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ORIGINAL ARTICLE

# Potential of Jackfruit Waste as Anaerobic Digestion and Slow Pyrolysis Feedstock

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## Abstract

**Purpose** The estimated annual worldwide production of jackfruit peelings (JP) and jackfruit seeds is 2.96 million tonnes. This study assesses the suitability of this jackfruit waste from soft and firm jackfruit varieties as potential feedstocks for anaerobic digestion and slow pyrolysis.

**Methods** Proximate, ultimate, calorific values, thermogravimetric, compositional and lignocellulosic analyses were conducted.

**Results** The volatile matter, fixed carbon, hydrogen and carbon content of soft and firm jackfruit waste (peelings and seeds) ranged between 76.81 and 78.83%, 18.28 and 19.42%, 5.43 and 7.13% and 43.89 and 48.08%, respectively. The higher heating values (HHV) of soft and firm jackfruit waste ranged between 17.42 and 19.81 MJ/kg. The ash content of jackfruit waste from both varieties varied within the recommended range of less than 8%. The starch content of jackfruit peelings and seeds from both soft and firm varieties ranged between 29.05 and 59.54% while the sugar content of jackfruit peelings and seeds from soft and firm varieties ranged from 2.04 to 68.8%. The maximum weight degradation rate for the jackfruit waste for both jackfruit varieties occurred in the temperature range of 450–550 °C which is within the slow pyrolysis regime. Generally, cellulose formed the biggest proportions of the lignocellulosic composition followed by hemicellulose and lignin.

**Conclusion** Jackfruit waste from both soft and firm varieties is a potential feed stock for slow pyrolysis while soft variety jackfruit waste is more suitable for biogas production compared to the firm jackfruit wastes.

**Keywords** Anaerobic digestion · Characterisation · Jackfruit waste · Peelings · Slow pyrolysis

## Introduction

The increasing energy needs and the depletion of fossil fuel reserves pose a considerable challenge to find alternative energy sources like lignocellulosic biomass feedstocks (Widjaja et al. 2018). Biomass has been recognised as a renewable energy source that can be used to replace fossil fuels, with the added bonus that crops, plants or trees can fixate $CO_2$ from the atmosphere, reducing the greenhouse effect (Chaiwong et al. 2013). Hence, the use of biomass from waste for renewable energy supports the resolutions of the United Nations Conference of Parties (COP 21) on climate change where all countries are required to lower greenhouse gases (United Nations Framework Convention on Climate Change (UNFCCC 2015). Agricultural and agro-industrial wastes are increasingly being used as biomass to generate energy via thermochemical conversations such as pyrolysis, gasification, combustion (Francisco et al. 2020) and biochemical processes such as anaerobic digestion. Incentives to obtaining bioenergy from agro-industrial waste can contribute to the

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development of a green economy hence contributing to the seventh Sustainable Development Goal (SDG) which advocates for all people to access affordable and clean energy (United Nations Development Programme (UNDP 2015). For this reason, generation of bioenergy from agricultural wastes has gained significant research attention.

Agricultural residues hold potential as resources for the recovery of energy, chemicals and materials in a biorefinery concept, without competing for land use for primary food production (Ghysels et al. 2020). Biorefining of agricultural residues can generate additional value for (developing) countries, where these agricultural residues are generated. For example, pyrolysis can convert these residues into value-added products like biochar at elevated temperatures in an oxygen-free atmosphere while anaerobic digestion can convert manures or dedicated energy crops into biogas for energy. While different products can be expected from anaerobic digestion/pyrolysis of agricultural residues, most studies focus on maximal energy recovery by combusting biogas and pyrolysis products. The characterisation of end-products from anaerobic digestion/pyrolysis and evaluation of their potential application besides combustion are often overlooked. This study evaluates the potential of jackfruit waste as an example case for production of different anaerobic digestion/pyrolysis products for further characterisation.

Jackfruit (*Actocarpus heterophyllus*) is a popular fruit that is widely grown in tropical countries such as India, Indonesia, Bangladesh, Thailand, Malaysia, Brazil (Suely et al. 2014) and Uganda (Nakintu et al. 2019). Jackfruit agribusiness in these countries is a relevant economic activity for the farmers and the traders involved. In Uganda, it is cultivated in the Central, Eastern and Western parts of the country (Nsubuga et al. 2020). Jackfruit waste can be categorised into jackfruit peelings (JP) and jackfruit seeds (JS) which are the main by-products of the jackfruit processing (Francisco et al. 2020). Jackfruit peelings and seeds constitute about 60% and 20% respectively of the ripe fruit's gross weight (Moorthy et al. 2017). Jackfruit peelings include the rind, arils and core (Swami et al. 2018). The estimated annual worldwide jackfruit waste production is 2.96 million tonnes (Francisco et al. 2020). This expressive volume of jackfruit waste represents a critical environmental issue for jackfruit-producing countries. Some other applications for jackfruit wastes include their use as a low-cost adsorbent for dye removal (Karmaker et al. 2015), as a precursor for activated carbon (Foo & Hameed 2012) and as a pectin source (Moorthy et al. 2017). The application of jackfruit waste as a new feedstock for anaerobic digestion or slow pyrolysis processes can increase the economic value of these wastes and reduce the final volume discarded. However, there is less experimental evidence regarding the potential of jackfruit waste as feedstocks for slow pyrolysis and anaerobic digestion. Since information about energy-related properties of agricultural wastes is usually unavailable, it limits their utilisation as feedstocks for bioenergy production processes. In addition, there is little concern about waste generation and its subsequent destination (Braga et al. 2015) especially in developing countries like Uganda.

