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ORIGINAL ARTICLE

Preliminary characterisation and valorisation of Ficus benjamina fruits for biofuel application

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Abstract

Ficus benjamina (FB) is a perennial plant that serves ornamental purposes. Its fruits are nonedible and considered 'waste' with no defined application. This paper discusses the valorisation and identification of the potential of *Ficus benjamina* fruits as a suitable biofuel feedstock. The whole fruit was characterised by scanning electron microscopy (SEM), energy dispersive X-ray (EDS), thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and bomb calorimeter. In addition, the proximate and ultimate analyses were performed to determine their physical, thermal, and chemical properties for potential biofuel application. Pulverised *Ficus benjamina* fruits (PFB) have a porous morphology that makes them less dense with a crystallinity index of 25.5%. The moisture, ash, volatile matter, and fixed carbon contents were 9.29, 6.26, 64.35, and 20.10%, respectively. The higher heating value (19.74 MJ/kg) and lower heating value (18.55 MJ/kg) are comparable to other biomass feedstocks. The results establish the possibility of using PFB as a solid biofuel.

Keywords *Ficus benjamina* fruits · Valorisation · Biofuel · Feedstock · Waste

1 Introduction

Increasing global energy demand and climate goals make it necessary to seek sustainable and eco-friendly energy generation sources. Wood is currently the most common plant biomass used for heating purposes. However, it contributes to the health and environmental challenges [1]. Hence, the search for sustainable and efficient energy sources that make use of other plant biomass as an alternative to both fossil and wood fuel [2]. Among the various renewable energy sources, plant biomass holds a high possibility due to advancements in conversion technologies such as gasification and pyrolysis. The conversion of lignocellulosic biomass can generate solid biofuel (e.g. pellet and briquettes that can substitute for wood fuel), bio-oil, bioethanol, and biogas.

First-generation biofuel requires food crops and oilseeds, raising food security issues [3]. Second-generation biofuel relies on lignocellulose-based biomass, such as field- and process-based residues, which do not compete with food [4],

Highlights
- *Ficus benjamina* fruits biomass waste is morphologically porous
- It is eco-friendly with low sulphur and nitrogen contents
- The higher heating value is comparable to wood dust and switchgrass
- These fruits have potential for solid biofuel and other applications

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though they contest with other applications such as livestock feed, mulching, and industrial purposes. Third-generation biofuel makes use of microalgae as feedstock. Although the latter has some prospects, it is not currently economical, and research is still at its relatively early stage. Fourth-generation fuel involves the genetic modification of plants and microalgae to reduce the lignin resistance during hydrolysis and increase CO_2 sequestration. This type of biomass possesses tremendous opportunities in contributing to the energy supply chain but poses various problems [5]. In this study, we investigate the potentials of nonedible whole fruits as biomass feedstock for energy production. Nonedible fruits from ornamental and forest trees are practically wasted. Generally, despite their rich lignocellulose contents, they are neither characterised nor included as possible biomass feedstock for biofuel production. It is important to note that the use of these fruits avoids the overdependence on crop residues. Also, the trees producing such fruits do not require replanting, which makes them economical and sustainable. Weeping fig, botanically called *Ficus benjamina* (FB), is one of such trees. FB is native to Asia and Oceania, although it has adapted beyond its native range, spreading to other continents [6]. The wide range of adaptability allows it to flourish on fertile and moistened soils with sufficient sunlight [7]. It can tolerate drought, a wide range of soil types, and pH range from acidic to alkaline [8]. Due to its appealing properties as an easy-to-grow species and its high-density foliage and dimensions, FB has been introduced massively in urban areas all over the world, becoming a predominant species [9]. FB tree is generally used for ornamental and landscaping purposes [10] and not for their fruit. Nevertheless, they are capable of producing fruits more than two times a year [11]. FB fruits have no known application; hence they have no value and thus can be found as waste in parks, gardens, streets, highways, and river banks. In this regard, the novelty and priority of the present study are to understand the potential economic value that can be obtained from pulverised *Ficus benjamina* fruits (PFB). In order to achieve this, we performed fundamental physical, chemical, and thermal characterisations. From the preliminary results, it was discovered that PFB showed a very good prospect as a feedstock for biofuel application. This work intends to attract the attention of the scientific community and the government, such that appropriate programmes for the collection of this fruit will be initiated.

To the authors' knowledge, this is probably the first paper that discusses the valorisation of *Ficus benjamina* (FB) fruits. Detailed information is provided to access its potential application. For this purpose, the physical, chemical, and thermal properties must be evaluated [12, 13] to allow suitable processing and policy decisions towards biofuel application.

As mentioned earlier, there are knowledge gaps with regard to the characterisation of FB fruits, especially as feedstock for biofuel production. Our motivation is to fill in some of the knowledge gaps by investigating the physicochemical and thermal properties. We also discuss the morphology, physical, and chemical compositions.

2 Materials and methods

2.1 FB fruit collection and preparation

FB fruits were collected from the grounds of AUST (African University of Science and Technology, Abuja, Nigeria). Figure 1 shows the oval-shaped FB fruits with yellow-orange colour.

