



Thermochemical Co-conversion of Sugarcane Bagasse-LDPE Hybrid Waste into Biochar

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Received: 7 April 2020 / Accepted: 5 November 2020 / Published online: 20 November 2020
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Abstract

Bagasse is a residue obtained from the processing of sugarcane (*Saccharum officinarum*). The aim of this study was to investigate the temperature profile, biochar yield and product quality of a locally designed thermochemical process for the conversion of sugarcane bagasse (SCB) and low-density polyethylene waste into biochar. Product quality was evaluated using Fourier transform infrared spectroscopy, scanning electron microscopy and Branauer–Emmett–Teller analyses. Product yield was 16.67 wt% and 45.46 wt% at 349°C and 250°C peak temperatures for SCB and hybrid biochar, respectively. Both SCB biochar and hybrid had a heterogeneous surface morphology and was mesoporous. The specific surface area of the SCB and hybrid biochar was 533.6 m²/g and 510.5 m²/g, respectively. The process has a three-pronged advantage of product development, waste management and resource conservation.

Keywords Biochar · Biomass · Sugarcane bagasse · LDPE

1 Introduction

Energy and environmental sustainability are some of the major challenges of humans for the long-term future [1]. Biomass is a material with a high energy content [2, 3], and its utilisation could assuage the impending energy crisis [4]. One of the most produced biomass globally is sugarcane, and it is a potential solution to these energy issues [5].

Sugarcane (*Saccharum officinarum*) was first cultivated in Southeast Asia and Western India [6]. Globally, the annual production of sugarcane is 1.6 billion tons, generating about 279 million metric tons of biomass residues [7]. Brazil is currently the largest producer of sugarcane in the world. Bagasse is a residue obtained from the processing of sugarcane via the crushing and extraction of the juice [7]. The bagasse constitutes about 35% of the total cane weight [8]. A minimum of 50% of the generated bagasse can be utilised to generate

heat and power for the sugar processing [9], and the rest is stacked for further processing into the value-added process (though this is not always the case) [10].

Moreover, low-density polyethylene (LDPE) is the main component of urban solid waste in our major urban centres; it is non-biodegradable and its volume generated is directly proportioned to the intensity of civic and social activities. Current information shows the startling rate at which plastic pollution from quantities of municipal solid waste (MSW) is ravaging the world [11]. For instance, in the USA, 39.3 million tons of LDPE is being generated annually, which is about 11% of the total MSW, apart from other forms of the plastic genre [11, 12]. In this case, the rate of its generation cannot catch up with the rate of recycling giving the presently available technologies if novel technology is not put in place for combining plastic with biomass wastes in doping magnitude [13]. Similar concerns about plastic pollution have also been raised in other continents like Africa, Europe, and Asia [14]. LDPE is selected in this study because it is one of the most significant plastic constituent in solid-waste streams [15, 16].

Researchers have studied several types of thermochemical processes for the conversion of energy from SCB [17]. These include pyrolysis, steam reforming [18, 19], supercritical water gasification [1], air gasification [20, 21] and hydrothermal carbonisation [22, 23]. The concept of recy-

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cling the heat from the controlled combustion of biomass for production of biochar from other biomass feedstock was earlier pitched by Abdelhafez, Abbas and Hamed [24] but was improved by other researchers [25–27]. In this study, a novel low-cost carbonisation process based on this process is employed that incorporates a retort heating system using controlled combustion of biomass fuel for heat generation. These contemplations make this study significant in the pursuit of energy and environmental sustainability in developing African countries.

The aim of this study is to investigate the temperature profile, biochar yield and product quality of a locally designed thermochemical process for the conversion of sugarcane bagasse (SCB) and low-density polyethylene (LDPE) waste. The biomass was converted in a singular process and a hybrid process with plastics. Product quality was evaluated using Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and Branueur–Emmett–Teller (BET) analyses. The relevance of this study is justified given the need to convert waste materials into a more useful product via energy-efficient processes. Furthermore, it is important for solid waste management and energy and environmental sustainability endeavours. The novelty of the study is justified in the types of the process employed. It is low-cost, easy to implement and has no electrical power requirement [25].

2 Materials Methodology

2.1 Feedstock

Sugarcane bagasse (*Saccharum officinarum*) was sourced from the Hausa community in Oja Gboro, Ilorin, Nigeria. Low-density polyethylene (LDPE) waste was sourced from a solid waste stream in Tanke, Ilorin, Nigeria. It was rinsed in distilled water to remove adhering dust and dirt. Both wastes were sundried for 2 days to remove moisture. The combustion fuel used were dry stems of *Daniella oliveri* picked also within the campus of the University of Ilorin, Nigeria.