Only a few studies are available on the characterisation of jackfruit waste as potential feedstock for bioenergy production in Indonesia, Brazil and India (Francisco et al. 2020; Pieter et al. 2014). However, no published studies have considered jackfruit varieties in characterising its waste as potential feedstocks for anaerobic digestion and slow pyrolysis. It is important to experimentally find out which jackfruit variety is more suitable for the different bioenergy generation processes for optimum results. It is against this background that the main objective of this study was to characterise the firm and soft jack fruit waste as potential feedstocks for anaerobic digestion and slow pyrolysis.

## Materials and Methods

### Materials Source and Preparation

Two common jackfruit varieties in Uganda, namely soft and firm varieties as described by Nsubuga et al. (2020), were utilised in this study. The soft variety, locally (in Uganda) known as 'Serebera', and the firm variety 'Namata' jackfruits harvested at physiological maturity were purchased from farmers in Kayunga district in the central part of Uganda. The jackfruits were washed with water and manually cut using a knife as suggested by Raj and Ranganathan (2018). The jackfruit bulbs were separated from the inedible jackfruit wastes. The jackfruit wastes were divided into jackfruit peelings (JP) and jackfruit seeds (JS) for both soft and firm varieties. The jackfruit peelings and seeds were separately shredded into small pieces of about 5 mm as suggested by Gumisiriza et al. (2019) to increase the surface area for drying. The initial moisture contents of the fresh jackfruit peelings and seeds were determined using the Inspector Pro Moisture and humidity metre. The probe pin was inserted into the fresh biomasses and moisture contents were displayed instantly. At first, the samples were sun dried for 2 days while moisture content was being determined by air-drying 50 g of the sample and weighing at an interval of 24 h until insignificant weight loss was obtained since the experiment was done in the rainy season.

The jackfruit peelings and seeds were then put in an oven at 50–60°C, to cover for weather variations, for 24 h to reach a moisture content of about 10–12% prior to grinding. The experiment was done during a rainy season. The dried jackfruit peelings and seeds were ground using a hammer mill (Brook Crompton series 2000 model) and sieved through a 2.5-mm size sieve to get samples suitable for feedstock characterization.

Samples of 100 g were kept in zip bags to ensure no moisture migration from the environment during storage at room temperature.

## Proximate Analysis and Thermal-Gravimetric Analysis

The proximate analysis of the jackfruit wastes from the firm and soft varieties was determined using an Eltra Thermostep non-isothermal thermo gravimetric analyser (TGA), Haan, Germany according to ASTM-D7582-15 (Eltra Elemental Analyzers 2018). This method allows for sequential determination of moisture, volatiles, ash content and fixed carbon up to 19 samples in a single analysis. In this method, standard operating procedure (SOP) in the computer was selected. The jackfruit waste (JP and JS) sample identifications (IDs) were entered into the software. Jackfruit samples in the crucible at a position assigned to the sample ID in the carousel were weighed by the integrated detection balance. After one sample had been weighed, the carousel automatically rotated to the next position and the next registered sample was then be weighed in the crucible until all 12 jackfruit waste the samples from the two jackfruit varieties were weighed. The average weight of the samples were 1.1501 g, 1.2040 g, 1.2034 g and 1.2838 g for firm jackfruit seeds, soft jackfruit seeds, soft jackfruit peelings and firm jackfruit peelings, respectively. The TGA experiments were carried out from room temperature to 920 °C with a heating rate of 16 °C/min as recommended by Lubwama et al. (2020). High-purity compressed air (oxygen:nitrogen = 21:79, >99.5%) was used for cleaning the crucibles and chamber prior to TGA experiments. Nitrogen gas was used as the purge gas for pyrolysis experimentation as recommended by Islam et al. (2015). The flow rate was maintained at 1 L/min and the sample masses averaged 1.2 g. The thermogravimetric analysis was used to determine the weight loss of the jackfruit wastes (JP and JS) with increase in temperature. The Eltra themostep thermogravimetric analyser was calibrated using calibration standard coal 92511-3030 Lot 20131211B with informative values for moisture wt.% wb, ash content wt.% db and volatile matter wt.% db of 4.0, 6.5 and 35.9, respectively. The moisture content (wt.%, wb), volatile matter (wt.% db), ash content (wt.% db) and fixed carbon (wt.% db) of the samples were calculated using Eq. (1), Eq. (2), Eq. (3) and Eq. (4) as described by LECO Corporation (2010).