The whole fruits collected were washed in clean water to remove impurities, sun dried, and pulverised in a blender (BLG-403, China). The pulverised FB fruit was labelled as PFB. The latter was sieved using a mesh of 425 μm to obtain particles with size $\leq$ 425 μm, then stored in clean, air-tight Ziploc bags for characterisation.

Figure 2 illustrates the schematic experimental process and flowchart for valorising FB fruits. The flowchart displays possible decisions that could be applied for further analysis.

Fig. 1 An image of *Ficus benjamina* plant with fruits

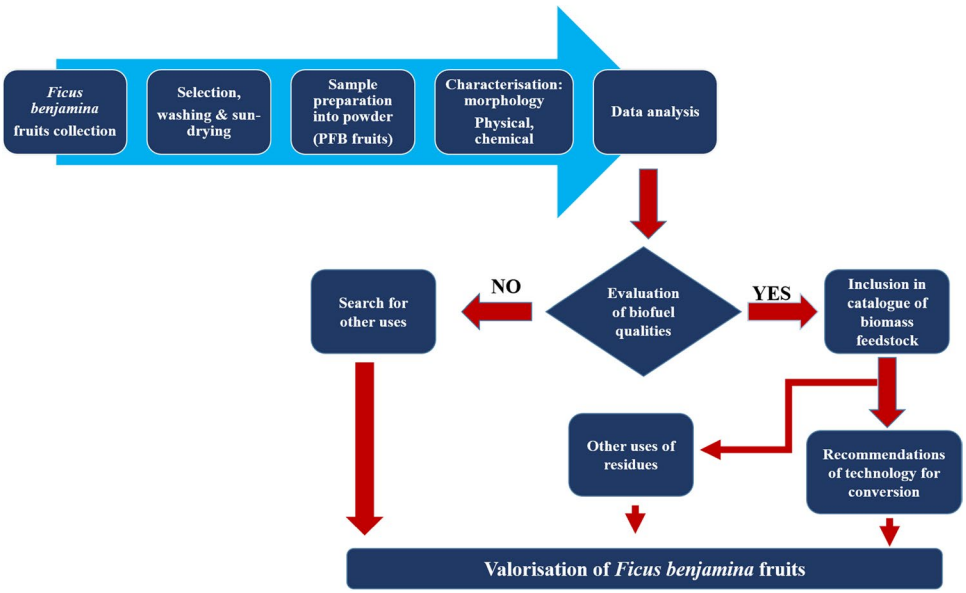

Fig. 2 Schematic showing the PFB valorisation flowchart carried out in this work

2.2 Characterisation of PFB

2.2.1 Morphological analysis

The morphology of the FB fruit (internal and external surface) and PFB was observed using a scanning electron microscope (ZEISS, EVO LS10, USA). The samples were mounted on conductive adhesive carbon tape then coated with a thin layer of gold to prevent surface charging. Energy-dispersive X-ray (EDAX, USA) was used for the quantitative elemental analysis of the FB fruit.

The bulk density of PFB was determined using modifications of the method described by Stella Mary et al. [14]. An amount of PFB was added to a graduated glass cylinder (25 ml) and slightly tapped for 1–2 min to compact the content [15].

2.2.2 Proximate and ultimate analysis

The moisture and ash content of PFB was determined using the ASTM D7582 method [16]. The dry solid obtainable from PFB was determined following the approach by Singh et al. [17]. The volatile matter was calculated according to UNE 32,019 [18]. The fixed carbon content was estimated from the proximate analysis [17]. The carbon, hydrogen, and nitrogen contents of PFB were determined using a LECO CHN-2000 analyser, while the sulphur content was determined in a LECO S-144DR analyser. The oxygen content was estimated according to [17, 19].

The ether extractives yield of PFB was obtained following the Randall method [20]. In a Soxhlet apparatus, PFB (1.0 g) was added in the sample chamber and 250 ml of petroleum ether in the receiver flask, then placed on a heating mantle. After 7 h of extraction, the petroleum ether was recovered using a rotary evaporator. The resulting extract was left in the oven at 70 ℃ until constant weight, then the ether extractive yield was calculated using Eq. 1.

$$\text{Ether extractives}(\%) = \frac{W_2 - W_1}{W} \times 100 \quad (1)$$

where W_1 = weight of empty oil flask; W_2 = weight of oil + flask after extraction; W = weight of PFB.

2.2.3 Fourier-transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) analyses

The functional groups in the PFB were characterised by means of FTIR spectroscopy (Thermo Fisher Scientific, USA). First, PFB was mixed with KBr in a ratio of 1:10 then compressed into a pellet. All spectra were recorded in the absorbance mode at the wavenumber range of 4000–400 cm^{-1}.

