



A review of progress on torrefaction, pyrolysis and briquetting of banana plant wastes for biofuels

Emmanuel Menya¹ · Collins Okello¹ · Henning Storz² · Joel Wakatuntu³ · Medard Turyasingura³ · David K. Okot⁴ · Simon Kizito⁵ · Allan John Komakech⁶ · Isa Kabenge⁶ · Samson Rwahwire⁷ · Peter Wilberforce Olupot³

Received: 28 June 2024 / Revised: 18 September 2024 / Accepted: 23 September 2024
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2024

Abstract

The banana value chain produces over 4 tonnes of waste biomass for every tonne of bananas harvested, including leaves, pseudostems, peels, rejected fruits, rhizomes, and empty fruit bunches. With rising fossil fuel costs and environmental concerns, these wastes present opportunities for alternative biofuel production through thermochemical processing and densification. This review examines the properties of various banana plant wastes, their pretreatments, and suitability for processes like pyrolysis, torrefaction, and hydrothermal carbonization, as well as briquetting. Banana plant wastes vary in physico-chemical properties depending on the biomass type. Their high volatile matter content (70.5–89.1%db) makes them better suited for bio-oil and gas production rather than biochar. Pretreatment methods such as water-washing, alkaline treatment, drying, pressing, chopping, grinding, and milling may be needed before thermochemical conversion of the wastes. Among conversion routes, pyrolysis is the most studied, followed by hydrothermal carbonization and dry torrefaction. The hydraulic press is the most commonly used technology for briquetting banana plant wastes. Depending on factors such as binder-to-biomass ratio, dwell time, and compaction pressure, this method can produce briquettes with compressive strength ranging from 1.33 to 38.39 MPa, which exceeds the minimum acceptable level of 0.38 MPa. However, these briquettes can have ash content as high as > 20%db, which can reduce their calorific value, increase the risk of ash slagging and fouling in combustion systems, as well as lead to increased emission of particulate matter during combustion. While thermochemical conversion and briquetting of banana plant wastes may incur significant costs, these could be offset by the low cost of the raw materials, improved fuel properties, and better handling, transportation, and storage. Research efforts should focus on ascertaining the emission potential of thermochemical conversion and briquetting of banana plant wastes, which could encourage wider acceptance of these technologies, especially considering growing awareness about the need for environmental protection.

Keywords Banana plant wastes · Torrefaction · Hydrothermal carbonization · Pyrolysis · Briquettes

1 Introduction

Banana plants hold great promise as a biomass source for production of biofuels and other valuable products, owing to their extensive cultivation and substantial biomass yield,

especially in Asia, Latin America, and Africa [1]. For every tonne of bananas picked, over 4 tonnes of biomass is generated in form of leaves, pseudo-stems, peels, rejected fruits, rhizomes and empty fruit bunches [2]. Some of this biomass materials have found useful applications, for instance, fresh leaves can be used as food wrapping material [3], compost material [4] and as plantation mulch [5]. Peels can be used as animal feed [5] and as compost material [4]. Meanwhile, pseudostems can be used as a source of starch [6], raw material for ropes, textile and paper [7] and as plantation mulch [8, 9]. Rejected fruits can be used as animal feed [5], while peduncle can be used as a compost material [4]. While these uses are beneficial, the limited scale of processing and the risk of spreading banana pests and diseases such as bacterial wilt limit the

Highlights

- A review on thermochemical processing and briquetting of banana plant wastes is presented.
- Properties and pretreatment of banana plant wastes are reviewed.
- Reactor types, operational requirements and thermochemical performance with banana plant wastes are reviewed.
- Briquetting parameters and technologies are reviewed.
- Properties and emission potential of fuel briquettes are presented.

Extended author information available on the last page of the article

extensive utilization of banana plant wastes. Consequently, about 60% of this biomass goes to waste through open dumping and burning, raising environmental and health concerns [10].

In light of growing concerns over greenhouse gas emissions and acute energy scarcity, there is a need to integrate banana production and value chain activities into a circular bioeconomy. Globally, from Asia to Latin America and sub-Saharan Africa, the burden of utilizing banana wastes beyond the farm remains a challenge. Consequently, research on the valorization of banana plant wastes for production of biofuels and other value-added products is gaining traction. Apparently, various valorization techniques are being studied which include; pyrolysis, torrefaction, hydrothermal carbonization (HTC) and briquetting. In all these techniques, the quality of the fuel products highly depend on the biomass composition, operating conditions and technology/or reactor type [11].

Pyrolysis involves heating the wastes in an oxygen-free environment at temperatures ranging between 400 and 900 °C to produce solid, liquid and gaseous fuels in the form of biochar, bio-oil and syngas, respectively [12]. Pyrolysis process is simple in design, results in high carbon yield [13], and is versatile in handling a wide range of waste types [14]. However, the process demands high operating temperatures, resulting in significant energy consumption. The process is also not suitable for biomass with a moisture content ≥ 10 wt%, since additional energy costs are incurred on pre-drying of biomass [13]. These concerns pave the way for torrefaction and HTC as potential alternatives to pyrolysis, but also as pretreatment methods for improving the fuel properties of banana plant wastes.

Torrefaction involves heating the biomass at temperatures ranging from 200 to 300 °C under an inert environment, producing bio-coal with improved fuel properties, such as low moisture content, reduced oxygen-to-carbon ratio, higher energy density, and cleaner combustion [15, 16]. Compared to pyrolysis and other thermochemical processes, torrefaction has the least global warming potential due to its minimal heat requirement [17]. Essentially, during torrefaction, the hydroxyl (OH) functional group is lost, making the material hydrophobic and more stable against chemical oxidation and microbial degradation [18]. Torrefied biomass also benefits from increased bulk density, easier grinding, and lower power requirements for subsequent briquetting or pelleting [15, 19]. These improved properties make torrefied biomass particularly suitable for co-firing in power plants and as an upgraded feedstock for gasification [20], pyrolysis and combustion [21]. However, similar to pyrolysis, torrefaction requires additional energy costs for pre-drying of biomass with inherently high moisture content [22]. To avoid this challenge, banana plant wastes can be pretreated via hydrothermal carbonization.

Hydrothermal carbonization also known as wet torrefaction is applied under subcritical conditions of water at mild temperatures ranging from 180 and 250 °C, converting wet biomass into a solid product, commonly known as hydrochar [13, 23]. The HTC process 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 [7, 23]. Furthermore, during HTC, the subcritical water dissolves most of inorganic components in the biomass, generating hydrochar with a typically lower ash content than its raw counterpart [23]. This reduction in ash content mitigates issues such as fouling, slagging, agglomeration, and corrosion of heat transfer surfaces during combustion, pyrolysis, and gasification of the hydrochar [7]. Despite these numerous advantages, HTC exhibits certain drawbacks, including the requirement for expensive, pressurized, and complex systems, the requirement for extra expenses associated with the separation of solid and liquid products, and the generation of process water, which poses disposal challenges [13]. Furthermore, like pyrolysis and torrefaction, the solid bio-fuel produced via hydrothermal carbonization is usually in dusty/or powdered form with low bulk density, making its handling, transportation and storage problematic [24–27]. The dusty form of these solid biofuels can also lead to air pollution, posing respiratory problems when inhaled [25]. These challenges can be addressed through briquetting of the raw or thermally treated banana plant wastes.

Briquetting is a process in which particles of low-density raw materials are converted by mixing and compaction into a denser product suitable for use as fuel [28]. Briquetting after thermal treatment of the waste biomass results in briquettes with enhanced fuel properties due to the lignin released upon heating of the biomass which subsequently acts as a binding agent during briquetting [25]. Moreover, briquetting of hydrochars may not require external binders due to their stronger binding capacity compared to biochar and bio-coal [29]. Various factors influence the quality of the fuel briquette, including feedstock type, particle size, binder type and amount, compression temperature, pressure, dwell time and briquetting technology [30, 31].

While studies have examined the conversion of banana plant wastes into biofuels [6, 32, 33], there remains a notable absence of comprehensive reviews specifically addressing thermochemical processing and briquetting of these wastes. This article, therefore, provides a comprehensive review of commonly used thermochemical processing techniques, particularly pyrolysis, torrefaction, and hydrothermal carbonization of banana plant wastes for energetic applications. It discusses the types of thermochemical reactors, their operational requirements, process parameters and performance with different banana plant wastes as feedstocks. The review

also provides in-depth insights into the properties of various banana plant wastes, their potential pretreatments and suitability as feedstocks for pyrolysis, torrefaction, and hydrothermal carbonization. Additionally, it discusses briquetting as a viable solution to address the challenges posed by the dusty nature and low bulk density of solid biofuels derived from these processes, facilitating their handling, transportation, and storage while also enhancing their fuel properties.

2 Methodology

Relevant literature was retrieved using various online search databases like Web of Science, PubMed, Scopus, and Google Scholar, as well as using publisher-specific search engines such as ScienceDirect, American Chemical Society, Taylor and Francis, Springer, Royal Society of Chemistry, and Wiley & Sons. The search focused primarily on four technologies, namely, pyrolysis, torrefaction, hydrothermal carbonization and briquetting using banana plant wastes as the key search word. The search also encompassed various aspects, including properties of banana plant wastes, pretreatment, reactor types, properties and emission potential of fuel briquettes.

Studies were included if: (i) they were peer-reviewed, (ii) published between 2013 and 2023, and (iii) were directly related to the thermochemical conversion of banana plant wastes. Additionally, studies covering topics such as waste characterization, reactor design, emissions, and fuel properties were considered. Studies were excluded if they: (i) did not specifically focus on banana plant wastes, (ii) were published in languages other than English, and (iii) focused on non-energy applications without a connection to the specified thermochemical technologies. In cases where research was limited, exceptions were made for older but seminal works.

The Boolean operator "AND" was used to combine multiple keywords in a single search, ensuring a precise focus on banana plant waste-related studies. The search terms included combinations such as "banana pseudostem AND pyrolysis," "banana peduncle AND torrefaction," "banana pseudostem AND hydrothermal carbonization," and "banana peels AND hydrothermal carbonization," "banana pseudostem AND briquetting," "banana peels AND briquetting." Tailored searches were also carried out for studies that delved into specific aspects like pretreatment of banana plant waste or the environmental impacts of pyrolysis, torrefaction, and briquetting. In total, 220 references were identified, primarily consisting of journal articles within the fields of materials science, chemistry, and engineering. The collected data was categorized based on the type of thermochemical conversion technology and the specific banana plant waste component used. Frequency analysis was employed

to identify trends over time, with specific attention to the number of publications per technology (Fig. 1).

For quantitative assessment, data from experiments reported in the literature were tabulated and compared across studies to provide insights into the potential of banana plant wastes for energy production. The results revealed a predominant focus on pyrolysis of banana plant wastes, followed by hydrothermal carbonization and torrefaction, as illustrated in Fig. 1. Notably, not all studies were geared towards energy applications; a significant number delved into areas such as adsorption [34–36] and soil amendment [37, 38]. Furthermore, certain banana plant wastes, such as banana rhizome and rejected banana fruits, remain unexplored in the context of the mentioned thermochemical conversion technologies. Torrefaction and hydrothermal carbonization studies on empty fruit bunches and peduncle, respectively are also yet to be undertaken. Recognizing the dual objective of seeking alternative renewable energy sources and addressing waste disposal challenges, redirecting more research efforts towards the thermochemical conversion of banana plant wastes would be of great significance.

3 Potential of banana plant wastes

The global annual production of banana fruits in 2018 was estimated to be 139.5 million tonnes, where about 22, 26 and 48% of the fruits were produced in the sub-Saharan Africa, Americas and Asia, respectively [39]. According to FAO [40], the ten major banana producing countries include India, China, Uganda, Philippines, Indonesia, Ecuador, Brazil, Cameroon, Democratic Republic of Congo, and Ghana. Banana plants generate huge quantities of waste biomass, as each plant produces only one fruit bunch in its lifetime [41]. For every tonne of banana fruits harvested, over 4 tonnes of banana plant wastes are produced, with rejected fruits accounting for 0.1 tonnes [42], banana leaves 0.48 tonnes [42], pseudostem 3 tonnes [42], stalks 0.16 tonnes [42], peduncle 0.13 tonnes [43] and banana peels 0.25 tonnes [44]. Considering these residue-to-product ratios and the global annual banana production, the global quantity and theoretical energy potential of each banana plant waste type were determined as shown in Table 1.

As can be seen from Table 1, the banana value chain generates over 570 million tonnes of waste biomass, with banana pseudostems contributing the highest amount, followed by banana leaves, banana peels, banana stalks, banana peduncle and rejected fruits. The global theoretical energy potential of banana pseudostems, banana leaves and peels were estimated to be 5120, 948, and 457 PJy⁻¹, respectively. The energy potential for the rest of the banana plant wastes could not be computed due to unavailability of data in the literature. Overall, the vast biomass and energy potential of

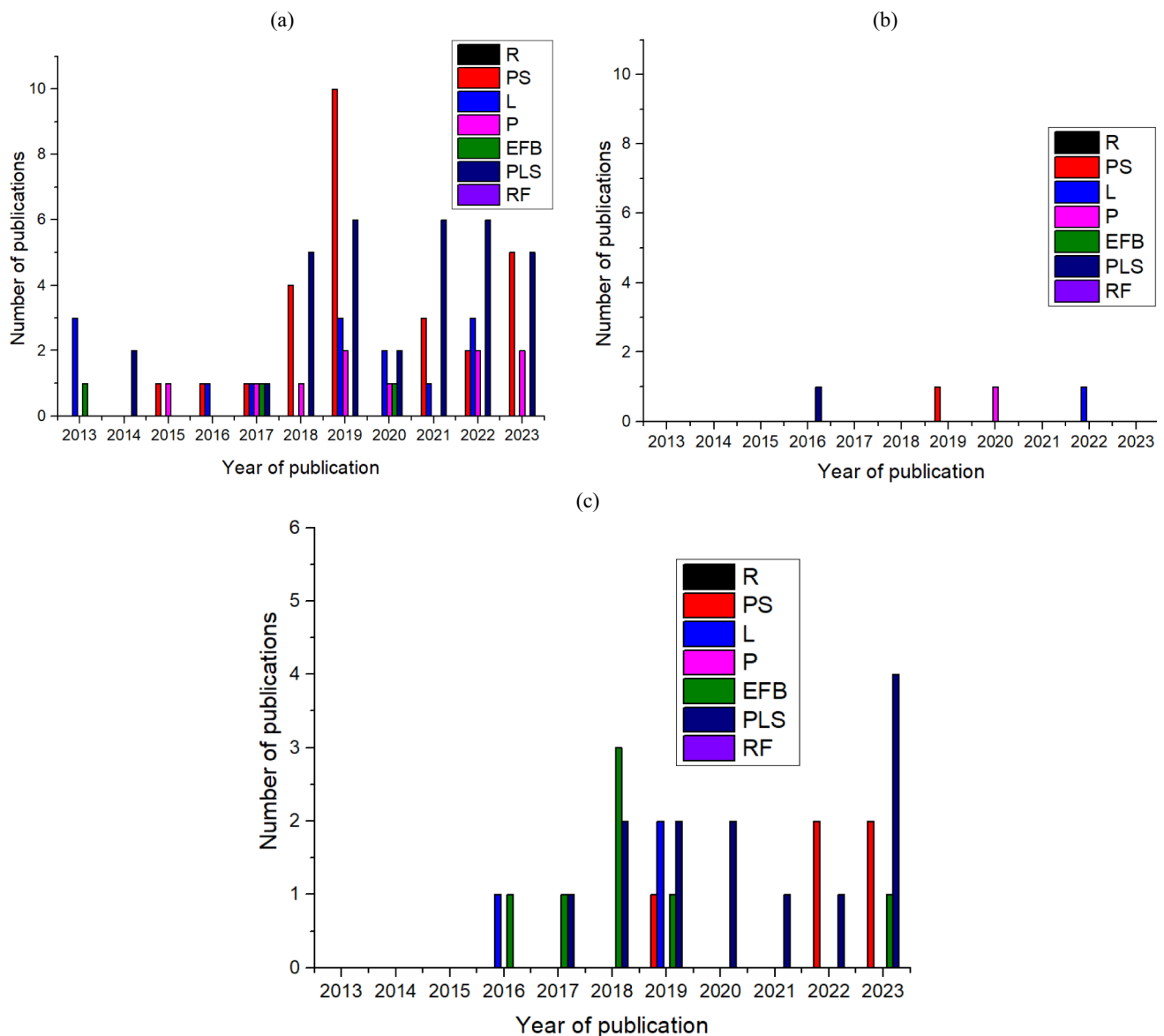


Fig. 1 Number of papers published on thermochemical conversion of different banana plant wastes via pyrolysis (a), torrefaction (b) and hydrothermal carbonization (c). Note: i) *R* implies banana rhizome, ii) *PS* implies banana pseudostem, iii) *L* implies banana leaves, iv) *P*

implies banana peduncle, v) *EFB* implies banana empty fruit bunch, vi) *PLS* implies banana peels, and vii) *RF* implies rejected banana fruits

Table 1 Global quantity and theoretical energy potential of the major banana plant wastes

Parameter	Banana plant wastes						Total (million tonnes)	Reference
	Leaves	Pseudostem	Peduncle	Peels	Stalks	Rejected fruits		
World production (million tonnes) ^a	66.96	418.50	18.14	34.88	22.32	13.95	574.75	
MC (wt%)	12.38	10.20	9.36	11.56	-	-	-	[45–48]
LHV (MJkg ⁻¹)	16.16	13.63	-	14.80	-	-	-	[48]
Energy potential (PJy ⁻¹)	948	5120	ND	457	ND	ND		

i) (^a) implies that the annual production of the different banana plant wastes was obtained as a product of residue-to-product ratio and the global annual production of bananas, ii) *LHV* implies lower heating value, iii) (-) implies data unavailable in the literature, and iv) *ND* implies not determined due to lack of sufficient data in the literature

the banana value chain presents an opportunity for leveraging banana plant wastes in biofuel production. This approach not only offers a sustainable alternative to fossil fuels, but also helps address challenges of waste management in the banana value chain.

4 Composition of banana plant wastes

Similar to other biomass types, banana plant wastes are heterogeneous in nature. It is thus crucial to determine the composition of banana plant wastes to guide their selection for specific thermochemical conversion systems. The composition can be categorized based on lignocellulosic, proximate, ultimate and mineral compositions, as well as heating values. Each of the different compositions is briefly discussed in the following sections.

4.1 Lignocellulosic composition

Banana plant wastes are lignocellulosic in nature, comprising of lignin, hemicellulose and cellulose. Lignin is an amorphous polymer consisting of a complex and heterogeneous three-dimensional network of aromatic substructures that provides coherence and toughness. Lignin together with cellulose, form the woody cell walls of plants and the cementing material between them [49]. Hemicelluloses are polysaccharides of variable composition, consisting of C₅ and C₆ sugars associated with cellulose, and are found in the cell wall regions of the biomass [49]. Cellulose, on the other hand, is a linear polysaccharide consisting of β-D glucopyranose units covalently linked with (1–4) glycosidic bonds [50]. In thermochemical conversion, lignin contributes predominantly to char formation due to its recalcitrance to thermal decomposition, while cellulose and hemicellulose contribute less, with a significant fraction of carbon being lost as volatiles [51]. Thus, lignin content directly influences the heating value of biomass.

Proportions of the lignocellulosic components can vary due to factors such as banana variety, type of banana plant waste, maturity stage, growing conditions and geographical origin [52, 53]. Specifically, the lignin content of banana plant wastes vary from 5–38%db, hemicellulose from 10–42%db, and cellulose from 10–70%db [2, 7, 46, 48, 54]. Due to their relatively low lignin content, banana plant wastes undoubtedly exhibit low heating values and char yields compared to their counterparts such as coconut coir pith with a high lignin content (40.9wt%) [55]. Table 2 provides an overview of the lignocellulosic composition, proximate and ultimate properties, higher heating values, bulk density of banana plant wastes from different geographical origins.

4.2 Proximate and ultimate compositions and HHV

Proximate and ultimate compositions, along with heating value, are important parameters of consideration when selecting biomass materials for fuel applications. The proximate components include moisture content, volatile matter, fixed carbon, and ash, while ultimate components include C, H, O, S, and N contents [2]. Table 2 provides an overview of the proximate and ultimate compositions, and higher heating values of various banana plant wastes from different geographical origins. The moisture content varies from 5–12wt% [46, 56], volatile matter content from 41–90%db [2, 57], fixed carbon content from 0.2–47%db [2, 46] and ash content from 6–25%db [42, 56]. These components influence the thermochemical conversion processes. Moisture content, for instance, reduces the heating value as useful heat is wasted in vaporizing water from the biomass. It also leads to incomplete combustion, which in turn results in gaseous emissions of CO, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and other pollutants [58]. High moisture content also adds to transport costs [59]. To avoid these foreseeable challenges, biomass should be thermochemically decomposed at moisture contents of ≤ 50wt% for combustion [60], 20–30wt% for gasification [61], ≤ 10wt% for pyrolysis [62, 63], ≤ 10wt% for torrefaction [18] and ≤ 80wt% for hydrothermal carbonization [62]. While biomass wastes with high moisture content can be dried prior to thermochemical conversion, the additional cost may significantly lower the economic viability of the thermochemical process [6].

For volatile matter, the higher the content, the more reactive the biomass is and the easier it is ignited [2]. The volatile matter content also directly influences bio-oil production [64]. Thus, due to their relatively high volatile matter content (70.5–89.1%db) [2, 4, 46, 48, 50, 56, 65, 66], banana plant wastes are better candidate materials for bio-oil and gas production than biochar production. For fixed carbon, the higher the content, the higher the energy density and ultimately a higher energy throughput of a given biomass conversion system [67]. A higher fixed carbon content also enables the replenishment of the char needed for thermal cracking of the tar [68]. Thus, banana plant wastes with a relatively high fixed carbon content, such as pseudostems (18.1%db) [42] and leaves (15.6–46.5%db) [2, 57] are better suited feedstocks for energy production than those with low fixed carbon content, including banana peels (2.70%db) [48], banana bunch waste (0.3–5.7%db) [4], banana fruit bunch waste (0.3%db) [46], banana pseudostem (0.2%db) [46] and banana stalks (5.0%db) [7]. A high ash content inherently lowers the heating value of biomass, while, at the same time, it increases the risk of operational problems such as slagging, fouling, corrosion, excessive tar formation, and reactor blockage [21, 67]. According to Akogun et al. [69],

Table 2 Composition and properties of banana plant wastes

Banana plant waste	Bulk density (kgm ⁻³)	Lignocellulosic composition			HHV (MJkg ⁻¹)	Proximate composition			Elemental composition					Geo-graphical origin	Reference	
		Lignin (%daf)	Hemicel-lulose (%daf)	Cellulose (%daf)		MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%daf)	H (%daf)	N (%daf)	S (%daf)			O (%daf)
Peels	-	8.90	41.38	9.9	-	11.56	88.02	2.70	9.28	35.65	6.19	1.94	0.00275	45.94	Uganda	[48]
Peels	-	-	-	-	-	-	-	-	-	41.30	4.90	<LOD	-	53.80	Costa Rica	[72]
Bunch waste	-	-	-	-	14.5–15.7	6.5–11.4	70.5–75.2	0.3–5.7	17.3–22.7	33.98–37.12	4.02–5.65	0.90–3.11	-	57.26–57.96	Indonesia	[4]
Fruit bunch stem	-	18	27.80	39.8	12.7	11.4	79.1	0.3	20.6	35.58	4.62	2.19	0.45	57.16	Malaysia	[46]
Dried leaves	-	-	-	-	17.1	7.8	78.2	15.6	6.2	43.50	6.20	0.86	0.95	42.30	Brazil	[70]
Leaves	-	-	-	-	17.10	7.91	78.16	15.6	6.23	43.28	6.23	0.98	0.49	-	Brazil	[57]
Leaves	122.46	-	-	-	15.90	12.38	77.79	11.31	10.9	44.85	6.23	0.58	0.17	48.17	Brazil	[45]
Leaves	-	-	-	-	16.3	-	72.6	18	9.1	41.4	5.4	2.5	0.29	41.4	Philippines	[71]
Leaves	46.0	-	-	-	17.1	7.81	78.2	15.6	6.23	43.30	6.24	0.98	0.49	42.80	Brazil	[42]
Wet leaves	-	15.40	28.50	53.5	5.5	74.7	41.3	46.5	12.2	15.9	9.2	1.4	0.05	73.4	Brazil	[2]
Semi-dried leaves	-	17	25.80	26.7	19.8	8.3	78.8	12.5	8.7	43.5	6.3	1.3	0.2	48.7	Brazil	[2]
Pseudo-stem fiber	-	5–12	10–30	60–70	-	-	-	-	-	-	-	-	-	-	Brazil	[54]
Pseudo-stem	-	-	-	-	13.70	5.09–10.89	89.10	18.00	8.04	38.92	5.92	0.38	0.49	-	Brazil	[57]
Pseudo-stem	153.0	-	-	-	13.7	10.9	74.5	18.1	7.42	38.90	5.93	0.38	0.49	46.80	Brazil	[42]
Pseudo-stem	-	37.30	17.50	44.0	15.5	10.2	88.8	0.2	11.0	37.93	4.46	1.87	0.37	55.37	Malaysia	[46]
Stalks	-	20.0	28.00	47.0	15.60	-	76.0	5.0	19.0	33.0	4.3	1.9	0.3	60.5	Bangladesh	[7]

i) *daf* implies dry-ash-free basis, ii) *HHV* is higher heating value in MJkg^{-1} , iii) *MC* implies moisture content, iv) *VM* implies volatile matter content, v) *FC* implies fixed carbon content, vi) *LOD* implies limit of detection, and vii) (–) implies that results were not available in the literature

biomass with low ash content (< 20%db) is better suited for thermal utilization than its counterparts with high ash content [69]. Thus, banana peels (9.28%db) [48], banana leaves (6.2–12.2%db) [2, 42, 45, 57, 70, 71], banana pseudostems (7.42–11.0%db) [42, 46, 57] and banana stalks (19.0%db) [7] would be better suited for thermal utilization than fruit bunch stem (20.6%db) [46] and bunch waste (22.7%db) [4] with relatively high ash content.

