%daf) and inflorescence (23.15%daf), while the peduncle exhibited the lowest content (16.26%daf). These differences underscore the variability in banana plant wastes, influenced by genetic factors, environmental conditions and agronomic practices [48]. The hemicellulose content of pseudostems within and across cultivars was found to be within the range of 10–30%daf reported in the literature [18,43,44,52]. For both cultivars, the hemicellulose content of the inflorescences was higher than 16.83%db reported in the literature [52]. The hemicellulose content of the peduncle from *Mpologoma* (23.28%daf) was found to be higher than 19.83%daf reported in the literature [53], while that from *Mbwazirume* (16.26%daf) was lower. Due to limited studies, the hemicellulose content of rhizomes could not be compared with the literature, thus the findings from this study provide novel insights into the characteristics of rhizomes for biofuel production.

The high hemicellulose contents exhibited by the rhizome and pseudostem from *Mpologoma* and *Mbwazirume*, respectively, suggest that thermochemical processing of these wastes would result in a significant loss of carbon as volatiles, contributing minimally to char formation [55]. This is due to the low thermal stability of hemicellulose as compared to lignin [56]. However, thermal decomposition of hemicellulose could contribute significantly to gas formation [57,58], as its weak chemical bonds facilitate decomposition to micromolecular volatiles [58].

Cellulose

For the *Mpologoma* cultivar, the cellulose content was found to be nearly constant across the banana plant wastes, particularly in the rhizome (18.21%daf) and pseudostem (18.15%daf) (Table 1). The peduncle, on the other hand, exhibited the highest cellulose content (29.25%daf), followed by the inflorescence (20.06%daf). In contrast, the *Mbwazirume* cultivar exhibited greater variation, with the peduncle exhibiting the highest cellulose content (42.16%daf), followed by the pseudostem (27.23%daf) and the rhizome (28.13%daf), while the inflorescence exhibited the lowest (22.08%daf). For both cultivars, the cellulose content of pseudostems, inflorescences and peduncles was lower than the contents reported in the literature [18,43,44,52,53,59]. These variations across plant wastes and cultivars can be attributed to factors discussed in Section 3.1.1

Although it is expected that the cellulose constitutes the major fraction of the plant cell wall [52], some banana plant wastes contained more hemicellulose than cellulose (Table 1), a trend also reported among some banana plant wastes [18,60]. Given the low thermal stability of cellulose [56], the high-cellulose peduncle from *Mpologoma* and *Mbwazirume* would not be suitable for biochar production, as a significant fraction of carbon would be lost as volatiles. Instead, their high cellulose content makes them more suitable for bio-oil production [58].

Proximate composition and fuel ratio

Moisture content

The moisture content of banana plant wastes within and across cultivars is presented in Table 1. Within the *Mpologoma* cultivar, the moisture content was nearly constant, ranging from 9.27 wt% to 11.57 wt%, with the rhizome exhibiting the highest moisture content (11.57 wt%), followed by the peduncle (11.27 wt%) and pseudostem (10.99 wt%), while the inflorescence exhibited the lowest moisture content (9.72 wt%). Similarly, within the *Mbwazirume* cultivar, the moisture content was nearly constant, ranging from 11.85 wt% to 13.81 wt%, with the pseudostem exhibiting the highest moisture content (13.81 wt%db), followed by the peduncle (12.71 wt%), rhizome (12.05 wt%), and inflorescence (11.85 wt%). In both cultivars, pseudostems exhibited moisture contents, consistent with those reported in the literature [18,43, 52,59], but lower than 5.24 wt% reported by Bueno et al. [61] for banana peduncle. Similarly, the moisture contents of inflorescences were consistent with those reported in the

literature [52,59]. However, due to limited data in the literature, no comparisons could be made for the banana rhizome. Based on moisture contents, all the banana plant wastes were found to be suitable as fuel for combustion systems, since the moisture content was within the limit $\leq$50wt% [62]. The banana plant wastes were also found to be suitable for gasification, since their moisture contents lay within the range 20–30wt% [30]. However, for application in pyrolysis and torrefaction, the inflorescence from *Mpologoma* was the only waste type found to be suitable since its moisture content was $\leq$10wt% [28,29]. Beyond these allowable limits, moisture content can have adverse effects on the performance of biomass conversion systems. For instance, in downdraft gasifiers, a high moisture content could lead to a tar entrainment problem, hindering the smooth operation of internal combustion engines for electricity production [32]. In pyrolysis systems, a high moisture content could lead to low char yields and high tar yields [31]. In combustion systems, a high moisture content increases the volume of exhaust gases, lowering the combustion temperature [63]. The reduced combustion temperature, in turn, hinders the complete combustion of flammable substances. A high moisture content also lowers the heating value of biomass, since useful heat energy is wasted on vaporization of moisture from the biomass [33].

Although banana plant wastes with high moisture content could be pre-dried prior to their deployment in thermochemical conversion systems, the energy requirement may be prohibitive, making the conversion processes less economically viable [64]. Thus, to avoid the need for pre-drying of the banana plant wastes and reduce energy costs, the wastes with a high moisture content can be pretreated *via* hydrothermal carbonization, as biomass with a moisture content $\leq$80 wt% is considered suitable for this process [29]. Hydrothermal carbonization is applied under sub-critical conditions of water at mild temperatures ranging from 180 to 250 °C, converting the wet biomass into hydrochar [65,66]. Hydrothermal carbonization is not only associated with a low energy requirement, but also results in hydrochar with a typically high calorific value, high energetic density, reduced sulphur content, improved combustion properties and better dewatering performance compared to its raw counterpart [11,66].

Volatile matter

The volatile matter content of the banana plant wastes across cultivars is presented in Table 1. Within the *Mpologoma* cultivar, the pseudostem exhibited the highest volatile matter content (80.84%db), followed by the peduncle (77.38%db), rhizome (75.58%db), and inflorescence (74.09%db). Similarly, in the *Mbwazirume* cultivar, the pseudostem exhibited the highest volatile matter content (81.72%db), followed by the peduncle (79.45%db), inflorescence (77.71%db), and rhizome (72.78%db). These contents compare well with those reported in the literature [11,18,43,47,53]. The high volatile matter content can be attributed to the high cellulose and hemicellulose contents of the banana plant wastes (Section 3.1). Thus, given their high volatile matter content, the banana plant wastes are suitable for thermochemical conversion, where the focus is on gas and bio-oil yields rather than biochar production. With a volatile matter content $>$10%db, the banana plant wastes are suitable for deployment in downdraft gasifiers [32]. In addition, due to the high volatile matter content, less heat energy would be required for the thermochemical reactions, allowing thermochemical processing of the banana plant wastes to occur at relatively low temperatures [34]. However, since the wastes would be readily devolatilised, higher bio-oil and gas yields would be expected than char yields.

Fixed carbon

The fixed carbon content of banana plant wastes varied across cultivars as shown in Table 1. Within the *Mpologoma* cultivar, the highest fixed carbon content was observed in the inflorescence (16.14%db), followed by the rhizome (15.71%db), pseudostem (15.32%db), and peduncle (13.09%db). Within the *Mbwazirume* cultivar, the highest fixed carbon content was observed in the rhizome (15.14%db), followed by the pseudostem (14.93%db), peduncle (13.79%db), and inflorescence (12.43%db). While the variations among the banana plant parts and between cultivars were relatively small, the *Mpologoma* cultivar generally exhibited higher fixed carbon content than *Mbwazirume*. The fixed carbon contents were considerably higher than those previously reported for banana plant wastes, such as banana pseudostem (0.2%db) [43], banana stalk (5.0%db) [11] and banana peels (2.70%db) [18]. However, they were comparable to those of other biomass types, including banana peel (15.32%db) [48], banana rachis (14.79%db) [48], pistachio shells (19.2%db) [67] and rice husks (19.9%db) [31]. As highlighted in Section

3.1, these variations in composition can be attributed to differences in biomass type, variety, soil conditions, agronomic practices, season and geographical origin [41].