The XRD analysis of PFB was carried out with Cu-Kα radiation of wavelengths 1.540598 Å generated at 40 mA and 45 kV (Empyrean). The crystallinity index (CrI) of the sample was estimated using the Ruland–Vonk method [21, 22]. This method is based on the ratio of the area of the crystalline profile to the total area (Eq. 2).

$$\text{Crystallinity index} = \left[\frac{\text{Area of crystal line peaks}}{\text{Area of all peaks (crystal line + armorphous)}}\right] \times 100 \quad (2)$$

The lignocellulose content which comprises hemicellulose, lignin, and cellulose was determined gravimetrically [23]. The PFB (1.0 g) obtained after the ether extractives experiment (i.e. extractive-free PFB) was mixed with 10 ml of 0.5 mol/L of NaOH and heated at 80 ℃ for 4 h. The

resulting mixture was washed till the pH became neutral then dried to a constant weight. The hemicellulose content is the difference between the initial (A) and final weights (B) (Eq. 3). For the lignin content determination, 1.0 g of extractive-free PFB was soaked overnight in 30 ml concentrated sulphuric acid (98%), after which, it was boiled at 100 ℃ for 1 h [24]. The resulting product was washed until no trace of sulphate ions was visible in the filtrate when tested with drops of barium chloride (10%). Afterwards, the residue was dried at 100 ℃ until constant weight was attained, then the lignin content was estimated (Eq. 4). Furthermore, the cellulose content was found by subtracting the ether extractives, hemicellulose, and lignin contents from 100 (Eq. 5).

$$\text{Hemicellulose content(wt.\%)} = \frac{A-B}{A} \times 100 \tag{3}$$

where A = weight of extractive-free sample; B = weight of dried hemicellulose; wt = weight.

$$\text{Lignin content(wt.\%)} = \frac{A-C}{A} \times 100 \tag{4}$$

where A = weight of extractive-free sample; C = weight of dried lignin.

$$\text{Cellulosecontent(wt.\%)} = 100 - (\text{Etherextractive(wt.\%)} + \text{Hemicellulose(wt.\%)} + \text{Lignin(wt.\%)}) \tag{5}$$

The calorific value of PFB was estimated as the higher heating value (HHV) and the lower heating value (LHV) using a bomb calorimeter (IKA C 4000). Moreover, the thermal behaviour was characterised using thermogravimetric analysis (TGA; PerkinElmer 4000, USA). The devolatilisation was investigated in the temperature range of 30–900 ℃ (10 ℃/min) in a nitrogen atmosphere with a flow rate of 60 ml/min.

3 Results and discussion

The biofuel potential of PFB is discussed based on their morphology, physical, chemical, and thermal properties.

3.1 Morphology

The morphology of the FB fruit revealed unique surface patterns, sizes, shapes, and orientations of the various parts (Fig. 3a–f). As shown in Fig. 3a–d, the internal structure has irregular patterns with several cavities, making it less dense. The endocarp (Fig. 3c) revealed a planar sheet-like structure, while the mesocarp (i.e. the region between the outer and the inner portion) showed pores (Fig. 3d). The lightweight and buoyancy of the dried FB fruit can be attributed to the less dense internal structure. In addition, the outer surface (epicarp) has a compact form with a uniformly distributed rough texture (Fig. 3e, f). For the PFB sample, the morphology (Fig. 3g) showed irregular shapes with the internal plant structure. This observation is different from that of pulverised unmodified Dikanut shell, which has a scattered orientation, few pores, and dense structure [25].

The bulk density of PFB is 0.32 g/ml. This can be related to the large granular particles from the epicarp (Fig. 3e, f) that create interparticle voids, leading to the low value obtained. The bulk density of PFB is lower than the rice kernels of various rice cultivars (0.77–0.87 g/cm^3) [26]. The density of feedstocks has been reported to significantly influence their behaviour during the thermochemical/biological conversion process [27].

The analysis of different parts (outer and inner portions) of the FB fruit by energy-dispersive X-ray spectroscopy (EDS) showed carbon, oxygen, and potassium elements in high concentrations (see Table 1). In principle, biomass with low metallic elements is more suitable for energy generation by combustion [28]. The alkali metals (calcium and potassium) identified by EDS can affect thermochemical conversion processes during biofuel production because they lead to unwanted by-products (such as slag, sinter, and foul formation) in the boiler. However, it must be noted that calcium is only present in the outer portion of the fruit and that potassium concentration is much higher in this part than in the inner portion of the fruit. Therefore, it may require the removal of the outer part of the fruit for its use as biofuel. The EDS analysis of other nonedible fruit waste [29] has been included in Table 2 for comparison purposes. PFB presents a similar carbon content to banana peel or orange bagasse but a lower oxygen content and a much higher potassium content (Table 3). It is worth noting that potassium may play a vital role as a catalyst, thus increasing the rate of conversion of biomass [13].