For ultimate composition (Table 2), the carbon content varies across banana plant wastes as follows: banana peels 35.65–41.30%daf [48, 72], banana bunch waste 33.98–37.12%daf [4], fruit bunch stem 35.58%daf [46] and leaves 15.9–44.85%daf [2, 42, 45, 57, 70, 71]. The hydrogen content of banana peels ranges from 4.90–6.19%daf [48, 72], banana bunch waste 4.02–5.65%daf [4], banana leaves 5.4–9.2%daf [2, 42, 45, 57, 71], banana pseudostem 4.36–5.93%daf [42, 46, 57], banana fruit bunch stem 4.62%daf [46], and banana stalks 4.3%daf [7]. Nitrogen content is low in banana pseudostem (0.38%daf) [42, 57], leaves (0.58–0.98%daf) [42, 45, 57, 70] and bunch waste (0.90%daf) [4], but higher in banana bunch waste (3.11%daf) [4], banana fruit bunch stem (2.19%daf) [46], banana peels (1.94%daf) [48] and banana stalks (1.9%daf) [7]. However, some studies report higher nitrogen content in banana leaves (1.3–2.5%daf) [2, 71] and banana pseudostems (1.87%daf) [46]. The sulphur content across banana plant wastes is generally low, ranging from 0.00275–0.95%daf (Table 2). The oxygen content varies, with banana peels at 45.94–53.80%daf [48, 72], banana fruit bunch stem at 57.16%daf [46], banana leaves at 41.4–73.4%daf [2, 42, 45, 70, 71], banana pseudostem at 46.80–55.37%daf [42, 46] and banana stalks at 60.5%daf [7]. The carbon and hydrogen contents directly correlate with the heating value, while the oxygen and nitrogen contents indirectly correlate with the heating value of a given biomass [73]. High oxygen content also results in the production of a large volume of flue gases during combustion [74]. Furthermore, beyond influencing heating value, nitrogen and sulphur contents are crucial indicators of the emission potential of biomass, as they correlate directly with NO_x and SO_x emissions of fuel [49]. The higher heating values of various banana plant wastes are as follows: banana peels 14–27–16.15 MJkg⁻¹ [75, 76], banana bunch wastes 14.5–15.7 [4], banana pseudostems 13.7–15.60 MJkg⁻¹ [42, 46, 57], dried leaves 15.90–19.8 MJkg⁻¹ [2, 70], wet leaves 5.5 MJkg⁻¹ [2], fruit bunch stem 12.7 MJkg⁻¹ [46], banana stalks 15.60 MJkg⁻¹ [7] and rachis 14.39 MJkg⁻¹ [56]. These values, along with other relevant information, are also summarized in Table 2.

Table 2 further shows that, for the same type of banana plant waste, the higher heating value and proximate and ultimate compositions do not vary widely with geographical origin. Instead, the variations in properties are more pronounced across different types of banana plant wastes. There

are, however, some exceptions; for example, wet leaves from Brazil exhibited a considerably low higher heating value of 5.5 MJkg⁻¹ [2], compared to 16.3 MJkg⁻¹ for banana leaves from the Philippines [71]. The wet leaves also exhibited a considerably lower carbon and higher oxygen contents compared to those from other countries (Table 2). These differences are likely due to the inherently high moisture content of the wet banana leaves (74.7wt%) [2], compared to those studied from other countries (Table 2).

4.3 Mineral composition

The distribution of metallic elements in biomass fuels affects the temperature of decomposition and product yields and composition; hence it is necessary to know their concentrations [21]. Banana plant wastes are composed of various mineral elements; the major ones being Na, K, Ca, Mg, P, Al, Cl, Si and Fe [77–79], while the minor ones include Cu, Zn, Mn, Mo, Pb, Ni, Cr, As, Cd, Co, Cs, Sb, Se, Sn and V [79]. These elements play a role in the reactions responsible for ash fouling and slagging in biomass conversion systems [80]. For instance, K, Na and Cl lower the melting point of ash, causing severe fouling, slagging and corrosion of heat transfer surfaces [58, 81]. Elements such as K, Cl, Na, Mg and P are responsible for the emission of particulate matter, for instance, a high Cl content increases the risk of emitting dioxins and furans during biomass combustion [81]. The composition of the metallic elements varies widely among banana plant wastes, due to variability in banana plant species, growth conditions, maturity stage and geographical origin [82]. Table 3 provides an overview of the mineral composition of various banana plant wastes. 1.

5 Pretreatments prior to thermochemical conversion

Banana plant wastes, like other biomass types, require pretreatment before thermochemical conversion into biofuels. Pretreatments are typically physico-chemical in nature, encompassing various methods such as water-washing [84], alkaline pretreatment [3], drying [85], pressing [57], chopping [42], grinding [45] and milling [86]. Other pretreatment options include screening or sieving to achieve desired particle sizes [45]. These pretreatments are further elaborated below.

Water-washing of biomass serves multiple purposes, including removal of dirt and any other organic matter present on the surface of the waste biomass [48]. Water-washing also lowers the ash-forming components of the biomass, reducing the risk of ash-related problems such as fouling, slagging, agglomeration and corrosion of heat transfer surfaces [87]. It can also reduce the chlorine

Table 3 Mineral composition of banana plant wastes

Inorganic elements	Banana plant wastes				
	Pseudostem	Leaves	Peels	Peels	Inflorescence
1. Major elements (mg/100 g)					
Al	76.7	-	-	1010	184.3
Ca	401	1.2	59.1	759	1065
Fe	306.5	0.2778	47.0	125	4055
K	1063	3.8	4.39	25900	5129
Mg	155	-	44.5	840	2355
P	209	1.8	211.3	-	410
Na	2	-	115.1	-	1834
2. Trace elements (mg/100 g)					
As	0.15	-	-	<3.0	0.16
Cd	10.6	-	-	<0.2	15.0
Co	37.9	-	-	<0.4	194.4
Cr	50.4	-	-	<5.0	39.3
Cs	-	-	-	<2.0	-
Cu	0.2	0.00797	0.51	440	5.2
Mn	278.6	0.25778	0.702	16,200	1338.0
Mo	0.28	-	-	140	0.42
Ni	4.6	-	-	380	9.9
Pb	1.5	-	-	<5.0	4.2
Sb	<0.1	-	-	<20	<0.1
Se	0.1	-	-	226	0.10
Sn	-	-	-	<3.0	-
V	-	-	-	<1.0	-
Zn	166.0	0.0322	0.033	4830	2079.0
Reference	[83]	[82]	[77]	[79]	[83]

(-) implies no figure or data were given in the literature

content of the biomass [88], thereby remarkably improving the ash fusion temperature and ultimately avoiding the aforementioned ash-related problems [58]. Alkali pretreatment improves the surface characteristics and bond orientations of the derived fuel briquettes [3], while drying removes moisture from biomass, enhancing its shelf stability by avoiding the growth of fungus and microorganisms [14]. Drying can be done in the sun, in ambient conditions or in a greenhouse [22]. Moisture reduction can also be achieved via pressing [57]. Chopping of banana plant wastes eases handling, transportation and storage of banana plant wastes [14]. Grinding and milling increases the surface area for drying [48, 85]. Particle size reduction and homogenization allow for better compaction of the feedstock, influencing its physical and mechanical characteristics [22]. In all these options, pretreatments should be carefully considered to avoid hindering downstream processes. For instance, banana peels milled to particle size ≤ 400 microns were considered undesirable for deployment in pyrolysis as these could lead to a risk of dust explosion, while accumulation of dust could cause blockage of the pyrolysis reactor outlet [11]. Additionally,

pretreatments can incur significant costs, potentially impacting the economic viability of thermochemical conversion processes [89]. The various pretreatments options are usually employed in combination as highlighted in Table 4.

6 Thermochemical conversion

Thermochemical conversion involves degradation of the organic components of biomass at moderate to high temperatures, either with or without oxygen to produce solid, liquid and/or gaseous biofuels [92]. These processes include pyrolysis, torrefaction, hydrothermal carbonization, gasification, liquefaction and combustion. The choice of a particular conversion process depends on factors such as the type and quantity of feedstock, desired form of energy, environmental standards, economic considerations and project-specific factors [93]. In this review, focus is on pyrolysis, torrefaction and hydrothermal carbonization, examining each process in detail and comparing their energy consumption.

Table 4 Pretreatment activities on various banana plant wastes prior to conversion into fuel

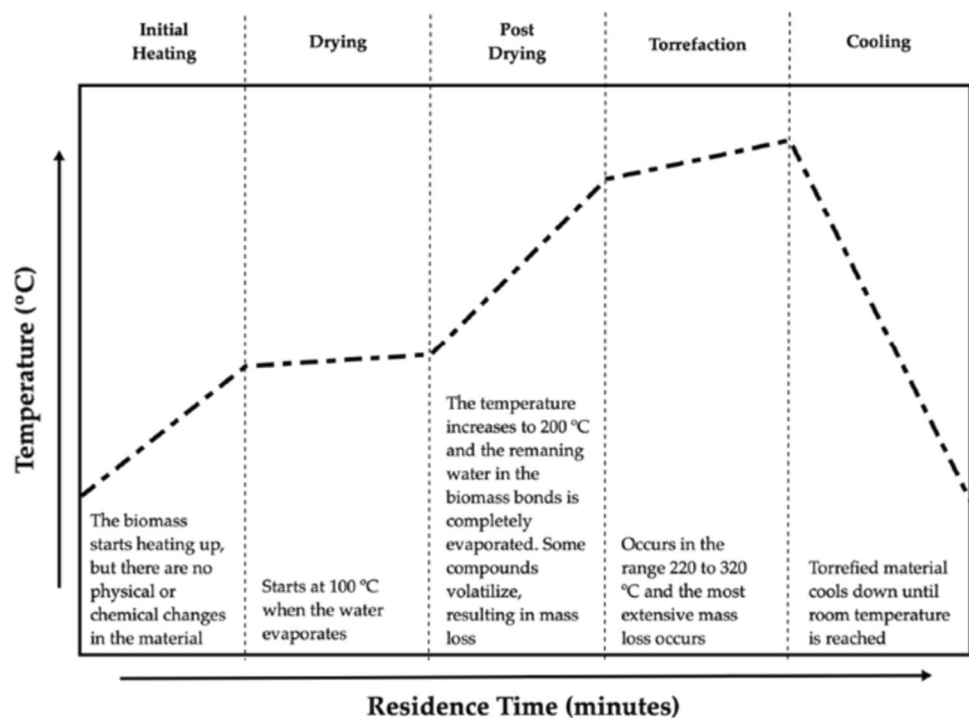
Banana plant waste	Pretreatments	Details of the pretreatments	Reference
Leaves	Alkaline pretreatment and drying	Banana leaves were soaked in 3% NaOH solution for 3 h at ambient temperature. Samples were then dried for 48 h at room temperature, followed by oven drying at 60 °C overnight	[3]
Leaves	Grinding and screening	Banana leaves at a moisture content of 12.5wt.% were mechanically ground, followed by screening using a 12-mesh sieve to achieve particles < 1.7 mm. Ground sample was then stored in sealed polyethylene bags until use	[45]
Pseudostem	Pressing, drying and chopping	Banana pseudostem were prepared through pressure to remove excess moisture prior to drying process. The waste was then cut into 30 cm long cylindrical pieces, sliced, and pressed	[42]
Leaves	Sun-drying and milling	Fresh samples of banana leaves were sundried for 1–2 weeks and milled to < 5 mm prior to hydrothermal carbonization	[90]
Pseudostem	Chopping and drying	Banana pseudo-stems were chopped into smaller sizes, oven-dried at 105 °C and then cut into pieces of 4 cm × 4 cm before further drying	[14]
Peels	Chopping, water-washing and drying	Sample were reduced to particle size of 5.0 mm, followed by water-washing and air-drying	[48]
Pseudostem	Water-washing, drying, crushing, milling and screening	Banana pseudostems were water-washed followed by oven-drying at 105 °C for 48 h, crushed, milled and screened to particle size < 0.125 mm	[84]
Peels	Cutting, drying, grinding and sieving	Banana peels were cut to smaller pieces prior to oven-drying at 80° C, followed by grinding to particle size ≤ 5 m and sieved to achieve particle sizes ranging from 425 microns to 2 mm	[11]
Rachis	Cutting, drying, milling and sieving	Banana rachis was cut, dried, milled, and then sieved to get a homogeneous particle size < 250 mm	[86]
Pseudostem	Pressing, drying and milling	Pseudostem was pressed in a hydraulic press, followed by drying at 60 °C for 24 h and milling to obtain a powdered sample with an average particle size of 2.5 mm	[57]
Leaves	Drying, pulverizing, water-washing, oven-drying and sieving	Fresh banana leaves were sundried, pulverized, rinsed with tap water, oven-dried at 105 °C for 24 h. The dried pulverized biomass was then sieved to average particle size of 2 mm and stored in air-tight containers until further use	[3]
Leaves	Drying, grinding and sieving	Banana leaves were sun-dried for about 15 days, cut into small pieces, ground using a mixer and grinder, followed by sieving to obtain particle size (250 µm)	[91]

6.1 Torrefaction

Torrefaction involves heating the biomass in an oxygen-starved environment at temperatures ranging from 200 to 300 °C at a heating rate ≤ 50 °Cmin⁻¹ and at ambient pressure [74]. The process involves several complex reactions through which biomass is converted into a mixture of solid, liquid, and gaseous products, with solid char being the main product [74]. Torrefaction occurs in five phases, namely, heating, pre-drying, post-drying, torrefaction and cooling phase [94], as illustrated in Fig. 2.

During the initial heating phase, biomass is gradually heated to 100 °C, evaporating free water in the pre-drying phase. Subsequently, as the temperature reaches 200 °C, the remaining water vaporizes in the post-drying phase, alongside decomposition of some biomass components which result in minor mass loss [15]. The major mass loss occurs during torrefaction at temperatures above 200 °C where the lignocellulosic components are decomposed.

Fig. 2 Different phases of torrefaction with respect to time and temperature (reprinted from [94], under open access without permission)



6.1.1 Torrefaction and fuel properties

Torrefaction is typically used for pre-treatment of biomass with the purpose of enhancing its fuel and combustion characteristics [23]. For instance, banana leaves, which typically have low carbon content, high oxygen content, and low energy content, can benefit from torrefaction to improve their fuel properties [45]. Similarly, banana bunch waste, characterized by low density and carbon ratio, faces challenges in its use as a fuel, necessitating torrefaction for their enhancement [4]. Torrefaction enhances fuel properties such as higher heating values, hydrophobicity, grindability, and energy density, which in turn influences storage, transportation, and material handling [95]. Islam et al. [7] torrefied banana stalks obtaining torrefied product with energy density, fuel ratio and energy recovery of 1.2, 0.2–0.9 and 0.7–0.9, respectively. Alves et al. [45] torrefied banana leaves and obtained torrefied product with mass and energy yields ranging from 61.77–64.40 and 76.96–80.62%, respectively. Torrefaction increases the carbon content, while decreasing the hydrogen and oxygen contents due to dehydroxylation and decarboxylation reactions that occur during thermal degradation of the hemicellulose fraction [45]. Consequently, torrefaction reduces the atomic oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C) ratios of the biomass so that they approach/or match those of low-rank coal, peat, and lignite [21]. These enhanced properties make torrefied biomass ideal for combustion [23], pyrolysis [95], or gasification [96]. The torrefied biomass can either be used directly as a solid fuel or densified to form fuel briquettes.

Table 5 provides detailed insights into recent studies on the torrefaction of banana plant wastes, conditions used, yields obtained and fuel properties of the resulting torrefied biomass. Notably, reports specific to the sub-Saharan African context are scarce in the literature.

6.1.2 Types of torrefaction processes

Biomass undergoes torrefaction under either dry or wet conditions, known as dry and wet torrefaction, respectively [17]. Torrefaction can also be classified as steam torrefaction as illustrated in Fig. 3. Each of these torrefaction types are described in detail in the subsequent sub-sections.

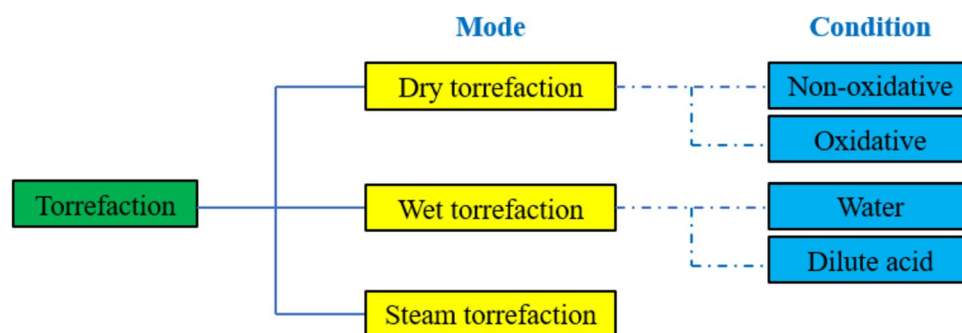
Dry torrefaction In dry torrefaction, biomass is heated in dry and non-oxidative (inert) or oxidative atmospheres [99], with the former involving the use of nitrogen and carbon dioxide as carrier gases during torrefaction [100]. Of the two gases, carbon dioxide offers better prospects as it is cost-effective, increasing the economics of the torrefaction process [101]. In oxidative torrefaction, air, flue gas and other gases containing varying concentrations of oxygen are normally used as carrier gases. The use of these gases lowers operating costs, as the gases do not have to be separated from the air, as is the case with nitrogen [17]. However, the presence of oxygen in the carrier gases, together with the exothermic reactions lead to higher reaction rates which shorten the duration of torrefaction reactions compared to its non-oxidative counterpart. Consequently, the yield of solids in oxidative torrefaction is typically lower than that obtained

Table 5 Torrefaction of banana plant wastes, product yields and fuel properties of torrefied biomass

Banana plant waste	Torrefaction type	Torrefaction conditions			Torrefaction yields		HHV (MJkg ⁻¹)	Proximate composition				Ultimate composition				Geographical location	Reference	
		Temp (°C)	Time (min)	Heating rate (°Cmin ⁻¹)	Mass yield (%)	Energy yield (%)		MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%daf)	H (%daf)	N (%daf)	S (%daf)			O (%daf)
Pseudostem	Dry	240	60	10	-	-	-	3.84	34.36	47.03	18.61	-	-	-	-	-	Brazil	[97]
Rachis	Dry	250	30	-	-	63.0	15.97	-	-	-	-	36.2	3.3	3.0	-	32.6	Colombia	[56]
Leaves	Dry	220–280	1	5	61.77–64.40	76.96–80.62	19.00–20.7	6.40–7.29	59.79–74.22	13.63–21.54	12.15–18.94	52.05–57.64	5.64–6.15	1.15–1.53	0.20–0.22	34.97–40.44	Brazil	[45]
Leaves	Hydrothermal	180–220	30	-	62.9–75.1	87.6–94.0	20.4–22.7	-	63.4–69.5	20.5–26.7	7.0–8.4	49.1–54.0	5.9–6.1	2.2–2.8	0.12–0.17	30.2–33	Philippines	[71]
Leaves	Hydrothermal	180	30	-	-	-	-	-	-	-	-	-	-	-	-	-	Philippines	[90]
Stalk	Hydrothermal	160–200	60–180	5	-	-	18.1–18.9	-	48.9–73.0	16.9–44.3	6.7–10.1	42.7–48.5	4.2–4.9	1.9–2.8	0.2–0.3	44.2–49.4	Bangladesh	[7]
Peels	Hydrothermal	150–300	60–120	-	-	-	-	-	-	-	-	53.7–72.2	5.8–6.0	LOD–1.2	-	20.9–40.5	Costa Rica	[79]
Bunch waste	Hydrothermal	180–200	15–45	-	-	-	18.21–28.48	-	61.12–64.74	25.85–30.03	6.94–11.96	44.56–49.97	5.66–6.00	0.68–0.83	0.07–0.08	37.06–38.64	Indonesia	[4]
Fruit bunch stem	Hydrothermal	225	30	-	-	-	17.64	-	-	-	-	-	-	-	-	-	Indonesia	[98]

i) HHV is higher heating value, ii) MC is moisture content, iii) VM is volatile matter, iv) FC is fixed carbon, v) db is dry basis, vi) daf is dry-ash free basis, vii) LOD is limit of detection and viii) (-) implies no figure or data was given in the literature

Fig. 3 Classification of torrefaction (adapted from [17], under open access without permission)



in non-oxidative torrefaction. In addition, as the oxygen concentration in the carrier gases increases, the higher heating value of the torrefied biomass decreases at torrefaction temperatures ≤ 300 °C [102]. By using carrier gases with oxygen concentrations $\leq 6\text{vol}\%$, torrefied biomass with fuel properties close to those of biomass torrefied with nitrogen can be obtained, though at the expense of low bio-coal yield [17].

The yield and quality of fuel products from dry torrefaction depend on the biomass type, operating conditions and reactor type [11]. In the case of biomass type, for instance, plantain peel exhibited a higher mass yield than the peduncle [103]. Banana pseudo-stems exhibited superior fuel properties compared to banana leaves [42]. These differences may be attributed to variations in the lignocellulosic composition of the banana plant wastes. The most important operating conditions include torrefaction temperature, heating rate, residence time, particle size, and moisture content [18]. Temperature and residence time significantly impact mass yield and final quality of the torrefied biomass, affecting parameters such as heating value, energy yield, energy density, and grinding throughput [16]. However, contrary reports suggest minimal influence of residence time on the torrefaction process [21, 104, 105, 106]. Particle size influences the reaction mechanism; for instance, larger particles promote inter-particle vapor-char interactions, which can increase the yield of undesirable light bio-oil fractions [107]. Torrefaction of biomass with larger particle sizes result in higher bio-coal yields [108], as particles take longer in the reaction zone due to slower heat and mass transfer rates compared to their smaller counterparts [109, 110]. For optimal dry torrefaction, biomass should have a moisture content $\leq 10\text{wt}\%$ [62]. If the moisture content exceeds this threshold, pre-drying the feedstock is necessary, albeit at the expense of increased energy costs. Various studies have examined the effects of the aforementioned parameters on torrefaction of banana wastes, including banana rachis [56], banana leaves [45], and pseudostem [97] as summarized in Table 5.

Wet torrefaction Wet torrefaction, also known as hydrothermal carbonization (HTC) is conducted under subcritical

water conditions, typically between 180 and 250 °C in an inert environment, for a reaction time of 5 to 240 min [17]. Other than water, wet mediums such as dilute acids are used for pretreatment of biomass. The process yields a solid product known as hydrochar with coal-like properties. The HTC process is particularly suitable for wet biomass with moisture content up to 80wt%, eliminating the need for pre-drying and thus reducing energy costs [62]. The resultant hydrochar has a higher energy density, better combustion properties and better dewatering performance compared to the original biomass [23]. The HTC process can favorably retain more oxygenated functional groups on the surface of hydrochar, giving it a slightly acidic pH compared to biochar derived from dry torrefaction, pyrolysis and gasification [111]. The acidic pH of hydrochar results from the washing away of inorganics in the wet media during HTC [112]. The HTC process also exhibits better hydrogen retention compared to dry torrefaction, maintaining a higher hydrogen content in the wet torrefied biomass [113]. Moreover, since subcritical water dissolves most of the inorganic components in biomass during HTC, the ash content of the resultant hydrochar is typically lower than that of the raw biomass, unlike dry torrefaction [23]. This reduces fouling during combustion, although tendencies such as slagging and bed agglomeration may still arise [114]. Other challenges associated with HTC include a need for advanced reactors capable of working at elevated pressures, and thus higher investments [115]. As both solid and liquid products are generated during HTC, a separation step may be necessary, which increases operating costs [79].

The important parameters that influence HTC include biomass type, temperature, residence time, heating rate, water-to-biomass ratio, particle size, and rotation speed [7, 23]. Of these, biomass type greatly influences hydrochar characteristics; thus, process parameters need to be investigated in detail for each type of banana plant waste. A few researches that have examined the effects of HTC on banana plant wastes include banana peels [79], banana bunch waste [4], banana stalk [7], banana leaves [71], and fruit bunch stem [98] (Table 5). Depending on the type of banana plant waste and process conditions, hydrochar yields can range

from 62–76% [71] and fuel ratio 0.2–0.9 [7]. However, despite these research efforts, further studies are needed to assess in detail the suitability and potential of banana plant wastes for hydrothermal carbonization.

Steam torrefaction In steam torrefaction, biomass is thermally treated at high pressure saturated steam at 200–260 °C for 5–10 min [79]. Upon rapid release of pressure, the steam causes swelling of the lignocellulosic matrix, leading to the separation of individual fibers and ultimately a reduction in mechanical strength and elasticity of the torrefied biomass [116]. Furthermore, steam torrefaction removes low molecular weight volatiles from the biomass, enhancing its carbon content, heating value and hydrophobicity. These improvements occur at lower temperatures and shorter treatment times compared to dry torrefaction. Additionally, steam-torrefied biomass exhibits advantages in densification processes, with pellets derived from it displaying higher elasticity and mechanical strength compared to those from raw biomass [79]. These benefits have been demonstrated in steam torrefaction studies involving various biomass sources such as eucalyptus [117], Douglas fir [118], olive husks and tomato peels [119]. However, studies on steam torrefaction of banana plant wastes are yet to be conducted.