In thermochemical conversion processes, biomass with a high fixed carbon content is preferred due to its higher energy density, resulting in a higher energy throughput of a given conversion system [34]. A higher fixed carbon content also enables the replenishment of the char needed for thermal cracking of the tar, particularly during gasification [39]. Given these attributes, the banana plant wastes from *Mpologoma* cultivar were more suitable for biochar production than those from *Mbwazirume*.

Ash content

The ash content of banana plant wastes varied both within and across cultivars (Table 1). In the *Mpologoma* cultivar, the inflorescence, peduncle and rhizome exhibited relatively similar ash content, ranging from 8.71 to 9.76%db, while the pseudostem exhibited the lowest (3.85%db). In contrast, in the *Mbwazirume* cultivar, the inflorescence exhibited the highest ash content (9.86%db), followed by the rhizome (12.08%db), peduncle (6.76%db), and pseudostem (3.35%db). These variations can be attributed to factors already cited in Section 3.1. Except pseudostem, the rest of the banana plant wastes exhibited ash contents comparable to those reported in the literature, such as banana pseudostem (11.0%db) [43], wet banana leaves (12.2%db) [42], banana peels (9.28%db) [18], banana peduncle (9.95 wt%) [61], banana peel (13.22%db) [48] and banana rachis (12.18%db) [48].

The relatively high ash content of rhizome, peduncle, and inflorescence indicates greater mineral composition, which may cause operational problems during thermochemical processing. Potential issues include slagging, fouling, corrosion, excessive tar formation, and blockage of the reactor [34,40]. To mitigate these problems and ensure smooth operation of conversion systems, it is preferable to pretreat the biomass and lower its ash content to a permissible level. Some of the pretreatment methods include water-washing [68], alkaline treatment [31], and hydrothermal carbonization [11]. However, if the banana plant wastes with high ash content are to be used without pretreatment, then the reactor temperature should be kept below 1000 °C to avoid the slagging tendencies [69]. In addition, careful selection of reactor type can be crucial to avoid operational problems related to slagging tendencies. For example, biomass that is prone to slagging is more suitable for downdraft gasification than updraft gasification. In downdraft gasification, a lower tar content in the gas and lower temperatures at the grate help to reduce ash slagging problems [34].

Fuel ratio

The fuel ratio varied slightly among banana plant wastes within and across cultivars, ranging from 0.16 to 0.22 (Table 1). These ratios are comparable to those reported for banana peels (0.21) [48] and rachis (0.20) [48]. However, they are lower than those of low-rank coals, suggesting inferior fuel properties. For instance, lignite and sub-bituminous coal have fuel ratios ranging from 1.9 to 21.0, and 3.4 to 20.3, respectively [70]. The low fuel ratios of banana plant wastes suggest a high volatile matter content, leading to more flaming combustion and lower char yields [71]. To enhance their fuel ratios and achieve fuel properties close to those of low-rank coals, these wastes can be pretreated *via* thermochemical processes such as torrefaction, pyrolysis and hydrothermal carbonization.

Elemental composition

Carbon

The carbon content of banana plant wastes varied slightly within and across cultivars, ranging from 48.01 to 48.75%daf, constituting the major fraction of biomass (Table 1). These contents fall within the typical range of 30–60%daf for biomass [54]. The contents are comparable to those reported in the literature for inflorescence (47.19%daf) [52], and pistachio shell (48.1%daf) [67]. However, they are higher than those reported for banana pseudostem (37.93%daf) [43], banana stalk (33.0%daf) [11], wet banana leaves (15.9%daf) [42], pseudostem (33.46%daf) [18] and rice husk (34.05%daf) [31]. The relatively high carbon content exhibited by the different banana plant wastes is beneficial as it contributes to increased heating value. According to Jenkins et al. [54], every 1% increase in carbon content increases the heating value by about 0.39 $MJkg^{-1}$.

Hydrogen

Hydrogen is the second major combustible element after carbon, making its presence in the banana plant wastes desirable for fuel applications [72]. The hydrogen content did not differ markedly within and across cultivars, ranging from 6.02 to 6.06%daf (Table 1). These values are consistent with those reported in the literature for banana plant wastes, such as pseudostems (6.44%daf) [18], leaves (6.44%daf) [18], banana peels (6.19%daf) [18], inflorescence (3.21%daf) [52] and banana stalk (4.3%daf) [11]. They also fall within the range of 3-11%daf, typical of biomass [72]. Given the slight variation in hydrogen content, the selection of these wastes for fuel applications becomes somewhat facile.

Oxygen

The oxygen content of banana plant wastes varied slightly within and across cultivars, ranging from 44.52% to 45.49%daf (Table 1). These values are consistent with those reported in the literature for banana plant wastes, such as inflorescence (43.08%daf) [52], pseudostem (49.94%daf) [18] and peels (46.64%daf) [47]. However, the values were considerably lower than those reported for banana stalk (60.50%daf) [11], pseudostem (55.37%daf) [43], and leaves (73.40%daf) [42]. These variations arise due to factors described in Section 3.1. The relatively high oxygen content, characteristic of lignocellulosic biomass [73], affects combustion properties by reducing the heating value [12] and a generating substantial amount of flue gases during combustion [74]. Unlike fossil fuels which have much lower oxygen content [73], banana plant wastes may require upgrading through torrefaction at temperatures $\leq$300 °C to reduce the oxygen content and enhance fuel properties [75]. During torrefaction, biomass undergoes deoxygenation, releasing oxygen in the form of CO_2, CO, and H_2O [76].

Sulphur

The sulphur content of banana plant wastes varied slightly within and across cultivars, ranging from 0.69% to 0.71%daf (Table 1). These values were slightly higher than those reported for banana plant wastes, such as pseudostem (0.37%daf) [43], inflorescence (0.17%daf) [52], leaves (0.05%daf) [42], peels (0.-30-0.36%daf) [47] and stalk (0.30%daf) [11]. However, the values were relatively low compared to fossil fuels, which typically contain higher sulphur levels [77]. The low sulphur content is advantageous for fuel applications, as it reduces the risk of SOx emissions, which otherwise lead to equipment corrosion, acid rain formation, and other environmental issues [77]. Given this favourable characteristic, banana plant wastes can be considered a cleaner alternative to high-sulphur fossil fuels for fuel application.

Nitrogen

The nitrogen content of banana plant wastes varied across cultivars as shown in Table 1. In both cultivars, the inflorescence exhibited the highest nitrogen content, which was almost constant, ranging from 2.47 to 2.56%daf. Similarly, in both cultivars, the rhizome and pseudostem exhibited similar nitrogen levels, ranging from 0.72 to 0.79%daf. The peduncle exhibited the lowest nitrogen content in both cultivars, with *Mpologoma* exhibiting 0.63%daf, while *Mbwazirume* exhibited 0.21%daf. Aside from the inflorescences, nitrogen levels were lower than those reported for banana pseudostem (1.87%daf) [43], inflorescence (1.96%daf) [52], leaves (1.40%daf) [42], stalk (1.90%daf) [11], and peels (1.94%daf) [18], but higher than those reported for banana peel (0.23-0.41%daf) [47] and pseudostem (0.80%daf) [18]. These variations are due to factors discussed in Section 3.1. Given the high nitrogen content of inflorescence, its thermochemical processing could result in higher NOx emissions than banana plant wastes with lower nitrogen levels. Pretreatment *via* torrefaction could help mitigate NOx formation by reducing nitrogen content through volatilization [48].

H/C And O/C ratios

Hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) atomic ratios provide insights into biomass reactivity and calorific value in thermochemical processes [48]. Essentially, biomass with a higher carbon content releases more energy during combustion due to the high-energy content of C-C bonds compared to O-H, C-H or C-O bonds [78]. Therefore, lower H/C and O/C ratios are preferred for better fuel properties. The H/C ratios of banana plant wastes were consistent across cultivars, ranging from 1.47 to

Table 2. H/C And O/C ratios for different banana plant wastes across *mpologoma* and *mbwazirume* cultivars.