2.2 Reactor Configuration

The reactor utilised was of a top-lit, updraft configuration. The concept was earlier pitched by Abdelhafez, Abbas and Hamed [24] but was improved by the current research group. In this study, a novel low-cost carbonisation process is employed that incorporate a retort heating system using controlled combustion. The description of the reactor used in this study is given in Fig. 1. Full dimensions of the reactor sizes have been described elsewhere [26, 27]. The heating process is self-regulating as recycled heat from the controlled combustion of biomass (stems of *Daniella oliveri*) in the heating gap is used to convert the biomass feed in the inner cham-

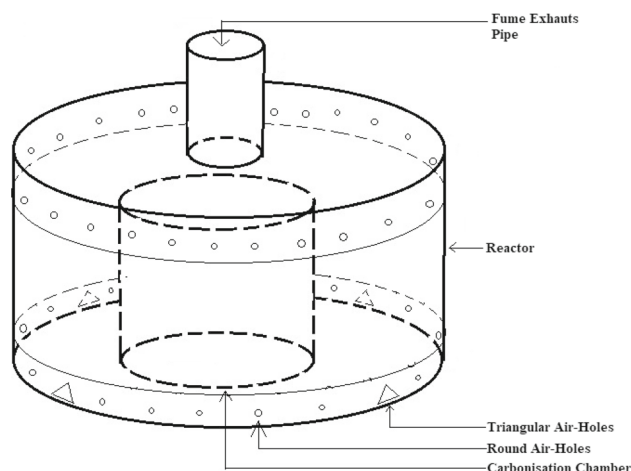


Fig. 1 Description of reactor used for the study.

ber. The configuration is ‘top-lit and updraft’. The heating gap is ignited at the top, and suction of air to the combustion zone occurs at the bottom air holes. The process is completed when the combustion fuel is used up. The process is easy to implement and has no electrical power requirement hence can be used in remote locations.

2.3 Process Description

Two experiments were conducted: SCB conversion and co-conversion of SCB-LDPE waste. The proportion of LDPE was 30 g for 900 g of the combined feed (giving a plastic content of 3.3%). This is to give allowance for plastic nature of LDPE and to allow effective co-conversion; similar position has been previously employed [28]. This is not as imbalanced as it seems when the effective density of the plastics is considered (as they use up much more space within the reactor). The SCB conversion was conducted in 48.5 cm high reactor with full dimensions described elsewhere [26]. The SCB-LDPE co-conversion was conducted in the 53-cm-high reactor with full dimensions described elsewhere [27]. A CASON CA380 infra-red thermometer (Accuracy; $\pm 0.1^\circ\text{C}$, Max; 380°C) was used for monitoring the process temperature so as the temperature profile can be achieved.

2.4 Biochar Yield

The degree of the feed carbonisation in the reactor used (Fig. 1) is expressed as the fraction of the biochar obtained relative to the feed converted. The biochar yield for the conversion process was computed using Eqn. 1–3. Similar expressions were previously employed [26, 27].

$$m_{\text{Bio-char}} = (M_3 - M_2)$$

$$m_{\text{raw}} = (M_1 - M_2)$$

Table 1. Summary of reactor performance

| Index | SCB conversion | Hybrid conversion |
|------------------|----------------|-------------------|
| Process time | 70 mins | 90 mins |
| Peak temperature | 349°C | 250°C |
| Bio-char yield | 16.67 wt% | 45.46 wt% |

$$\text{Yield}_{\text{Bio-char}} = \frac{m_{\text{Bio-char}}}{m_{\text{raw}}} \times 100\%$$

where M_1 = mass of feed chamber + feed (in grams), M_2 = mass of feed chamber alone (in grams), M_3 = Weight of feed chamber + product (in grams). For the single conversion of sugarcane bagasse, the values obtained were $M_1 = 600$ g, $M_2 = 480$ g, $M_3 = 500$ g. For the co-conversion of sugarcane bagasse with LDPE waste, the values obtained were $M_1 = 900$ g (plastic = 30g), $M_2 = 625$ g and $M_3 = 750$ g. Computing these values, we obtain biochar yields summarised in Table 1.