$$M.C(\mathrm{wt.\%}) = \frac{A(g)-B(g)}{A(g)} \times 100 \quad (1)$$

$$V.M(\mathrm{wt.\%}) = \frac{B(g)-C(g)}{A(g)} \times 100 \quad (2)$$

$$A.C(\mathrm{wt.\%}) = \frac{D(g)}{A(g)} \times 100 \quad (3)$$

$$F.C(wt.\%) = 100-(M.C(wt.\%) + V.M(wt.\%) + A.C(wt.\%)) \quad (4)$$

where $M.C$ is the moisture content (wt.%), $A(g)$ is the initial mass (g), $B(g)$ is the moisture mass (g), $V.M$ is the volatile matter (wt.%), $C(g)$ is the volatile mass (g), $A.C$ is the ash content (wt.%), $D(g)$ is the ash mass (g) and $F.C$ is the fixed carbon (wt.%).

## Calorific Value Analysis

The jackfruit samples were formed into small briquettes using a briquettes machine with weight of 0.8–1.1 g. A bomb calorimeter (Ika 2000 model) was given six (6) minutes to stabilise before the briquettes were fed beneath the firing string in the crucible. After calibration, the measuring cell cover closed automatically and the decomposition vessel was immersed with the sample into the inner vessel. Pure oxygen (99.95%) was introduced until a pressure of 30 bars was reached. The briquette fuel sample ignited electrically within the ignition device and the increase in temperature of the water in the inner vessel was measured resulting in the determination of the higher heating values (HHV) in MJ/kg. The lower heating values (LHV) in MJ/kg were calculated from the HHV by discounting the latent heat required to vaporise water using Eq. (5) as described by Francisco et al. (2020).

$$LHV_{d.b}(\mathrm{MJ/kg}) = HHV_{d.b}(\mathrm{MJ/kg}) - 1.2183 \times H(\mathrm{wt.\%})_{d.b} \quad (5)$$

where $H$ is the percentage hydrogen content.

## Ultimate Analysis

Nitrogen content was determined by calorimetric method as described by Okalebo et al. (2002) on dry basis. Jackfruit digests were obtained by treating the four jackfruit waste samples with hydrogen peroxide to oxidise the organic matter and the sulphuric acid to complete the digestion at elevated temperatures. The selenium powder was added to act as a catalyst. The entire digest was diluted with the blanks to a ratio of 1:9 (v/v) with diluted water to match the standards. With a micropipette, 0.2 mL of the sample digest was added to 5.0 mL of the solution containing 34 g sodium silicate, 25 g sodium citrate and 25 g sodium tartrate in 750 mL of distilled water, vortexed and 5.0 mL solution containing 30 g sodium hydroxide in 750 mL of distilled water.

The mixture was allowed to stand for 2 h and the absorbency measured by spectrophotometer at 650 nm. The blue colour was stable for at least 2 h and a plot of calibration curve and concentration of nitrogen were generated. The nitrogen concentration in the sample material expressed as %N was calculated according to Eq. (6).

$$\mathrm{N(wt.\%)} = \frac{(a-b) \times v}{w \times al \times 1000000} \times 100 \tag{6}$$

where $a$ is concentration of N in the solution (mg/L), b is concentration of N in the blank (mg/L), v is total volume at the end of analysis procedure (mL), w is weight of the dried sample (g) and al is aliquot of the solution taken (mL).

On the other hand, the carbon, hydrogen and sulphur contents were determined using ELTRA CHS-580 elemental analyser on dry basis. The ELTRA-CHS-580 analyser resistance furnace had a horizontal orientation and utilised oxygen gas of purity of 99.5% to heat up to 1550 °C at steps of 1 °C. The samples were homogenised and then weighed by electronic balance to weights ranging between 250 and 500 mg. The values of the weights were then input to the PC system manually before the ceramic boats fed into the combustion chamber of the furnace using tongs. Oxygen content was obtained by difference according to Eq. (7) and described by Francisco et al. (2020).

$$\begin{aligned}\mathrm{O(wt.\%d.b)} &= 100(\%)\mathrm{–C(wt.\%d.b)–H(wt.\%d.b)} \\ &\quad \mathrm{–N(wt.\%d.b)–S(wt.\%d.b)–Ash(wt.\%d.b)}\end{aligned} \tag{7}$$

## Compositional Analysis

The starch and sugars in jackfruit seeds and peelings from the soft and firm varieties were determined using the anthrone method (Clegg 1956). Twenty milligrams of jackfruit waste samples were weighed into a centrifuge tube with 5 mL of ethanol to extract the sugars. The solution was filtered and the supernatant was kept for soluble sugar analysis. To the residue, 5 mL of perchloric acid were added to hydrolyse the starch to sugars. From the supernatant and the sugar solution from starch, 2.0 mL were pipetted from each into a pyrex glass tube and kept at 0 °C. Ten millilitres of anthrone reagent, which was cooled to 0 °C before use, were added to the 2.0-mL test solution. The reaction mixture was shaken thoroughly and heated for 11 min at 100 °C until there was a colour change from yellow to green depending on the concentration of sugars in the solutions. After this treatment, the tubes were rapidly cooled to 0 °C and the absorbance at 630 nm measured against distilled water within 1 h. The concentration of starch and sugars was calculated using a standard graph obtained using pur glucose in the range of 50–200 μg/mL.