6.1.3 Torrefaction reactors

Dry torrefaction reactors Torrefaction reactors have evolved from existing reactor concepts, originally employed in processes such as drying, pyrolysis, or gasification [17]. They are classified as laboratory, pilot and commercial types, with varying production capacities as < 20, 20–600 and > 600 kg h⁻¹, respectively [120]. Laboratory-scale reactors, including fixed bed, microwave, rotary drum, and fluidized bed types, are crucial for research and development, and allow testing of process parameter for scalability [120]. Pilot and commercial reactors include various reactor types, including those of the laboratory type. The other reactor types in this category include the screw, moving-bed, torbed, belt drier, multiple hearth, vibrating electrical elevator and reactor (REVE), rotating-packed bed, and spouted-bed reactors. Below is a brief description of selected reactor types common to the three reactor categories, with other types described in detail in previous studies [17, 121].

Fixed and moving bed reactors The fixed bed reactor is commonly used in laboratories to conduct preliminary studies. Consequently, it is the most widely used reactor for torrefaction of banana plant wastes. It has no moving parts or unique components, making it simple to design, construct, and operate [121]. Its configuration can be either horizontal or vertical. Heat transfer is done indirectly, causing a greater energy consumption [94]. Additionally, temperature

variations occur along the reactor, leading to non-uniform heat distribution in the reactor. This creates a low-temperature zone in the reactor, where torrefaction cannot occur. Consequently, this limits scaling up of fixed bed reactors for torrefaction at pilot or commercial scale [121]. In contrast, a moving bed reactor allows biomass particles to move relative to the reactor wall, which can be horizontal, vertical, or inclined, with movement facilitated by either gravity, a rotating disk, or a vibrating belt [110]. Figure 4 illustrates a typical example of a moving bed reactor.

Microwave reactor In this type of reactor, microwave radiation, typically at 2.45 GHz, is employed to heat biomass by causing the water molecules in it to vibrate, resulting in an increase in temperature [120]. This heating mechanism occurs mainly through dipolar polarization and ionic conductivity. The extent of heating depends on the ability of the material to absorb microwaves and convert them into heat [121]. Heating of biomass occurs from the core to the surface. The torrefaction process is usually relatively fast, and the temperature can be easily controlled. However, substantial electricity is needed to generate microwaves, raising concerns about high energy requirements [121]. Figure 5 illustrates a typical microwave reactor.

Rotary drum reactor In a rotary drum reactor, biomass is torrefied under an inert atmosphere using a rotating drum. Heating can be achieved directly by passing hot gases through the reactor or indirectly by circulating hot gases

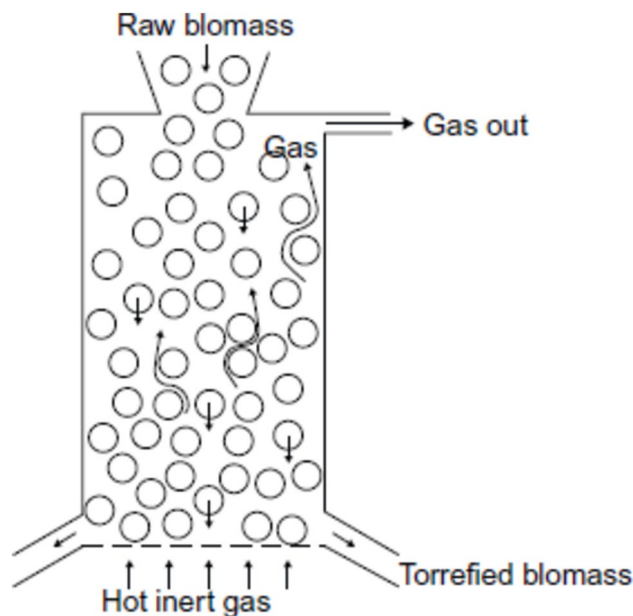


Fig. 4 Moving bed reactor (reprinted from Biomass Gasification, Pyrolysis and Torrefaction, Second edition, by Basu [122], Torrefaction, pp. 87–145, Copyright (2024), with permission from Elsevier)

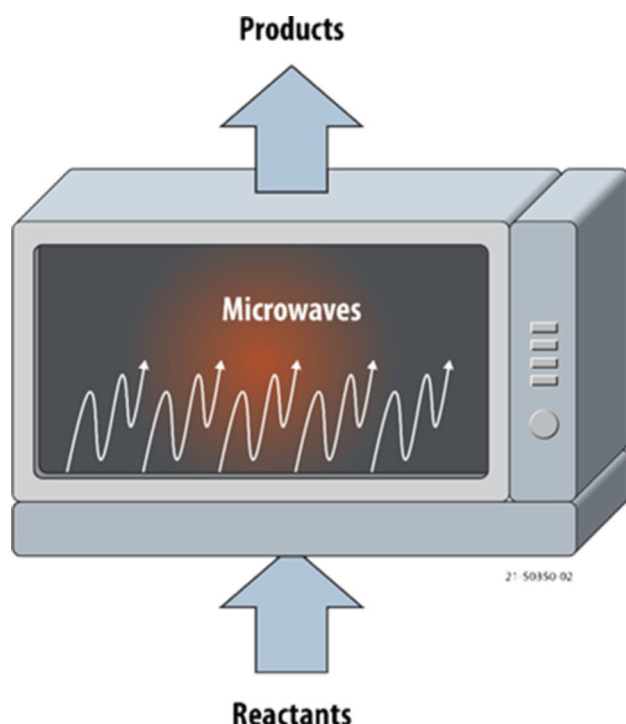


Fig. 5 Microwave reactor for torrefaction of biomass (reprinted from [123], under open access without permission)

through the reactor shells [121]. Hybrid heating modes may also be employed [94]. The rotary motion of the drum ensures constant mixing of the biomass, resulting in relatively uniform heating compared to fixed bed reactors. However, controlling the process temperature is challenging due to radiative heat on the drum surface. Scaling up the rotary drum reactor is complex because the reactor volume increases faster than the heat transfer area as the reactor diameter increases. Moreover, the presence of moving parts makes the design, construction, and operation of the rotary drum reactor more intricate than fixed bed reactors. Figure 6

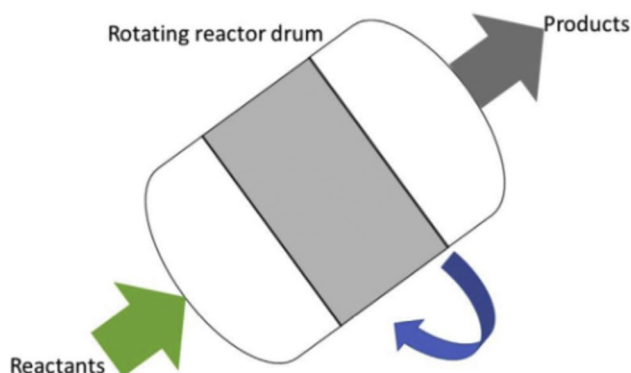


Fig. 6 Small scale rotary drum reactor for torrefaction of biomass (reprinted from [124], under open access without permission)

illustrates a typical small-scale rotary drum reactor used in biomass torrefaction.

Fluidized bed reactor In a fluidized bed reactor, biomass is placed on a grate, and hot inert gas from the lower part of the reactor flows through the biomass bed. This keeps the biomass in suspension and behaves like a fluid, ensuring uniform temperature distribution throughout the biomass bed and ultimately uniform quality of the torrefied biomass [120]. Despite this advantage, studies exploring the use of fluidized bed reactors for torrefaction of banana plant wastes are rare in the literature. Fluidized bed reactors also pose some challenges in terms of design, construction, and operation. Their design, for instance, requires strict adherence to defined fluidization parameters such as particle size and mass, fluidization speed, heat flux, and reactor geometry [121].

Hydrothermal carbonization reactor Figure 7 shows the schematic drawing of a typical hydrothermal carbonization rig used at laboratory scale. The rig includes an autoclave with a stirrer placed in a temperature-controlled oven, operating under autogenous pressure. A K-type thermocouple, connected to a PLC controller is used to measure and control the process temperature [125]. A desired ratio of biomass-to-water is carefully loaded into the reactor. The system is pressurized to keep the water in its liquid state, followed by heating until the desired maximum temperature is reached [126]. The reactor maintains this temperature for a set holding time to complete the torrefaction. Upon completion, the

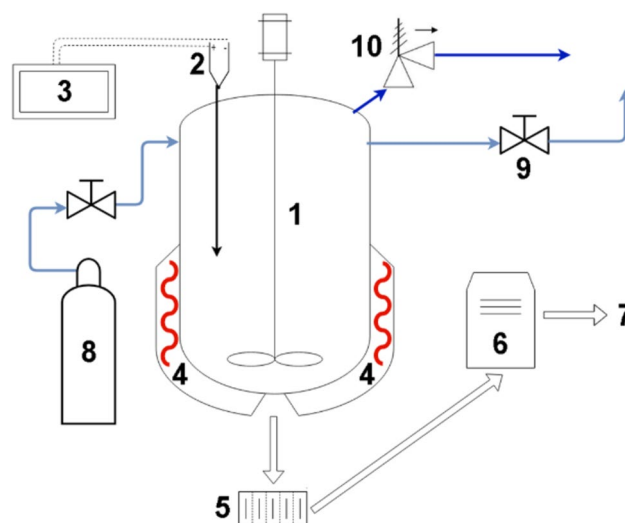


Fig. 7 Schematic drawing of the experimental hydrothermal carbonization rig (1–Autoclave; 2–type K thermocouple; 3–programmable logic controller (PLC); 4–heating mantle, with band heaters; 5–draining; 6–dryer; 7–analysis of dry sample; 8–nitrogen for purging; 9–purging valve; 10–pressure relief valve) (reprinted from [125], under open access without permission)

reactor is rapidly cooled in an ice bath, bringing it back to room temperature. The pressure is then safely released, and the reactor opened to collect, separate, and store the resulting torrefaction products.

Steam torrefaction reactors Figure 8 illustrates a typical batch pressurized reactor used by Brachi et al. [127] for steam torrefaction of biomass at a laboratory scale. The reactor is equipped with a pressure indicator (PI) and a K-type thermocouple (TT) to monitor temperature at the top of the glass tube and pressure inside the chamber. The dry biomass is placed at the bottom of the glass tube, and distilled water is added until the desired water-to-biomass ratio is achieved. The top of the glass tube is filled by a wad of ceramic fiber wool, inserted into a steel tube, and sealed. To create an inert atmosphere, the reactor is purged with argon by pressurizing and venting it 4–5 times. The reactor is then placed in an electric tube furnace, and the oven temperature is set to the desired torrefaction temperature, while the temperature and pressure inside the reactor pressure vessel are continuously monitored. The holding time begins once the reactor temperature nears the set point, during which pressure increases due to water evaporation, volatile release, and gas compression. After the holding period, the reactor is quickly removed and cooled in a water bath. If residual pressure remains, the gas is released into a 100 mL syringe for volume measurement. Finally, the reactor is opened, and the glass tube is retrieved for further processing.

6.2 Pyrolysis

Pyrolysis involves thermochemical conversion of biomass in an oxygen-free atmosphere to produce condensable liquids (bio-oil), solid char (bio-char) and gases [9]. These pyrolysis products can be used to produce heat, power, and chemicals. For instance, the produced biochar can be used as a fuel in combustion and gasification systems [128]. Pyrolysis gas can be used to power gas engines and gas turbines, generating electricity in a more efficient manner than conventional steam boilers [12]. Bio-oil, on the other hand, can be used as an alternative liquid fossil fuel in various applications [9]. Despite these benefits, pyrolysis is not without challenges. For instance, bio-oil contains a complex mixture of oxygen functional groups responsible for its highly corrosive nature, low heating value, high viscosity and low stability, hindering its production at industrial-scale [129, 130]. Pyrolysis process demands biomass with low moisture content, particularly $\leq 10\text{wt}\%$, if additional energy costs for pre-drying of biomass are to be avoided [13]. Biomass with high ash content is also not suitable for pyrolysis as agglomeration of ash can lead to blockage of the reactor. Other ash-related concerns include fouling, slagging, and corrosion of heat transfer surfaces during pyrolysis. Banana plant wastes, such as

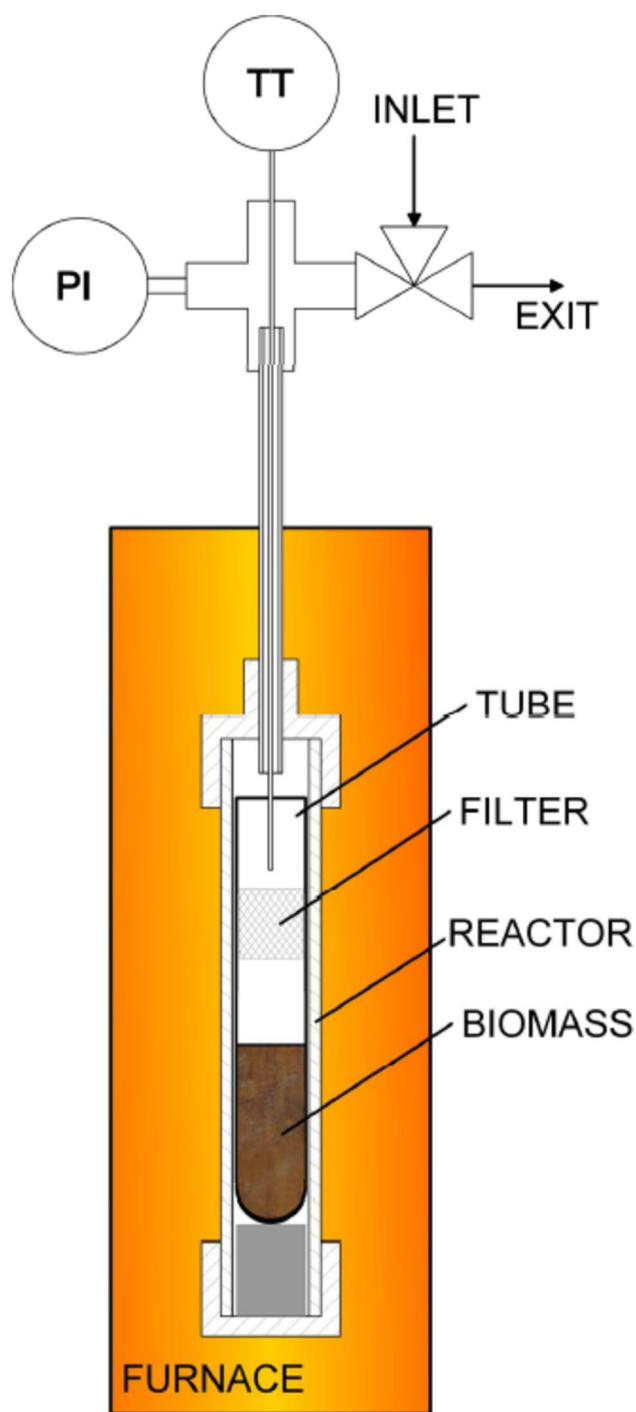


Fig. 8 A typical experimental setup for pressurized steam-assisted torrefaction (reprinted from [127]. Copyright (2024) American Chemical Society)

pseudostems with ash content ranging from 18.61–23.53%db [97, 131], banana stalks (19%db) [7], rachis (24.7%db) [56], and banana fruit bunch stems (20.60%db) [46] would not be suitable for pyrolysis without pretreatment to lower their ash content. Besides the aforementioned challenges, pyrolysis

requires high investment costs before it can be carried out commercially for energy harnessing [12]. Compared to torrefaction, pyrolysis of banana plant wastes has been widely researched for production of biofuel (see Tables 5 and 7).

6.2.1 Types of pyrolysis

Pyrolysis can be classified as slow, intermediate, fast, flash, microwave, vacuum and hydrolysis. This classification is based on operating conditions, including heating rate, temperature, residence time and biomass particle size (Table 6). Consequently, due to differences in pyrolysis conditions, product yields and quality vary with pyrolysis type [99]. In the subsequent sections, brief descriptions are provided for the most commonly employed pyrolysis types.

Slow pyrolysis involves heating biomass at relatively low heating rates ranging from 6 to 60 °C to temperatures

ranging from 300–600 °C for prolonged residence time > 1800s [132]. Unlike fast and flash pyrolysis, slow pyrolysis does not need finely ground feedstock, resulting in higher biochar yields [14]. However, slow pyrolysis suffers from drawbacks, such as prolonged heating to reach the target temperature, high heat loss, un-even heating and long reaction time, which increase the cost of biochar production. These shortcomings can be reduced using microwave-assisted pyrolysis [99]. In this type of pyrolysis, microwaves are used to generate heat inside the feedstock samples without any contact between the sample and heating source as in slow pyrolysis. The sample is heated from the core to the surface, while in slow pyrolysis, the sample is heated by convective heat transfer from the surface to the core [135, 136], as illustrated in Fig. 9.

Research on slow pyrolysis of banana plant wastes, including pseudostem [14, 48, 131], peels [11, 48, 75], and

Table 6 Classification of pyrolysis [132–134]

Pyrolysis conditions/biochar yield	Classification of pyrolysis					
	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis	Flash pyrolysis	Vacuum pyrolysis	Hydrolysis
Temperature (°C)	300–600	400–650	850–1250	>1000	300–600	350–600
Heating rate (°Cmin ⁻¹)	6–60	60–600	600–12000	>60,000	6–60	60–18000
Residence time (s)	>1800	600	0.5–10	<0.5	0.001–1.0	> 15
Pressure (MPa)	0.1	0.1	0.1	0.1	0.01–0.02	5–20
Particle diameter (mm)	>5	1–5	<1	<0.5	-	-
Biochar yield (%)	25–35	25–40	10–25	10–25	-	-
Bio-oil yield (%)	20–50	35–50	60–75	60–75	-	-
Gas yield (%)	20–50	20–30	10–30	10–30	-	-

(–) implies no figure or data was given in the literature

Fig. 9 Schematic diagram of temperature distribution, heat transfer and mass transfer in the conventional and microwave heating (reprinted from Rapid Pyrolysis of Wood Block by Miura et al. [137], pp. 187–199, Copyright (2024), with permission from Elsevier)

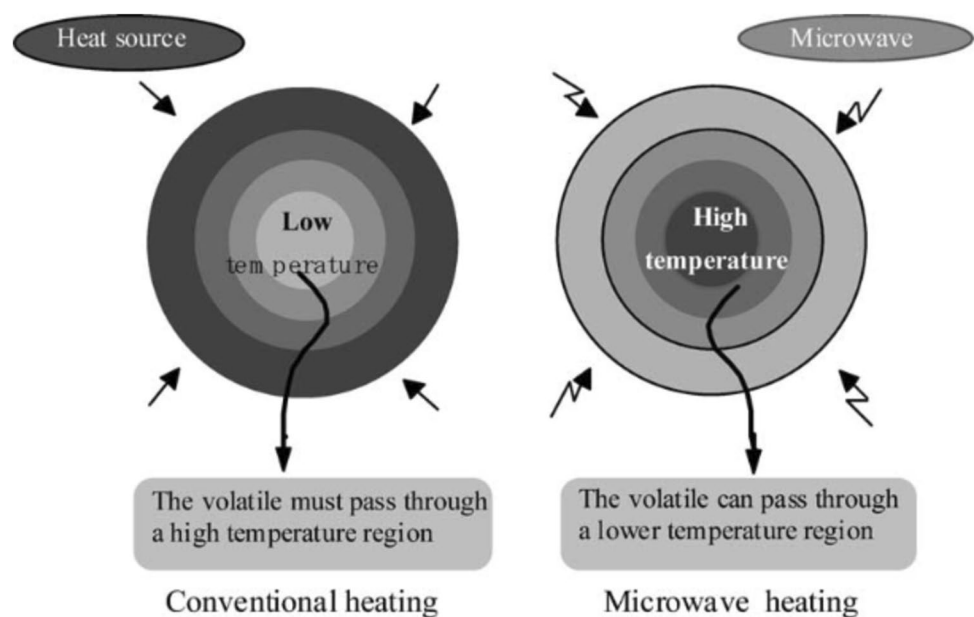


Table 7 Pyrolysis of banana plant wastes, product yields and properties

Banana plant waste	Pyrolysis type	Reactor type	Pyrolysis conditions			Product yields		Proximate properties of biochar				Ultimate properties of biochar				Reference				
			Particle size (µm)	Temp (°C)	Heat-ing rate (°Cmin ⁻¹)	Resi-dence time (s)	N ₂ flowrate (Lmin ⁻¹)	Biochar yield (wt%)	Bio-oil yield (wt%)	HHV (MJkg ⁻¹)	MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%daf)		H (%daf)	N (%daf)	S (%daf)	O (%daf)
Pseu-dostem	Slow pyroly-sis	Bench-scale fixed bed	-	400–600	10	-	0.5	34.0–43.0	29.8–45.3	23.4	6.1	33.2	32.8	34.0	43.23	0.09	28.48	0.00	32.8	[14]
Pseu-dostem	Fast pyroly-sis	Fluid-ized bed	400–600	470–540	-	1.02	-	32.8–45.9	32.8–39.3	13.6	11.4	28.5	32.2	39.3	41.28	0.0	19.96	0.0	36.81	[14]
Pseu-dostem	Slow pyroly-sis	TGA	5000	50–900	15	-	70	10	-	-	-	-	-	-	-	-	-	-	-	[48]
Pseu-dostem	Pyrolysis	TGA	380–250	800	-	-	100	32.69	-	-	-	-	-	-	-	-	-	-	-	[131]
Pseu-dostem	Fast pyroly-sis	Fluid-ized bed	400–600	470–540	-	0.9–1.2	-	39.4	-	-	-	-	-	-	-	-	-	-	-	[9]
Peels	Slow pyroly-sis	TGA	5000	50–900	15	-	70	10	-	-	-	-	-	-	-	-	-	-	-	[48]
Leaves	Slow pyroly-sis	TGA	5000	50–900	15	-	70	10	-	-	-	-	-	-	-	-	-	-	-	[48]
Peels	Catalytic pyroly-sis	Heinze retort	-	400–700	7	1200	-	-	18.64	-	-	-	-	-	-	-	-	-	-	[159]
Peels	Slow pyroly-sis	Tube fur-nace	-	200–600	5–15	3600–10800	-	31.62–95.30	-	-	-	-	-	-	54.45–71.33	-	0–2.953	0–0.253	14.58–38.9	[11]
Rachis	Fast pyroly-sis	Free-fall	<250,000	25–600	10	-	2000	71	22	-	-	-	-	-	-	-	-	-	-	[86]
Peels	Slow pyroly-sis	Drum	-	400	-	900	-	-	-	-	-	-	-	-	-	-	-	-	-	[75]
Pseu-dostem	-	-	-	500	-	-	-	67	26.7	-	-	-	-	-	-	-	-	-	-	[8]
Peels	-	-	-	500	-	-	-	51.4	39.9	-	-	-	-	-	-	-	-	-	-	[8]
Leaves	-	-	-	500	-	-	-	56.3	35.0	-	-	-	-	-	-	-	-	-	-	[8]
Leaves	Oxida-tive fast pyroly-sis	Fluid-ized bed	-	500	10	-	2000	23.3	27.0	-	-	-	-	-	-	-	-	-	-	[70]

Table 7 (continued)

Banana plant waste	Pyrolysis type	Reactor type	Pyrolysis conditions			Product yields		Proximate properties of biochar				Ultimate properties of biochar				Reference			
			Particle size (μm)	Temp ($^{\circ}\text{C}$)	Heat- ing rate ($^{\circ}\text{Cmin}^{-1}$)	Resi- dence time (s)	N_2 flowrate (Lmin^{-1})	Biochar yield (wt%)	Bio-oil yield (wt%)	HHV (MJkg^{-1})	MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%daf)		H (%daf)	N (%daf)	S (%daf)
Leaves	Slow	TGA	-	900	10–30	-	20	-	-	-	-	-	-	-	-	-	-	-	[91]

i) *Temp* implies temperature ($^{\circ}\text{C}$), ii) *MC* is moisture content, iii) *VM* is volatile matter content, iv) *FC* is fixed carbon content, v) *TGA* implies thermogravimetric analyzer, vi) *daf* implies dry-ash-free basis, and vii) Note: (–) implies no figure or data was given in the literature

leaves [48, 91], has been conducted. However, there is still a need to explore banana plant wastes further, including tailoring pyrolysis to specific banana cultivars and optimizing process conditions. These efforts could encourage maximum exploitation of the banana value chain.

Intermediate pyrolysis employs intermediate temperature and heating rates between slow and fast pyrolysis. It occurs at heating rates of $60\text{--}600\text{ }^{\circ}\text{Cmin}^{-1}$ and temperature $400\text{--}650\text{ }^{\circ}\text{C}$ [132]. The process has the ability to treat a wide range of feedstock with high moisture content up to 40wt% [138], producing biochar with low volatile matter content and high carbon content, due to interaction with steam [133]. The process also results in a good products distribution, offering good prospects for co-production of biochar, bio-oil, and gas, with the liquid product easily separable into organic and aqueous phases. Moreover, the organic phase has properties similar to those of biodiesel [133]. Compared to fast pyrolysis-derived bio-oil, the organic phase exhibits better quality in terms of viscosity and heating value [139]. This is attributed to the relatively long residence time and catalytic effects from by-product char. Despite these numerous advantages, the potential of intermediate pyrolysis for the conversion of banana plant wastes remains insufficiently explored.

Fast pyrolysis involves high heating rate ($> 100\text{ }^{\circ}\text{Cs}^{-1}$) [138, 140, 141], and temperatures ranging from $400\text{--}600\text{ }^{\circ}\text{C}$ [122, 140], for short residence time $0.5\text{--}10\text{ s}$ [132, 142]. The high heating rate allows conversion of the input biomass to a liquid product (bio-oil) before it could react to form the undesired char [134]. To allow high heat transfer rate and facilitate quick chemical reactions, fine particle sizes of biomass are required in fast pyrolysis [14]. This process results in high bio-oil yield, which is often the most desired product [143]. However, with careful control of the pyrolysis conditions, higher yields of either gas or biochar can be achieved. For instance, fast pyrolysis of banana pseudostem resulted in a relatively low bio-oil yield (32.8–39.3wt%) compared to biochar yield (32.8–45.9wt%) [14]. Similarly, fast pyrolysis of banana rachis resulted in a relatively low bio-oil yield (22wt%) compared to biochar yield (71wt%) [86]. Fast pyrolysis of dried banana leaves resulted in bio-oil yield (27.0wt%) lower than the gas yield (49.6wt%), but higher than biochar yield (23.3wt%) [86]. Further details about the pyrolysis conditions in each of the aforementioned studies, with corresponding product yields and characteristics can be found in Table 7.