2.5 Product Characterisation

Product quality was evaluated using Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and Branauer–Emmett–Teller (BET) analyses. FTIR (Shimadzu, FTIR-8400S, Japan) spectrum was recorded using the transmittance in the $4000\text{--}650\text{ cm}^{-1}$ region with 30 sample scans. SEM (SEM, Phenom ProX, Phenom-World BV, Netherlands) was done with an acceleration voltage of the microscope set to 15 kV. BET (Quantachrome NovaWin ©1994–2013, Quantachrome Instruments v11.03) was done by N_2 adsorption test at 77K.

3 Results and Discussion

3.1 Temperature Profile

The temperature profile for the process was monitored for both SCB conversion and the hybrid co-conversion (and shown in Fig. 2a, b, respectively). T_a , T_b , T_c and T_d are the temperatures obtained at the base (side), middle (side), top (side) and centre of the reactors, respectively. The T_d gives a better representation of the temperature within the reactor chamber whilst T_a , T_b and T_c help in the monitoring of the movement of the combustion zone within the heating space as it proceeds from the top to the bottom of the reactor. Higher T_d in both profiles indicates a synergistic heating effect of the circular heating gap on the central chamber. The progression of each peak through T_c to T_b then T_a indicates the downward progression of the combustion zone within the heating gap. The peak temperatures of 349°C and 250°C for the

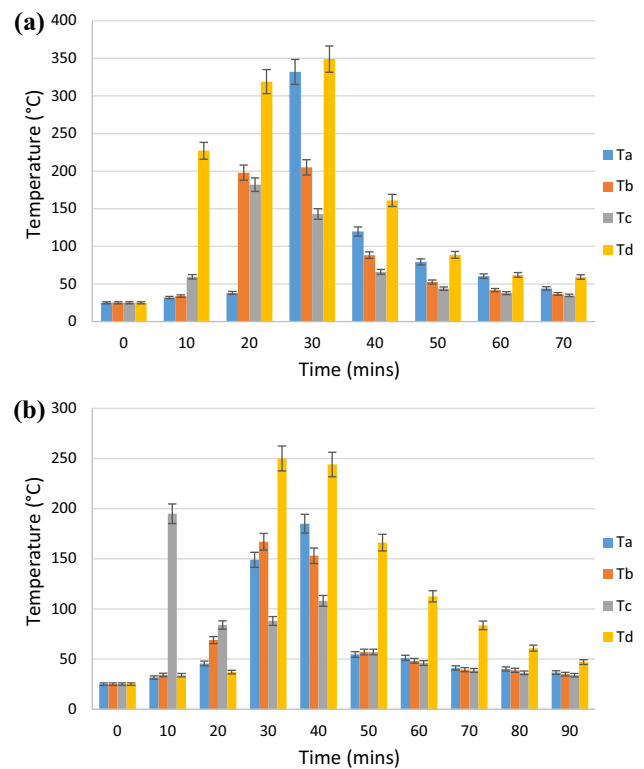


Fig. 2 Temperature profile for the biomass conversion **a** hybrid co-conversion **b** of sugarcane bagasse and LDPE waste

biomass and hybrid conversion can be observed from Fig. 2a, b, respectively. The peak temperatures and process times are different because the process is self-regulating. The heating effects are dependent on the volume and heating value of the combustion fuel utilised in the process.

3.2 Biochar Yield

It can be observed from Table 1 that the biochar yield was 16.67 and 45.46 wt% at 349 and 250°C peak temperatures for SCB and hybrid biochar, respectively. The biochar yield for the biomass conversion of SCB is higher than 6.98 wt% (peak temperature of 220°C) for plantain fibres [27] and 14.29 wt% (peak temperature of 300°C) for elephant grass [26] obtained using the same apparatus. The noticeable difference in peak temperature and process time occurs because the process is self-regulating and does not involve external parameter controls. Future explorations will be needed in this regard to achieve the requisite optimality and true generalisation of process conditions.