The pH values of jackfruit wastes were determined using an electronic digital pH metre (HI 220 model). The metre probe was dipped into a 50-mL beaker containing a sample that had been thoroughly mixed with distilled water. The pH values ware then directly read from the digital screen.

## Lignocellulosic Analysis

Lignocellulosic fractions (cellulose, hemicellulose and lignin) of the jackfruit waste samples were investigated by the Van-Soet methodology as described by Kabenge et al. (2018). The analysis was done using two analytical methods: (1) using neutral detergent fibre (NDF) in Eq. (8) and (2) ash contained in acid detergent fibre (ADF) in Eq. (9). NDF analysed the total fibre in the samples, that is, the residue that remains after treatment of the biomass with neutral detergent solution (sodium lauryl sulphate and EDTA). The difference between the ADF and NDF was interpreted as hemicellulose content. Similarly, the cellulose content was established by determining the mass difference of the dry sample residues which resulted from the lignin content analysis after putting them in a muffle furnace set at 500–550 °C for a period of 3h. Lignin, cellulose and hemicellulose contents determination is illustrated by Eq. (10), Eq. (11) and Eq. (12).

$$NDF(\mathrm{wt.\%}) = \frac{W_2(g)-W_3(g)}{W_1(g)} \times 100 \tag{8}$$

where $W_1$ is weight of sample in g, $W_2$ is weight of crucible + fibre in g and $W_3$ is weight of crucible + ash in g:

$$A.A(\mathrm{wt.\%}) = \frac{W_3(g)-W_5(g)}{W_1(g)} \times 100 \tag{9}$$

$$L.C(\mathrm{wt.\%}) = \frac{W_4(g)-W_5(g)}{W_1(g)} \times 100 \tag{10}$$

$$C.C(\mathrm{wt.\%}) = \frac{W_5(g)-W_2(g)}{W_1(g)} \times 100 \tag{11}$$

$$H.C(wt.\%) = NDF(wt.\%)-ADF(wt.\%) \tag{12}$$

where $W_1$ is weight of air-dried sample in g, $W_2$ is weight of empty crucible in g, $W_3$ is weight of crucible + ADF in g, $W_4$ is weight of crucible + lignin+ ash in g and $W_5$ is weight of crucible + ash in g; *NDF* is neutral detergent fibre, *ADF* is acid detergent fibre lignin, *A.A* is ash contained in *ADF*, *L.C* is lignin content, *C.C* is cellulose content and *H.C* is hemicellulose content.

## Statistical Analysis

All experiments were conducted in triplicates and all the data collected from proximate analysis, ultimate analysis, compositional analysis (starch and sugar content), calorific value analysis, lignocellulosic analysis and thermogravimetric analysis. The data was analysed using Genestat software (14th edition). A one-way analysis of variance (ANOVA) was performed for the results of jackfruit peelings and seeds results from soft and firm jackfruit varieties. The differences between

**Table 1** Proximate analysis of soft and firm jackfruit varieties' waste

| Proximate analysis, wt.% | Jackfruit Peelings | | Jackfruit seeds | |
|---|---|---|---|---|
| | Soft variety | Firm variety | Soft variety | Firm variety |
| Moisture content | $10.44^{a} \pm 0.36$ | $10.33^{a} \pm 0.10$ | $10.84^{a} \pm 0.02$ | $10.76^{a} \pm 0.03$ |
| Volatile matter | $68.79^{a} \pm 0.31$ | $70.28^{b} \pm 0.23$ | $70.30^{a} \pm 0.38$ | $69.45^{a} \pm 0.61$ |
| Ash content | $4.17^{b} \pm 0.10$ | $2.60^{a} \pm 0.16$ | $1.66^{a} \pm 0.10$ | $1.69^{a} \pm 0.05$ |
| Fixed carbon | $16.58^{a} \pm 014$ | $16.78^{a} \pm 0.24$ | $17.22^{a}\pm0.37$ | $17.97^{b}\pm0.53$ |

Means in the same row with different superscripts are significantly different at $p \leq 0.05$

mean values were evaluated to find out if they were statistically different at $p \leq 0.05$.

## Results and Discussion

The initial moisture content of fresh jackfruit peelings were 72% and 77 % for firm and soft varieties respectively while the values for the seeds were 34% and 36% for soft and firm varieties, respectively. However, after oven drying, the proximate, ultimate and thermogravimetric analysis was done. Other analyses included determination of calorific values, lignocellulosic composition, starch, sugar and pH content.