	Mpologoma cultivar				*Mbwazirume* cultivar			
Parameter	Rhizome	Pseudostem	Peduncle	Inflorescence	Rhizome	Pseudostem	Peduncle	Inflorescence
H/C ratio	1.48	1.49	1.50	1.47	1.48	1.49	1.50	1.50
O/C ratio	0.69	0.70	0.70	0.69	0.69	0.70	0.70	0.71

Table 3. HHV in $MJkg^{-1}$ for different banana plant wastes across *mpologoma* and *mbwazirume* cultivars.

Mpologoma cultivar				*Mbwazirume* cultivar			
Rhizome	Pseudostem	Peduncle	Inflorescence	Rhizome	Pseudostem	Peduncle	Inflorescence
14.16	14.56	13.48	15.85	13.65	13.86	13.94	14.55

1.50, with corresponding O/C ratios, ranging from 0.69 to 0.71 (Table 2). The H/C ratios were relatively lower than those reported for banana pseudostem (1.71) and rachis (1.74). The O/C ratios were close to the ratio reported for banana pseudostem (0.66), but lower than that exhibited by banana rachis (0.90) [48]. The relatively high H/C and O/C ratios confirm that banana plant wastes are inherently poor in fuel properties compared to low-rank coals such as lignite and sub-bituminous with O/C ratios as low as 0.22 and 0.17, respectively [70]. Given these high ratios, banana plant wastes need pretreatment before being used in combustion, pyrolysis or gasification. Torrefaction is a potential pretreatment method that can lower the O/C and H/C ratios, enhancing the fuel properties of the biomass to levels comparable to low-rank coal [40].

Higher heating value

The HHV of banana plant wastes varied slightly across cultivars, ranging from 13.48 to 15.85 $MJkg^{-1}$ (Table 3). The *Mpologoma* cultivar exhibited slightly higher HHV than *Mbwazirume* across most components, except for the peduncle. Though minor, these variations suggest that cultivar differences can influence fuel quality. In both cultivars, the inflorescence exhibited the highest HHV at 15.85 and 14.55 $MJkg^{-1}$, respectively, suggesting its higher energy content, possibly due to its relatively high lignin content [54]. These HHV values are comparable to those reported for banana pseudostem (15.50 $MJkg^{-1}$) [43], banana stalk (15.60 $MJkg^{-1}$) [11], and banana peels (16.5 $MJkg^{-1}$) [18], but higher than those reported for wet banana leaves (5.5 $MJkg^{-1}$) [42]. The observed variations can be attributed to factors discussed in Section 3.1. Given their relatively low HHV compared to fossil fuels [79], pretreatment methods such as torrefaction could enhance the HHV of the banana plant wastes prior to deployment in thermochemical processes such as pyrolysis and gasification.

Biomass selection

From the earlier sections of this article, it can be seen that banana plant wastes from *Mpologoma* were best suited for biochar production due to their relatively higher lignin and fixed carbon contents, while the pseudostems from *Mbwazirume* were the most suitable due to their relatively higher hemicellulose content and considerably low ash content, enabling thermochemical processing with minimal risks of slagging and fouling. For bio-oil production, plant wastes from *Mbwazirume* were best suited for bio-oil production due to their relatively higher cellulose content compared to *Mpologoma.* Despite these distinctions, the banana plant wastes from both cultivars exhibit relatively low fuel ratios and high H/C and O/C ratios, indicating poor inherent fuel properties. To enhance their suitability for combustion, pyrolysis, and gasification, pretreatment through torrefaction is necessary. This process enhances the fuel ratio, lowers H/C and O/C ratios, increases the heating value, and minimises NOx and SOx emissions. Given the greater prospects of plant wastes from *Mpologoma* for biochar production compared to *Mbwazirume*, the subsequent sections of this article focus on further thermochemical analyses of the former, including mineral composition, oxygen functional groups, and thermal behaviour.

Table 4. Mineral composition of banana plant wastes from *mpologoma* cultivar.

	Banana plant wastes			
Mineral element (ppm)	Rhizome	Pseudostem	Peduncle	Inflorescence
Na	192	217	235	261
Mg	3091	2184	1120	4929
Al	744	5	531	182
Si	2000	2000	2000	9000
P	273	32	299	75
K	18894	15888	19788	28363
Ca	15660	18780	8164	24630
Fe	477	186	192	579
Reference	This study	This study	This study	This study
Other studies				
Na	–	20	1100	18340
Mg	–	1550	–	23550
Al	–	7.67	–	18.43
Si	–	–	–	–
P	–	2090	750	4100
K	–	10630	39000	51290
Ca	–	4010	550	10650
Fe	–	30.65	–	405.50
Reference	–	[52]	[61]	[52]

Mineral composition

The distribution of mineral elements significantly impacts the performance of thermochemical conversion systems. Table 4 shows the mineral composition of banana plant wastes from *Mpologoma* cultivar. The predominant mineral elements were found to be K, Ca, Si and Mg with concentrations ranging from 15888 to 28363 ppm, 8164–24630 ppm, 2000–9000 ppm and 1120–4929 ppm, respectively. These concentrations are close to those reported by Ramu et al. [52], but relatively higher than those reported by Kumari & Tiwari [80]. The significant differences may have to do with variability in banana plant species, growth conditions, maturity stage and differences in geographical origin [80]. High levels of K and Ca in biomass can lead to ash-related problems such as fouling, slagging, and corrosion of heat transfer surfaces, as these elements lower the ash melting point [40]. Additionally, elements such as Mg, K, Na, Fe and P contribute to the emission of particulate matter, including harmful dioxins and furans, during thermochemical decomposition [40,81]. To mitigate these challenges, pretreatment of banana plant wastes before their deployment in thermochemical conversion processes is recommended. Specifically, water washing can be employed to reduce the level of the ash-forming elements in the banana plant wastes, thereby minimizing the risk of ash-related issues [82]. This process is of low cost and is effective, with removal efficiencies ranging from 60 to 90%, depending on the type of mineral element, leaching temperature and time [83].

Oxygen functional groups

Figure 3 shows the FTIR spectra of rhizome, pseudostem, peduncle and inflorescence from *Mpologoma* cultivar. The banana plant wastes exhibited similar FTIR spectra, suggesting the presence of similar surface functional groups. The prominent bands around 3320-3301 cm^{-1} can be attributed to the stretching vibrations of -OH functional groups arising from physically adsorbed moisture [84], as well as hydrogen-bonded –OH groups in the phenolic structure of lignin and aliphatic structure of cellulose and hemicellulose [85,86]. The obvious bands around 2908-2900 cm^{-1} correspond to the CH stretching vibration in the aromatic methoxyl group, and methyl and methylene groups [85]. The weak band observed around 2338-2244 cm^{-1} could not be unambiguously assigned to stretching vibrations of nitrile (C≡N) or alkyne (C≡C) groups [87,88], since such groups are not characteristic of raw biomass. This band was also not obvious in some of the banana plant wastes, particularly the pseudostems. The band around 1615-1590 cm^{-1} can be attributed to C=C and C=O vibrations in aromatic structures [87,89], confirming the presence of lignin across the banana plant wastes. The band around 1380-1345 cm^{-1} can be attributed to C-O stretching vibrations of syringyl ring units [90], O-H deformation [91] and C-H deformations

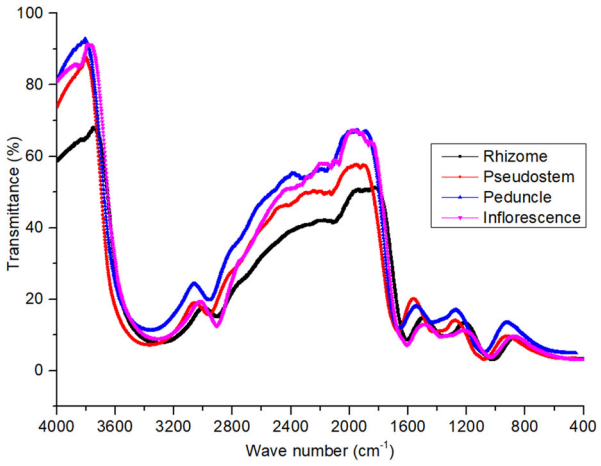


Figure 3. FTIR spectra for rhizome, pseudostem, peduncle and inflorescence from *Mpologoma* cultivar.