Moreover, biochar yield from the hybrid process is higher than that of the biomass process due to the effect of the plastics in the reactor. This is due to the carbon content of plastics (composed mainly of carbon and hydrogen) [11] being higher than for biomass (composed mainly of carbon, oxygen and hydrogen) [29]. The higher oxygen in the system due to

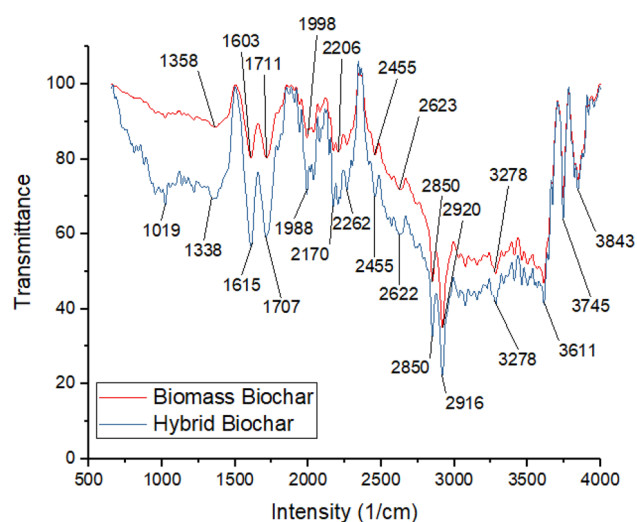


Fig. 3 FTIR spectra of SCB biochar (a) and hybrid biochar (b) of sugarcane bagasse and LDPE waste

Table 2. Summary of FTIR peaks and assignments

| Peaks (cm^{-1}) | | Possible assignment | References |
|----------------------------|------------------|-----------------------------------|--------------|
| SCB biochar | Hybrid biochar | | |
| 3843, 3745, 3611 | 3843, 3745, 3611 | O–H stretch | [30, 33] |
| 3278 | 3278 | N–H stretch | [33] |
| 2920 | 2916 | Assymmetric CH_2 stretch | [30, 35] |
| 2850 | 2850 | Symmetric CH_2 stretch | [35, 39] |
| 1711 | 1707 | C=O stretch | [40] |
| 1603 | 1615 | Aromatic C=C stretch | [30, 37, 40] |
| 1358 | 1338 | C–O or C–N stretch | [30, 33, 39] |
| | 1019 | C–O–C | [37, 39] |

biomass leads to the synthesis of more oxidised conversion products (CO and CO_2). These oxidised products take up carbon atoms with them, thereby reducing the char yield. Another reason could be the higher peak temperature for the SCB conversion leading to a greater intensity of thermal degradation hence lesser solid product.

3.3 Biochar Functional Groups

The FTIR spectra for the SCB biochar and the hybrid biochar are presented in Fig. 3. The spectra are presented in transmission mode ranging from 4000 to 650 cm^{-1} wavelength. The possible functional groups attributed to the peaks observed are shown in Table 2.

The peaks in the region of 3600–3850 cm^{-1} are attributed to the –OH group of the water, alcohols and phenol present in

the biomass samples [30–32]. The peak 3278 cm^{-1} observed in both samples indicate the presence of amide (N–H) groups [33]. The peaks 2920 cm^{-1} and 2850 cm^{-1} observed in SCB biochar correspond to the aliphatic C–H stretch of alkanes [32]. The intensity of these two peaks was observed to increase with the addition of LDPE. This may be attributed to the fact that LDPE is characterised by the presence of asymmetric and symmetric $-\text{CH}_2$ (ethyl) stretch commonly observed at these peaks [34–36]. The peak 1603 cm^{-1} observed in the SCB biochar correspond to the stretching vibrations of the alkene group (C=C) and was seen to shift to 1615 cm^{-1} and increase in intensity with the addition of LDPE to the biochar mixture. The shift and increased intensity may be due to the aromatic carbon content of LDPE [37, 38].

The peak observed at 1358 cm^{-1} for the SCB biochar is attributed to the C–O stretch of ether [30]. This peak was seen to shift to 1338 cm^{-1} with the addition of LDPE in the biochar production. The peak may also indicate the presence of C–N since nitrogen possible accumulated in the plant during cultivation [33]. The peaks ranging from 2622 to 1988 cm^{-1} were not assigned in past works of sugarcane bagasse within the author’s search scope. However, peaks in this range are commonly assigned to unsaturated carbon groups alkenes (C=C) and alkynes (C≡C), which may be bonded by nitrogen (C≡N, C≡C).

3.4 Biochar Morphology

The SEM micrograph of the SCB biochar and hybrid biochar is shown in Fig. 4a, b, respectively. Both SCB biochar and hybrid have a heterogeneous surface morphology with globular features. These globular features led to the generation of interstices on the surface of the char. These interstices are likely to lead to biochar with large specific surface area [25] which could also impact on its potential catalytic activity and adsorptive capacity [41]. The high specific surface area was confirmed by the BET analysis.