### Proximate Analysis of Jackfruit Waste

Generally, moisture content, volatile matter, ash content and fixed carbon results in Table 1 for the jackfruit peelings and seeds from both varieties were in agreement with results of Francisco et al. (2020) who studied insights into the bioenergy potential of jackfruit wastes considering their physicochemical properties, bioenergy indicators, combustion behaviours and emission characteristics.

Volatile matter content indicates the amount of substance other than moisture that can evaporate as a result of the decomposition of compounds that are still present in the solid. The volatile matter content of jackfruit peelings from the soft and firm varieties were 68.79% and 70.28%, respectively (Table 1), whereas the values for the jackfruit seeds from the soft and firm varieties were 70.30% and 69.45%. These values were less than the 74% reported by Pieter et al. (2014) for jackfruit waste. The difference could have been due to the different jackfruit cultivars considered in both studies. High percentage of volatile matter indicates that the fuel can easily ignite although the combustion is fast and difficult to control (Pathak et al. 2017). Lower volatile matter, on the other hand, is an indication that the fuel might not be easy to ignite, but once ignited, they would burn smoothly (Falemara et al. 2018).

The ash content values of jackfruit peelings and the seeds from both varieties were within the recommended range of less than 8% according to Waluyo and Pratiwi (2018) for materials to undergo slow pyrolysis. The ash content represents the incombustible part of the solid material (Pathak et al. 2017), and so, the low ash content value indicates that the substrate is suitable for thermal utilisation (Efomah & Gbabo 2015). A high percentage of ash similarly indicates the possibility of heavy metals thus characterisation before use is important.

The fixed carbon content of jackfruit peelings from soft and firm varieties were 16.58% and 16.78% while the values for the jackfruit seeds from soft and firm varieties were 17.22% and 17.97%, respectively (Table 1). These values for jackfruit peelings were greater than the 13.21% obtained by Francisco et al. (2020) but they were less than the 19.2% that was reported by Pieter et al. (2014). By definition, fixed carbon is the carbon that remains after volatile matter is released during the combustion process (Sukarta et al. 2018). Fixed carbon gives a significant indication of the fraction of char that remains after the pyrolysis phase and this char can be mixed with soil to produce *terra preta* soils. A high percentage of fixed carbon will enhance the higher heating values and lower heating values (HHV and LHV) because the amount of fixed carbon present acts as a major generator of heat during combustion (Suryaningsih et al. 2017). Hence, jackfruit seeds have more HHV and LHV compared to jackfruit peelings as indicated in Table 3.

### Ultimate Analysis of Jackfruit Waste

The ultimate analysis is critical in determining the biomass fuel potential, calorific values and expected environmental impact (Fernandes et al. 2012). The presence of elements like carbon, hydrogen, nitrogen and oxygen highly influence the heating values while presence of elements like sulphur indicates, if released, negative environmental impact (Kabenge et al. 2018). The ultimate analysis results are helpful in determining the HHV according to Luo and Resende (2014) by incorporating individual elemental percentages. Similarly, the presence of N in the jackfruit peelings and seeds was an indicator that their biochar is a suitable ingredient for soil fertility enhancement for crop production (Timmons et al. 2017).

Generally, the ultimate analysis results of jackfruit peelings and seeds (Table 2) were similar to the results obtained by Francisco et al. (2020) in Brazil. However, the jackfruit peeling results from both soft and firm varieties were different from the ones obtained by Pieter et al. (2014) in Indonesia which were 63.60% carbon, 7.84% hydrogen, 0.03% sulphur, 0.61% nitrogen and 27.92% oxygen. The difference in the results might be attributed to the different jackfruit cultivars used in the experiments.

The C/N ratio for both jackfruit peelings and seeds from soft and firm varieties was 28.37–31.79. These C/N ratio values were close to the 33.1 obtained by Viswanath et al. (1992). According to Das and Mondal (2016) and Dioha et al. (2013), the recommended C/N ratio for optimum biogas production is 20–30. Hence, the firm variety C/N ratios for both peelings (31.60) and seeds (31.79) were higher than the recommended range. The C/N ratios of soft variety peelings (28.37) and seeds (28.61) were found to be within the recommended range for biogas production. For optimum biogas production, co-digestion of jackfruit waste (JP and JS) with low C/N ratio feedstocks like activated sludge with C/N ratio of 6–9 (Xie 2012) is advised to maintain the C/N ratio within the recommended range. The advantage of using of activated sludge is that being a lower C/N ratio substrate, it will required less quantities of it to modify the jackfruit waste C/N ratio hence reducing the cost of transport. This will also help in providing a wide range of nutrients in addition to increasing the buffering capacity of the co-substrate mixture.