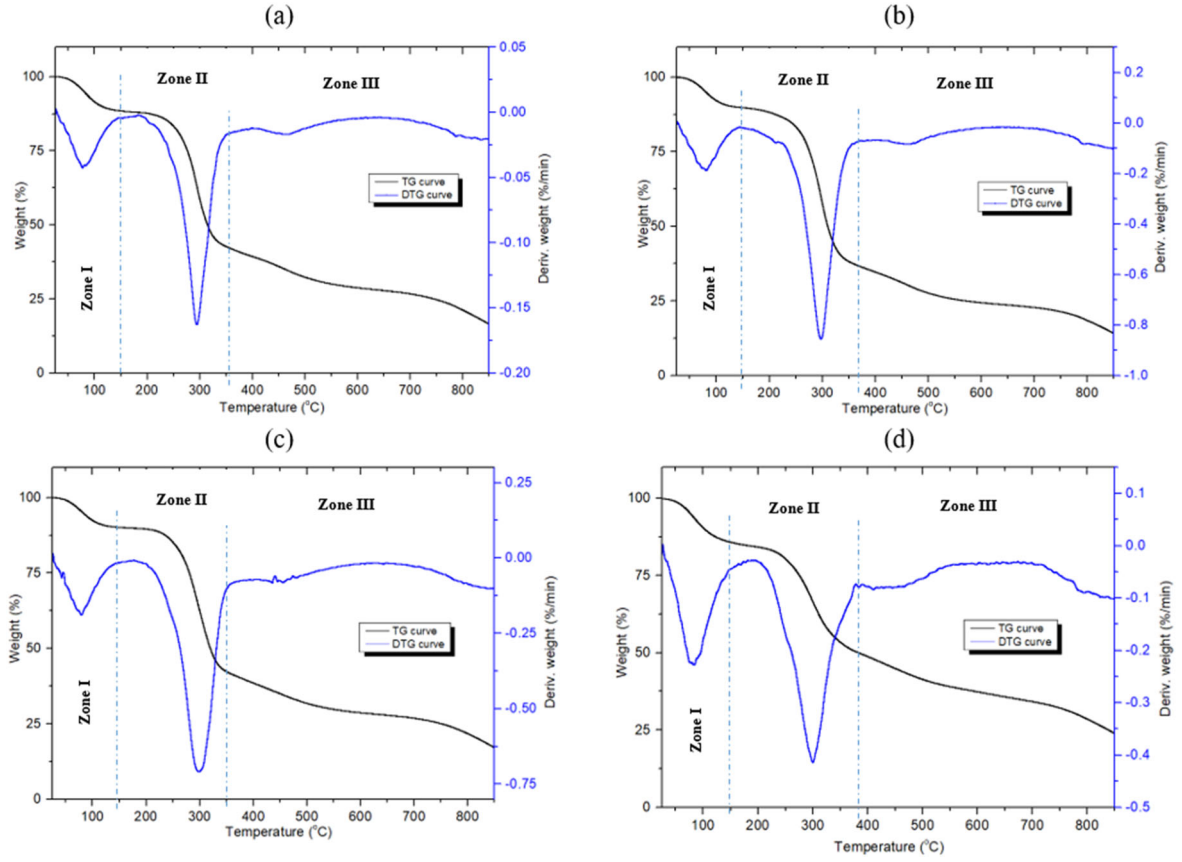


Figure 4. TG and DTG curve for (a) banana rhizome, (b) banana pseudostem, (c) banana peduncle and (d) banana inflorescence from *Mpologoma* cultivar.

[89,92]. The band around 1039-1020 cm^{-1} can be attributed to the C–O stretching vibration of alcohol, phenol, ester or ether groups in the biomass [89,93,94].

Thermal behaviour

The TG/DTG curves in Figure 4 illustrate the thermal behaviour of different banana plant wastes from *Mpologoma*, including rhizome, pseudostem, peduncle and inflorescence. The curves reveal three temperature zones of thermal decomposition, typical of lignocellulosic biomass. Similar TG/DTG curves were obtained for banana pseudostem [24]. The description of each temperature zone is given in sub-sections 3.9.1 to 3.9.3.

Temperature zone I

The first temperature zone spans from room temperature to approximately 150 °C, resulting in a mass loss ranging from 9.70 to 14.11 wt%, depending on the type of banana plant waste (see Figure 4). This mass loss has to do with the evaporation of the physically adsorbed water from the banana plant wastes [56]. Depending on the banana plant waste, the first zone further extended to about 240-262 °C, with slight mass losses (4.06–8.11 wt%) likely due to the release of light volatiles. These slight mass losses also suggest that the organic components of the banana plant wastes are still thermally stable within this temperature range [56].

Temperature zone II

In the second temperature zone, major decomposition commenced at temperatures ranging from 240 to 261 °C to 354-380 °C, with mass loss ranging from 31 to 47wt%, depending on the banana plant waste type (see Figure 4 and Table 5). Based on the initial decomposition temperature, banana inflorescence (240.0 °C) was found to be the least thermally stable, followed by pseudostem (248.1 °C), peduncle (259.2 °C) and rhizome (261.3 °C). The mass losses within this temperature zone have to do with the decomposition of hemicellulose and cellulose, and to a lesser extent lignin, occurring at temperatures ranging from 100 to 380 °C, 250-380 °C and 180-900 °C, respectively [95]. The decomposition of hemicellulose at a lower temperature range is due to the presence of acetyl groups in its amorphous and random structure with many branched units, which renders it less thermally stable [96]. In contrast, the decomposition of cellulose at a higher temperature is due to its partly crystalline structure made of ordered microfibrils, which renders it more thermally stable than hemicellulose [97]. Based on the offset temperature (T_{offset}), the minimum temperature for thermochemical decomposition of rhizome, pseudostem, peduncle and inflorescence was found to be 357.6, 364.9, 354.2 and 380.0 °C, respectively. At these temperatures, most of the volatiles are released from the biomass, leaving behind char with relatively good fuel properties.

Variations in mass loss across banana plant wastes were expected due to the differences in cellulose, hemicellulose, and lignin contents (Table 1). However, from the DTG curves for the different banana plant wastes, the low-temperature shoulder peaks were not obvious (Figure 4), making it difficult to find the lower peak temperature at which maximum thermal degradation of the hemicellulose occurred. While some researchers have associated this phenomenon with low hemicellulose content in biomass [98], this assertion could not be confirmed as all banana plant wastes exhibited high hemicellulose contents (Table 1). A plausible explanation is that the low-temperature shoulder peak of hemicellulose overlapped with that of cellulose due to the presence of less reactive components, such as glucomannan and arabinogalactan, which delayed the thermal decomposition of hemicellulose, causing it to coincide with that of cellulose [98]. Similar trends were observed in the thermal decomposition of rice husks [99]. The maximum thermal decomposition of cellulose was depicted by the higher temperature peaks ranging from 294.93 to300.10 °C, depending on the banana plant waste type (Table 5).

The DTG evolution profiles within the second temperature zone exhibited a narrow range of peak positions (295-300 °C) (Table 5), indicating comparable reactivity across banana plant wastes. Since the temperature corresponding to peak height is inversely proportional to reactivity [100], the rhizome demonstrated a slightly higher reactivity, followed by the pseudostem, inflorescence and peduncle.