3.2 Proximate and ultimate analysis

The moisture content of PFB, 9.29 wt.%, is lower than eucalyptus wood sawdust and comparable to that of wheat straw [38], suggesting its suitability for energy purposes (such as pellets and briquettes) (see Table 3). Hence, it is suitable for application in thermal conversion systems for rapid heat

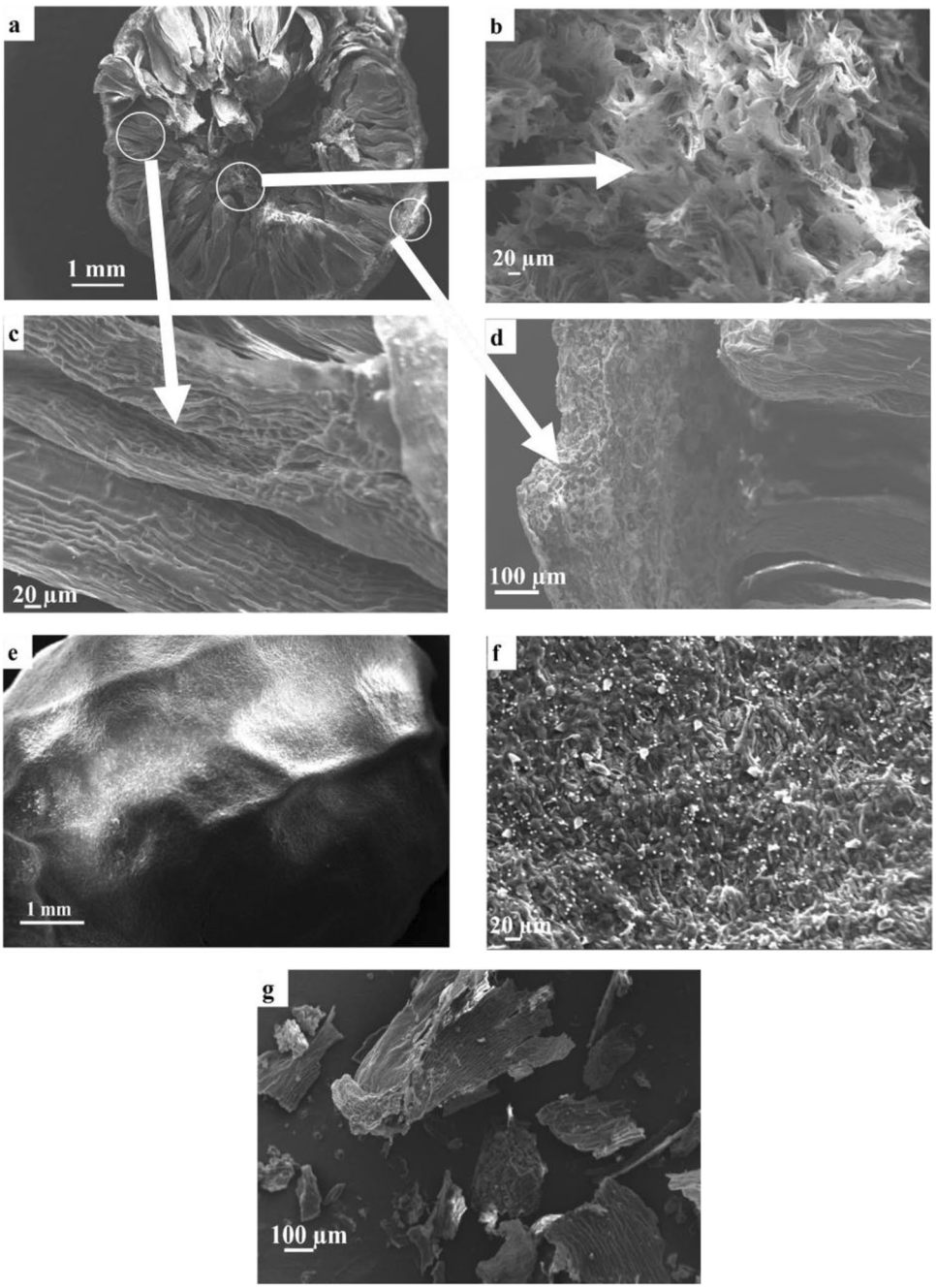

Fig. 3 Morphology of *Ficus benjamina* (FB) fruit: **a** the inner structure; **b**, **c**, and **d** are the magnified portion of **a**; **e** the outer layer; **f** the magnified outer layer; and **g** pulverised FB (PFB)

Table 1 Elemental composition of FB fruits by EDS

Sample	Elements (%)						
	C	O	Ca	K	Zr	Mo	Al
Outer portion of the fruit	0.03	31.95	36.83	38.54	ND	24.60	ND
Inner portion of the fruit	76.25	10.25	ND	8.85	4.66	ND	ND
PFB	53.41	15.65	ND	24.54	5.18	ND	1.19

ND, not detected

Table 2 Comparison of the EDS elemental composition of the FB fruit with other nonedible biomass

Element	PFB	Banana peel [29]	Orange bagasse [29]
C	53.41	52.32	61.94
O	15.65	39.67	37.12
Ca	-	-	0.70
K	24.54	5.93	0.24
Zr	5.18	-	-
Al	1.19	-	-
Si	-	0.49	-
Cl	-	1.59	-

transfer and storage. Furthermore, the low moisture content of PFB is beneficial as little energy input may be needed to remove moisture, thus reducing the cost of processing the feedstock. Compared to the other biomasses included in Table 3, PFB has the lowest volatile matter content, 64.35 wt.%, although this is just below that of pinewood and wheat straw. Volatile matter is combustible organic matter that may contribute to heat energy generation. Generally, plant biomass is known to have high volatile matter [17, 34], making it readily reactive to oxygen. During pyrolysis, some liquid products (such as bio-oil) can also be obtained, in which case, less char will be generated from the feedstock. The fixed carbon of PFB is 20.10 wt.%, which is higher than that of eucalyptus sawdust [30], pinewood [32], grasses [34], seeds [13], and fruit peels [40], and slightly lower than that of a wheat stalk.