## Calorific Values of Jackfruit Waste

The HHV and LHV for the jackfruit peelings and seeds for both soft and firm varieties were in agreement with results of Francisco et al. (2020). Soft jackfruit variety peelings had higher HHV and LHV than the firm jackfruit variety peelings (Table 3). Likewise, firm jackfruit variety seeds had higher HHV and LHV than the soft jackfruit variety seeds.

The HHV of the jackfruit peelings from soft and firm varieties were 17.42 and 19.03 MJ/kg respectively whereas the values for the jackfruit seeds from soft and firm varieties were 19.14 and 19.81 MJ/kg, respectively (Table 3). These values were higher than 3.03 MJ/kg reported by Pratiwi et al. (2019).

Thus, jackfruit seeds had both higher HHV and LHV compared to the jackfruit peelings due to higher amount of carbon and hydrogen with a strong correlation with the heating value of jackfruit seeds, signifying that higher C and H contents correlate to higher heating values (Pighinelli et al. 2014). Compared to the HHV of other lignocellulosic biomasses: wheat straw (19 MJ/kg), douglas fir (18.4 MJ/kg) and coffee (22.7 MJ/kg) (Kabenge et al. 2018), jackfruit peelings and seeds from both varieties have similar values except for coffee.

## Starch, Sugar and pH Content of Jackfruit Waste

The pH values of jackfruit peelings for the soft and firm varieties were not significantly different (Table 4). The pH values of jackfruit peelings and seeds were acidic (<7). However, the recommended pH for optimum biogas production is 7.0–8.5 (Teghammar 2013). Hence, use of alkaline solutions like sodium hydroxide (Meegoda et al. 2018) to raise the pH values to the recommended range is advised. This is because outside the recommended pH range, the anaerobic digestion process would face imbalances (Teghammar 2013).

The starch content of jackfruit peelings and seeds from both soft and firm varieties was found to be higher than 4.12% recorded by Sundarraj and Ranganathan (2017). The sugar content of soft jackfruit peelings (68.8%) was higher than the 19.75% recorded by Sundarraj and Ranganathan (2017) while that of the firm variety (8.92%) was lower. The difference in the sugar contents of between the soft and firm varieties could be attributed to differences in their inherent physiological properties like stage of ripening. The sugar contents of the jackfruit seeds for the soft variety (2.04%) and the firm variety (9.02%) were also lower than the 19.75% obtained by Sundarraj and Ranganathan (2017). The difference can

**Table 2** Ultimate analysis of soft and firm jackfruit varieties' waste

| Ultimate analysis, wt.% | Jackfruit peelings | | Jackfruit seeds | |
|---|---|---|---|---|
| | Soft variety | Firm variety | Soft variety | Firm variety |
| Carbon | $43.89^{a} \pm 0.86$ | $44.90^{a} \pm 0.08$ | $45.04^{a} \pm 0.79$ | $48.08^{b} \pm 0.52$ |
| Hydrogen | $5.43^{a} \pm 0.36$ | $6.26^{a} \pm 0.52$ | $6.13^{a} \pm 0.22$ | $7.13^{b} \pm 0.31$ |
| Sulphur | $0.41^{a} \pm 0.02$ | $0.51^{b} \pm 0.04$ | $0.11^{a} \pm 0.00$ | $0.29^{b} \pm 0.06$ |
| Nitrogen | $1.55^{a} \pm 0.08$ | $1.42^{a} \pm 0.07$ | $1.57^{a} \pm 0.06$ | $1.50^{a} \pm 0.03$ |
| Oxygen* | $44.04^{a} \pm 0.96$ | $43.97^{a} \pm 0.45$ | $45.27^{b} \pm 0.81$ | $41.06^{a} \pm 0.82$ |
| C/N ratio | 28.37 | 31.60 | 28.62 | 31.97 |

Means in the same row with different superscripts are significantly different at $p \leq 0.05$

*Calculated by difference

**Table 3** Calorific values of selected jackfruit varieties' waste

| Calorific values, MJ/kg | Jackfruit peelings | | Jackfruit seeds | |
|---|---|---|---|---|
| | Soft variety | Firm variety | Soft variety | Firm variety |
| HHV | $17.42^{a} \pm 0.39$ | $19.03^{b} \pm 0.71$ | $19.14^{a} \pm 0.34$ | $19.81^{a} \pm 0.56$ |
| LHV* | $16.24^{a} \pm 0.42$ | $17.66^{b} \pm 0.61$ | $17.81^{a} \pm 0.30$ | $18.25^{a} \pm 0.53$ |

Means in the same row with different superscripts are significantly different at $p \leq 0.05$

*Calculated by equation

be attributed to the fact that the study by Sundarraj and Ranganathan (2017) considered jackfruit peelings only and not seeds as in this study. During the hydrolysis stage of anaerobic digestion, starch is converted into additional sugars (Ranasinghe & Marapana 2019). The sugars are then converted into intermediate volatile fatty acids (Shabih et al. 2018) and other products like alcohols, hydrogen, ammonia and carbon dioxide (Teghammar 2013). Therefore, given their starch and sugar content, jackfruit peelings and seeds are potential biogas feedstocks with soft jackfruits peelings and seeds being highly recommended for anaerobic digestion.