Temperature zone III

In the third temperature zone, thermal degradation commenced at temperatures ranging from 352 to 380 °C, and was completed at 850 °C (see Figure 4 and Table 6). Within this zone, mass loss was highest with thermal degradation of banana inflorescence (26.03 wt%), followed by banana rhizome (25.57 wt%), banana peduncle (24.33 wt%), and then banana pseudostem (22.91 wt%) (Table 6). On the DTG curve (Figure 4), this zone is represented by a relatively flat trailing section, which has to do with the slow decomposition of lignin over a wide temperature range [101]. Mass loss in this zone may also be attributed to further decomposition of carbon residues formerly produced at the lower decomposition temperatures [56]. The residual weight at 850 °C was char, with yields of 26.99, 19.51, 18.57 and 15.72%db resulting from thermal degradation of inflorescence, peduncle, rhizome and pseudostem, respectively

Table 5. Important results of the TGA derived from the TG/DTG curves for banana plant wastes from *Mpologoma* cultivar.

	TG/DTG parameters within temperature zone II				
Banana plant waste	T_{onset}- T_{offset} (°C)	$M_{loss,2}$ (wt%)	T_{hem} (°C)	$DTG_{peak\ temp}$ (°C)	$R_{peak\ temp}$ (%min^{-1})
Rhizome	261.3-357.6	38.33	*	294.9	0.1622
Pseudostem	248.1-364.9	46.67	*	297.9	0.8522
Peduncle	259.2-354.2	41.19	*	300.1	0.7064
Inflorescence	240.0-380.0	31.54	*	299.0	0.4131

Note: 1) T_{onset}- T_{offset} is the temperature range corresponding to the second temperature zone, where major thermal decomposition occurred, 2) T_{onset} and T_{offset} are the temperatures at which devolatilisation of the banana plant wastes were considered to start and complete, respectively, 3) $M_{loss,2}$ is the mass loss in the second temperature zone, 4) T_{hem} is the lower peak temperature at which maximum thermal degradation of the hemicellulose occurred, 5) $DTG_{peak\ temp}$ is the higher peak temperature at which maximum thermal degradation of the cellulose occurred, 6) $R_{peak\ temp}$ is the maximum thermal degradation rate corresponding to the DTG peak temperature, and 7) * implies the low-temperature shoulder of the rice husk variety was not obvious.

Table 6. Important results of the TGA derived from the TG/DTG curves for banana plant wastes from *Mpologoma* cultivar.

Banana plant waste	Temperature zone III	$M_{loss,3}$ (wt%)	Residual weight at 850 °C (%db)
Rhizome	356.6-850	25.57	18.57
Pseudostem	363.0-850	22.91	15.72
Peduncle	352.4-850	24.33	19.51
Inflorescence	380.0-850	26.03	26.99

Note: $M_{loss,3}$ is the mass loss in the third temperature zone.

(Table 6). The high char yield due to thermal degradation of the inflorescence further affirms its promising prospects for biochar production.

Limitations and future research

This study involved characterization of banana rhizomes, pseudostems, peduncles and inflorescences from *Mbwazirume* and *Mpologoma* sourced from Mukono ZARDI in Uganda. As such, the findings in this study may not be generalizable to other cultivars such as *Nakitembe*, *Ntika*, *Musakala*, and *Kisansa*, or to banana plant wastes from other agroecological zones. The variations in banana species, climate, soil conditions, and agronomic practices could influence the biomass characteristics [41]. Additionally, the study did not explore pretreatment strategies to enhance fuel properties of banana plant wastes. Thermochemical conversion of the plant wastes was also not carried out to ascertain biofuel yield and quality under specific conversion processes such as pyrolysis and gasification. Future studies should extend characterization to a broader range of banana cultivars, plant wastes and agroecological zones to inform a robust criterion for selection of banana plant wastes for biofuel production. Future studies should also investigate pretreatment strategies, as well as conduct thermochemical conversion experiments to gain insights into the practical suitability of selected banana plant wastes for biofuel production.

Conclusion

In this study, banana rhizome, pseudostem, peduncle and inflorescences from *Mbwazirume* and *Mpologoma* banana cultivars were characterized for potential utilization in thermochemical conversion processes. Moisture content of the plant wastes ranged from 9.72–13.81 wt%, suggesting that pre-drying of the wastes would be necessary prior to torrefaction or pyrolysis. Volatile matter content ranged from 74.09 to- 81.72%db, suggesting that the plant wastes can be used for bio-oil and/or gas production. Inflorescences exhibited the highest nitrogen content (2.47-2.56%daf), suggesting higher potential for NOx emissions. Inflorescences also exhibited the highest higher heating value across cultivars (14.55–15.85 MJkg^{-1}) compared to rhizome (13.65–14.16 MJkg^{-1}), pseudostem (13.86–14.56 MJkg^{-1}) and peduncle (13.48–13.94 MJkg^{-1}). While pseudostems exhibited a relatively low ash content across cultivars (3.35-3.85%db), the rhizomes, peduncle and inflorescences exhibited higher ash contents ranging from 8.71–12.08, 6.76–9.53, and 9.76-9.86%db, respectively. This high ash content poses operational risks such as slagging and fouling of heat transfer surfaces. The predominant mineral elements in the wastes were

found to be K (15888–28363 ppm), Ca (2000–9000 ppm), Si (2000–9000 ppm), and Mg (1120–4928 ppm), which could have catalytic functions during thermal decomposition. However, the level of mineral elements may need to be reduced to allow smooth operation of the thermochemical conversion systems. The low fuel ratio (0.16–0.22) and high H/C ratio (1.48–1.50) and O/C ratio (0.69–0.71) of the plant wastes suggest poor fuel properties, which could be enhanced through torrefaction. Overall, for biochar production, the lignin levels are lower than ideal for economic viability, despite inflorescence being comparatively higher (15-17%). To enhance the economic viability of thermochemical conversion of banana plant wastes, co-production of biochar with syngas and/or bio-oil should be prioritized.

Acknowledgements

Funding support from the Carnegie Corporation of New York (CCNY) through the Consolidating Early Career Academic Programme at Makerere and Partner Universities ((CECAP); 2022–2024) is gratefully acknowledged. Additionally, we appreciate the support from the Mukono Zonal Agricultural Research and Development Institute (MuZARDI) for providing the banana plant wastes used in this study.

Author contributions

Emmanuel Menya: Conceptualization, Methodology, Validation, Writing-original Draft, Fund Acquisition and Project Administration. Joel Wakatuntu: Conceptualization, Writing-original Draft, Review & Editing. Medard Turyasingura: Conceptualization, Writing-original Draft, Review & Editing. Christopher Okot: Conceptualization, Methodology & Editing. Writing-original Draft, Review & Editing. Henning Storz: Conceptualization, Supervision, Writing – Review & Editing. Peter Wilberforce Olupot: Conceptualization, Supervision, Writing – Review & Editing. Collins Okello: Conceptualization, Supervision, Writing – Review & Editing.

Statements and declarations

The authors affirm that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported with funding from the Carnegie Corporation of New York (CCNY) through the Consolidating Early Career Academic Programme at Makerere and Partner Universities ((CECAP); 2022–2024). Grant No. G-20-57626.

ORCID

Emmanuel Menya http://orcid.org/0000-0002-4034-5308

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Tock JY, Lai CL, Lee KT, et al. Banana biomass as potential renewable energy resource: a Malaysian case study. Renew. Sustain. Energy Rev. 2010;14:798–805. doi: 10.1016/j.rser.2009.10.010.

[2] Adeniyi AG, Ighalo JO, Amosa MK. Modelling and simulation of banana (Musa spp.) waste pyrolysis for bio-oil production. Biofuels. 2021;12(7):879–883. doi: 10.1080/17597269.2018.1554949.