The ash content of PFB is 6.26 wt.%. This is well below the high limit of 10%, which indicates that it possesses a good potential for thermal utilisation [17, 45]. However, the ash content of PFB is higher than most of the biomass types considered in Table 3, except King grass. Moreso, the ash content is inversely proportional to the energy derived from the feedstock [46]. The formation of slag from the metallic elements in the ash presents operational challenges in boilers during thermal conversion at high temperatures. PFB may be suitable as briquettes and pellets for cooking and heating purposes in rural areas. Low ash content makes pyrolysis a suitable energy conversion route [29, 47]. The VM/FC ratio is an indicator of the quality of fuels. This ratio is lower for PFB than most of the biomass types included in Table 3 but comparable to pinewood and wheat straw.

The ultimate analysis showed a relatively high carbon content, of 50.56 wt.% (daf). Hydrogen, nitrogen, and sulphur contents are 5.82, 1.66, and 0.11 wt.% (daf), respectively, and the estimated oxygen content is 41.85 wt.% (daf). The comparison with other biomass feedstocks, presented in Table 3, shows the third-highest C content, the fifth-lowest H content, and the third-lowest O content for PFB. The sulphur content in PFB is low, as expected for biomass sources [19]. This finding is essential because a low oxide concentration of these elements will be formed during combustion. Therefore, PFB can be identified as eco-friendly during combustion and suitable for energy production via gasification as pollutants are limited [1].

3.3 Ether extractives

PFB produces low-yield ether extractives, 1.48 wt.% (Table 4). Since the latter is below 10%, its effect on the thermal conversion is negligible [47]. Therefore, it indicates that fewer liquid products (such as bio-oil) will be produced during pyrolysis. The extractives (majorly the oil content) are low and solidify even at room temperature, making them not appropriate for biodiesel production. This result agrees

Table 3 Proximate and ultimate analysis in comparison with other biomass feedstock

Biomass/residues		Proximate analysis (wt. %)						Ultimate analysis (wt.%, daf)					Reference(s)
		Mc	VM	Ac	FC	DS*	VM:FC*	C	H	N	S	O[a]	
Wood sawdust	Eucalyptus	10.10	83.88	0.11	16.00	89.90	5.24	49.90	5.8	0.2	0.03	44.07	[30, 31]
	Pine wood	14.00	67.72	0.4	17.88	86.00	3.79	54.30	5.20	0.40	0.00	40.00	[32, 33]
Grasses	Switchgrass	6.01	73.32	4.01	16.66	93.99	4.40	49.33	7.31	0.52	0.08	42.58	[34, 35]
	King grass	-	78.2	7.1	14.7	-	4.44	46.91	5.89	0.70	0.21	46.30	[36, 37]
Field-based	Corn stover	4.01	75.63	5.13	15.23	95.99	4.97	49.33	5.53	0.88	0.88	44.18	[34, 35]
	Wheat straw	8.45	65.59	4.99	20.97	91.55	3.13	43.20	5.00	0.60	0.01	39.41	[38, 39]
Processed-based	Orange peel	7.91	86.70	5.25	0.14	92.09	619.29	48.74	5.92	1.43	0.19	43.72	[40, 36, 41]
	Coffee husk	7.22	76.60	0.68	15.50	92.78	4.94	46.51	6.77	0.43	0.09	46.20	[42]
	Coconut shell	7.82	79.91	0.23	12.04	92.18	6.64	51.6	5.60	0.10	0.00	42.70	[43, 44]
Nonedible whole fruits	PFB	9.29	64.35	6.26	20.10	90.71	3.20	50.56	5.82	1.66	0.11	41.85	This study

*Estimated by the current author; a: calculated by difference (Eq. 4); *daf*, dry ash-free basis

Table 4 Summary of the characterisation of PFB

Characterisation	Properties	Value
	Bulk density	0.32 g/ml
	Ether extractives	1.48 wt.%
Proximate analysis	Moisture content	9.29 wt.%
	Ash content	6.26 wt.%
	Volatile matter	64.35 wt.%
	Fixed carbon	20.10 wt.%
	Dry solid	90.71 wt.%
Ultimate analysis	Carbon (C)	50.56 wt.% (daf)
	Hydrogen (H)	5.82% wt.% (daf)
	Nitrogen (N)	1.66 wt.% (daf)
	Sulphur (S)	0.11 wt.% (daf)
	Oxygen (O)	41.85 wt.% (daf)
Biofuel reactivity	VM/FC	3.20
	H:C (daf)	1.37
	O:C (daf)	0.62
Lignocellulose composition	Cellulose	27.76 wt.%
	Hemicellulose	48.30 wt.%
	Lignin	21.30 wt.%
	Cellulose/lignin ratio	1.30
	Cellulose/hemicellulose ratio	0.57
Calorific value	Higher heating value (HHV)	19.743 MJ/kg (daf)
	Lower heating value (LHV)	18.549 MJ/kg (daf)

with the study on different walnut shells where the extractives were in the range of 1.4–1.7% [47].