Flash pyrolysis can be considered as an improved and modified form of fast pyrolysis [134]. It involves heating biomass in an inert environment at a heating rate $> 60,000\text{ }^{\circ}\text{Cmin}^{-1}$ to temperature $> 1000\text{ }^{\circ}\text{C}$ for a residence time $< 0.5\text{ s}$ [132]. It is normally adopted to maximize bio-oil yield [144]. However, flash pyrolysis requires specific reactors capable of accommodating high temperature and pressure

[145]. Despite being a well-established technology, reports on the flash pyrolysis of banana plant wastes are scarce in the literature.

6.2.2 Factors affecting pyrolysis

Pyrolysis is influenced by several factors that subsequently impact the distribution, yield and composition of pyrolysis products. The most important factors include biomass type, temperature, residence time, heating rate, particle size, pressure, catalyst and sweeping gas type and flowrate as discussed below.

Type of biomass The type of biomass can significantly influence the yield and composition of the pyrolysis products. For example, banana leaves were found to exhibit a higher fixed carbon content compared to banana peels and pseudostem [48]. Fast pyrolysis of banana peels yielded more bio-oil (39.9wt%) than that obtained from banana pseudostems (26.7wt%) and banana leaves (35.0wt%) [8]. This study also found that pseudostems resulted in a higher biochar yield compared to the other banana plant wastes. These variations are attributed to differences in composition of the biomass species [135]. Essentially, of the lignocellulosic components, lignin contributes the most to char formation, while cellulose and hemicellulose contribute most to the volatile fraction of pyrolysis products [51]. Biomass with a high oxygen content exhibits a high reactivity during pyrolysis, which consequently affects the yield and quality of the final product. Additionally, biomass with high moisture content necessitates more energy for vaporization, which prolongs the residence time due to reduced heating rates [134].

Temperature Temperature significantly influences the pyrolysis product yields and composition. The desired operating temperature is selected based on the type of pyrolysis and desired product (Table 7). Regardless of the pyrolysis type, increasing temperature leads to increased devolatilization of biomass and tar cracking, resulting in increased gas yields and reduced biochar yields [11, 14, 146]. Increase in temperature also causes secondary cracking of the pyrolytic gases, which leads to higher bio-oil yield [147]. Moreover, as the temperature increases, the carbon content increases, enhancing the aromaticity of biochar alongside introducing more surface oxygen functionalities in its carbon structure, thus improving its suitability as a fuel [128]. The decrease in H/C and O/C atomic ratios with increasing pyrolysis temperature can be attributed to the removal of H- and O-containing functional groups, resulting in biochar with high aromaticity and low polarity [148]. As temperature increases, carbon and fixed carbon contents of biochar increase, leading to enhanced heating value of biochar [149]. The increase in pH with increase in temperature can be attributed to the

devolatilization of the acidic groups containing oxygen through decarboxylation and decarbonylation of the carboxyl and carbonyl groups, respectively [150]. The increase in electrical conductivity with increase in temperature can be attributed to increased detachment of alkali salts from organic compounds [148]. Ash content increases with increase in temperature due to increased mineralization of the mineral matter, which is subsequently converted into ash during pyrolysis [151]. Increase in porosity and surface area with increasing temperature can be attributed to the greater devolatilization of biochar at higher pyrolysis temperature [152]. However, if not carefully considered, increase in pyrolysis temperature can lead to the collapse of pore structures, resulting in biochar with reduced specific surface area [150].

Residence time Residence time can have a significant effect on the yield and quality of pyrolysis products. At longer residence times, the vapors in the hot zone of the reactor are converted into smaller molecules by cracking or partial oxidation, resulting in more gaseous product [153]. More biochar is also formed at longer residence times due to repolymerization of the vapors during secondary reactions [154]. Conversely, a decrease in residence time results in low biochar yields due to insufficient time for repolymerization of biomass constituents [134]. Besides biochar yield, residence time also affects the quality of biochar, for instance, in terms of its surface area, pore structure, proximate and elemental composition [155].

Sweeping gas The type of sweeping gas and flowrate influence the yield and quality of the pyrolysis products. Inert gasses such as N₂, Ar, and steam can be used to purge the hot pyrolysis vapors. Of these gasses, N₂ gas is the most commonly used due to its relatively low cost [153]. At a higher sweeping gas flowrate, the vapors are rapidly removed from the reaction medium, reducing the char yield due to reduced repolymerization of the pyrolysis vapors in the reactor zone [135]. The gas yields are also lower due to reduced thermal cracking of the vapors in the hot zone of the reactor. Conversely, lower gas flow rates favor higher char yields, as the pyrolysis vapors in the reactor have more time to undergo secondary reactions, resulting in more char formation [156].

Heating rate The rate at which biomass is heated significantly influences pyrolysis, impacting product distributions and quality. For instance, at higher heating rates, higher yields of bio-oil are obtained with low biochar yields [146]. This phenomenon occurs because rapid heating reduces exposure time of the pyrolysis vapor, limiting secondary cracking reactions that would otherwise lead to increased biochar/or gas formation. Conversely, slower heating rates result in higher biochar yields due to prolonged exposure of

pyrolysis vapor to heat, responsible for secondary char formation. However, there exists an optimal heating rate where increased residence time fosters secondary decomposition reactions, favoring gas formation [157].

Particle size Particle size plays a crucial role in thermochemical reactions as it affects the distribution of solid, liquid, and gas products. The selection of particle size depends on the type of pyrolysis and desired product yields and quality (Table 6). As particle size decreases, the interparticle and intraparticle heat transfer increases, leading to rapid decomposition of biomass which favors bio-oil production. Conversely, as particle size increases, more biochar is formed due to increased resistance to release of primary product of pyrolysis, which favors secondary cracking to yield solid product [135]. However, excessively small particles can reduce bio-oil yield, which leads to higher gas yields due to rapid decomposition and secondary reactions [157]. Additionally, very small particles could lead to overheating or the particles being blown out of the reactor quickly before pyrolysis takes place, resulting in a low biochar yield. Conversely, larger particles may suffer from insufficient heating due to limitations in heat and mass transfer, resulting in incomplete pyrolysis [14]. Thus, selecting the optimal particle size is necessary to maximize product yields and quality from the pyrolysis process.

Pressure Pressure can significantly influence the pyrolysis product yield and quality. For instance, increase in pressure above atmospheric level leads to higher yields of biochar and syngas due to prolonged residence time of pyrolysis vapor in the reactor, which facilitates secondary cracking reactions and consequently reducing bio-oil yield [157]. A higher pressure also increases the carboxylic groups ($-\text{COOH}$), phenolic groups ($-\text{OH}$), lactonic groups ($-\text{COO}-$) and acidic groups, while reducing the basic groups ($\text{C}-\text{H}$ and $\text{C}-\text{C}$) [154]. This reduction in basic groups is attributed to higher pressure inhibiting the precipitation of acidic substances, leading to their longer residence time on the biochar surface [154]. Operating at high pressures also requires more stringent reactor design and thus higher construction or capital costs, alongside high maintenance costs for the pyrolysis reactors [158].

Catalyst The use of catalysts in pyrolysis can enhance bio-oil yield and quality by reducing oxygenated components and carboxylic acids while enriching hydrocarbons [157]. Among the catalysts that can be used include silicon, zeolite-based catalysts, metal oxide catalysts, noble metal catalysts, and activated char [129, 130, 157].

6.2.3 Pyrolysis reactors

Different types of pyrolysis reactors have been designed to convert biomass into liquid, solid and/or gaseous products. These include fixed bed, fluidized bed, rotating cone, vacuum pyrolysis, microwave, ablative, screw (auger), and plasma reactors [160]. Of these, fixed bed and fluidized bed reactors are the most widely used [161]. A description of each reactor type is given below.

Fixed bed reactor Figure 10 shows a typical fixed bed pyrolysis reactor. It consists of a cylindrical body and is usually designed vertically to leverage the gravitational force for the movement of reactants/products through the reactor [162]. This technology is simple, reliable, and proven effective for fuels with biomass feed particles of uniform size [160]. However, the fixed bed reactor suffers from low heating rate and non-uniform heating of biomass feed particles due to limited heat transfer coefficient and lack of particle mixing [162]. Fixed bed reactors are usually operated in batch mode, limiting their economic viability. As a result, fixed bed reactors are mainly used for research and small-scale heat and power applications [160].

Fluidized bed reactors Fluidized bed reactor is a vessel comprising heated particles such as sand, which attain fluid properties by passing a fluidizing gas through the distributor to the particle bed. Biomass is fed into or above the particle bed using a feeder. The fluidized gas causes suspension of the biomass particles in the gas stream, facilitating good contact between fluid and solid media, and ultimately a uniform temperature gradient in the reactor [162]. Due to efficient heat transfer, moderate to very short residence time, and excellent control over pyrolysis reactions, fluidized bed reactors are most suitable for fast and flash pyrolysis [164]. They are also the most popular configurations used from laboratory to commercial scale [160]. Fluidized bed reactors can be classified as bubbling fluidized bed (Fig. 11a) and circulating fluidized bed (Fig. 11b).

In a bubbling fluidized bed (Fig. 11a), the bed media material is fluidized from the bottom of the bed via distributor plates or gas nozzles at velocities of 1 to 3 ms^{-1} [166]. This type of reactor allows good temperature control and very efficient heat transfer to the biomass particles due to the high density of solids in the bed [167]. During pyrolysis, the non-condensable gas and fine biochar are discharged from the upper part of the reactor, while the larger biochar remains in the reactor [168]. To prevent the catalytic effect of the char, which could lead to undesirable secondary reactions and reduce the bio-oil yield, it is important to remove the biochar from the reactor. The

Fig. 10 Typical fixed bed pyrolysis reactor (reprinted from Production of Bio-oil from Fixed Bed Pyrolysis of Bagasse by Asadullah et al. [163], pp. 2514–2520, Copyright (2024), with permission from Elsevier)

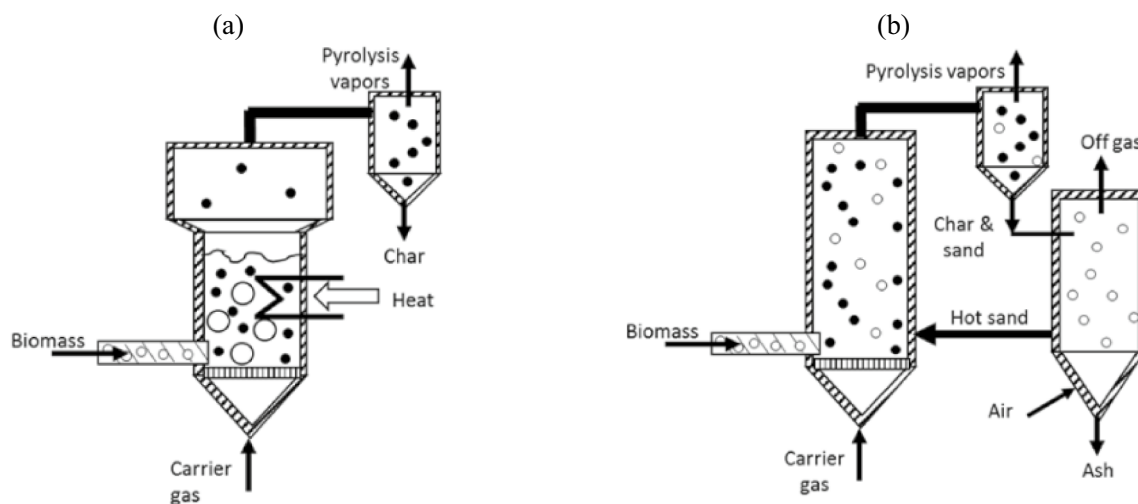
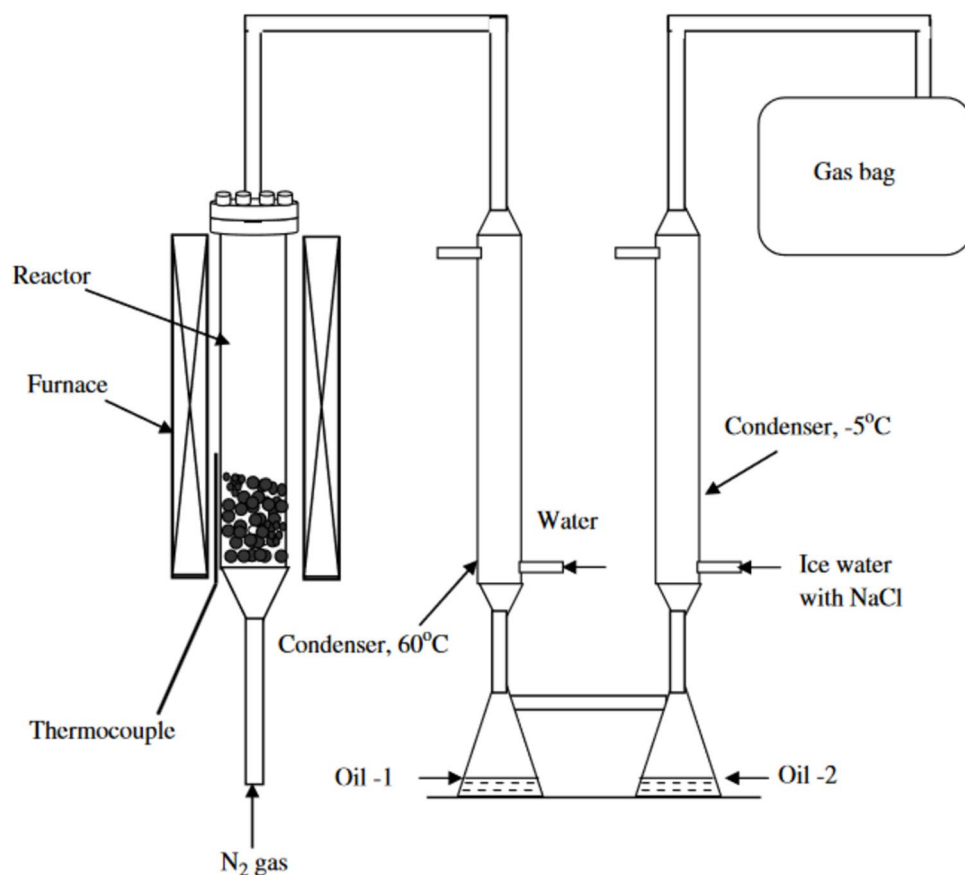


Fig. 11 **a** Bubbling fluidized bed reactor and **(b)** circulating fluidized bed reactor (reprinted with permission from [165]. Copyright (2024) American Chemical Society)

separated char particles can then be burned to generate heat for sustaining the pyrolysis process [169].

In a circulating fluidized bed reactor (Fig. 11b), gas superficial velocities are typically higher, and are three to five times ($5\text{--}10\text{ ms}^{-1}$) the velocity in a bubbling fluidized

bed reactor [166]. This increased velocity causes char and bed particles to be entrained in the gas stream, resulting in a higher solids concentration in the freeboard. Using a cyclone separator, char and bed particles are separated from the gas stream and recirculated back into the reactor. This

recirculation extends the residence time of the particles, improves the efficiency of carbon conversion, and ultimately reduces tar production.

Rotating cone reactor In a rotating cone reactor, a mixture of biomass particles and heat carrier particles, such as hot sand, is fed to the bottom of an inverted cone (Fig. 12). The pyrolysis reaction is initiated through a combination of heat transfer and high-pressure. By rotating the cone at speeds up to 600 rpm, the mixed solids are transported upwards by centrifugal forces [169]. Residence time can be controlled by adjusting the speed of the rotating cone [164]. Vapors produced are directed towards the condenser for bio-oil production, while the generated biochar is burnt to meet the heat requirements [164].

Vacuum reactor In a vacuum reactor, biomass feedstock is pyrolyzed at a pressure of about 15–20 kPa [164, 169]. By operating under vacuum, the residence time of pyrolysis vapors is reduced, which limits secondary reactions in the vapor-phase and enhances bio-oil yields [169]. Due to the reduced heat transfer requirements, relatively larger particle sizes can be used compared to conventional fast pyrolysis [169]. However, vacuum reactors are associated with high capital and maintenance costs [164]. Figure 13 illustrates a typical vacuum pyrolysis reactor.

Microwave reactor A microwave reactor consists of a microwave generator, quartz reactor, temperature probe, gas-flow

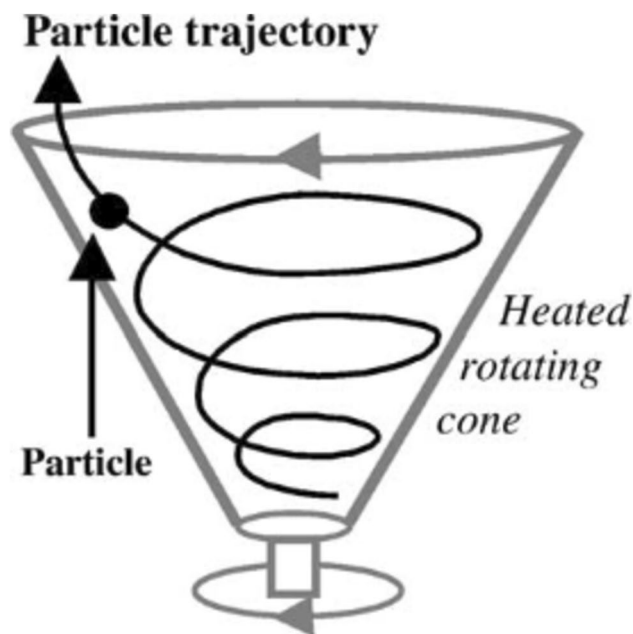


Fig. 12 Rotating cone reactor (reprinted from Renewable Fuels and Chemicals by Thermal Processing of Biomass by Bridgwater [170], pp. 87–102, Copyright (2024), with permission from Elsevier)

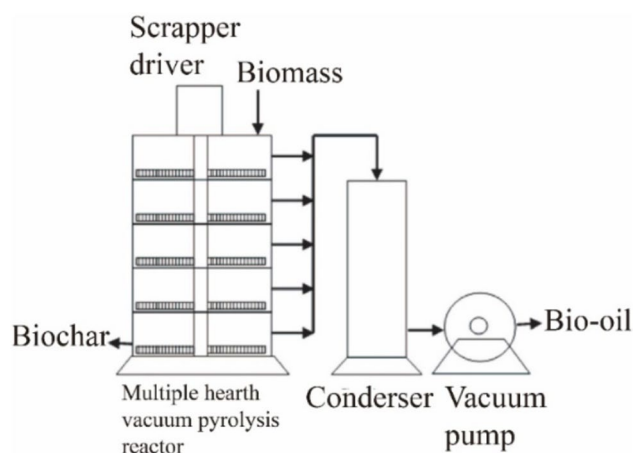
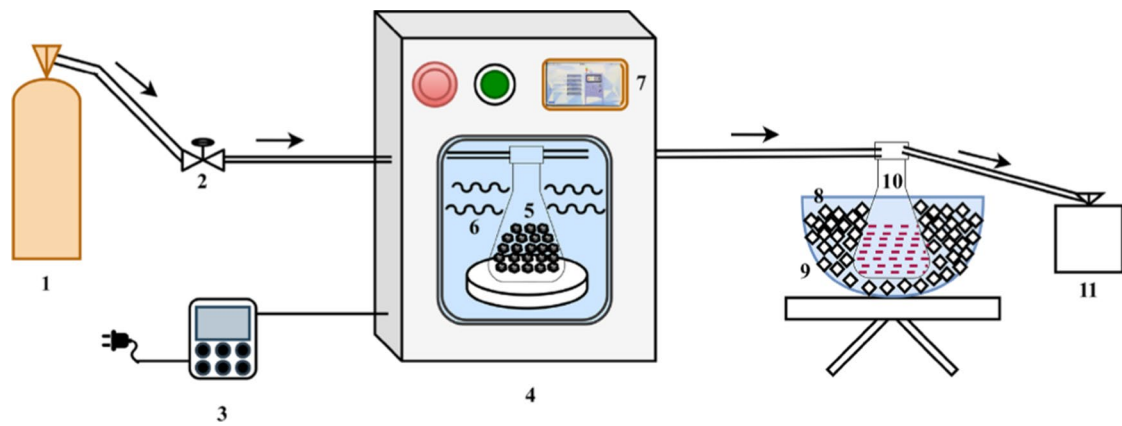


Fig. 13 Typical vacuum pyrolysis reactor (reprinted from [171], under open access without permission)

regulator, steam generator, and product collection chambers (Fig. 14). Designs of microwave reactors include fixed bed and fluidized bed. Catalytic microwave-assisted pyrolysis can occur in-situ, where the catalyst is mixed with biomass, or ex-situ, where the catalyst is heated separately, upgrading pyrolysis vapors in an external catalytic reactor supported by an external heating source [172]. Microwave pyrolysis offers several advantages over conventional technologies, including rapid heating, cleaner operation, ease of control, modularization for small-scale applications, lower reactor surface temperatures due to internal heat generation of the material, high energy-to-heat conversion efficiencies (80–85%), and the use of higher power densities [165]. However, disadvantages include limited information on microwave-relevant properties of waste materials, uneven heating affecting product quality, high electricity costs, electrical hazards necessitating containment with an appropriate Faraday cage, risk of equipment damage due to presence of metals that may generate arcing, and higher investment costs compared to the traditional heating systems [165].

Ablative reactor In an ablative reactor, biomass is brought into contact with a hot reaction surface at a temperature of about 600 °C [164, 169], as shown in Fig. 15. This high temperature is attained by heating the reactor surface with hot flue gases generated from the combustion of pyrolysis gases or char [167]. The process throughput is limited by the amount of heat that can be transferred from the heat source to the hot reactor surface [169]. The ablative reactor allows the use of relatively large feed particles, up to 20 mm, due to the absence of heat transfer limits within the particles [164]. When the biomass contacts the hot surface, vapors are formed at the interface between the biomass and the hot surface. This type of reactor, however, suffers from difficulty of achieving sufficient heat transfer from the hot



(1) Inert gas cylinder, (2) regulator/control valve, (3) energy meter for direct measurement, (4) microwave heating reactor, (5) quartz container for sample testing, (6) microwave irradiation from magnetron, (7) display for readings and control of setup, (8) cooling container (9), ice cubes, (10) collector of condensable gases, and (11) Tedlar bag.

Fig. 14 Experimental setup of a microwave reactor (reprinted from [173], under open access without permission)

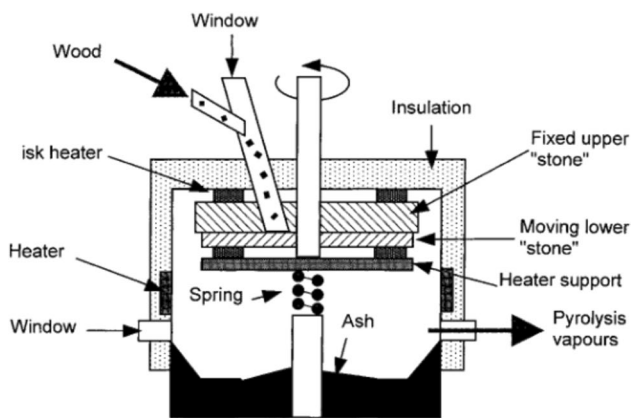


Fig. 15 A typical example of an ablative pyrolysis reactor (reprinted from *Fast Pyrolysis Processes for Biomass* by Bridgwater and Peacocke [174], pp. 1–73, Copyright (2024), with permission from Elsevier)

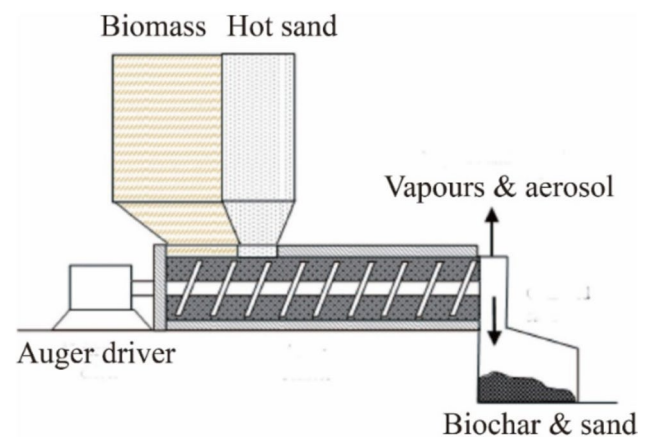


Fig. 16 A typical example of a screw (auger) reactor (reproduced from [171], under open access without permission)

gases to the ablative surface and in contacting feedstock of diverse morphologies with the ablative surface. To improve the ablation process, the pressure exerted by the biomass on the hot surface must be increased. This is usually done by centrifugal or mechanical forces or by the mechanical movement of the biomass over the hot surface [169]. Despite its potential, ablative pyrolysis is practically limited to a few suitable feedstocks [167]. In addition, the mechanical nature of the ablative process increases the complexity and cost of the process [169].

Screw (auger) reactor Screw reactors consist of a heated tube through which biomass is fed and pyrolyzed (Fig. 16).

To ensure that no oxygen enters with the biomass, an inert gas is fed into the biomass hopper. This gas also creates positive pressure to move pyrolysis vapors through the reactor. Smaller diameter tubes can be heated externally, while larger-scale operations may use a heated solid heat carrier to intimately interact with biomass particles. Steel or ceramic pellets are commonly used as solid heat carriers. Pyrolysis vapors are condensed into liquid bio-oil, while resulting char is transported by the auger to a collection pot. If a solid heat carrier is used, it is separated by a sieving system. The carrier, heated by the exothermic reaction and reactor tube walls, requires reheating for sufficient pyrolysis heat [160].