[3] de Oliveira Maia BG, Oliveira APNd, Oliveira TMNd, et al. Characterization and production of banana crop and rice processing waste briquettes. Env Prog and Sustain Energy. 2018;37(4):1266–1273. doi: 10.1002/ep.12798.
[4] Pazmiño-Hernandez M, Moreira CM, Pullammanappallil P. Feasibility assessment of waste banana peduncle as feedstock for biofuel production. Biofuels. 2019;10(4):473–484. doi: 10.1080/17597269.2017.1323321.
[5] P. Wilaipon, The effects of briquetting pressure on banana-peel briquette and the banana waste in northern thailand patomsok wilaipon department of mechanical engineering, faculty of engineering. Am J Appl Sci. 2009;6(1):167–171. doi: 10.3844/ajassp.2009.167.171.
[6] Bamisaye A, Ayodeji I. Effect of binder type on the NaOH-treated briquettes produced from banana leaves. Biomass Convers Biorefinery. 2023;13:8939–8947. doi: 10.1007/s13399-021-01771-9.
[7] Sulaiman SM, Nugroho G, Saputra HM, et al. Valorization of banana bunch waste as a feedstock via hydrothermal carbonization for energy purposes. J Ecol Eng. 2023;24(7):61–74. doi: 10.12911/22998993/163350.
[8] Gumisiriza R, Hawumba JF, Okure M, et al. Biomass waste-to-energy valorisation technologies: a review case for banana processing in Uganda. Biotechnol Biofuels. 2017;10(1):11. doi: 10.1186/s13068-016-0689-5.
[9] Taib RM, Abdullah N, Syairah N, et al. Bio-oil derived from banana pseudo-stem via fast pyrolysis process. Biomass Bioenergy. 2021;148:106034. doi: 10.1016/j.biombioe.2021.106034.
[10] Bhushan S, Rana MS, Nandan N, Prajapati SK. Energy harnessing from banana plant wastes: a review. Bioresour Technol Reports 2019;7:100212. doi: 10.1016/j.biteb.2019.100212.
[11] Islam A, Akber A, Limon SH, et al. Characterization of solid biofuel produced from banana stalk via hydrothermal carbonization. Biomass Conv Bioref. 2019;9(4):651–658. doi: 10.1007/s13399-019-00405-5.
[12] Menya E, Okello C, Storz H, et al. A review of progress on torrefaction, pyrolysis and briquetting of banana plant wastes for biofuels. Biomass Convers Biorefinery. 2025;15:13227–13269. doi: 10.1007/s13399-024-06204-x.
[13] Zhang J, Zhang X. 15. The thermochemical conversion of biomass into biofuels. In: Verma D, Fortunati E, Jain S, Zhang X, editors. Biomass, biopolymer-based materials, and bioenergy. Elsevier; 2019. p. 327–368. doi: 10.1016/B978-0-08-102426-3.00015-1.
[14] Neto JM, Komesu A, H. da S. Martins L, et al. Third generation biofuels: an overview. In: Rai M, Ingle AP, editors. Sustainable bioenergy. Amsterdam, Netherlands: Elsevier Inc.; 2019. p. 283–298. doi: 10.1016/B978-0-12-817654-2.00010-1.
[15] Mopoung S, Udeye V. Characterization and evaluation of charcoal briquettes using banana peel and banana bunch waste for household heating. Am J Eng Appl Sci. 2017;10(2):353–365. doi: 10.3844/ajeassp.2017.353.365.
[16] Yusuf I, Flagiello F, Ward NI, et al. Valorisation of banana peels by hydrothermal carbonisation: potential use of the hydrochar and liquid by-product for water purification and energy conversion. Bioresour Technol Reports. 2020;12:100582. doi: 10.1016/j.biteb.2020.100582.
[17] Te WZ, Muhanin KNM, Chu Y-M, et al. Optimization of pyrolysis parameters for production of biochar from banana peels: evaluation of biochar application on the growth of ipomoea aquatica. Front Energy Res. 2021;8(February):1–16. doi: 10.3389/fenrg.2020.637846.
[18] Kabenge I, Omulo G, Banadda N, et al. Characterization of banana peels wastes as potential slow pyrolysis feedstock. JSD. 2018;11(2):14–24. doi: 10.5539/jsd.v11n2p14.
[19] Alves JLF, da Silva JCG, Sellin N, et al. Upgrading of banana leaf waste to produce solid biofuel by torrefaction: physicochemical properties, combustion behaviors, and potential emissions. Environ Sci Pollut Res Int. 2022;29(17):25733–25747. doi: 10.1007/s11356-021-17381-x.
[20] Mosqueda A, Medrano K, Gonzales H, et al. Hydrothermal treatment of banana leaves for solid fuel combustion. Biofuels. 2021;12(9):1123–1129. doi: 10.1080/17597269.2019.1594590.
[21] Sellin N, Ricardo D, Marangoni C, et al. Oxidative fast pyrolysis of banana leaves in fl uidized bed reactor. Renew. Energy. 2016;96:56–64. doi: 10.1016/j.renene.2016.04.032.
[22] Faria FA, Faria FA, Mattiolli L, et al. Fertilizer release kinetics incorporated to torrefied banana - crop residues. J Therm Anal Calorim. 2022;147(5):3659–3671. doi: 10.1007/s10973-021-10764-9.
[23] Wang X, Yang S, Shen B, et al. Pyrolysis of biomass pineapple residue and banana pseudo-stem: kinetics, mechanism and valorization of bio-char. Catalysts. 2022;12(8):840. doi: 10.3390/catal12080840.
[24] Abdullah N, Mohd R, Syairah N, et al. Banana pseudo-stem biochar derived from slow and fast pyrolysis process. Heliyon. 2023;9(1):e12940. doi: 10.1016/j.heliyon.2023.e12940.
[25] Granados DA, Velásquez HI, Chejne F. Energetic and exergetic evaluation of residual biomass in a torrefaction process. Energy. 2014;74:181–189. doi: 10.1016/j.energy.2014.05.046.
[26] Streitwieser DA, Villamil DO, Gutierrez E, et al. Fast pyrolysis as a valorization mechanism for banana rachis and low-density polyethylene waste. Chem Eng & Technol. 2021;44(11):2092–2099. doi: 10.1002/ceat.202100232.
[27] Prawisudha P, Azka GR, Triyono B, et al. Multi-production of solid fuel and liquid fertilizer from organic waste by employing wet torrefaction process. AIP Conf. Proc. 2018, vol. 1984, pp. 1–6. doi: 10.1063/1.5046629.