3.4 van Krevelen diagram and biofuel reactivity

The atomic ratio of H/C and O/C defines the reactivity of biofuels. The H/C ratio reflects the degree of condensation and aromaticity in the plant material. The lower the H/C (high aromaticity), the higher the energy content. On the other hand, oxygen does not make any useful contribution to the heating value but makes it difficult for the transformation of biomass into liquid fuels [19]. In this study, PFB showed the second-lowest O/C ratio compared to all the lignocellulosic materials reviewed in Table 5, including coconut shells. Figure 4a shows the position of PFB in the van Krevelen diagram. The location of PFB is closer to fossil fuels than most of the biomass types included in this work, with the exception of that of pinewood and similar to that of coconut shell (Fig. 4a). It therefore implies that high energy density, stored as chemical energy, may be embedded in the C–C and C–O bonds [17].

The biofuel reactivity plot (Fig. 4b) revealed that the atomic ratios (H:C and O:C) of PFB are comparable to other biomass residues. The VM/FC ratio ranges from 3.20 to 6.64, and PFB was found in a similar position with the wheat straw and king grass. The VM/FC is higher than the atomic ratios, thus showing potential for biofuel, possibly solid biofuel [13].

3.5 Cellulose/hemicellulose ratio

The cellulose/hemicellulose ratio is indispensable in estimating ethanol yield [27]. Biomass feedstock with a high cellulose/hemicellulose ratio yields high ethanol. However, this ratio is low in PFB (0.57) due to the high hemicellulose content (Table 5). Therefore, the production of ethanol from PFB will require pretreatment and additional enzymes for hydrolysis.

3.6 X-ray diffraction analysis

In the XRD pattern of PFB (Fig. 5a), a broad peak was identified demonstrating its low crystallinity. The dominating amorphous nature may be a consequence of the rich carbon content. The latter could be linked to its lignocellulosic character, particularly its high hemicellulose content (48.30%), as shown in Table 5. The crystallinity index for PFB is 25.5%, which is similar to that of soy peels (25%) but lower than Açaí and coffee husk (30%) [30].

Table 5 Biofuel reactivity of other biomass compared to PFB fruits

Biomass/residues	Name	Lignocellulose composition					Bioenergy activity				Reference(s)
		Cellulose (%)	Hemicellulose (%)	Lignin (%)	C:L*	C:H*	O/C daf	H/C daf	HHV (MJ/kg)	LHV (MJ/kg)	
Wood sawdust	Eucalyptus	43.80	20.70	27.10	1.62	2.11	0.66	1.39	20.00	-	[30, 31, 48]
	Pine wood	37.00	19.00	31.00	1.19	1.95	0.55	1.14	19.66	-	[33, 49, 50]
Grasses	Switchgrass	37.00	28.00	18.00	2.06	1.32	0.65	1.77	17.36		[34, 35, 51]
	King grass	36.90	34.20	6.10	6.05	1.08	0.74	1.50	17.98		[37, 52, 53]
Field-based	Corn stover	37.72	20.62	30.50	1.24	1.83	0.67	1.34	17.31	-	[34, 35, 54]
	Wheat straw	45.12	9.16	37.41	1.21	4.93	0.68	1.38	17.25	-	[39]
Processed-based	Orange peel	11.93	14.46	2.17	5.50	0.83	0.67	1.45	18.92		[29, 37, 55]
	Coconut shell	36.13	20.36	32.33	1.12	1.77	0.62	1.29	17.35	-	[44, 56, 57]
	Coffee husk	43.18	10.20	17.42	2.48	4.23	0.75	1.73	15.20	-	[42, 58, 59]
Nonedible whole fruits	PFB	27.76	48.30	21.30	1.30	0.57	0.62	1.37	19.74	18.55	This study

*Estimated by current authors; *C:L*, cellulose-lignin ratio; *C:H*, cellulose-hemicellulose ratio; H/C and O/C are atomic ratios determined using the formula reported by Pach et al. [60] and Ascough et al. [61], respectively

Generally, low crystallinity is associated with fast degradation. A narrower peak can also be identified in Fig. 5a. This corresponds to calcium oxalate hydrate oxide ($C_2Ca_5O_4.H_2O$), according to the International Centre for Diffraction Data (ICDD) reference card number 00–016-0379, which is identified as whewellite, with a monoclinic structure.

The XRD results are in good agreement with the EDS results, shown in Table 1, where Ca and C were identified. The presence of these elements makes PFB a suitable reinforcement agent in composites such as particleboards.