Plasma reactor In a plasma reactor, biomass is fed into the reactor and heated under limited supply of oxygen. A hot plasma field is created by a high voltage electrical field [160]. The plasma is generated by feeding the reactor with an inert gas, which also purges oxygen from the reactor [164]. Within the plasma zone, there is a high reactivity characterized by a significant presence of electrons, ions, excited molecules and radiative energy. Upon injection into the plasma, biomass undergoes rapid heating, leading to the release of volatiles. These volatiles are cracked, producing hydrogen and light hydrocarbons. Despite their potential, plasma reactors are not widely used due to their high power consumption, significant heat release into the environment, and the associated high operating costs [160]. Figure 17 illustrates a typical process flow diagram of a pyrolysis plasma reactor.

Table 8 summarizes the advantages and disadvantages associated with each type of pyrolysis reactor.

6.3 Comparative energy consumption

Torrefaction, hydrothermal carbonization and pyrolysis require significant energy consumption during the reaction stage. Additional energy is consumed during drying of the biomass, except for the HTC process. This energy consumption can escalate production costs, impacting the economic viability of thermochemical conversion processes. There is, thus a need for judicious selection of thermochemical conversion processes based on their energy requirements. For instance, Gonzalez-Arias et al. [176] found torrefaction

to be the most preferred in terms of energy consumption if only the solid phase is considered, followed by hydrothermal carbonization and pyrolysis [176]. Specifically, the energy consumption per kg of biochar produced through torrefaction ranged from 5.85 to 20.76 MJkg⁻¹, compared to 8.44 to 44.88 MJkg⁻¹ for hydrothermal carbonization, and 18.18 to 155.33 MJkg⁻¹ for pyrolysis [176]. The authors attributed the highest energy consumption in pyrolysis to the greater severity of the process compared to torrefaction and hydrothermal carbonization. Consequently, pyrolysis for solid fuel alone may not be economically feasible at industrial scale. Combining biochar production with biofuels like gas and bio-oil could enhance the economic viability of these processes.

7 Briquetting

Briquetting plays a crucial role in facilitating the handling, transportation and storage of torrefied biomass and biochar which otherwise occur in loose form with typically low bulk density [26, 27]. This process can also be employed to address the inherent properties of raw biomass such as low density and high moisture content, which make its handling, transportation and storage problematic [30]. Briquetting can be done with or without the aid of external binders [26, 177]. Essentially, the particles undergo compaction under pressure, leading to mechanical interlocking and increased adhesion between particles, forming intermolecular bonds. This compaction ensures that there is no risk of separation during transportation, storage, or combustion. As a result,

Fig. 17 Schematic of plasma pyrolysis system (reprinted from Thermal Performance Analysis and Experimental Validation of Primary Chamber of Plasma Pyrolysis System during Preheating Stage using CFD Analysis in ANSYS CFX by Sharma et al. [175], Copyright (2024), with permission from Elsevier)

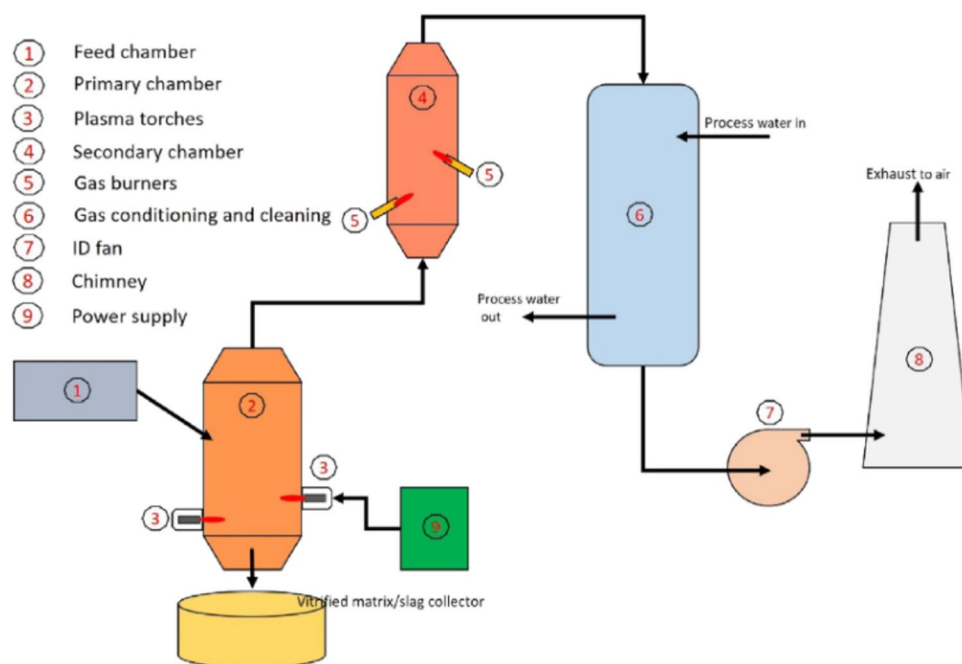


Table 8 Advantages and disadvantages of different types of pyrolysis reactors [162, 164, 165, 169]

Reactor type	Advantages	Disadvantages
Fixed bed	- Simple design and operation - Reliable - Low cost - High flexibility according to feed size - Easy maintenance - Ease of control - Used for different waste types	- Low heating rate - Long residence time - Low ash carryover - Non-uniform heating - Low efficiency - Low bio-oil yield - Quick deactivation of the catalyst in the entrance section of feedstock - Different reaction pathways in different sections of the reactor - Difficulty of the control of the reactions, especially the coke formation reaction
Fluidized bed	- High heat transfer efficiency - High reaction rates - Uniform heating is possible - High bio-oil yields - Delayed coke formation compared with fixed bed reactor	- High operating costs - Complex design of the reactor and control system - Very sensitive to biomass particle size - Steam reforming can be a problem - Residual fine char particles in the bio-oil reduce its stability and heating value
Bubbling fluidized bed	- Simple design and operation - Flexible temperature control - Large scale production	- Small size of feed is required - Char removal is difficult
Circulating fluidized bed	- Mature technology - Flexible temperature control - Large feed size can be used	- Biochar removal is difficult - Not suitable for large production - Pyrolysis process is complex
Microwave	- Large feed size can be used - The heating of feedstock is quick and efficient - Control of the system is simple - Flexible temperature control - Exhibits good control on heat transfer - Cleaner operation - Modularization for small-scale applications possible - High power densities - High energy-to-heat conversion efficiencies	- Feedstock should be in powder form - High electric consumption - Having a hot spot on the surface of the feedstock and catalyst is possible - Possibility of producing unwanted compounds due to secondary reactions is high - Pyrolysis reactions not efficient and equal in all parts of the feedstock - High flow rate of carrier gas is required to prevent the secondary reactions - Not much data available on lab and industrial scales - uneven heating affecting product quality - Electrical hazards necessitating containment with an appropriate Faraday cage - Risk of equipment damage due to presence of metals that may generate arcing - High investment costs compared to traditional heating systems
Ablative	- Large feed size can be used - Moderate temperature control - Inert gas is not required	- High capital cost - Slow reaction rate - Produces fine char difficult to remove from bio-oil - Process throughput limited by the amount of heat that can be transferred to the hot surface from the heat source
Screw (auger)	- Compact size - Carrier gas not required - Process temperature is low	- Process have moving parts - Not efficient heat transfer
Plasma	- Highly efficient heat transfer, coupled with ease of reaching target temperature	- Requires small feedstock size

Table 8 (continued)

Reactor type	Advantages	Disadvantages
	- Exhibits good temperature control - Feasible for low and high feeding rates - Easy to control composition of gaseous products - High energy density - Good control on heat transfer - Industrial data available for single feedstocks such as plastics and hazardous substances	- The working temperature of the reactor is > 1000 °C, making it appropriate for processes like gasification process - Not suitable for production of bio-oil as it is not produced during plasma pyrolysis - High capital and operating costs - High electric consumption - Very new technology with very few studies - Possibility of having a hot spot on the waste and reactor body is very high - Necessity of monitoring body strength of the reactor continuously due to hot spots

the physico-mechanical and combustion properties of the fuel briquettes are also improved. The manufacturing process of briquettes, includes crushing, mixing with or without a binder, briquetting, and finally drying of the briquettes [75]. Crushing biomass into smaller particle sizes before briquetting is crucial for enhancing inter-particle bonding. Essentially, upon crushing of the material, the lignin is partially broken down, increasing the specific surface area which ultimately contributes to improved binding capability [18]. Crushing also improves the flow of biomass during the briquetting process [72].

7.1 Properties of briquettes

The properties of briquettes include physico-mechanical and combustion properties. The physico-mechanical properties include density, strength, durability, and water resistance capacity, while combustion properties include the proximate and ultimate properties, heating value, ignition time and burning rate [42, 57, 178, 179, 181]. Most of these properties are briefly discussed in the subsequent sub-sections.

7.1.1 Physico-mechanical properties

Density The density of briquettes can be described in terms of bulk density, compressed density, and relaxed density. Compressed density is measured immediately after compression, while relaxed density is determined after the briquette has stabilized [182]. Compaction ratio is then obtained as the ratio of compressed density to initial density of the mixture of biomass and binder [183]. Relaxation ratio is obtained as the ratio of compressed density to relaxed density. A high relaxation ratio implies more void in the compressed materials, while a low relaxation ratio implies more volume displacement, which is an important property for packaging, storage and transportation of briquettes [180]. Lower

relaxation ratios and higher relaxed densities are associated with better stability of briquettes [183].

Briquettes with higher densities are generally preferred due to their higher energy-to-volume ratio, which improves transportation, storage, and handling [181]. However, the reduced porosity in high-density briquettes can make them harder to ignite [184]. For efficient transportation and safe storage, briquettes should have a minimum compressed density of 600 kg^{-3} [183]. The density of briquettes is influenced by the density of the original biomass, moisture content, compacting pressure, and, to some extent, the briquetting temperature and time [179, 184]. Briquettes made from banana plant wastes can have bulk densities ranging from 330 to 1010 kgm^{-3} [57, 181]. depending on factors such as the type of waste, binder, briquetting technology, and conditions. However, detailed reports on the compressed and relaxed densities of briquettes derived from banana plant wastes are scarce in the literature.

Strength The mechanical strength of briquettes is influenced by factors such as particle size, moisture content, compaction parameters, and material type [179]. It can be expressed in terms of compressive, tensile, ultimate, or bending strength, with compressive strength being the most commonly reported for briquettes derived from banana plant wastes (see Table 9). Compressive strength measures a briquette's ability to withstand destructive forces during handling, storage, and transportation, indicating the amount of force needed to break the briquette [185]. The compressive strength of non-carbonized briquettes from banana plant wastes ranges from 1.33 to 38.39 MPa, exceeding the industry's minimum acceptable level of 0.38 MPa (see Table 9). However, there are no available reports on the compressive strength of carbonized briquettes.

Durability Durability represents the measure of shear and impact forces a briquette could withstand during their

Table 9 Properties of briquettes derived from raw and carbonized banana plant wastes

Banana plant waste type	Binder type	Briquetting technology	Briquetting conditions		Physical properties of briquettes			Proximate properties of briquettes				Ultimate properties of briquettes				Reference			
			Biomass-to-binder ratio	Compressive pressure (MPa)	Dwell time (s)	HHV (MJkg ⁻¹)	Bulk density (kgm ⁻³)	Energy density (MJm ⁻³)	Compressive strength (MPa)	MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%db)	H (%db)		N (%db)	O (%db)	S (%db)
a) Properties of briquettes derived from raw banana plant wastes																			
Leaves	-	-	-	-	-	17.7	990–1000	-	3.60–5.30	7.17	75.30	18.25	10.63	44.28	6.23	0.80	<0.3	-	[57]
Leaves	-	Hydraulic press	-	18	0.6 and 1 s	17.70	990–1000	17,523	3.60–5.30	-	-	-	-	-	-	-	-	-	[198]
Leaves	-	-	-	-	-	17.7	990.0–1000	17,523	3.60–5.30	7.17	75.3	18.3	10.7	44.3	6.23	0.8	0.3	37.7	[42]
NaOH-treated leaves	Wastepaper	Hydraulic press	Banana leaves-to-binder ratio 5:1	-	-	25.77	910	-	1.33	10.33	67.19	17.10	15.71	-	-	-	-	-	[3]
Peels	Molasses	Hydraulic press	Banana peels-to-binder ratio 1:0.2	3–11	10	18.89	-	-	-	-	-	-	-	-	-	-	-	-	[44]
Peels	Banana starch	Hydraulic press	Banana peels-to-binder ratio 10:1–10:2	-	-	-	-	-	38.01–38.39	71–75	-	-	-	-	-	-	-	-	[66]
Pseudo-stem	-	-	-	-	-	14.9	990–1010	-	9.50–15.03	9.74	71.70	18.74	9.85	37.7	5.58	0.19	<0.3	-	[57]
Pseudo-stem	-	-	-	-	-	14.9	990	14,752	15.0	9.74	71.7	18.7	9.85	37.7	5.58	0.19	0.13	46.6	[42]
Leaves and peels	Banana peels	Hydraulic press	-	-	-	13.25	-	-	13.4	-	-	-	-	-	-	-	-	-	[65]
Leaves and pseudo-dostems	Paper 30%	-	-	-	-	15.60	330	-	-	11.04	68.74	15.27	4.94	-	-	-	-	-	[181]
Leaves and pseudo-dostem	Banana peels	-	-	-	-	19.16	-	-	13.4	-	-	-	-	-	-	-	-	-	[65]

Table 9 (continued)

Banana plant waste type	Binder type	Briquet- ting tech- nology	Briquetting conditions		Physical properties of briquettes			Com- pressive strength (MPa)	Proximate properties of briquettes			Ultimate properties of briquettes				Refer- ence		
			Biomass-to- binder ratio	Com- pressive pressure (MPa)	Dwell time (s)	HHV (MJkg ⁻¹)	Bulk density (kgm ⁻³)		Energy density (MJm ⁻³)	MC (wt%)	VM (%db)	FC (%db)	Ash (%db)	C (%db)	H (%db)		N (%db)	O (%db)
Leaves, peels and pseudostem	Banana peels	-	-	-	-	17.5	-	-	11.58–21.75	-	-	-	-	-	-	-	-	[65]
b) Properties of briquettes derived from carbonized banana plant wastes																		
Peels	Cassava starch	Manual mould	10%binder-water:90%	6	10	16.98	-	-	-	7.64	60.92	FC 19.49	11.95	-	-	-	-	[75]
Peels	Starch-based adhesive 5–15%	-	-	-	-	-	569–596	-	-	8.35–9.17	47.0–52.6	-	24.9–27.9	-	-	-	-	[199]
Peels	Clay	Roller press machine	Charcoal-to-binder ratio 100:0, 95:5, 90:10, 85:15	-	-	22.74–26.76	-	-	-	-	24.06–28.30	34.80–39.17	32.52–41.14	-	-	-	-	[76]
Leaves and pseudostems	None	Screw extruder	-	-	-	10.30	720	-	-	10.33	27.09	-	48.3	-	-	-	-	[181]
Leaves and pseudostems	-	-	-	-	-	12.73	440	-	-	7.23	32.34	32.34	49.43	-	-	-	-	[181]
Bunch waste	Clay	Roller press machine	Charcoal-to-binder ratio 100:0, 95:5, 90:10, 85:15	-	-	21.40–25.06	-	-	-	-	24.83–29.21	37.14–41.93	28.86–38.03	-	-	-	-	[76]

i) *Temp* denotes temperature, ii) low compaction technology was used to produce beehive briquettes, ii) medium compaction technology refers to one where the hydraulic press was employed for briquetting purposes, and iii) (–) implies no figure or data were given in the literature

handling, storage and transportation [182]. In industrial production, the minimum acceptable durability is 80% [179]. Compared to non-carbonized briquettes, carbonized briquettes are more durable [186]. High durability is beneficial for transporting briquettes, as it reduces the production of fines or dust, which can pose health hazards and create an inconvenient environment for workers [182]. While there is no specific limit for fines, a level up to 5wt% is generally acceptable; more than 5wt% can reduce storage capacity and affect flow characteristics [187]. Durability mainly depends on feedstock type, briquetting technology used, and process variables [187]. However, studies on the durability of briquettes derived from banana plant wastes are scarcely reported in the literature.

Water resistance capacity Water resistance capacity indicates the hydrophobic nature of briquettes [188], with a higher water resistance capacity indicating greater stability [182]. Briquetting of biomass without a binder is reported to result in fuel briquettes with low water resistance capacity, and vice versa [184]. However, reports on the water resistance capacity of briquettes derived from banana plant wastes are scarce in the literature.

7.1.2 Combustion properties

Moisture content Moisture content has a strong influence on durability, storage, ignition time, burning rate and heating value of the briquettes [187]. Increased moisture content prolongs ignition time, as well as reduces burning rate [189]. High moisture content leads to wastage of heat energy, as it is used to vaporize excess water, resulting in lower heating value, increased smoke production, and sometimes causing the briquettes to break apart [183, 184]. Additionally, higher moisture content increases the risk of rotting and decomposition, reducing shelf stability [181]. While briquettes with low moisture content ignite easily and burn efficiently, excessively low moisture content can accelerate burning and reduce combustion efficiency [65]. To avoid these challenges, fuel briquettes should have a moisture content ranging from 5–10% [190]. This can be achieved through careful control of the process variables during briquetting [184]. The moisture content of fuel briquettes made from banana plant wastes varies widely, ranging from 7.17 to 75wt% [57, 66] (Table 9).

Volatile matter content Higher volatile matter content eases ignition and enhances combustion due to increased chemical reactivity [181]. However, a high volatile matter content reduces energy efficiency, as well as leads to increased emissions production during combustion [176]. Thus, for good-quality briquettes, a low volatile matter content is required [191]. Depending on banana plant waste type, binder type,

briquetting technology and briquetting conditions, the volatile matter content of uncarbonized briquettes from banana plant wastes ranges from 67.19 to 75.3%db (Table 9). For carbonized briquettes, the volatile matter content ranges from 24.06 to 60.92%db (Table 9).

Fixed carbon content Fixed carbon content represents the percentage of carbon available for combustion after volatile matter and ash have been removed from the briquette [192]. A higher fixed carbon content is desirable, as it increases the heating value of the briquettes [181]. Carbonized briquettes derived from banana plant wastes have a higher fixed carbon content compared to their non-carbonized counterparts (see Table 9).

Ash content Ash is the inorganic matter left after complete combustion of biomass [193]. A high ash content is undesirable, as it is incombustible, lowers heating value and complicates handling [181, 194, 195]. Additionally, it increases the risk of ash slagging and fouling in thermochemical systems, as well as leading to increased emission of particulate matter during combustion. The ash content of briquettes from banana plant wastes ranges from 4.94 to 49.43%df, with carbonized briquettes exhibiting higher ash contents compared to their non-carbonized counterparts (Table 9).

Heating value Heating value is one of the most important property for determining the suitability of briquette as fuel [196]. A high heating value of briquettes indicates that more thermal energy is generated during combustion, while a low heating value indicates less energy is produced [178]. The higher heating value of briquettes derived from banana plant wastes ranges from 10.30 to 26.76 MJkg⁻¹ (Table 9).

Ignition time and burning rate The ignition time is influenced by volatile matter content, as briquettes with a higher content ignite easily compared to their counterparts with a lower content. Thus, non-carbonized briquettes with typically high volatile matter content are easier to ignite than their carbonized counterparts [186]. Ignition time is also influenced by density, as high-density briquettes are harder to ignite due to reduced porosity, which hinders oxygen infiltration [181]. Burning rate is influenced by the hardness of the briquette, with harder briquettes burning more slowly [197]. However, there is limited literature on the ignition time and burning rate of briquettes made from banana plant wastes.

Table 9 provides a summary of the physico-mechanical and combustion properties of fuel briquettes derived from various banana plant wastes under different briquetting conditions.

7.2 Factors affecting quality of fuel briquettes

The factors that affect the quality of fuel briquettes have to do with the characteristics of feedstock, process variables and type of briquetting technology. The characteristics of feedstock include moisture content, lignocellulosic composition, particle size, type and amount of binder, while process variables include temperature, pressure, and dwell time [18]. Each of these factors are briefly described below.

7.2.1 Characteristics of feedstock

The characteristics of feedstock influence the quality of fuel briquettes in terms of their physico-mechanical and combustion properties. Key characteristics include the proximate and ultimate compositions of the feedstock. A high carbon content of the feedstock enhances the calorific value and mechanical strength of the resultant briquettes [200]. A low volatile matter content is desirable to minimize the release of emissions during combustion and lower the risk of smoke production, though with difficult ignition [200]. A low ash content results in a higher calorific value of the briquettes and avoids operational challenges such as ash fouling and slagging in thermochemical conversion systems. A low ash content also makes ignition of the briquette easier, avoiding the need for flammable substances such as petroleum to ease ignition [201]. Elemental components like nitrogen and sulphur influence combustion behaviour, with higher levels correlating to increased nitrogen oxide (NO_x) and sulphur oxide (SO_x) emissions, respectively. The presence of sulphur and chlorine further elevates the acidity of the emissions [186].

For densification, moisture content of biomass is crucial, as different briquetting technologies require specific moisture contents for their optimal performance. For instance, piston and screw presses operate optimally with a moisture content of 10–15 wt% and 8–9 wt%, respectively [202]. A lower moisture content weakens interactions between biomass particles, reducing the mechanical properties of the fuel briquettes. While an increase in moisture content can enhance interactions between particles, the moisture content should be carefully selected to avoid excessive steam generation, which can disrupt compaction and reduce the mechanical properties of the briquettes [190]. A high moisture content also hinders complete flattening and release of natural binders due to the incompressibility of water [203].

Particle size plays a crucial role in determining the quality of fuel briquettes. The recommended particle size is ≤ 6 mm, regardless of whether carbonized or non-carbonized briquettes are to be produced [186]. Smaller particle sizes result in larger surface areas and increased contact points for bonding and ultimately enhanced density and shatter resistance of the briquettes [204]. Mixing particles of different sizes further enhances the bonding ability, as

larger particles get filled with the smaller particles to form an interlocking bond [186]. Additionally, reducing particle size aids in the release of natural binding components like proteins, starch, and lignin from biomass, which promote cohesion and bonding during compaction [30]. Conversely, larger particle sizes reduce surface area and contact points, leading to lower density and shatter resistance, ultimately resulting in lower-quality fuel briquettes [205].

7.2.2 Type of binder

Binders are substances of organic or inorganic composition that have the ability to link, solidify and connect particles of briquette material, giving briquettes solid form and satisfactory mechanical properties [177]. They form a gel with water, improving the cohesive characteristic of biomass which helps produce a more durable fuel briquette. Binders also help reduce the wear on production equipment and increase the abrasion resistance of the fuel [18]. The influence of type and amount of binder on the quality of fuel briquettes is discussed below.

Binders can be classified as either organic binders such as molasses, water hyacinth, banana peels, gum Arabic, lignin or inorganic binders such as clay, lime, cement, limestone, calcium oxide, bentonite and sodium silicate [205]. Organic binders exhibit good adhesion properties but poor thermal stability, while inorganic binders exhibit good bonding strength due to their higher compressive strength and compaction ratio, have good thermal stability, and are hydrophobic. However, inorganic binders exhibit a high ash content, which reduces heat generation and burnout temperature of the biomass [26]. The limitations of organic and inorganic binders can be addressed by taking advantage of compound binders formed through a combination of organic and inorganic binders [25].

Each of the organic and inorganic binders exhibits specific pros and cons which should be carefully considered during binder selection. For instance, briquettes made using organic binders such as molasses exhibit excellent mechanical strength, but they disintegrate upon contact with water [206]. Molasses also exhibit a high content of phosphorus and sulfur, which could be introduced into the biomass during briquetting, raising air pollution concerns upon combustion of the fuel briquettes [26]. Increase in molasses mass fraction of the briquette significantly increases its ash content, moisture content, relaxed density, shatter index and reduces calorific value [207]. Briquettes developed using starch as a binder exhibit good hydrophobicity, but they have low density and low mechanical strength [26].

Use of clay as a binder increases ash content, reducing the combustion efficiency and calorific value of the fuel briquettes [205]. The high ash content also leads to operational challenges in biomass combustion systems, including

fouling and slagging. Besides these operational challenges, some binders outperform their counterparts due to their inherent properties such as higher calorific value [205]. For instance, starch-bonded briquettes exhibited a higher calorific value than its counterparts made using waste paper as a binder [3]. Some binders are also costly or form part of the food chain, limiting their use in the briquetting process.

7.2.3 Temperature

Temperature affects the feedstock and the die of the briquetting machine before and during the briquetting process [72]. In low temperature briquetting, binders are added to the feedstock with little/or no lignin content and compressed under low temperature and pressure to enhance the mechanical and combustion properties of the resultant fuel briquette. Conversely, in high temperature briquetting, a feedstock with a high lignin content is compressed under high temperature and pressure, releasing lignin which acts as a natural binder during the briquetting process [177]. However, once the desired die temperature is exceeded (280–290 °C), the friction between the feedstock and the die wall is reduced, which allows densification to occur at lower pressure, producing briquettes with inferior properties [202]. Conversely, at low die temperature, the friction forces are high, necessitating high pressure briquetting which results in briquettes with better properties. This process route, however, is associated with high power requirements and low throughput [72].