[28] Wang L, Cheng D, Wang L, et al. Biomass pyrolysis and bio-oil utilization. In: Wang L, editor. Sustainable Bioenergy Production. Boca Raton, FL: CRC Press: taylor & Francis; 2014. p. 367–387.
[29] Lim HY, Rashidi NA, Othman MFH, et al. Recent advancement in thermochemical conversion of biomass to biofuel. Biofuels. 2024;15(5):587–604. doi: 10.1080/17597269.2023.2261788.
[30] Knoef H. Practical aspects of biomass gasification. In: Knoef H, editor. Handbook biomass gasification. Enschede, Netherlands: BTG Biomass Technology Group; 2005.
[31] Menya E, Olupot PW, Storz H, et al. Characterization and alkaline pretreatment of rice husk varieties in Uganda for potential utilization as precursors in the production of activated carbon and other value-added products. Waste Manag. 2018;81:104–116. doi: 10.1016/j.wasman.2018.09.050.
[32] FAO. Wood as gas engine, forest industries division, fao forestry department. Rome: FAO; 1986. p. 173.
[33] Demirbas A. Relationships between heating value and lignin, moisture, ash and extractive contents of biomass fuels. Energy Explor Exploit. 2002;20(1):105–111. doi: 10.1260/014459802760170420.
[34] Olupot PW, Candia A, Menya E, et al. Characterization of rice husk varieties in Uganda for biofuels and their techno-economic feasibility in gasification. Chem Eng Res Des. 2016;107:63–72. doi: 10.1016/j.cherd.2015.11.010.
[35] Madhu P, Dhanalakshmi CS, Mathew M. Multi-criteria decision-making in the selection of a suitable biomass material for maximum bio-oil yield during pyrolysis. Fuel. 2020;277:118109. doi: 10.1016/j.fuel.2020.118109.
[36] Babatabar MA, Yousefian F, Mousavi MV, et al. Pyrolysis of lignocellulosic and algal biomasses in a fixed-bed reactor: a comparative study on the composition and application potential of bioproducts. Intl J Energy Res. 2022;46(7):9836–9850. doi: 10.1002/er.7855.
[37] Devi GS, Vaishnavi S, Srinath S, et al. Energy recovery from biomass using gasification. In: Current developments in biotechnology and bioengineering. Amsterdam, Netherlands: Elsevier; 2020. p. 363–382.
[38] Guo Q, Cheng Z, Chen G, et al. Assessment of biomass demineralization on gasification: from experimental investigation, mechanism to potential application. Sci Total Environ. 2020;726:138634. doi: 10.1016/j.scitotenv.2020.138634.
[39] Tilman D, Hill J, Lehman C. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science (1979). 2006;314(5805):1598–1600. doi: 10.1126/science.1133306.
[40] Khairy M, Amer M, Ibrahim M, et al. The influence of torrefaction on the biochar characteristics produced from sesame stalks and bean husk. Biomass Conv. Bioref. 2024;14(15):17127–17148. doi: 10.1007/s13399-023-03822-9.
[41] Gumisiriza R, Funa J, Peter AS, et al. Processing of East African highland green bananas: waste generation and characterization as a potential feedstock for biogas production in Uganda. Am. Sci. Res. J. Eng. Technol. Sci. 2019;53(1):215–236.
[42] Fernandes ERK, Marangoni C, Souza O, et al. Thermochemical characterization of banana leaves as a potential energy source. Energy Convers Manag. 2013;75:603–608. doi: 10.1016/j.enconman.2013.08.008.
[43] Abdullah N, Sulaiman F, Miskam MA, et al. Characterization of banana (Musa spp.) Pseudo-stem and fruit-bunch-stem as a potential renewable energy resource. Int J Biol Vet Agric Food Eng. 2014;8(8):712–716.
[44] Cecci RR, Ramos AA, Passos TC, et al. Banana pseudostem fibers characterization and comparison with reported data on jute and sisal fibers. SN Appl Sci. 2020;2(1):1–6. doi: 10.1007/s42452-019-1790-8.
[45] Sellin N, Oliveira BGD, Marangoni C, et al. Use of banana culture waste to produce briquettes. Chem Eng Trans. 2013;32:349–354.
[46] Kpalo SY, Zainuddin MF, Manaf LA, et al. A review of technical and economic aspects of biomass briquetting. Sustainability. 2020;12(11):4609. doi: 10.3390/su12114609.
[47] Yusuf AA, Inambao FL. Characterization of Ugandan biomass wastes as the potential candidates towards bioenergy production. Renew Sustain Energy Rev. 2020;117:109477. doi: 10.1016/j.rser.2019.109477.
[48] Mendonça IF, do Vale GS, Evaristo RBW, et al. Optimizing torrefaction of banana waste (peels and rachis) for sustainable biocoal production in rural communities. Biomass Bioenergy. 2025;196:107726. doi: 10.1016/j.biombioe.2025.107726.
[49] Van Soest P, Robertson JB, Lewis BA. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci. 1991;74(10):3583–3597. doi: 10.3168/jds.S0022-0302(91)78551-2.
[50] Parikh J, Channiwala SA, Ghosal GK. A correlation for calculating elemental composition from proximate analysis of biomass materials. Fuel. 2007;86(12-13):1710–1719. doi: 10.1016/j.fuel.2006.12.029.
[51] International AACC. Crude protein—improved kjeldahl method 46-10.01. 1999. doi: 10.1094/AACCIntMethod-46-10.01.
[52] Ramu R, et al. Assessment of nutritional quality and global antioxidant response of banana. Pharmacogn Res. 2017;9: s 74–83. doi: 10.4103/pr.pr.
[53] Benish PMR, Mozhiarasi V, Nagabalaji V, et al. Optimization of process parameters for enhanced methane production from banana peduncle by thermal pretreatment. Biomass Conv. Bioref. 2023;13(16):15251–15265. doi: 10.1007/s13399-022-02917-z.
[54] Jenkins BM, Baxter LL, M TR, Jr, et al. Combustion properties of biomass. Fuel Process. Technol. 1998;54(1-3):17–46. doi: 10.1016/S0378-3820(97)00059-3.

[55] Menya E, Olupot PW, Storz H, et al. Production and performance of activated carbon from rice husks for removal of natural organic matter from water: a review. Chem Eng Res Des. 2018;129:271–296. doi: 10.1016/j.cherd.2017.11.008.
[56] Menya E, Olupot PW, Storz H, et al. Effect of alkaline pretreatment on the thermal behavior and chemical properties of rice husk varieties in relation to activated carbon production. J Therm Anal Calorim. 2020;139(3):1681–1691. doi: 10.1007/s10973-019-08553-6.
[57] Shen DK, Gu S, Bridgwater AV. The thermal performance of the polysaccharides extracted from hardwood: Cellulose and hemicellulose. Carbohydr Polym. 2010;82(1):39–45. doi: 10.1016/j.carbpol.2010.04.018.
[58] Zhao C, Jiang E, Chen A. Volatile production from pyrolysis of cellulose, hemicellulose and lignin. J Energy Inst. 2017;90(6):902–913. doi: 10.1016/j.joei.2016.08.004.
[59] Amutha K, Sudha A, Saravanan D. Characterization of natural fibers extracted from banana inflorescence bracts characterization of natural fibers extracted from banana inflorescence bracts. J Nat Fibers. 2022;19(3):872–881. doi: 10.1080/15440478.2020.1764437.
[60] Li W, Zhang Y, Li J, et al. Characterization of cellulose from banana pseudo-stem by heterogeneous liquefaction. Carbohydr Polym. 2015;132:513–519. doi: 10.1016/j.carbpol.2015.06.066.
[61] Bueno CM, Sedano SA, Ramirez T, et al. Chemical, cooking and sensory characteristics of burger patties with different levels of banana peduncle powder. Philipp J Vet Anim Sci. 2012;38(1):45–52.
[62] Mckendry P. Energy production from biomass (part 2): conversion technologies. Bioresour Technol. 2002;83(1):47–54. doi: 10.1016/s0960-8524(01)00119-5.
[63] Mierzwa M, Krzysztof H, Marcin G, et al. Assessment of energy parameters of biomass and biochars, leachability of heavy metals and phytotoxicity of their ashes. J Mater Cycles Waste Manag. 2019;21:786–800. doi: 10.1007/s10163-019-00832-6.
[64] Fu M, Mo C, Li H, et al. Comparison of physicochemical properties of biochars and hydrochars produced from food wastes. J Clean Prod. 2019;236:117637. doi: 10.1016/j.jclepro.2019.117637.
[65] Ercan B, Alper K, Ucar S, et al. Comparative studies of hydrochars and biochars produced from lignocellulosic biomass via hydrothermal carbonization, torrefaction and pyrolysis. J Energy Inst. 2023;109:101298. doi: 10.1016/j.joei.2023.101298.
[66] Balmuk G, Cay H, Duman G, et al. Hydrothermal carbonization of olive oil industry waste into solid fuel: fuel characteristics and combustion performance. Energy. 2023;278:127803. doi: 10.1016/j.energy.2023.127803.
[67] Hosseinzaei B, Hadianfard MJ, Aghabarari B, et al. Pyrolysis of pistachio shell, orange peel and saffron petals for bioenergy production. Bioresour. Technol. Reports. 2022;19:101209. doi: 10.1016/j.biteb.2022.101209.
[68] Deng L, Zhang T, Che D. Effect of water washing on fuel properties, pyrolysis and combustion characteristics, and ash fusibility of biomass. Fuel Process Technol. 2013;106:712–720. doi: 10.1016/j.fuproc.2012.10.006.
[69] Brunner T, Kanzian W, Obernberger I, Theissl A. Combustion properties of maize cobs-results from lab and pilot-scale tests. In: Proceedings of the 19th European Biomass Conference & Exhibition, ETA-Renewable Energies (Ed.), Italy; 2011. p. 944–951.
[70] Odeh AO. Comprehensive conventional analysis of southern hemisphere coal chars of different ranks for fixed bed gasification. Glob J Res Eng Civ Struct Eng. 2015;15(4):4–16.
[71] Adeleke AA, Odusote JK, Ikubanni PP, et al. The ignitability, fuel ratio and ash fusion temperatures of torre fied woody biomass. Heliyon. 2020;6(3):e03582. doi: 10.1016/j.heliyon.2020.e03582.
[72] Adamovics A, Platace R, Gulbe I, et al. The content of carbon and hydrogen in grass biomass and its influence on heating value. Eng. Rural Dev. 2018;1(1):1277–1281. doi: 10.22616/ERDev2018.17.N014.
[73] Luik H, Johannes I, Palu V, et al. Transformations of biomass internal oxygen at varied pyrolysis conditions. J. Anal. Appl. Pyrolysis. 2007;79(1-2):121–127. doi: 10.1016/j.jaap.2006.12.028.
[74] Orisaleye JI, Jekayinfa SO, Pecenka R, et al. Investigation of the effects of torrefaction temperature and residence time on the fuel quality of corncobs in a fixed-bed reactor. Energies (Basel). 2022;15(14):5284. doi: 10.3390/en15145284.
[75] Khumsak O, Wattananoi W, Worasuwannarak N. Bio-oil production from the torrefied biomass. In: 2011 IEEE Conference on Clean Energy and Technology (CET), 2011. p. 68–71. doi: 10.1109/CET.2011.6041438.
[76] Mamvura TA, Danha G. Biomass torrefaction as an emerging technology to aid in energy production. Heliyon. 2020;6(3):e03531. doi: 10.1016/j.heliyon.2020.e03531.
[77] Kraszkiewicz A, Santoro F, Pascuzzi S. Emmission of sulphur oxides from agricultural solid biofuels combustion. Agric Eng. 2020;24(4):35–45. doi: 10.1515/agriceng-2020-0034.
[78] Pahla G, Mamvura TA, Ntuli F, et al. Energy densification of animal waste lignocellulose biomass and raw biomass. South African J Chem Eng. 2017;24:168–175. doi: 10.1016/j.sajce.2017.10.004.
[79] Kazimierski P, Januszewicz K, Godlewski W, et al. The course and the effects of agricultural biomass pyrolysis in the production of high-calorific biochar. Materials (Basel). 2022;15(3):1038. doi: 10.3390/ma15031038.
[80] Kumari P, Gaur SS, Tiwari RK. Banana and its by - products: A comprehensive review on its nutritional composition and pharmacological bene fi ts. eFood. 2023;4(5):1–23. doi: 10.1002/efd2.110.
[81] Zhao P, Shen Y, Ge S, et al. Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment. Appl Energy. 2014;131:345–367. doi: 10.1016/j.apenergy.2014.06.038.