3.7 Fourier transform infrared spectroscopy (FTIR) analysis

In the FTIR spectra of PFB, shown in Fig. 5b, alkanes, aliphatic-primary amines, and hydrocarbons are identified (see Table 6). These groups provide binding sites for other elements in the fuel matrix [29]. The fingerprint region exhibits peaks that can be attributed to C–H, C–N, and S = O, amongst others. In the diagnosis region, N–H, C = O, C = C, and N–O have strong stretching and bending vibration bonds. The broad band related to the OH bond confirms the presence of alcohols or phenols in the carbohydrate and lignin contents. During thermal hydrolysis, the OH groups in the lignocellulose and the C = O bond from the carboxylic ends may be released. The stretching vibration of C–H could be related to the hemicellulose or the alkyl chain of the lipid content. However, the lignin decomposition might further generate the C = C bond. The existence of OH, C–O, C–H, and C = C functional groups in the structure of corn cob has been reported in the literature to facilitate the formation of condensable and non-condensable liquid with gaseous by-products [62].

3.8 Thermal analysis

The calorific value of biomass is an important parameter to measure its biofuel potential. For PFB, the higher heating value (HHV) and lower heating value (LHV) are 19.743 and 18.549 MJ/kg, respectively (dry ash-free basis). The HHV value is higher than most of the biomass feedstocks included in Table 5 and similar to wood sawdust. This relatively high value is connected to the chemical composition, specifically the extractives and lignin. Furthermore, the HHV results from the energy density associated with the C–C chemical bond. The high calorific value of PFB implies that it is suitable for solid biofuel application.

The thermochemical behaviour of PFB was investigated using TGA to determine the thermal parameters that

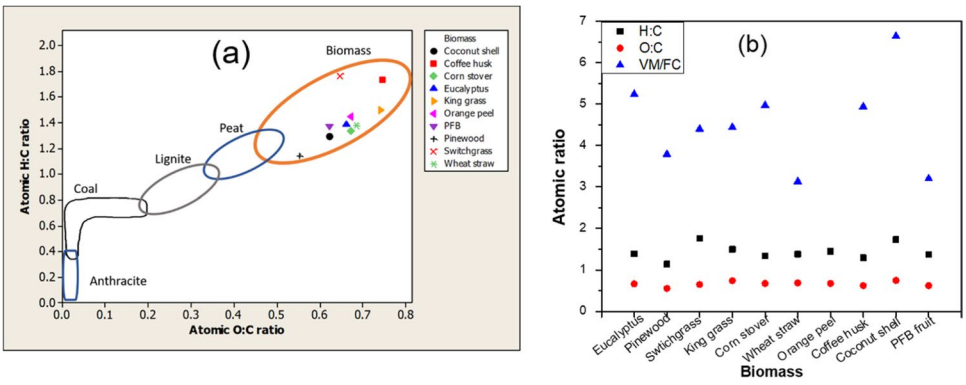

Fig. 4. **a** The van Krevelen diagram of biomass showing the position of PFB; **b** biofuel reactivity plot, comparing PFB with other biomasses

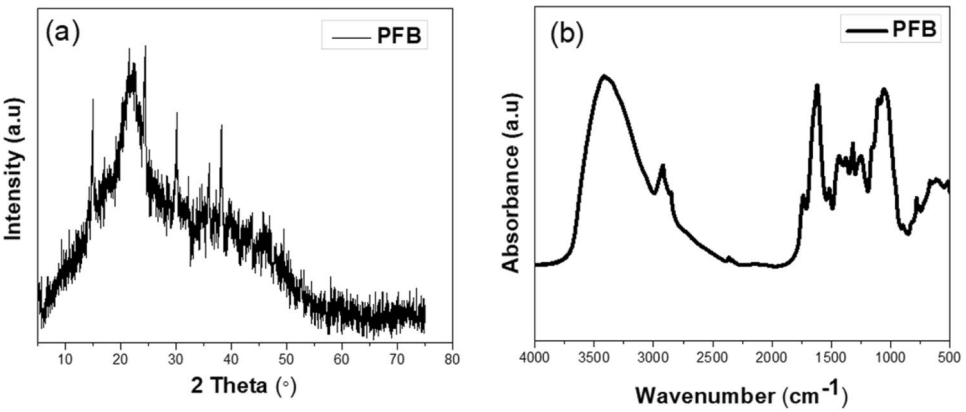

Fig. 5 **a** X-ray diffraction pattern; **b** Fourier transform infrared spectroscopy spectra of PFB

Table 6 FTIR spectra band assignment of PFB

Band frequency (cm^{-1})	Bond	Functional group
3411.32	**OH** stretching	Alcohol, phenol
3420.67	**N–H** stretching	Aliphatic primary amines
2919.08	**C–H** stretching	Alkane
2360.69	**O = C = O** stretching	Carbon dioxide
1734.75	**C = O** stretching	Aldehyde
1617.78	**C = C** stretching	α, β-unsaturated ketone
1521.97	**N–O** stretching	Nitro compound
1382.81	**C–H** bending	Alkane
1317.93	**C–N** stretching	Aromatic amine
1250.96	**C–N** stretching	Amine
1062.09	**S = O** stretching	Aliphatic amine
781.07	**C–H** bending	1,2,3-trisubstituted hydrocarbons
520.36	**C–Br** stretching	Halo compound

influence gasification. Results are shown in Fig. 6. The high cellulose and hemicellulose contents enhance the thermal degradation of PFB as it decomposes at 200–700 ℃. Three stages of degradation can be observed in Fig. 6: in the first stage, moisture removal occurred with 8.98% mass loss; a moderate mass loss (28.72%) was identified between 279 and 367 ℃, at the second stage, accompanied by the release of gases from the volatile and other organic matters; finally, at 367–535 ℃, a high weight loss (42.39%) occurred due to the breakdown of cellulose, hemicellulose, and lignin with gaseous by-products, constituting the third stage of mass loss. The latter stage may be regarded as the active pyrolysis zone where the minor and major reactions take place. The thermal decomposition of PFB further affirms its chemical constituents. This result agrees with the lignocellulose components of biomass [29, 30].