7.2.4 Pressure

The quality of fuel briquettes is influenced by the compaction pressure applied during the briquetting process, with options for high, medium, or low compaction pressures. At high pressure, feedstock with high lignin content is compressed, raising the temperature of the feedstock to a level sufficient to melt the lignin fraction, which subsequently acts as a binder during the briquetting process. However, high pressure briquetting is associated with high electrical energy consumption and high wear rate of machine parts [202]. In medium pressure compaction, additional heating of the feedstock is required to melt the lignin fraction, eliminating the need for additional binder [208]. On the other hand, at low compaction pressure, the lignin fraction of the feedstock is not melted due to a considerably low temperature of the feedstock. Consequently, addition of a binder is required during the briquetting process. This type of briquetting is suitable for materials with little or no lignin content, such as carbonized materials. While an increase in pressure increases the physico-mechanical properties of briquettes, a further increase in pressure beyond a certain limit ceases to enhance fuel properties of the briquette [22].

7.2.5 Dwell time

Dwell time is the the duration for which maximum pressure is applied at the peak of the compression sequence [209]. This parameter influences the extent of relaxation that occurs when the briquette is removed from the die. Typically, the length of relaxation of the briquette decreases with increasing dwell time until a certain limit where further increases do not significantly affect the final relaxation characteristics. In general, a dwell time of 20–40 s produces a briquette with minimum relaxation [209]. However, dwell times both below and above this range have been reported in various studies. For instance, banana peels were compressed with a dwell time of 10 s [44, 75], while banana leaves were compressed with dwell times as short as 0.6 and 1 s [198], and olive cake with a dwell time of 5 s [210]. On the other hand, charcoal particles and pine sawdust were briquetted with a dwell time of 300 s [211]. Compared to binder type, dwell time impacts has less influence on the overall quality of the fuel briquette [212].

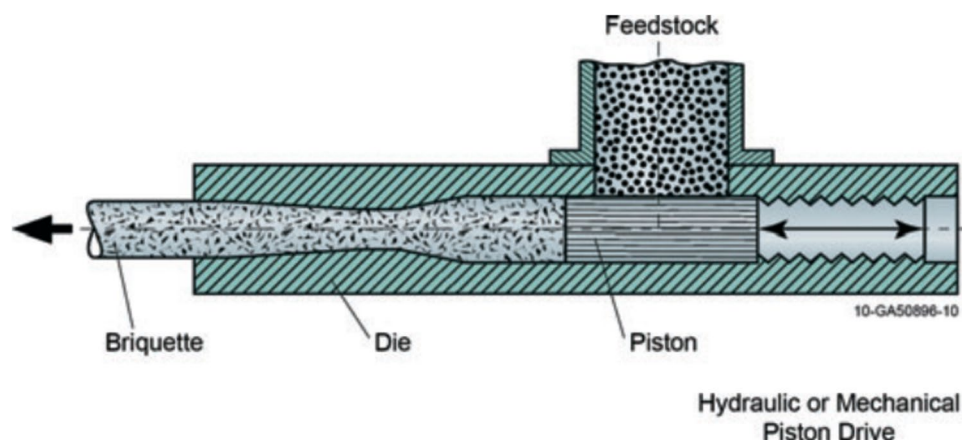
7.3 Briquetting technologies

Briquetting is usually performed using a mechanical piston press, hydraulic piston press, roller press or screw press. Of these, the hydraulic press is the most widely employed for briquetting of banana plant wastes (Table 9). Piston and screw presses can be classified as high pressure briquetting technologies, with piston presses producing briquettes that are completely solid, while screw presses produce briquettes with a concentric hole, giving it better combustion characteristics due to a large specific area [202]. Screw press-derived briquettes are also homogeneous, do not easily disintegrate and have a high combustion rate [31]. Further description of each of these briquetting technologies is given below.

7.3.1 Mechanical piston press

The mechanical piston press consists of a ram (piston) and a die, where biomass is punched by a reciprocating ram under high compaction pressure to form a briquette [72] (Fig. 18). Mechanical piston presses are used for large scale production, typically in the range of 200–1800 kg h⁻¹ [213]. Without the addition of a binder, the press can develop a compression pressure as high as 2000 kg cm⁻², producing briquettes with a density > 1000 kg m⁻³ [18]. A briquette string leaves the press while hot, due to the friction in the nozzle. The briquette breaks into random lengths depending on the binding capacity of the raw material. To obtain briquettes of uniform length, the briquette string is cut either with a saw or a cutter. The cooling and transport line mounted on the press influences the quality of the resulting briquettes. For instance, the longer a briquette remains in

Fig. 18 Piston press (reprinted from [214], under open access without permission)



the cooling line, the harder it becomes [213]. Despite the numerous attributes of the mechanical piston press, reports about its performance with banana plant wastes as feedstock could not be found in the literature.

7.3.2 Hydraulic piston press

The hydraulic piston press functions similarly to the mechanical piston press (Fig. 18), however, instead of the mechanical force, the energy exerted on the piston is generated by a hydraulic system that works via a cylinder [215]. It consists of a hydraulic cylinder specially designed to generate pressure for compaction of biomass into fuel briquettes. The developed pressure, however, is usually limited, resulting in briquettes with a density $\leq 1000 \text{ kgm}^{-3}$ [18]. The compacted briquette is released once the required pressure is reached. Compared to mechanical presses, hydraulic presses exhibit a lower output due to the relatively slow movement of the hydraulic cylinder. Despite its disadvantages, the hydraulic press is the most commonly used technology for briquetting banana plant wastes such as banana peels [44, 65, 66] and banana leaves [3, 198]. For example, using a hydraulic press, banana peels and banana starch (binder) were compacted at ratios ranging from 10:1 to 10:2, producing briquettes with a compressive strength of 38.01–38.39 MPa [66]. Similarly, banana leaves and peels were compacted with banana peels as a binder, resulting in briquettes with a higher heating value of 13.25 MJkg^{-1} and compressive strength of 13.4 MPa [65]. Banana leaves were compacted at 18 MPa and compression time of 0.6 to 1 s, producing briquettes with a compressive strength of 3.60–5.30 MPa, a higher heating value of 17.70 MJkg^{-1} , a bulk density of $990\text{--}1000 \text{ kgm}^{-3}$, and an energy density of $17,523 \text{ MJm}^{-3}$ [198]. These studies highlight the promising potential of banana plant wastes as feedstocks for briquetting. However, there is still a need for comprehensive studies into the physico-mechanical properties of briquettes derived from banana plant wastes. Moreover, other banana plant wastes, such as rhizomes,

peduncles, and inflorescences are yet to be explored for briquette production.

7.3.3 Roller press

Roller presses consist of two cylindrical rollers of the same diameter, rotating horizontally in opposite directions on parallel axes [26] (Fig. 19). When the ground biomass is forced into the gap between the two rollers, it is pressed into small pockets, forming fuel briquettes. The counter-current rotation of the rollers ensures that biomass enters from one side and discharges on the opposite side as fuel

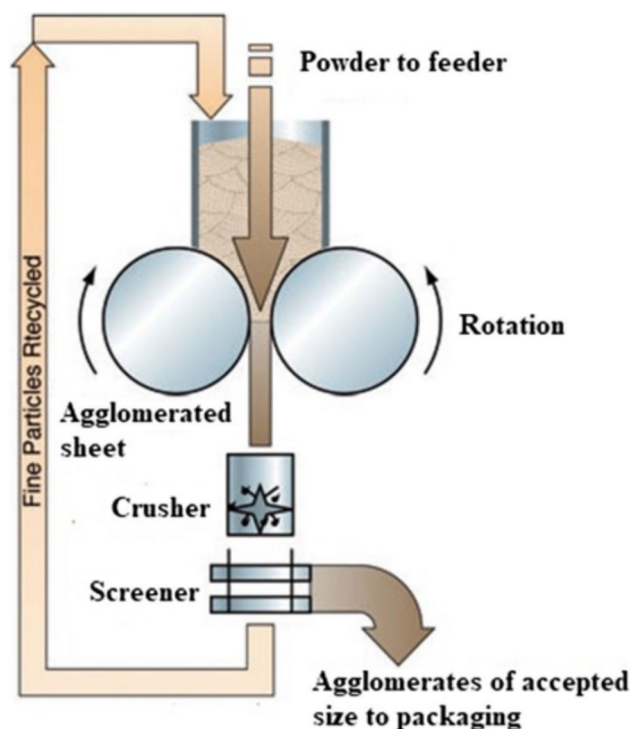


Fig. 19 Roller press (reprinted from [214], under open access without permission)

briquette. The quality of the resultant briquette is influenced by a number of factors, including diameter of the rollers, gap width, roller force, and shape of the die. The bulk density of the resultant briquettes typically ranges from 450 to 550 kgm⁻³ [18]. It is worth noting that limited reports on briquetting of banana plant wastes using roller press were found in the literature. For instance, using clay as a binder, banana bunch waste was carbonized at 350 °C and then compacted, producing briquettes with high heating value, hardness and ultimate strength of 25.06 MJkg⁻¹, 25.90 kg, and 2.26 kgcm⁻², respectively [76]. Banana peels were also carbonized at the same temperature and compacted, producing briquettes with high heating value, hardness and ultimate strength of 27.76 MJkg⁻¹, 23.31 kg, and 2.0 kgcm⁻², respectively [76]. To optimize the utilization of banana plant wastes for briquetting purposes, there is a need to direct more research efforts towards optimization of the conditions for briquetting banana plant wastes using the roller press technology. Comprehensive studies into the physico-mechanical properties of the produced briquettes are also needed to provide insights which could inform the suitability of the respective banana plant wastes for briquetting using the roller press technology.

7.3.4 Screw press

A screw press operates by extruding feedstock continuously through a heated taper die [186]. It comprises a feed port, rotating screw, barrel, and die. When the biomass enters through the feed port, the rotating screw propels it along the barrel towards the die. This process results in a significant pressure gradient and friction due to shearing of the biomass. The combined effects of wall friction in the barrel, internal friction within the material, and the high rotational speed of the screw (~600 rpm) increase the temperature of the biomass [18]. Binders can be used in a small amount for this type of technology, however, at low die temperature (200 to 250 °C), a higher amount of binder is required as softening of the lignin is not achieved in this temperature range [26]. The heated biomass is forced through the extrusion die to form briquettes (Fig. 20). The screw press was used to co-briquette banana leaves and pseudostems at a die temperature of 300 °C, resulting in briquettes with density, higher heating value, moisture content, fixed carbon and ash contents of 720 kgm⁻³, 10.30 MJkg⁻¹, 10.33wt%, 27.09%db and 48.3%db, respectively [181]. Similar to the other briquetting technologies, there is a need to explore other banana plant wastes, as well as investigate comprehensively the physico-mechanical properties of the produced briquettes.

Table 10 summarizes the advantages and disadvantages associated with the different types of briquetting technologies.

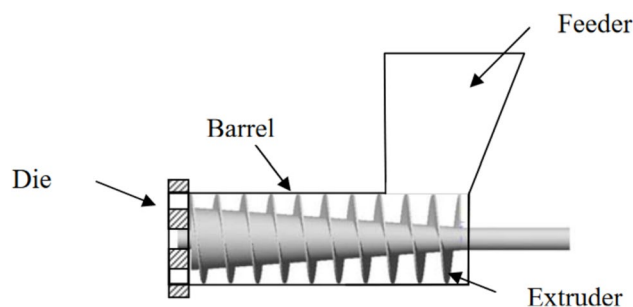


Fig. 20 Screw press (reprinted from [216], under open access without permission)

7.4 Emission potential of briquettes

The conversion of banana plant wastes into briquettes offers an environmentally benign solution, by reducing carbon footprint and emission of harmful gases like CO₂, CO, volatile organic compounds (VOCs), H₂S, NO_x, SO_x, unburned/or partially burned hydrocarbons (C_xH_y) and particulate matter (PM). For instance, cooking with carbonized briquettes reduced emissions of CO₂, CO, and PM_{2.5} by 60, 72 and 88%, respectively, compared to conventional charcoal [218]. Jiao [27] reported lower PM_{2.5} emissions from burning carbonized briquettes compared to raw fuels. However, briquettes with high ash content (> 5–20%) tend to emit more PM in form of dust particles when burnt [3]. Briquettes with such high ash content reported in the literature include carbonized briquettes from banana peels 32.52–41.14% [76], banana leaves and pseudostems 48.3% [181] and banana bunch waste 41.93% [76]. Compared to carbonized briquettes, the non-carbonized briquettes tend to produce more smoke due to poor combustion properties [186]. To ensure wider adoption, especially amid growing environmental concerns, efforts should focus on minimizing the emission potential of briquettes. Unfortunately, comprehensive reports on the emission potential of briquettes derived from banana plant wastes could not be found in the literature.

8 Future prospects

Banana plant wastes are lignocellulosic in nature, containing high contents of cellulose and hemicellulose relative to lignin. However, some studies reported relatively high lignin content in specific banana wastes, such as pseudostem (37.30%daf) [46] and stalks (20.0%daf) [7]. Banana pseudostem fibres were reported to have hemicellulose content as low as 10%daf [54], while elsewhere [46], banana pseudostems was reported to have a hemicellulose content as high as 17.5%db. These contrasting

Table 10 Advantages and disadvantages of different types of briquetting technologies [18, 26, 28, 217]

Briquetting technology	Advantages	Disadvantages
Mechanical piston press	- Exhibits a higher throughput - Briquettes exhibit higher unit densities - Energy loss in the machine is low - Operating life considerably longer - Better return on investment	- Tolerates moisture contents $\leq 15\%$ -
Hydraulic piston press	- Tolerates higher moisture contents than the mechanical piston press - Light and compact	- Developed pressure is limited, leading to briquettes with lower unit densities - Requires binder - low throughput ($50\text{--}400\text{ kg hr}^{-1}$) due to the relatively slow movement of the hydraulic cylinder - Operating life considerably shorter - Lower return on investment
Roller press	- Moderate combustion performance - Low maintenance requirements	- Requires binder - High wear of contact parts
Screw press	- Low capital, and operation costs - Briquettes do not disintegrate easily	- Low pressure developed - Low production capacity (between 5 and 50 kg hr^{-1}) - Requires binder - High specific energy demands compared to piston presses - Substantial wear on the screws - High maintenance costs

results point to a wide variation in properties of banana plant wastes, even within the same type. This wide variation in properties may be due to differences in growth conditions, maturity stage and geographical origin [82]. Despite these insights, banana plant wastes such as rhizome and inflorescences are yet to be characterized for use in thermochemical conversion processes. Future studies should, therefore, explore these wastes for their potential utilization in thermochemical conversion processes.

Of the thermochemical conversion processes, pyrolysis is the most widely employed process for valorising banana plant wastes (see Tables 5 and 7). Notably, reports on torrefaction of banana plant wastes specific to the sub-Saharan African context are scarce in the literature, which can hinder their tailored application in biofuel production. Pyrolyzed banana plant wastes are the most widely used for briquette production compared to its torrefied counterparts (see Table 10). Future studies should evaluate the feasibility of briquetting torrefied banana plant wastes.

During thermochemical processing for solid biofuels as biochar, bio-coal or hydrochar, a significant portion of the lignocellulosic components is lost as volatiles. While these volatiles hold potential value as biofuels in the form of syngas or bio-oil, studies investigating their co-production with the solid biofuels are still scarce in the literature. Therefore, future studies could explore the possibility of co-production of biofuels from various banana plant

wastes, which could potentially enhance the economic viability of thermochemical conversion processes.

As the production of biofuels from banana plant wastes gains traction, concerns about raw material shortages may emerge due to seasonality and competing uses of the feedstocks. Research efforts to address this challenge have been made, including co-briquetting of banana plant wastes with other agricultural residues [65, 183, 184, 186, 207]. However, co-thermochemical conversion of banana plant wastes with other agricultural wastes remains scarcely reported in the literature. Future studies should investigate this possibility to ascertain the impact of this approach on the conversion process in terms of yields and quality of the solid, liquid and gaseous products.

The hydraulic press is the most commonly used technology for briquetting banana plant wastes. Depending on factors such as binder-to-biomass ratio, dwell time, and compaction pressure, this method can produce briquettes with compressive strengths ranging from 1.33 to 38.39 MPa [3, 66]. With other briquetting technologies, including manual mould [75], roller press [76] and screw extruder [181], reports on the mechanical properties of briquettes derived from banana plant wastes could not be found in the literature. Consequently, there is a need for comprehensive studies on the physico-mechanical properties of fuel briquettes derived from banana plant wastes. However, briquettes can have ash content as high as $> 20\%$ db [76, 181], which not

only reduces their calorific value, but also leads to increased emission of particulate matter during combustion. For enhanced fuel properties, banana plant wastes with inherently high ash content need to be pretreated prior to their thermochemical conversion and/or densification.

Binders are an important component of the briquetting process as they improve the cohesive characteristic of biomass, producing more durable fuel briquettes. Organic binders have mostly been used for briquetting banana plant wastes, including banana peels [65], molasses [44], banana starch [66], waste paper [3], cassava starch [3], starch-based adhesive [199]. On the other hand, the use of inorganic binders has been mainly limited to clay [76]. Given a wide range of inorganic binders available, the use of alternative inorganic binders should be explored to find the most effective binders for briquetting of banana plant wastes. Moreover, both inorganic and organic binders have their limitations, which can be overcome by using composite binders, for instance, banana peels, waste paper and clay [221]. Unfortunately, studies exploring the use of composite binders in the production of fuel briquettes from banana plant wastes are rare in the literature. Future studies should investigate this possibility to find the best combinations of organic and inorganic binders suitable for producing briquettes with better fuel properties.

Using torrefied and pyrolyzed banana plant wastes as fuels in combustion facilities may have positive environmental impacts, as they produce lower emissions of primary pollutants compared to raw biomass [45]. Reports to provide deeper insights into the emission potential of using the torrefied and pyrolyzed wastes are limited. A review of the literature found only one study by Mopoung et al. [76] that examined dust and CO emissions from briquettes made from banana peels and banana bunch wastes. More comprehensive studies are needed to better understand the emission profiles of converting banana plant wastes into bio-fuels, particularly for pollutants like CO₂, H₂S, SO₂, NO_x, NO, NO₂, and C_xH_y. Such research could inform strategies to minimize emissions and encourage broader adoption of these technologies, especially given the growing focus on environmental protection. Lastly, while thermochemical conversion and briquetting of banana plant wastes may incur significant costs, these could be offset by the low cost of the raw materials, improved fuel properties, and better handling, transportation, and storage.

9 Conclusion

This review article delves into the current progress on torrefaction, hydrothermal carbonization, pyrolysis and briquetting of banana plant wastes for fuel. The article highlights the properties of different banana plant wastes, their

potential pretreatments and suitability for pyrolysis, torrefaction, hydrothermal carbonization and briquetting. These processing techniques are also comprehensively discussed, including various reactor types and briquetting technologies, their operational requirements and performance with different banana plant wastes as feedstocks. Banana plant wastes are rich in cellulose and hemicellulose but low in lignin, making them better suited for producing syngas and bio-oil compared to solid biofuels like biochar, bio-coal, or hydrochar. Of the thermochemical conversion processes, pyrolysis is the most widely employed process for valorising the banana plant wastes. Notably, reports on torrefaction of banana plant wastes specific to the sub-Saharan African context are scarce in the literature, which can hamper their tailored application in biofuel production. The hydraulic press is the most commonly used technology for briquetting banana plant wastes. Depending on factors such as binder-to-biomass ratio, dwell time, and compaction pressure, this method can produce briquettes with compressive strengths ranging from 1.33 to 38.39 MPa. With other briquetting technologies, including manual mould, roller press and screw extruder, reports on the mechanical properties of briquettes derived from banana plant wastes could not be found. Consequently, there is a need for comprehensive studies on the physico-mechanical properties of fuel briquettes derived from banana plant wastes. Briquettes from banana plant wastes can have ash content as high as > 20%db, which not only reduces their calorific value, but also leads to increased emission of particulate matter during combustion. For enhanced fuel properties, banana plant wastes with inherently high ash content need to be pretreated prior to their thermochemical conversion and/or densification. Overall, this review offers a comprehensive perspective of research on thermochemical processing and briquetting of banana plant wastes, providing direction for future research aimed at advancing the use of these resources for energetic applications while addressing environmental concerns.

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.

Author contribution **Emmanuel Menya:** Conceptualization, Methodology, Validation, Writing-original draft, Fund Acquisition and Project Administration. **Collins Okello:** Conceptualization, Supervision, Writing – review & editing. **Henning Storz:** Conceptualization, Supervision, Writing – review & editing. **Joel Wakatuntu:** Conceptualization, Writing-original draft, review & editing. **Medard Turyasingura:** Conceptualization, Writing-original draft, review & editing. **David K. Okot:** Conceptualization, Writing-original draft, review & editing. **Simon Kizito:** Conceptualization, Writing-original draft, review & editing. **Allan J. Komakech:** Conceptualization, Writing-original draft, review & editing. **Isa Kabenge:** Conceptualization, Writing-original draft, review & editing. **Samson Rwahwire:** Conceptualization, Visualization, Writing-original draft. **Peter Wilberforce Olupot:** Conceptualization, Supervision, Writing – review & editing.

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.

Declarations

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

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

- Castillo M, de Guzman MJK, Aberilla JM (2023) Environmental sustainability assessment of banana waste utilization into food packaging and liquid fertilizer. *Sustain Prod Consum* 37:356–368
- Fernandes ERK, Marangoni C, Souza O, Sellin N (2013) Thermochemical characterization of banana leaves as a potential energy source. *Energy Convers Manag* 75:603–608. <https://doi.org/10.1016/j.enconman.2013.08.008>
- Bamisaye A, Ayodeji I (2023) Effect of binder type on the NaOH-treated briquettes produced from banana leaves. *Biomass Convers Biorefinery* 13:8939–8947. <https://doi.org/10.1007/s13399-021-01771-9>
- Sulaiman SM et al (2023) Valorization of banana bunch waste as a feedstock via hydrothermal carbonization for energy purposes. *J Ecol Eng* 24(7):61–74. <https://doi.org/10.12911/22998993/163350>
- Gumisiriza R, Hawumba JF, Okure M, Hensel O (2017) Biomass waste-to-energy valorisation technologies: A review case for banana processing in Uganda. *Biotechnol Biofuels* 10(1):1–29. <https://doi.org/10.1186/s13068-016-0689-5>
- Bhushan S, Rana MS, Nandan N, Prajapati SK (2019) Energy harnessing from banana plant wastes : A review. *Bioresour Technol Reports* 7:100212. <https://doi.org/10.1016/j.biteb.2019.100212>
- Islam A, Akber A, Limon SH, Akbor A, Islam A (2019) Characterization of solid biofuel produced from banana stalk via hydrothermal carbonization. *Biomass Convers Biorefinery* 9:651–658
- Adeniyi AG, Ighalo JO, Amosa MK (2021) Modelling and simulation of banana (*Musa spp.*) waste pyrolysis for bio-oil production. *Biofuels* 12(7):879–883. <https://doi.org/10.1080/17597269.2018.1554949>
- Taib RM, Abdullah N, Syairah N, Aziz M (2021) Bio-oil derived from banana pseudo-stem via fast pyrolysis process. *Biomass Bioenerg* 148:106034. <https://doi.org/10.1016/j.biombioe.2021.106034>
- Acevedo SA, Carrillo ÁJD, Flórez-López E, Grande-tovar CD (2021) Recovery of banana waste-loss from production and processing: a contribution to a circular economy. *Molecules* 26:5282
- Te WZ et al (2021) Optimization of pyrolysis parameters for production of biochar from banana peels: evaluation of biochar application on the growth of *Ipomoea aquatica*. *Front Energy Res* 8(February):1–16. <https://doi.org/10.3389/fenrg.2020.637846>
- Gumisiriza R, Hawumba JF, Okure M, Hensel O (2017) Biomass waste - to - energy valorisation technologies : a review case for banana processing in Uganda. *Biotechnol Biofuels* 10(11):1–29. <https://doi.org/10.1186/s13068-016-0689-5>
- Ercan B, Alper K, Ucar S, Karagoz S (2023) Comparative studies of hydrochars and biochars produced from lignocellulosic biomass via hydrothermal carbonization, torrefaction and pyrolysis. *J Energy Inst* 109:101298. <https://doi.org/10.1016/j.joei.2023.101298>
- Abdullah N, Mohd R, Syairah N, Aziz M, Rabie M, Disa N (2023) Banana pseudo-stem biochar derived from slow and fast pyrolysis process. *Heliyon* 9:e12940. <https://doi.org/10.1016/j.heliyon.2023.e12940>
- Liu X, Li D, Yang J, Yuan L (2022) Kinetic mechanisms and emissions investigation of torrefied pine sawdust utilized as solid fuel by isothermal. *Materials (Basel)* 15:8650
- Orisaleye JI, Jekayinfa SO, Pecenk R, Ogundare AA, Akin-seloyin MO, Fadipe OL (2022) Investigation of the effects of torrefaction temperature and. *Energies* 15:528
- Chen W, Lin B, Lin Y, Chu Y, Ubando AT, Loke P, Chyuan H, Chang J, Ho S, Culaba AB, Pétrissans A, Pétrissans M (2021) Progress in biomass torrefaction : principles, applications and challenges. *Prog Energy Combust Sci* 82:100887. <https://doi.org/10.1016/j.pecs.2020.100887>
- Tumuluru JS, Sokhansanj S, Hess JR, Wright CT, Boardman RD (2011) A review on biomass torrefaction process and product properties for energy applications. *Ind Biotechnol* 7(5):384–401. <https://doi.org/10.1089/ind.2011.0014>
- Negi S, Jaswal G, Dass K, Mazumder K, Elumalai S, Roy JK (2020) Torrefaction : a sustainable method for transforming of agri- wastes to high energy density solids (biocoal). *Rev Environ Sci Bio/Technol* 19:463–488. <https://doi.org/10.1007/s1157-020-09532-2>
- Simonic M, Goricanec D, Urbancl D (2020) Impact of torrefaction on biomass properties depending on temperature and operation time. *Sci Total Environ* 740:140086. <https://doi.org/10.1016/j.scitotenv.2020.140086>
- Khairy M, Ibrahim MAM, Sekiguchi SOH (2024) The influence of torrefaction on the biochar characteristics produced from sesame stalks and bean husk. *Biomass Convers Biorefinery* 14:17127–17148. <https://doi.org/10.1007/s13399-023-03822-9>
- Marreiro HMP, Peruchi RS, Andersen SLF, Lopes RMBP, Eliziário SA, Junior PR (2021) Empirical studies on biomass briquette production : A literature review. *Energies* 14(24):8320
- Balmuk G, Cay H, Duman G, Kantarli CI, Yanik J (2023) Hydrothermal carbonization of olive oil industry waste into solid fuel: Fuel characteristics and combustion performance. *Energy* 278:127803
- Mohammadi A, Venkatesh G, Sandberg M, Eskandari S (2020) A Comprehensive environmental life cycle assessment of the use of hydrochar pellets in combined heat and power plants. *Sustainability* 12(21):9026
- Waheed MA, Akogun OA, Enweremadu CC (2022) An overview of torrefied bioresource briquettes : quality - influencing parameters, enhancement through torrefaction and applications. *Bioresour Bioprocess* 1:1–18. <https://doi.org/10.1186/s40643-022-00608-1>
- Sithole T, Pahl G, Mashifana T, Mamvura T (2023) A review of the combined torrefaction and densification technology as a source of renewable energy. *Alexandria Eng J* 82:330–341. <https://doi.org/10.1016/j.aej.2023.09.080>
- Jiao W et al (2020) Optimization of process variables for briquetting of biochar from corn stover. *BioResources* 15(3):6811–6825
- Ibitoye SE, Jen TC, Mahmood RM, Akinlabi ET (2021) Densification of agro - residues for sustainable energy generation: an overview. *Bioresour Bioprocess* 8:75. <https://doi.org/10.1186/s40643-021-00427-w>
- Lu Y, Brabie L, Karasev AV, Wang C (2022) Applications of hydrochar and charcoal in the iron and steelmaking industry — Part 2: Carburation of liquid iron by addition of iron – carbon briquettes. *Sustainability* 14(9):5383
- Setter C, Ataíde CH, Mendes RF, José T, De Oliveira P (2021) Influence of particle size on the physico-mechanical and energy