## Lignocellulosic Composition of Jackfruit Waste

Lignocellulosic fraction refers to the mixture of lignin, cellulose and hemicellulose fractions. Generally, cellulose formed the biggest proportions of the lignocellulosic composition followed by hemicellulose and lignin except for the firm jackfruit seeds where hemicellulose formed the highest percentage followed by cellulose and lignin (Table 5). Raj and Ranganathan (2018) and Sundarraj and Ranganathan (2017) also observed the same general trend for cellulose, hemicellulose and lignin.

Lignin and cellulose content of jackfruit peelings from soft and firm varieties of were significantly different unlike the hemicellulose. The cellulose and hemicellulose content of jackfruit seeds from soft and firm varieties' seeds were significantly different whereas lignin content was not significantly different.

In terms of biogas production from jackfruit peelings and seeds, the presence of lignin, cellulose and hemicellulose implies the need of pre-treatment of the feedstock. Hence, their presence could be a major problem in using jackfruit waste as a substrate for anaerobic digestion unless if pretreatment methods that are cost-effective and produces less inhibitors (Tayyab et al. 2018) are used. Pre-treatment improves degradability and the rate of enzyme hydrolysis of jackfruit peelings and seeds to increase the methane yield during anaerobic digestion process (Aboderheeba 2013).

## Thermogravimetric Analysis

The pyrolytic properties of jackfruit peelings and seeds from soft and firm varieties were studied using thermogravimetric analysis (Pieter et al. 2014) for weight loss and rate of weight loss at temperatures range of 20–900 °C (Fig. 1, Fig. 2). The pyrolysis process occurred in three stages: dehydration process, devolatization and endothermic decomposition of lignin (Ceylan & Topçu 2014).

In the first stage at temperatures below 105 °C, jackfruit peelings and seeds for both varieties remain at a plateau during combustion from room temperature to 104 °C, followed by undergoing a major weight loss at about 105 °C. This weigh loss occurred due to the evaporation of moisture from the samples as also observed by Lubwama et al. (2020) and Biswas et al. (2016). Here, the lignocellulosic part of the jackfruit samples was stable until a temperature of 200 °C.

In the second stage, the main component of the jackfruit peelings and seeds from both varieties: cellulose and hemicellulose, started degradation within the temperature range of 200–335 °C. The weight loss in this stage was due to the breakdown of hemicelluloses, cellulose and the volatile matter removal. Ceylan and Topçu (2014) noted that the decomposition of cellulosic part of the biomass occurs in two ways. In the first way which occurs at low temperatures (up to 355 °C in this study), break down of bonds in polymers and

**Table 4** Starch, sugar and pH content selected jackfruit varieties' waste

| Composition | Jackfruit peelings | | Jackfruit seeds | |
|---|---|---|---|---|
| | Soft variety | Firm variety | Soft variety | Firm variety |
| pH | $5.32^{a} \pm 0.07$ | $5.37^{a} \pm 0.08$ | $5.36^{a} \pm 0.03$ | $5.26^{a} \pm 0.05$ |
| Starch (wt.%) | $31.76^{a} \pm 0.97$ | $41.34^{b} \pm 0.70$ | $59.54^{b} \pm 0.58$ | $29.05^{a} \pm 0.68$ |
| Sugar (wt.%) | $68.87^{b} \pm 0.59$ | $8.92^{a} \pm 0.63$ | $2.04^{a} \pm 0.56$ | $9.02^{b} \pm 0.74$ |

Means in the same row with different superscripts are significantly different at $p \leq 0.05$

**Table 5** Lignocellulosic composition of soft and firm jackfruit varieties' wastes

| Composition, wt.% | Peelings | | Seeds | |
|---|---|---|---|---|
| | Soft variety | Firm variety | Soft variety | Firm variety |
| Lignin | $4.03^b \pm 0.36$ | $3.08^a \pm 0.32$ | $1.91^a \pm 0.45$ | $1.79^a \pm 0.28$ |
| Cellulose | $17.71^a \pm 0.65$ | $26.43^b \pm 0.89$ | $17.97^b \pm 0.63$ | $5.35^a \pm 0.43^a$ |
| Hemicellulose | $7.32^a \pm 0.75$ | $6.81^a \pm 0.73$ | $9.06^a \pm 0.22$ | $10.66^b \pm 0.74$ |

Means in the same row with different superscripts are significantly different at $p \leq 0.05$

CO, $CO_2$ and carbonaceous are formed. In the second way, at high temperatures (355–600 °C), integration of bonds which leads to liquid formation takes place (Çepelioğullar & Pütün 2013).