3.9 Suitability of PFB as a biofuel feedstock and other applications

The moisture and ash contents of PFB are less than 10 wt.%, which makes it suitable for direct combustion or pyrolysis. In addition, the ether extractives of negligible value further support combustion. From our findings, PFB can favourably compete with the other documented biomass feedstock such as switchgrass and sawdust. Moreover, the rich calcium content makes it a suitable biomaterial for other applications, such as fillers in particleboard and biocomposite, while the high carbon content can be processed into bio-charcoal and activated carbon.

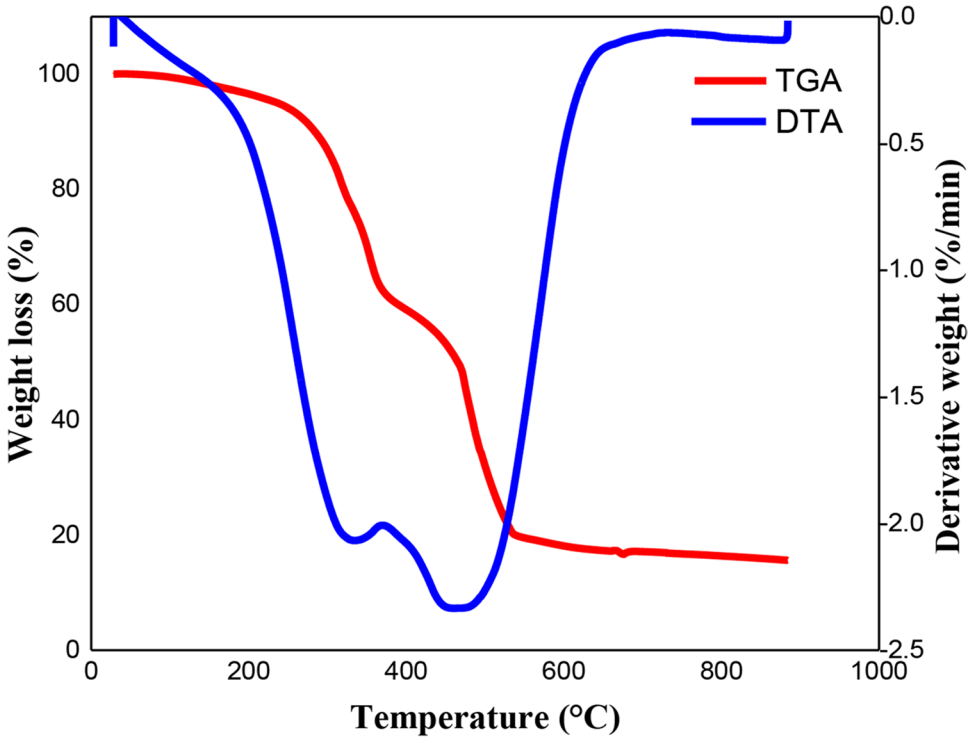

Fig. 6 Thermogravimetric analysis of PFB

4 Conclusions

In this work, pulverised *Ficus benjamina* fruits (PFB) were extensively characterised for their potential biofuel application. The PFB are amorphous, rich in carbon, have negligible extractives, with low nitrogen and sulphur contents, which makes it eco-friendly as a solid biofuel. Also, the low bulk density and moisture content make PFB cost-effective to process into biofuel. The structural analysis by XRD showed a low crystallinity index value. Furthermore, PFB revealed a high heating value of 19.74 MJ/kg, thus having a high prospect as an alternative to sawdust and wood fuel. However, further research is needed prior to its application in local stoves and boilers, such as optimised pellet densification, analysis of the pellet's combustion properties, and storage. From the EDS analysis results, the outer portion of the fruit holds all the calcium and most of the potassium present in the whole pulverised *Ficus benjamina* fruits. Considering the ether extractives content (1.48 wt.%) and the volatile matter (64.35 wt.%), these also have the potential to generate biogas via decomposition and should be further explored. Other envisaged applications of *Ficus benjamina* fruits that deserve attention, given their high carbon content and biogenic origin, may include biochar, activated carbon, biocomposite production for soil remediation and environmental sustainability.

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Author contribution USE: manuscript writing, conceptualisation, and data analysis. BNE: graph analysis and manuscript review and editing. MGP: characterisations and manuscript review and editing. END: characterisations. KF: manuscript review and editing. LEKA: manuscript review, editing, and general supervision**.** APO: manuscript review, editing, and general supervision.

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Data availability Data supporting the findings of this study is available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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