- properties of briquettes produced with coffee husks. *Environ Sci Pollut Res* 28:8215–8223
31. Kataki R, Kataki MD (2022) Chapter 20 - weeds as a renewable bioresource: prospects for bioconversion to biofuels and biomaterials through a cascade of approaches. In: Gurunathan B, Sahadevan R, Zakaria ZA (eds) *Biofuels and bioenergy: opportunities and challenges*, pp 437–461. <https://doi.org/10.1016/B978-0-323-85269-2.00021-6>
 32. Eixenberger D et al (2022) Tropical agroindustrial biowaste revalorization through integrative biorefineries — review part II : pineapple, sugarcane and banana by - products in Costa Rica. *Biomass Convers Biorefinery*. <https://doi.org/10.1007/s13399-022-02721-9>
 33. Giwa AS, Sheng M, Maurice NJ, Liu X, Wang Z (2023) Biofuel recovery from plantain and banana plant wastes : Integration of biochemical and thermochemical approach biofuel recovery from plantain and banana plant wastes : Integration of biochemical and thermochemical approach. *J Renew Mater* 11(6):2593–2629. <https://doi.org/10.32604/jrm.2023.026314>
 34. Liu S, Li J, Xu S, Wang M, Zhang Y, Xue X (2019) A modified method for enhancing adsorption capability of banana pseudostem biochar towards methylene blue at low temperature. *Bioresour Technol* 282(December 2018):48–55. <https://doi.org/10.1016/j.biortech.2019.02.092>
 35. Sivasdas DL, Damodaran A, Raghavan R (2019) Microporous carbon monolith and fiber from freeze-dried banana stems for high efficiency carbon dioxide adsorption. *ACS Sustain Chem Eng* 7(15):12807–12816. <https://doi.org/10.1021/acssuschemeng.9b01653>
 36. Xu S, Yu W, Liu S, Xu C, Li J, Zhang Y (2018) Adsorption of hexavalent chromium using banana pseudostem biochar and its mechanism. *Sustain* 10:1–12. <https://doi.org/10.3390/su10114250>
 37. Vimal V et al (2022) Nutrients enriched biochar production through Co-Pyrolysis of poultry litter with banana peduncle and phosphogypsum waste. *Chemosphere* 300:134512. <https://doi.org/10.1016/j.chemosphere.2022.134512>
 38. Karim AA, Kumar M, Singh SK, Panda CR, Mishra BK (2016) Potassium enriched biochar production by thermal plasma processing of banana peduncle for soil application. *J Anal Appl Pyrolysis* 123:165–172. <https://doi.org/10.1016/j.jaap.2016.12.009>
 39. Lescot T (2020) Banana genetic diversity: Estimated world production by type of banana. *FruiTrop* 269:98–103
 40. FAO (2023) FAOSTAT: production: crops and livestock products. Rome. Cited November, 2023. Retrieved from <https://www.fao.org/faostat/en/#data/QCL>
 41. Sogi DS (2020) Value-added processing and utilization of banana by-products. In: Siddiq M, Ahmed J, Lobo MG (Eds.) *Handbook of Banana Production, Postharvest Science, Processing Technology, and Nutrition*, First Edit. John Wiley & Sons Ltd, pp. 191–206. <https://doi.org/10.1002/9781119528265.ch10>
 42. de Oliveira Maia BG, de Oliveira APN, de Oliveira TMN, Marangoni C, Souza O, Sellin N (2018) Characterization and production of banana crop and rice processing waste briquettes. *Environ Prog Sustain Energy* 37(4):1266–1273. <https://doi.org/10.1002/ep.12798>
 43. Pazmiño-Hernandez M, Moreira CM, Pullammanappallil P (2019) Feasibility assessment of waste banana peduncle as feedstock for biofuel production. *Biofuels* 10(4):473–484. <https://doi.org/10.1080/17597269.2017.1323321>
 44. Wilaipon P (2009) 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* 6(1):167–171
 45. Alves JLF et al (2022) Upgrading of banana leaf waste to produce solid biofuel by torrefaction: physicochemical properties, combustion behaviors, and potential emissions. *Environ Sci Pollut Res* 29:25733–25747
 46. Abdullah N, Sulaiman F, Miskam MA, Taib RM (2014) Characterization of banana (Musa spp.) pseudo-stem and fruit-bunch-stem as a potential renewable energy resource. *Int J Biol Vet Agric Food Eng* 8(8):712–716
 47. Manimaran P, Sanjay MR, Senthamaraikannan P, Jawaid M, George R (2019) Synthesis and characterization of cellulosic fiber from red banana peduncle as reinforcement for potential applications. *J Nat Fibers* 16(5):768–780. <https://doi.org/10.1080/15440478.2018.1434851>
 48. Kabenge I, Omulo G, Banadda N, Seay J, Zziwa A, Kiggundu N (2018) Characterization of banana peels wastes as potential slow pyrolysis feedstock. *J Sustain Dev* 11(2):14–24. <https://doi.org/10.5539/jsd.v11n2p14>
 49. De Jong W (2014) Biomass composition, properties, and characterization. In: De Jong W, Van Ommen JR (Eds.) *Biomass as a Sustainable Energy Source for the Future: Fundamentals of Conversion Processes*, pp. 36–68. <https://doi.org/10.1002/9781118916643.ch2>
 50. Santiago B, Moreira MT, Feijoo G, Gonz S (2022) Environmental comparison of banana waste valorisation strategies under a biorefinery approach. *Waste Manag* 142:77–87. <https://doi.org/10.1016/j.wasman.2022.02.005>
 51. Menyá E, Olupot PW, Storz H, Lubwama M, Kiros Y (2018) Production and performance of activated carbon from rice husks for removal of natural organic matter from water: a review. *Chem Eng Res Des* 129:271–296. <https://doi.org/10.1016/j.cherd.2017.11.008>
 52. Gumisiriza R, Funa J, Peter AS, Okure M, Hensel O (2019) 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* 53(1):215–236
 53. Zaini HM et al (2023) Banana biomass waste : A prospective nanocellulose source and its potential application in food industry – A review. *Heliyon* 9(8):e18734
 54. Cecci RRR, Passos AA, De Anguir Neto TC, Silva LA (2020) Banana pseudostem fibers characterization and comparison with reported data on jute and sisal fibers. *SN Appl Sci* 2:1–6. <https://doi.org/10.1007/s42452-019-1790-8>
 55. Lebedeva D, Hijmans S, Mathew AP, Subbotina E, Samec JSM (2022) Waste-to-fuel approach: valorization of lignin from coconut coir pith. *Agric Sci Technol* 2:349–358. <https://doi.org/10.1021/acsaagstech.1c00248>
 56. Granados DA, Velasquez HI, Chejne F (2014) Energetic and exergetic evaluation of residual biomass in a torrefaction process. *Energy* 74:181–189. <https://doi.org/10.1016/j.energy.2014.05.046>
 57. Sellin N, De Oliveira BG, Marangoni C, Souza O, de Oliveira PN, de Oliveira TMN (2013) Use of banana culture waste to produce briquettes. *Chem Eng Trans* 32:349–354
 58. Kan T, Strezov V (20114) Combustion of Biomass. In: Kan T, Strezov V (Eds.) *Biomass Processing Technologies*, Boca Raton, FL: CRS Press: Taylor & Francis, pp. 53–80. <https://doi.org/10.1201/b17093-4>
 59. IRENA (2023) Agricultural residue-based bioenergy: regional potential and scale-up strategies. International Renewable Energy Agency, Abu Dhabi
 60. Mckendry P (2002) Energy production from biomass (part 2): conversion technologies. *Bioresour Technol* 83:47–54
 61. Knoef H (2005) Practical aspects of biomass gasification. In: Knoef H (ed) *Handbook Biomass Gasification*. BTG Biomass Technology Group, Enschede

62. Lim HY et al (2023) Recent advancement in thermochemical conversion of biomass to biofuel. *Biofuels* 0(0):1–18. <https://doi.org/10.1080/17597269.2023.2261788>
63. Wang L, Cheng D, Wang L, Cheng D (2014) Biomass pyrolysis and bio-oil utilization. In: Wang L (Ed.) *Sustainable Bioenergy Production*. Boca Raton: CRC Press: Taylor & Francis, pp. 367–387. in *Sustainable Bioenergy Production*, L. Wang, Ed., Boca Raton, FL: CRS Press: Taylor & Francis, 2014, pp. 367–387
64. Cai J et al (2017) Review of physicochemical properties and analytical characterization of lignocellulosic biomass. *Renew Sustain Energy Rev* 76:309–322. <https://doi.org/10.1016/j.rser.2017.03.072>
65. Ku Ahmad K, Sazali K, Kamarolzaman AA (2018) Characterization of fuel briquettes from banana tree waste. *Mater Today Proc* 5:21744–21752. <https://doi.org/10.1016/j.matpr.2018.07.027>
66. Sindol KN, Gadat AST, Joan E, Sanchez JJ, Philip E, Sanchez DC (2022) Development and characterization of briquettes made from unsalable banana peel wastes : A preliminary evaluation. In : *Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES)*, pp. 265–270. [Online]. Available: <https://doi.org/10.5109/5909102%0A出版情報: Proceedings>
67. Olupot PW, Candia A, Menya E, Walozi R (2016) Characterization of rice husk varieties in Uganda for biofuels and their techno-economic feasibility in gasification. *Chem Eng Res Des* 107:63–72. <https://doi.org/10.1016/j.cherd.2015.11.010>
68. Tilman D (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* (80-) 314:1598. <https://doi.org/10.1126/science.1133306>
69. Akogun OA, Waheed MA, Ismaila SO, Dairo OU (2020) Co-briquetting characteristics of cassava peel with sawdust at different torrefaction pretreatment conditions. *Energy Sources Part A Recover Util Environ Eff* pp. 1–19. <https://doi.org/10.1080/15567036.2020.1752333>
70. Sellin N, Ricardo D, Marangoni C, Souza O (2016) Oxidative fast pyrolysis of banana leaves in fluidized bed reactor. *Renew Energy* 96:56–64. <https://doi.org/10.1016/j.renene.2016.04.032>
71. Mosqueda A et al (2021) Hydrothermal treatment of banana leaves for solid fuel combustion. *Biofuels* 12(9):1123–1129. <https://doi.org/10.1080/17597269.2019.1594590>
72. Kpalo SY, Zainuddin MF, Manaf LA, Roslan AM (2020) A review of technical and economic aspects of biomass briquetting. *Sustainability* 12(11):4609. <https://doi.org/10.3390/su12114609>
73. Demirbas A (1997) Calculation of higher heating values of biomass fuels. *Fuel* 76(5):431–434
74. Orisaleye JI, Jekayinfa SO, Pecenka R, Ogundare AA, Akinseyin MO, Fadipe OL (2022) Investigation of the effects of torrefaction temperature and residence time on the fuel quality of corncobs in a fixed-bed reactor. *Energies* 15:5284
75. Bot BV, Thierry O, Jean S, Tamba G, Lekane E, Bikai J, Ndam MK (2023) Preparation and characterization of biomass briquettes made from banana peels, sugarcane bagasse, coconut shells and rattan waste. *Biomass Convers Biorefinery* 13:7937–7946. <https://doi.org/10.1007/s13399-021-01762-w>
76. Mopoung S, Udeye V (2017) Characterization and evaluation of charcoal briquettes using banana peel and banana bunch waste for household heating. *Am J Eng Appl Sci* 10(2):353–365. <https://doi.org/10.3844/ajeassp.2017.353.365>
77. Hikal WM et al (2022) Banana peels : A waste treasure for human being. *Evid-Based Complement Altern Med* 2022:1–9
78. Pereira ALS et al (2014) Banana (*Musa sp. cv. Pacovan*) pseudostem fibers are composed of varying lignocellulosic composition throughout the diameter. *BioResources* 9(4):7749–7763. <https://doi.org/10.15376/biores.9.4.7749-7763>
79. Yusuf I, Flagiello F, Ward NI, Arellano- H, Avignone-rossa C, Felipe-sotelo M (2020) Valorisation of banana peels by hydrothermal carbonisation: potential use of the hydrochar and liquid by-product for water purification and energy conversion. *Biore-sour Technol Rep* 12:100582. <https://doi.org/10.1016/j.biteb.2020.100582>
80. Jenkins BM, Baxter LL, M TR Jr, Miles TR (1998) Combustion properties of biomass. *Fuel Process Technol* 54:17–46
81. Zhao P, Shen Y, Ge S, Chen Z, Yoshikawa K (2014) Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment. *Appl Energy* 131:345–367. <https://doi.org/10.1016/j.apenergy.2014.06.038>
82. Kumari P, Tiwari RK (2023) Banana and its by - products : A comprehensive review on its nutritional composition and pharmacological benefits. *eFood* 4:1–23. <https://doi.org/10.1002/efd2.110>
83. Ramu R et al (2017) Assessment of nutritional quality and global antioxidant response of banana. *Pharmacogn Res* 9:S74–83. <https://doi.org/10.4103/pr.pr>
84. Cheng Q, Jiang M, Chen Z, Wang X, Xiao B (2016) Pyrolysis and kinetic behavior of banana stem using thermogravimetric analysis. *Energy Sources A Recover Util Environ Eff* 38(22):3383–3390. <https://doi.org/10.1080/15567036.2016.1153754>
85. Devaraja UMA, Dissanayake CLW, Gunarathne DS, Chen W (2022) Oxidative torrefaction and torrefaction-based biorefining of biomass : a critical review. *Biofuel Res J* 35:1672–1696. <https://doi.org/10.18331/BRJ2022.9.3.4>
86. Streitwieser DA, Villamil DO, Gutierrez E, Salazar S, Mora JR, Bejarano ML (2021) Fast pyrolysis as a valorization mechanism for banana rachis and low-density polyethylene waste. *Chem Eng Technol* 44(11):2092–2099. <https://doi.org/10.1002/ceat.20210232>
87. Jiang F et al (2023) Combustion of the banana Pseudo-stem hydrochar by the High-Pressure CO₂-Hydrothermolysis: Thermal conversion, kinetic, and emission analyses. *Fuel* 331(Part 1):125798. <https://doi.org/10.1016/j.fuel.2022.125798>
88. Deng L, Zhang T, Che D (2013) Effect of water washing on fuel properties, pyrolysis and combustion characteristics, and ash fusibility of biomass. *Fuel Process Technol* 106:712–720. <https://doi.org/10.1016/j.fuproc.2012.10.006>
89. Patricia E, Alves R, Salcedo-puerto O, Emebu S, Mendoza-martinez C (2023) Renewable energy potential and CO₂ performance of main biomasses used in Brazil. *Energies* 16:3959
90. Mosqueda A, Medrano K, Gonzales H, Yoshikawa K (2019) Effect of hydrothermal and washing treatment of banana leaves on co-gasification reactivity with coal co-gasification reactivity with coal. *Energy Procedia* 158:785–791
91. Singh RK, Pandey D, Patil T, Sawarkar AN (2020) Pyrolysis of banana leaves biomass : Physico-chemical characterization, thermal decomposition behavior, kinetic and thermodynamic analyses. *Bioresour Technol* 310(April):123464. <https://doi.org/10.1016/j.biortech.2020.123464>
92. Neto JM, Komesu A, da S. Martins LH, Goncalves VOO, de Oliveira JAR, Rai M (2019) Third generation biofuels : an overview. In: Rai M, Ingle AP (Eds.) *Sustainable Bioenergy*, Elsevier Inc., pp. 283–298. <https://doi.org/10.1016/B978-0-12-817654-2.00010-1>
93. Goyal HB, Seal D, Saxena RCĀ (2008) Bio-fuels from thermochemical conversion of renewable resources : A review. *Renew Sustain Energy Rev* 12:504–517. <https://doi.org/10.1016/j.rser.2006.07.014>
94. Nunes LJR, Ribeiro JMC, Sá LCR, Loureiro LMEF, Godina R, Matias JCO (2020) Development of a low-cost experimental procedure for the production of laboratory samples of torrefied

- biomass. *Clean Technol* 2(4):406–421. <https://doi.org/10.3390/cleantechnol2040025>
95. Chen Z, Wang M, Jiang E, Wang D, Zhang K, Ren Y (2018) Pyrolysis of torrefied biomass. *Trends Biotechnol* 36(12):1287–1298. <https://doi.org/10.1016/j.tibtech.2018.07.005>
 96. Xue G et al (2014) Gasification of torrefied *Miscanthus x giganteus* in an air-blown bubbling fluidized bed gasifier. *Bioresour Technol* 159:397–403
 97. Faria FA et al (2022) Fertilizer release kinetics incorporated to torrefied banana - crop residues. *J Therm Anal Calorim* 147:3659–3671. <https://doi.org/10.1007/s10973-021-10764-9>
 98. Prawisudha P, Azka GR, Triyono B, Pasek AD (2018) Multi-production of solid fuel and liquid fertilizer from organic waste by employing wet torrefaction process. *AIP Conf Proc* 1984:1–6. <https://doi.org/10.1063/1.5046629>
 99. Menya E, Jjagwe J, Kalibbala HM, Storz H, Olupot PW (2023) Progress in deployment of biomass-based activated carbon in point-of-use filters for removal of emerging contaminants from water : A review. *Chem Eng Res Des* 192:412–440
 100. Li SX, Chen CZ, Li MF, Xiao X (2018) Torrefaction of corncob to produce charcoal under nitrogen and carbon dioxide atmospheres. *Bioresour Technol* 249:348–353. <https://doi.org/10.1016/j.biortech.2017.10.026>
 101. Pathomrotsakun J, Nakason K (2020) Fuel properties of biochar from torrefaction of ground coffee residue : effect of process temperature, time, and sweeping gas. *Biomass Convers Biorefinery* 10:743–753
 102. Kuo P, Wu W, Chen W (2014) Gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis. *Fuel* 117:1231–1241. <https://doi.org/10.1016/j.fuel.2013.07.125>
 103. Ola FA, Jimoh FA, Okeyode IT, Ogunsola AD (2020) Torrefaction of Plantain (*Musa Paradisiaca*) fruit bunch biomass. *LAUTECH J Civ Environ Stud* 4(1):99–106. [https://doi.org/10.36108/lauijoces/0202/40\(0111\)Abstract](https://doi.org/10.36108/lauijoces/0202/40(0111)Abstract)
 104. Olugbade TO (2020) Biomass torrefaction for the production of high-grade solid biofuels : a review. *BioEnergy Res* 13:999–1015
 105. Valdez E, Tabil LG, Mupondwa E, Cree D, Moazed H (2021) Microwave torrefaction of oat hull: Effect of temperature and residence time. *Energies* 14:4298
 106. Canabal AI, Castineiras JP, Anon JAR, Fraga CE, Soalleiro RR (2023) Predicting the energy properties of torrefied debarked pine pellets from torrefaction temperature and residence time Andr e. *Renew Energy* 218:119346. <https://doi.org/10.1016/j.renene.2023.119346>
 107. Medic D, Darr M, Shah A, Rahn S (2012) The effects of particle size, different corn stover components, and gas residence time on torrefaction of corn stover. *Energies* 5:1199–1214. <https://doi.org/10.3390/en5041199>
 108. He Y, Zhang S, Liu D, Xie X, Li B (2023) Effect of biomass particle size on the torrefaction characteristics in a fixed-bed reactor. *Energies* 16:1104. <https://doi.org/10.3390/en16031104>
 109. Eseyin AE, Steele PH, P CU Jr (2015) Current trends in the production and applications of. *BioResources* 10(4):8812–8858
 110. Moscicki KJ, Niedzwiecka Ł, Owczarek P, Wnukowski M (2014) Commoditization of biomass : dry torrefaction and pelletization — a review. *J Power Technol* 94(4):233–249
 111. Yang X, Wang B, Song X, Cheng F (2024) Evolution characteristics and mechanism of carbon structure during co-hydrothermal carbonization of sewage sludge and sub-bituminous coal. *J Clean Prod* 434:140382
 112. Khedulkar AP, Pandit B, Dang VD, Doong R (2023) Agricultural waste to real worth biochar as a sustainable material for supercapacitor. *Sci Total Environ* 869:161441. <https://doi.org/10.1016/j.scitotenv.2023.161441>
 113. Wu Q et al (2023) Co-torrefaction of corncob and waste cooking oil coupled with fast co-pyrolysis for bio-oil production. *Bioresour Technol* 370:128529
 114. Duman G, Balmuk G, Cay H, Kantarli IC, Yanik J (2020) Comparative evaluation of torrefaction and hydrothermal carbonization : Effect on fuel properties and combustion behavior of agricultural wastes. *Energy Fuels* 34:11175–11185. <https://doi.org/10.1021/acs.energyfuels.0c02255>
 115. Bach Q-V, Tran K-Q (2015) Dry and wet torrefaction of woody biomass – A comparative study on combustion kinetics. *Energy Procedia* 75(1876):150–155. <https://doi.org/10.1016/j.egypro.2015.07.270>
 116. Zhang D et al (2021) Superheated steam as carrier gas and the sole heat source to enhance biomass torrefaction. *Bioresour Technol* 331(March):124955. <https://doi.org/10.1016/j.biortech.2021.124955>
 117. Arteaga-pérez LE, Grandón H, Flores M, Segura C, Kelley SS (2017) Steam torrefaction of *Eucalyptus globulus* for producing black pellets : A pilot-scale experience. *Bioresour Technol* 238:194–204. <https://doi.org/10.1016/j.biortech.2017.04.037>
 118. Lam SP, Sokhansanj S, Bi XT, Lim CJ, Larsson SH (2012) Drying characteristics and equilibrium moisture content of steam-treated Douglas fir (*Pseudotsuga menziesii* L.). *Bioresour Technol* 116:396–402. <https://doi.org/10.1016/j.biortech.2012.03.093>
 119. Brachi P, Miccio F, Ruoppolo G, Stanzione F, Miccio M (2018) Pressurized steam torrefaction of wet agro-industrial residues. *Chem Eng Trans* 65:49–54. <https://doi.org/10.3303/CET1865009>
 120. Djurdjevic M, Papuga S (2023) Torrefaction: Process parameters and reactor design. *Period Polytech Chem Eng* 67(3):416–426
 121. Piersa P et al (2022) An extensive review and comparison of modern biomass torrefaction reactors vs. biomass pyrolysis—Part 1. *Energies* 15:2227. <https://doi.org/10.3390/en15062227>
 122. Basu P (2013) Biomass Gasification, Pyrolysis, and Torrefaction, Practical Design and Theory, Second ed. Elsevier Inc., <https://doi.org/10.1016/B978-0-12-396488-5.00007-1>
 123. Tumuluru JS, Ghiasi B, Soelberg NR, Sokhansanj S (2021) Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts. *Front Energy Res* 9:1–20. <https://doi.org/10.3389/fenrg.2021.728140>
 124. Mamvura TA, Danha G (2020) Biomass torrefaction as an emerging technology to aid in energy production. *Heliyon* 6:e03531. <https://doi.org/10.1016/j.heliyon.2020.e03531>
 125. Jackowski M et al (2020) HTC of wet residues of the brewing process: comprehensive characterization htc of wet residues of the brewing process: comprehensive characterization of produced beer, spent grain and valorized residues. *Energies* 13(8):1–20. <https://doi.org/10.3390/en13082058>
 126. Bach QV, Skreiberg O (2016) Upgrading biomass fuels via wet torrefaction: A review and comparison with dry torrefaction. *Renew Sustain Energy Rev* 54:665–677. <https://doi.org/10.1016/j.rser.2015.10.014>
 127. Brachi P, Miccio F, Ruoppolo G, Miccio M (2017) Pressurized steam torrefaction of biomass : focus on solid, liquid and gas phases distribution Pressurized steam torrefaction of biomass : focus on solid, liquid and gas. *Ind Eng Chem Res* 56(42):12163–12173. <https://doi.org/10.1021/acs.iecr.7b02845>
 128. Zou X et al (2024) In-depth understanding of the microscopic mechanism of biochar carbonaceous structures during thermochemical conversion : Pyrolysis, combustion and gasification. *Fuel* 361:130732
 129. Norouzi O, Taghavi S, Arku P, Jafarian S, Signoretto M, Dutta A (2021) What is the best catalyst for biomass pyrolysis? *J Anal Appl Pyrolysis* 158:105280. <https://doi.org/10.1016/j.jaap.2021.105280>
 130. Zarnegar S (2018) A review on catalytic-pyrolysis of coal and biomass for value-added fuel and chemicals. *Energy Sources A*