The third stage (above 600 °C) is governed by thermal decomposition of inorganic minerals like carbonates and clay owing to decomposition of lignin (Widjaja et al. 2018). At approximately 900 °C, lignin in the jackfruit peelings and seeds had decomposed off, implying that the remaining weight percentage was mainly composed of residues including ash, tars and fixed carbon. From Fig. 1, analysis of the percentage weight remaining corresponding to residual matter tallies well with the summation of ash and fixed carbon contents already shown in proximate analysis results in Table 1.

Similarly, the DTA curves also illustrate the degradation of the jackfruit peelings and seeds from both varieties in relation to their lignocellulosic constituents such as the cellulose, hemicellulose and lignin. Fig. 2 also shows the temperatures (450–550 °C) at which the maximum weight change for all the four jackfruit samples occurred for this experiment. The thermal stability of the jackfruit peelings and seeds from both varieties between 100 and 150 °C and the thermal degradation between 450 and 550°C showed similarities with other plant biomasses. This observation was in agreement with what Lubwama et al. (2020), Ghysels et al. (2020) and Kabenge et al. (2018) observed with rice husks, coffee husks, groundnuts shells, banana peels and cocoa waste. This is an indication that jackfruit peelings and the seeds from both varieties are potential slow pyrolysis feedstocks.

## Conclusions

Characterisation of biomass before conducting anaerobic digestion and slow pyrolysis should be determined to establish its suitability for use in the production of biogas, biochar and other products. This study was done to characterise jackfruit peelings and seeds from firm and soft jack fruit varieties as potential feedstocks for anaerobic digestion and slow pyrolysis.

The proximate, ultimate, calorific value and TGA results of jackfruit peelings and seeds from soft and firm varieties were comparable to other lignocellulosic biomasses reported in literature, and hence, these wastes are potential slow pyrolysis feedstocks. The maximum weight degradation rate for the jackfruit peelings and seeds from both varieties occurred in the temperature range of 450–550 °C which is the slow pyrolysis regime. It can be concluded that jackfruit peelings and seeds from soft and firm varieties are potential feedstocks for slow pyrolysis for production of biochar that could be used as a soil amendment.

On the other hand, the starch, sugar, pH and lignocellulosic composition of peelings and seeds were also comparable to other lignocellulosic materials, and hence, jackfruit wastes are potential anaerobic digestion feedstocks. However, the jackfruit peelings and seeds from the soft variety contained more sugars and starch compared to the jackfruit peelings and seeds from the firm variety. Hence, the soft jackfruit peelings and seeds are recommended for anaerobic digestion for production of biogas and other products. Given their cellulose,

**Fig. 1** Thermogravimetric analysis (TGA) plots for pyrolysis of jackfruit peeling and seeds

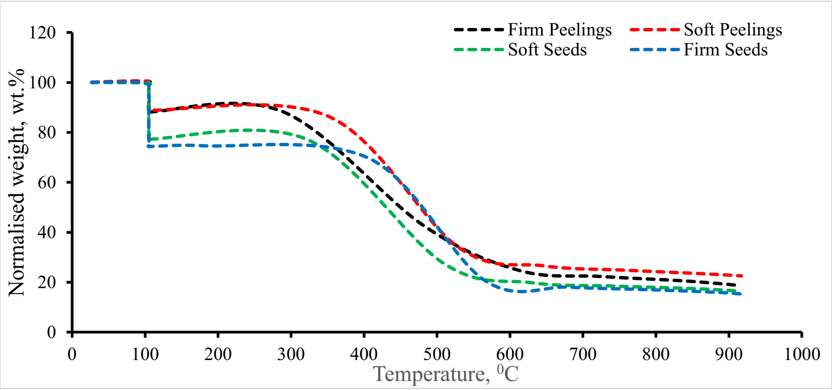
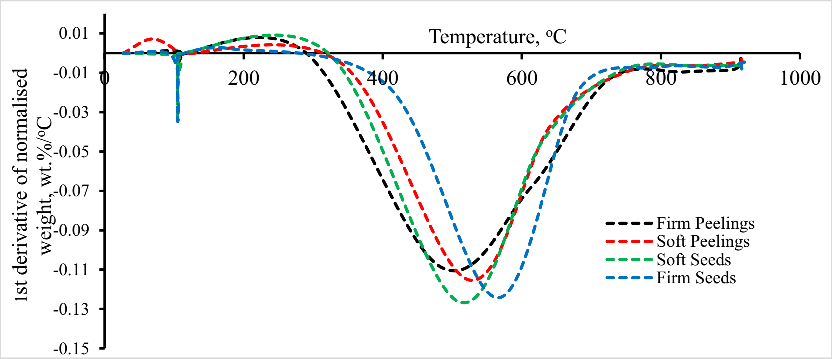


**Fig. 2** Differential thermal analysis (DTA) plots for pyrolysis of jackfruit peelings and seeds



hemicellulose and lignin content, pre-treatment of jackfruit waste by soaking in water for at least 10 days before anaerobic digestion is highly recommended. Also, co-digestion with low C/N ratio feedstocks like cow dung and chicken dropping is recommended.

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## Declarations

**Conflict of Interest** The authors declare no competing interests.

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