3.5 Biochar Porous Properties

The results of the Branueur–Emmett–Teller (BET) analysis of the SCB biochar and hybrid biochar is summarised in Table 3. It can be observed that the specific surface area of the SCB and hybrid biochar is 533.6 and 510.5 m^2/g , respectively. This is relatively high for a biochar sample obtained without the use of any chemical or physical activation process. Moreover, the summary of the reactor performance as presented in Table 1 confirms the variance in operating parameters for SCB and hybrid biochar production; in this case, SCB was produced at the lower temperature. Notwithstanding the fact that the surface area of hybrid biochar was slightly lower than that of the SCB, it was found to be more porous (Table 3).

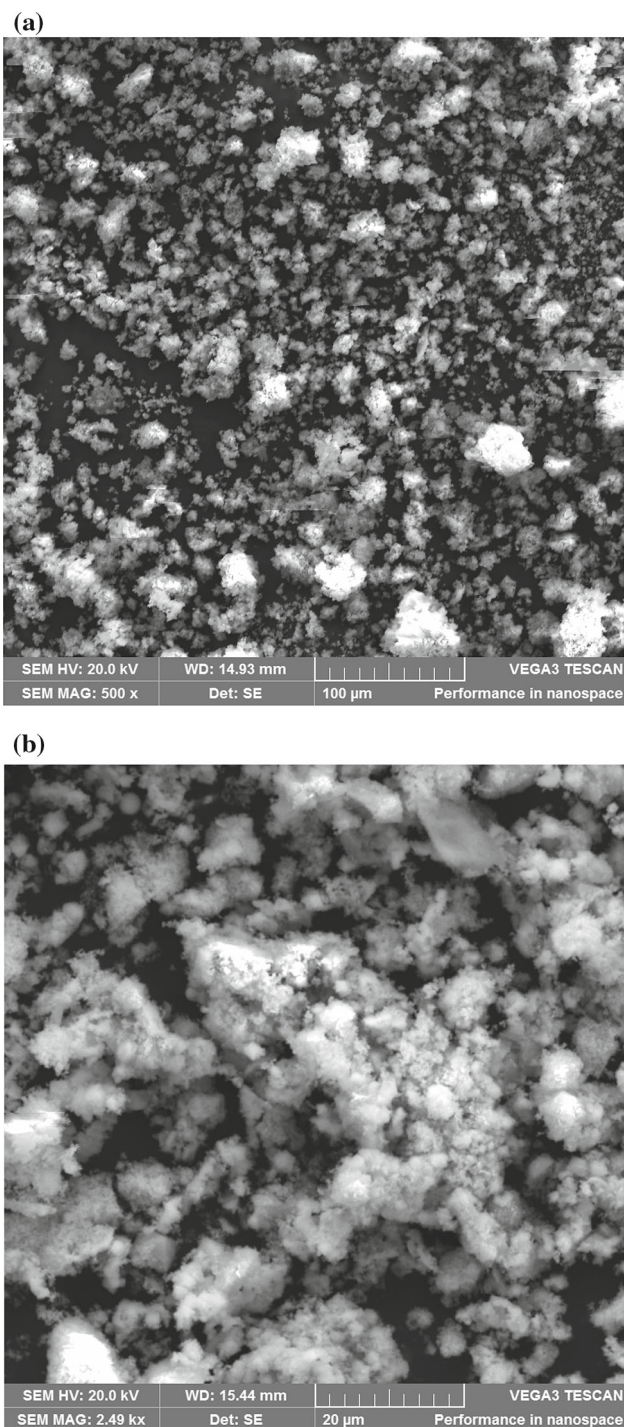


Fig. 4 SEM micrograph of SCB biochar (a) and hybrid biochar (b) of sugarcane bagasse and LDPE waste

The pores in the hybrid biochar were found to be larger than that of SCB, as further confirmed in Fig. 4a, b.

This further underlines the usefulness of this biochar for various applications. From the values of the pore diameter, it can be observed that the biochar samples are mesoporous. They are > 2 nm but < 50 nm. Both samples had technically

Table 3. Summary of textural properties of the products

| Properties | SCB biochar | Hybrid biochar |
|---|-------------|----------------|
| BET surface area (m ² /g) ^a | 533.6 | 510.5 |
| Total pore volume (cm ³ /g) ^b | 0.2301 | 0.2317 |
| Pore diameter (nm) ^b | 4.422 | 3.684 |

^aMultipoint Brunauer, Emmett and Teller (BET) method

^bBarrett, Jovner and Halenda (BJH) adsorption method

impressive pore volumes appropriate for numerous applications. This confirms that the doping LDPE with bagasse (at 3.3%) in biochar production improves the surface area and other textural properties of the produced biochar. A recent report of similar category equally confirmed that [28].