- Recover Util Environ Eff 40(12):1427–1433. <https://doi.org/10.1080/15567036.2018.1472680>
131. Wang X, Yang S, Shen B, Yang J, Xu L (2022) Pyrolysis of biomass pineapple residue and banana Pseudo-stem: kinetics, mechanism and valorization of bio-char. *Catalysts* 12(8):840. <https://doi.org/10.3390/catal12080840>
 132. Bindar Y, Budhi YW, Hernowo P, Wahyu S, Saquib S, Setiadi T (2023) Sustainable Technologies for Biochar. In: Ngo HH, Guo W, Pandey A, Varjani S, Tsang DCW (Eds.) *Current Developments in Biotechnology and Bioengineering: Biochar Towards Sustainable Environment*, India: Elsevier Inc., pp. 1–40. <https://doi.org/10.1016/B978-0-323-91873-2.00013-3>
 133. Kazawadi D, Ntalikwa J, Kombe G (2021) A Review of Intermediate Pyrolysis as a Technology of Biomass Conversion for Coproduction of Biooil and Adsorption Biochar. *J Renew Energy*, pp. 1–10. <https://doi.org/10.1155/2021/5533780>
 134. Tripathi M, Sahu JN, Ganesan P (2016) Effect of process parameters on production of biochar from biomass waste through pyrolysis : A review. *Renew Sustain Energy Rev* 55:467–481. <https://doi.org/10.1016/j.rser.2015.10.122>
 135. Mehdi R, Khoja AH, Naqvi SR, Gao N, Amin NAS (2022) A review on production and surface modifications of biochar materials via a review on production and surface modifications of biochar materials via biomass pyrolysis process for supercapacitor applications. *Catalysts* 12:798. <https://doi.org/10.3390/catal12070798>
 136. Li S, Li C, Shao Z (2022) Microwave pyrolysis of sludge: a review. *Sustain Environ Res* 32:23. <https://doi.org/10.1186/s42834-022-00132-z>
 137. Miura M, Kaga H, Sakurai A, Kakuchi T, Takahashi K (2004) Rapid pyrolysis of wood block by microwave heating. *J Anal Appl Pyrolysis* 71:187–199. [https://doi.org/10.1016/S0165-2370\(03\)00087-1](https://doi.org/10.1016/S0165-2370(03)00087-1)
 138. Hornung A (2013) Intermediate pyrolysis of biomass. In: Rosen-dahl L (Ed.) *Biomass Combustion Science, Technology and Engineering*, pp. 172–186. <https://doi.org/10.1533/9780857097439.2.172>
 139. Santos AJ, Ouadi M, Jahangiri H, Hornung A (2019) Integrated intermediate catalytic pyrolysis of wheat husk. *Food Bioprod Process* 114:23–30. <https://doi.org/10.1016/j.fbp.2018.11.001>
 140. Mansor AM, Theo WL, Lim JS, Ani FN, Hashim H, Ho WS (2018) Potential commercialisation of biocoke production in Malaysia—A best evidence review. *Renew Sustain Energy Rev* 90:636–649. <https://doi.org/10.1016/j.rser.2018.03.008>
 141. Tsubaki S, Nakasako Y, Ohara N, Nishioka M, Fujii S, Wada Y (2020) Ultra-fast pyrolysis of lignocellulose using highly tuned microwaves: synergistic effect of a cylindrical cavity resonator and a frequency- auto-tracking solid-state microwave generator. *Green Chem* 2:342–351. <https://doi.org/10.1039/c9gc02745a>
 142. Inayat A, Ahmed A, Tariq R, Waris A, Jamil F (2022) Techno-economical evaluation of bio-oil production via biomass fast pyrolysis process : a review. *Front Energy Res* 9:1–9. <https://doi.org/10.3389/fenrg.2021.770355>
 143. Bieniek A, Jerzak W, Magdziarz A (2023) Fast pyrolysis of agricultural biomass in drop tube reactor for bio-oil production : Numerical calculations. *J Anal Appl Pyrolysis* 176:106241. <https://doi.org/10.1016/j.jaap.2023.106241>
 144. Aboelela D, Saleh H, Attia AM, Elhenawy Y, Majozzi T, Bassyouni M (2023) Recent advances in biomass pyrolysis processes for bioenergy production : optimization of operating conditions. *Sustainability* 15:11238
 145. Silva OW, Nagar B, Soutrenon M, Girault HH (2022) Chemical Science irradiation †. *Chem Sci* 13:1774–1779. <https://doi.org/10.1039/d1sc06322g>
 146. Safdari M, Amini E, Weise DR, Fletcher TH (2019) Heating rate and temperature effects on pyrolysis products from live wildland fuels ☆. *Fuel* 242:295–304. <https://doi.org/10.1016/j.fuel.2019.01.040>
 147. Gogoi S et al (2020) Influence of Temperature on Quality and Yield of Pyrolytic Products of Biofuel Process Wastes. In: Ghosh SK (ed) *Energy Recovery Processes from Wastes*. Springer, Singapore, pp 129–142
 148. Qurat-ul-Ain, Shafiq M, Capareda SC, Firdaus-e-Bareen (2021) Effect of different temperatures on the properties of pyrolysis products of Parthenium hysterophorus. *J Saudi Chem Soc* 25:101197. <https://doi.org/10.1016/j.jscs.2021.101197>
 149. Demirbas A (2007) Effect of temperature on pyrolysis products from biomass. *Energy Sources A Recover Util Environ Eff* 29(4):329–336. <https://doi.org/10.1080/009083190965794>
 150. Iaccarino A, Gautam R, Sarathy SM (2021) Bio-oil and biochar production from halophyte biomass: effects of pre-treatment and temperature on *Salicornia bigelovii* pyrolysis. *Sustain Energy Fuels* 5:2193–2384. <https://doi.org/10.1039/d0se01664k>
 151. Muigai HH, Bordoloi U, Hussain R, Ravi K, Moholkar VS, Kalita P (2020) A comparative study on synthesis and characterization of biochars derived from lignocellulosic biomass for their candidacy in agronomy and energy applications. *Energy Res* pp. 1–17. <https://doi.org/10.1002/er.6092>
 152. Chatterjee R, Sajjadi B, Chen W, Mattern DL, Hammer N (2020) Effect of pyrolysis temperature on physicochemical properties and acoustic-based amination of biochar for efficient CO₂ adsorption. *Front Energy Res* 8:1–18. <https://doi.org/10.3389/fenrg.2020.00085>
 153. Varma AK, Shankar R, Mondal P (2018) A Review on Pyrolysis of Biomass and the Impacts of Operating Conditions on Product Yield, Quality, and Upgradation. In: Sarangi P, Nanda S, Mohanty P (Eds.) *Recent Advancements in Biofuels and Bioenergy Utilization*, Springer, Singapore. <https://doi.org/10.1007/978-981-13-1307-3>
 154. Qin L, Wu Y, Hou Z, Jiang E (2020) Influence of biomass components, temperature and pressure on the pyrolysis behavior and biochar properties of pine nut shells. *Bioresour Technol* 313:123682. <https://doi.org/10.1016/j.biortech.2020.123682>
 155. Wang Z, Liu K, Xie L, Zhu H, Ji S, Shu X (2019) Effects of residence time on characteristics of biochars prepared via co-pyrolysis of sewage sludge and cotton stalks. *J Anal Appl Pyrolysis* 142:104659. <https://doi.org/10.1016/j.jaap.2019.104659>
 156. Li Y, Gupta R, Zhang Q, You S (2023) Review of biochar production via crop residue pyrolysis : Development and perspectives. *Bioresour Technol* 369:128423. <https://doi.org/10.1016/j.biortech.2022.128423>
 157. Perera SMHD, Wickramasinghe C, Samarasinghe BKT, Narayana M (2021) Modeling of thermochemical conversion of waste biomass – a comprehensive review. *Biofuel Res. J.* 32:1481–1528. <https://doi.org/10.18331/BRJ2021.8.4.3>
 158. Li Y, Gupta R, Zhang Q, You S (2023) Review of biochar production via crop residue pyrolysis : Development and perspectives bioresource technology review of biochar production via crop residue pyrolysis : Development and perspectives. *Bioresour Technol* 369(November):128423. <https://doi.org/10.1016/j.biortech.2022.128423>
 159. Ozbay N, Yargic AS, Yarbay Sahin RZ, Yaman E (2019) Valorization of banana peel waste via in-situ catalytic pyrolysis using Al-Modified SBA-15. *Renew Energy* 140:633–646. <https://doi.org/10.1016/j.renene.2019.03.071>
 160. Guda VK, Steele PH, Penmetsa VK, Li Q (2015) Fast pyrolysis of biomass : Recent advances in fast pyrolysis technology. In *Recent Advances in Thermo-Chemical Conversion of Biomass*, pp. 177–211. <https://doi.org/10.1016/B978-0-444-63289-0.00007-7>
 161. Saravanathamizhan R, Perarasu VT, Vetriselvan K (2023) Chapter 11 - Thermochemical conversion of biomass into valuable

- products and its modeling studies. In: Shah MP (Ed.) *Green Approach to Alternative Fuel for a Sustainable Future*, Elsevier Inc., pp. 137–152. <https://doi.org/10.1016/B978-0-12-824318-3.00004-7>
162. Gholizadeh M, Li C, Zhang S, Wang Y (2020) Progress of the development of reactors for pyrolysis of municipal waste. *Sustain Energy Fuels* 4(12):5885–5915. <https://doi.org/10.1039/d0se01122c>
 163. Asadullah M et al (2007) Production of bio-oil from fixed bed pyrolysis of bagasse. *Fuel* 86(16):2514–2520. <https://doi.org/10.1016/j.fuel.2007.02.007>
 164. Yan J, Salman CA (2023) Chapter 2 - Waste-to-energy (WtE): Current technologies and their future potential. In *Waste Biorefineries Advanced Design Concepts for Integrated Waste-to-Energy Processes*, pp. 25–61. <https://doi.org/10.1016/B978-0-323-91761-2.00005-2>
 165. Garcia-Nunez JA et al (2017) Historical developments of pyrolysis reactors : a review. *Energy Fuels* 31(6):5751–5775. <https://doi.org/10.1021/acs.energyfuels.7b00641>
 166. Iannello S, Morrin S, Materazzi M (2020) Fluidised bed reactors for the thermochemical conversion of biomass and waste. *KONA Powder J* 37:114–131. <https://doi.org/10.14356/kona.2020016>
 167. Wu LM, Zhou CH, Tong DS, Yu WH (2014) Catalytic Thermochemical Processes for Biomass Conversion to Biofuels and Chemicals. In: Gupta VK, Tuohy MG, Kubicek CP, Saddler J, Xu F (Eds.) *Bioenergy Research: Advances and Applications*, Elsevier, pp. 243–254. <https://doi.org/10.1016/B978-0-444-59561-4.00015-2>
 168. Park HC, Choi HS (2022) Influence of cross - sectional aspect ratio on biochar segregation in a bubbling fluidized bed. *Sci Rep* 12:10600. <https://doi.org/10.1038/s41598-022-14282-y>
 169. Nachenius RW, Ronsse F, Venderbosch RH, Prins W (2013) Biomass pyrolysis. In: Murzin DY (Ed.) *Chemical Engineering for Renewables Conversion*, 1st ed. Elsevier Inc., pp. 75–139. <https://doi.org/10.1016/B978-0-12-386505-2.00002-X>
 170. Bridgwater AV (2003) Renewable fuels and chemicals by thermal processing of biomass. *Chem Eng J* 91:87–102
 171. Zhang S et al (2019) Liquefaction of biomass and upgrading of bio-oil: a review. *Molecules* 24(12):2250
 172. Mruthyunjaya V (2022) 9 - Catalysis for bio-BTX (benzene, toluene, and xylene) synthesis. In: Sudarsanam P, Li H (Eds.) *Advanced Catalysis for Drop-in Chemicals*, pp. 223–256. <https://doi.org/10.1016/B978-0-12-823827-1.00003-1>
 173. Singh R, Lindenberger C, Chawade A, Vivekanand V (2024) Unveiling the microwave heating performance of biochar as microwave absorber for microwave - assisted pyrolysis technology. *Sci Rep* 14(9222):1–12. <https://doi.org/10.1038/s41598-024-59738-5>
 174. Bridgwater AV, Peacocke GVC (2000) Fast pyrolysis processes for biomass. *Renew Sustain Energy Rev* 4:1–73
 175. Sharma D et al (2020) Thermal performance analysis and experimental validation of primary chamber of plasma pyrolysis system during preheating stage using CFD analysis in ANSYS CFX. *Therm Sci Eng Prog* 18:100525. <https://doi.org/10.1016/j.tsep.2020.100525>
 176. Gonzalez-Arias J, Gomez X, Gonzalez-Castano M, Sanchez ME, Rosas JG, Cara-Jimenez AJ (2022) Insights into the product quality and energy requirements for solid biofuel production : A comparison of hydrothermal carbonization, pyrolysis and torrefaction of olive tree pruning. *Energy* 238:122022. <https://doi.org/10.1016/j.energy.2021.122022>
 177. Obi OF (2015) Effect of briquetting temperature on the properties of biomass briquettes. *African J Sci Technol Innov Dev* 7(6):386–394. <https://doi.org/10.1080/20421338.2015.1096508>
 178. Urbanovičová O, Křištof K, Findura P, Jobbágy J, Angelovič M (2017) Physical and mechanical properties of briquettes produced from energy plants. *Acta Univ Agric Silv Men- delianae Brun* 65(26):219–224. <https://doi.org/10.11118/actaun201765010219>
 179. Gendek A, Aniszewska M, Malaťák J, Velebil J (2018) Evaluation of selected physical and mechanical properties of briquettes produced from cones of three coniferous tree species. *Biomass Bioenerg* 117:173–179. <https://doi.org/10.1016/j.biombioe.2018.07.025>
 180. Ajimotokan HA, Ibitoye SE, Odusote JK, Adesoye OA, Omoniyi PO (2019) Physico-mechanical properties of composite briquettes from corncob and rice husk. *J Bioresour Bioprod* 4(3):159–165. <https://doi.org/10.12162/jbb.v4i3.004>
 181. Yadav Y, Neupane S (2021) Assessment of the physical and combustion properties of briquettes produced from banana tree waste. *J Innov Eng Educ* 4(1):62–68
 182. Obi OF (2015) Evaluation of the physical properties of composite briquette of sawdust and palm kernel shell. *Biomass Convers Biorefinery* 5:271–277. <https://doi.org/10.1007/s13399-014-0141-7>
 183. Aransiola EF, Oyewusi TF, Osunbitan JA, Ogunjimi LAO (2019) Effect of binder type, binder concentration and compacting pressure on some physical properties of carbonized corncob briquette. *Energy Rep* 5:909–918. <https://doi.org/10.1016/j.egy.2019.07.011>
 184. Demirbaş A (1999) Physical properties of briquettes from waste paper and wheat straw mixtures. *Energy Convers Manag* 40:437–445. [https://doi.org/10.1016/S0196-8904\(98\)00111-3](https://doi.org/10.1016/S0196-8904(98)00111-3)
 185. Feng Z, Zhang T, Yang J, Gao Q, Ni L, Liu Z (2020) Fuel characteristics of briquettes manufactured by natural stacking bamboo/Chinese fir mixtures. *ACS Omega* 5:25281–25288. <https://doi.org/10.1021/acsomega.0c03413>
 186. Asamoah B, Nikiema J, Gebrezgabher S, Odonkor E, Njenga M (2016) A review on production , marketing and use of fuel briquettes. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 51p. (Resource Recovery and Reuse Series 7). Colombo, Sri Lanka. <https://doi.org/10.5337/2017.200>
 187. Karunanithy C, Wang Y, Muthukumarappan K, Pugalandhi S (2012) Physiochemical characterization of briquettes made from different feedstocks. *Biotechnol Res Int* 2012:1–12. <https://doi.org/10.1155/2012/165202>
 188. Ibitoye SE, Mahamood RM, Jen T, Akinlabi ET (2022) Combustion, physical, and mechanical characterization of composites fuel briquettes from carbonized banana stalk and corncob. *Int J Renew Energy Dev* 11(2):435–447. <https://doi.org/10.14710/ijred.2022.41290>
 189. Siritheerasas P, Chunniyom C, Sethabunjong P (2008) Combustion of moist coal briquettes. *Chiang Mai J Sci* 35(1):35–42
 190. Nurek T, Gendek A, Roman K, Dąbrowska M (2019) The effect of temperature and moisture on the chosen parameters of briquettes made of shredded logging residues. *Biomass Bioenerg* 130:105368. <https://doi.org/10.1016/j.biombioe.2019.105368>
 191. Kebede T, Berhe DT, Zergaw Y (2022) Combustion characteristics of briquette fuel produced from biomass residues and binding materials. *J Energy* pp. 1–10. <https://doi.org/10.1155/2022/4222205>
 192. Amira Atan N, Mohamed Nazari M, Ayuni Azizan F (2018) Effect of torrefaction pre-treatment on physical and combustion characteristics of biomass composite briquette from rice husk and banana residue. *MATEC Web Conf* 150:06011. <https://doi.org/10.1051/mateconf/201815006011>
 193. Adu-Poku KA et al (2022) Characterization of fuel and mechanical properties of charred agricultural wastes: Experimental and statistical studies. *Energy Rep* 8:4319–4331. <https://doi.org/10.1016/j.egy.2022.03.015>

194. Lubwama M, Yiga VA, Muhairwe F, Kihedu J (2020) Physical and combustion properties of agricultural residue bio-char bio-composite briquettes as sustainable domestic energy sources. *Renew Energy* 148:1002–1016. <https://doi.org/10.1016/j.renene.2019.10.085>
195. Mansyur S, Apriani E (2023) Analysis of the effect of temperature and raw material mixes on the pyrolysis process with single retort-rocket stove technology on the characteristics of sawdust charcoal briquettes. *Int J Ind Optim* 4(1):38–46. <https://doi.org/10.12928/ijio.v4i1.6688>
196. Himbane PB, Ndiaye LG, Napoli A, Kobor D (2018) Physico-chemical and mechanical properties of biomass coal briquettes produced by artisanal method. *African J Environ Sci Technol* 12(12):480–486. <https://doi.org/10.5897/AJEST2018.2568>
197. Sirun A, Siwi H, Umboh MK (2018) Effect of density and hardness on burning rate of water hyacinth and coconut shell briquettes. In: 2018 International Conference on Applied Science and Technology (iCAST), IEEE, pp. 555–558. <https://doi.org/10.1109/iCAST1.2018.8751547>
198. De Oliveira BG, Souza O, Marangoni C, Pedro A, De Oliveira N, Sellin N (2014) Production and characterization of fuel briquettes from banana leaves waste. *Chem Eng Trans* 37:439–444. <https://doi.org/10.3303/CET1437074>
199. Rahmawati SS, Abram PH, Afadil NGAMP, Anggraini (2022) Characteristics of charcoal briquettes from kepok banana peel waste (Musa paradisica F.) as alternative fuel. *Rasayan J Chem* 15(1):108–115. <https://doi.org/10.31788/RJC.2022.1516607>
200. Oyelaran OA, Olorunfemi BJ, Sanusi OM, Fagbemigun AO, Balogun O (2018) Investigating the performance and combustion characteristics of composite bio-coal briquette. *J Mater Eng Struct* 5:173–184
201. Jelonek Z, Drobniak A, Mastalerz M, Jelonek I (2020) Environment Environmental implications of the quality of charcoal briquettes and lump charcoal used for grilling. *Sci Total Environ* 747:141267. <https://doi.org/10.1016/j.scitotenv.2020.141267>
202. Grover PD, Mishra SK (1996) Biomass briquetting. In: Technology and practices (field document no. 46). Regional wood energy development programme in Asia, Bangkok
203. Eling J, Okot DK, Meny E, Atim MR (2024) Densification of raw and torrefied biomass: a review. *Biomass Bioenergy* 184:107210. <https://doi.org/10.1016/j.biombioe.2024.107210>
204. Mitchual SJ, Frimpong-mensah K, Darkwa NA (2013) Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes. *Int J ofEnergy Environ Eng* 4(30):1–6
205. Gebrekidan A, Goitom M, Berhe G, Berhe M (2024) Production and characterization of briquettes from sugarcane bagasse of Wonji Sugar Factory, Oromia, Ethiopia. *Mater Renew Sustain Energy* 13:27–43. <https://doi.org/10.1007/s40243-023-00248-1>
206. Deniz V (2016) A new binder in production of water-resistant briquettes from bituminous coals: Co-polymer binder. *Energy Sources A Recover Util Environ Eff* 38(8):1068–1074. <https://doi.org/10.1080/15567036.2011.654311>
207. Tanui KJ, Kioni PN, Karuiki PN, Ngugi JM (2018) Influence of processing conditions on the quality of briquettes produced by recycling charcoal dust. *Int J Energy Environ Eng* 9:341–350. <https://doi.org/10.1007/s40095-018-0275-7>
208. Hood AH (2010) Biomass briquetting in Sudan: a feasibility study. In: The United States Agency for International Development (USAID) and the women's refugee commission
209. Chaney J (2010) Combustion characteristics of biomass briquettes. PhD Thesis, University of Nottingham, Nottingham. Retrieved from https://eprints.nottingham.ac.uk/11732/1/Combustion_Characteristics_of_Biomass_Briquettes.pdf
210. Al-Widyan MI, Al-Jalil HF, Abu-Zreig MM, Abu-Hamdeh NH (2002) Physical durability and stability of olive cake briquettes. *Can Biosyst Eng* 44:41–45
211. Ajimotokan HA, Ehindero AO, Ajao KS, Adeleke AA, Ikubanni PP (2019) Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. *Sci Afr* 6:e00202. <https://doi.org/10.1016/j.sciaf.2019.e00202>
212. Borowski G, Stepniewski W, Wójcik-oliveira K (2017) Effect of starch binder on charcoal briquette properties. *Int Agrophysics* 31:571–574. <https://doi.org/10.1515/intag-2016-0077>
213. Nikolaisen LS, Jensen PD (2013) 3 - Biomass feedstocks: categorisation and preparation for combustion and gasification. In: Rosendahl L (Ed.) *Biomass Combustion Science, Technology and Engineering*, pp. 36–57. <https://doi.org/10.1533/9780857097439.1.36>
214. Tumuluru JS, Wright CT, Hess JR, Kenney KL, National I (2011) A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels Bioprod Biorefining* 5(6):683–707. <https://doi.org/10.1002/bbb.324>
215. Kpalo SY, Zainuddin MF, Manaf LA, Roslan AM (2020) A review of technical and economic aspects of biomass briquetting. *Sustainability* 12:4609. <https://doi.org/10.3390/su12114609>
216. Abakr YA, Abasaeed AE (2014) Experimental evaluation of a conical-screw briquetting machine for the briquetting of carbonized cotton stalks in Sudan. *J Eng Sci Technol* 1(2):212–220
217. Vaish S, Sharma NK, Kaur G (2022) A review on various types of densification/briquetting technologies of biomass residues. *IOP Conf Ser Mater Sci Eng* 1228:012019. <https://doi.org/10.1088/1757-899X/1228/1/012019>
218. Njenga M et al (2013) Implications of charcoal briquette produced by local communities on livelihoods and environment in Nairobi- Kenya Additional cooking fuel supply and reduced global warming potential from recycling charcoal dust into charcoal briquette in Kenya. *J Clean Prod* 81:81–88. <https://doi.org/10.1016/j.jclepro.2014.06.002>
219. Karimibavani B, Busra A, Eylem S (2020) Converting briquettes of orange and banana peels into carbonaceous materials for activated sustainable carbon and fuel sources. *Energy Ecol Environ* 5:161–170. <https://doi.org/10.1007/s40974-020-00148-4>
220. Duangkham S, Thuadaij P (2023) Characterization of charcoal briquettes produced from blending rice straw and banana peel. *Heliyon* 9:e16305. <https://doi.org/10.1016/j.heliyon.2023.e16305>
221. Sweya LN, Chacha NT, Saitoti J (2024) Briquette quality assessment from corn husk, bagasse, and cassava roots using banana peels, wastepaper, and clay soil as binders. *Environ Qual Manag* 33(3):47–59

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Emmanuel Menya¹  · **Collins Okello¹** · **Henning Storz²** · **Joel Wakatuntu³** · **Medard Turyasingura³** · **David K. Okot⁴** · **Simon Kizito⁵** · **Allan John Komakech⁶** · **Isa Kabenge⁶** · **Samson Rwahwire⁷** · **Peter Wilberforce Olupot³**

✉ Emmanuel Menya
E.menya@gu.ac.ug

¹ Department of Biosystems Engineering, Gulu University,
P.O. Box 166, Gulu, Uganda

² Thuenen Institute of Agricultural Technology, Bundesallee
47, 38116 Braunschweig, Germany

³ Department of Mechanical Engineering, College
of Engineering, Design Art and Technology, Makerere
University, P.O. Box 7062, Kampala, Uganda

⁴ Department of Physics, Faculty of Science, Mbarara
University of Science and Technology, Mbarara, Uganda

⁵ Department of Forestry, Biodiversity and Tourism, Makerere
University, P.O. Box 7062, Kampala, Uganda

⁶ Department of Agricultural and Biosystems Engineering,
Makerere University, P.O. Box 7062, Kampala, Uganda

⁷ Department of Polymer, Textile, and Industrial Engineering,
Busitema University, Busitema, Uganda