[82] Jiang F, Cao D, Zhang Y, et al. Combustion of the banana Pseudo-stem hydrochar by the High-Pressure CO2-Hydrothermolysis: thermal conversion, kinetic, and emission analyses. Fuel. 2023;331:125798. doi: 10.1016/j.fuel.2022.125798.
[83] Wang Y, Guo S, Cao F, et al. Leaching mechanisms of ash-forming elements during water washing of corn straw. Biomass Conv Bioref. 2024;14(1):133–146. doi: 10.1007/s13399-021-02184-4.
[84] Mierzwa-Hersztek M, Gondek K, Nawrocka A, et al. FT-IR analysis and the content of phenolic compounds in exogenous organic matter produced from plant biomass. J Elem. 2019;24(3/2019):879–896. doi: 10.5601/jelem.2018.23.3.1716.
[85] Salim R, Asik J, Sani M. Chemical functional groups of extractives, cellulose and lignin extracted from native Leucaena leucocephala bark. Wood Sci Technol. 2021;55:295–313. doi: 10.1007/s00226-020-01258-2.
[86] Marković Nikolić DZ, et al. The green modification of lagenaria vulgaris agro-waste: spectroscopic and morphological analysis. Zast Mater. 2019;60:197–209. doi: 10.5937/zasmat1902197M.
[87] Tu P, Zhang G, Wei G, et al. Influence of pyrolysis temperature on the physicochemical properties of biochars obtained from herbaceous and woody plants. Bioresour Bioprocess. 2022;9(1):131. doi: 10.1186/s40643-022-00618-z.
[88] Bindar Y, Budhi YW, Hernowo P, et al. Sustainable technologies for biochar. In: Ngo HH, Guo W, Pandey A, Varjani S, Tsang DCW, editors. Current developments in biotechnology and bioengineering: biochar towards sustainable environment. India: Elsevier Inc.; 2023. pp. 1–40. doi: 10.1016/B978-0-323-91873-2.00013-3.
[89] Varol EA, Mutlu U. TGA-FTIR Analysis of Biomass Samples Based on the Thermal. Energies. 2023;16:3674.
[90] Zhang C, Ho S, Chen W, et al. Comparative indexes, fuel characterization and thermogravimetric- Fourier transform infrared spectrometer-mass spectrogram (TG-FTIR-MS) analysis of microalga Nannochloropsis Oceanica under oxidative and inert torrefaction. Energy. 2021;230:120824. doi: 10.1016/j.energy.2021.120824.
[91] Goren AY, Dincer I. Development of newly designed biomass-based electrodes used in water electrolysis for clean hydrogen production. Int. J. Hydrogen Energy. 2025;189:152122. doi: 10.1016/j.ijhydene.2025.152122.
[92] Neves S, Muylaert F, Leite R, et al. Characterization of banana fibers functional groups by infrared spectroscopy. Mater Sci. 2014;775–776:250–254. doi: 10.4028/www.scientific.net/MSF.775-776.250.
[93] Akter M, Bin F, Rahman A, et al. Adsorption characteristics of banana peel in the removal of dyes from textile effluent. Textiles. 2021;1(2):361–375. doi: 10.3390/textiles1020018.
[94] Memon JR, Memon SQ, Bhanger MI, et al. Colloids and Surfaces B: biointerfaces Characterization of banana peel by scanning electron microscopy and FT-IR spectroscopy and its use for cadmium removal. Colloids Surf B Biointerfaces. 2008;66(2):260–265. doi: 10.1016/j.colsurfb.2008.07.001.
[95] Zhang J, Zhang X, Li C, et al. A comparative study of enzymatic hydrolysis and thermal degradation of corn stover: understanding biomass pretreatment. RSC Adv. 2015;5(46):36999–37005. doi: 10.1039/C5RA01930C.
[96] Quan C, Gao N, Song Q. Pyrolysis of biomass components in a TGA and a fixed-bed reactor: thermochemical behaviors, kinetics, and product characterization. J Anal Appl Pyrolysis. 2016;121:84–92. doi: 10.1016/j.jaap.2016.07.005.
[97] Wang P, Zhang J, Shao Q, et al. Physicochemical properties evolution of chars from palm kernel shell pyrolysis. J Therm Anal Calorim. 2018;133(3):1271–1280. doi: 10.1007/s10973-018-7185-z.
[98] Shen DK, Gu S, Luo KH, et al. Kinetic study on thermal decomposition of woods in oxidative environment. Fuel. 2009;88(6):1024–1030. doi: 10.1016/j.fuel.2008.10.034.
[99] Menya E, Olupot PW, Storz H, et al. Optimization of pyrolysis conditions for char production from rice husks and its characterization as a precursor for production of activated carbon. Biomass Conv. Bioref. 2020;10(1):57–72. doi: 10.1007/s13399-019-00399-0.
[100] Vamvuka D, Kakaras E, Kastanaki E, et al. Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite. Fuel. 2003;82(15-17):1949–1960. doi: 10.1016/S0016-2361(03)00153-4.
[101] Wang T, Yin J, Liu Y, et al. Effects of chemical inhomogeneity on pyrolysis behaviors of corn stalk fractions. Fuel. 2014;129:111–115. doi: 10.1016/j.fuel.2014.03.061.