3.6 Comparison with Other Feedstock

Care was taken not to draw comparisons with other feedstock in other areas of the study due to the intricacies of the current research approach. There would, of course, be several reasons why there would be differences in such comparison (besides the nature of the feed composition). In this section, a comparison is made for investigations where the same apparatus/set-up was used. Table 4 shows a comparison of the biochar obtained in this study with those from other biomass material also performed by the current research team using the same process (and arranged in order of decreasing BET specific surface area). It can be observed that SCB feedstock gives biochar with the highest specific surface area than others like elephant grass, plantain fibres, orange peels and orange albedo. This is a pointer towards the inherent suitability of the biomass in obtaining high-quality biochar from the process. Furthermore, the yield for the SCB alone was also higher than for elephant grass and plantain fibres. The pore diameter obtained in the current study was intermediate albeit mesoporous like the others.

3.7 Practical Implications of the Study

Some important advantages can be derived from the current study approach which makes it impactful in developing African countries (of which this research is domiciled). The current design and experimental methodology did not require electrical powers as energy from biomass controlled combustion are recycled to carbonise the feed. This ensures the process is low cost and can be used in remote locations. This is of great advantage especially in agricultural applications where large quantities of biochar are needed in remote location [42]. Sugarcane bagasse and LDPE are waste materials with no competitive use in contemporary Nigeria. Valorisation of this biomass for biochar production gives a three-pronged advantage.

Table 4. Comparison with other biochar obtained using the same process

| Biomass source | Peak temp (°C) | Process time (min) | Biochar yield (wt%) | BET surface area (m ² /g) | Pore diameter (nm) | References |
|------------------------|----------------|--------------------|---------------------|--------------------------------------|--------------------|---------------|
| SCB | 349 | 70 | 16.67 | 533.6 | 4.422 | Current study |
| SCB + LDPE | 250 | 90 | 45.46 | 510.5 | 3.684 | Current study |
| Elephant grass | 300 | 120 | 14.29 | 475.1 | 6.522 | [26] |
| Plantain fibres | 220 | 150 | 6.98 | 424.8 | 6.243 | [27] |
| Oil Palm fibres + LDPE | 529 | 80 | 62.7 | 391.4 | 2.121 | [28] |
| Orange albedo | 300 | 120 | – | 356.3 | 2.138 | [25] |
| Oil Palm fibres | 387 | 80 | 15.9 | 352.9 | 2.133 | [28] |
| Orange peel | 300 | 120 | – | 352.5 | 2.132 | [25] |

There is the conversion of energy sources into more useful forms that can be applied in other energy, agricultural and environmental processes. Several environmental [43], energy and agricultural issues [42] have been reported in developing Nigeria making the findings of this study relevant in the local context.

It is also relevant in solid waste management and resource conservation. The study has successfully implemented a low-cost technology for biochar production from biomass.

It is important in environmental pollution abatement as LDPE is a non-biodegradable waste material.

4 Conclusion

In this study, the temperature profile, biochar yield and product quality during the thermochemical conversion of sugarcane bagasse (SCB) and low-density polyethylene (LDPE) waste into biochar was investigated. Product quality was evaluated using Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and Branauer–Emmett–Teller (BET) analyses. The product yield was 16.67 wt% and 45.46 wt% at 349 and 250°C peak temperatures for SCB and hybrid biochar, respectively. FTIR analysis revealed that the intensity of some of the peaks was increased by LDPE addition to the feed. Both SCB biochar and hybrid had a heterogeneous surface morphology with globular features. The specific surface area of the SCB and hybrid biochar is 533.6 m²/g and 510.5 m²/g, respectively, and they were observed to be mesoporous. It was observed that SCB as the feedstock gave biochar with the highest specific surface area than others like elephant grass, plantain fibres, oil palm fibres, orange peels and orange albedo using the same experimental apparatus and methodology. The process had a three-pronged advantage of product development, waste management and resource conservation. It is recommended that such technology be implemented in the urban and rural context for waste management, product development and other endeavours tar-

geted at achieving environmental sustainability. In terms of the experiments, the effect of varying LDPE doping of the feedstock on product quality can also be investigated.

Compliance with Ethical Standards

Conflict of interest No potential conflict of interest was reported by the authors.

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