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Co-Carbonisation of Biomass-Plastic Wastes in an Integrated Thermochemical Process

Adewale George Adeniyi[1*], Sulyman A. Abdulkareem[1], Joshua O. Ighalo[1, 2]

[1]Department of Chemical Engineering, University of Ilorin, P. M. B. 1515, Ilorin, Nigeria
[2]Department of Chemical Engineering, Nnamdi Azikiwe University, P. M. B. 5025, Awka, Nigeria

Corresponding Author Email address: adeniyi.ag@unilorin.edu.ng

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***Abstract*— The aim of this study was to convert different biomass/agricultural wastes and LDPE to hybrid biochar in a thermochemical reactor. The LDPE was added in doping amount (4%) in all processes considered. The conversion was a hybrid one involving the simultaneous carbonisation process. The yield of hybrid biochar was in the range of 27.8 wt% and 71.43 wt%, higher than convention biochar yield. The products were characterised using SEM-EDS, and BET analyses. The specific surface areas of the hybrid biochar were all above 300 m^2/g. It was observed that the quantity and quality of were higher for hybrid conversion process than for biomass conversion alone. The study has been able to successfully achieve the twin goal of solid waste management and product development.**

I. INTRODUCTION

The continuous and connecting increment in global population, energy demand and waste generation are jointly interwoven and evidently proportional! A remarkable indication of this increase and associated impact are experienced in developing countries, where diverse economic and technological growth are ongoing (Joshua O. Ighalo & Adeniyi, 2021; Nejat, Jomehzadeh, Taheri, Gohari, & Majid, 2015). On its part, the increase in energy demand is pressing for a more sustainable source of energy (Ranganatham, 2018). Coming along the energy sustainability is the subject of its environmental effects with the human population increase as a major controller of the effects. Along with these increasing global change pressures coupled with existing non-sustainability factors, it is becoming evident that cities in developing countries are most likely to experience difficulties in efficiently managing municipal solid wastes. This leads to increasing quantities and complexity of the generated wastes (Amuda, Adebisi, Jimoda, & Alade, 2014).

Given the call to reach energy and environmental sustainability, renewable (such as biomass) and waste (such as plastics) materials are been investigated as energy sources (Oyedun, Gebreegziabher, Ng, & Hui, 2014). Thermochemical processes (such as gasification, pyrolysis and carbonisation) are efficient routes of harnessing the energetic content of these renewable and waste materials. Biomass and plastics can be co-converted for the generation of value-added products(Block et al., 2019). Due to the large volumes of biomass and plastic in municipal solid waste content, they have been identified as waste materials that can be harnessed for other more valuable products (Adeniyi et al 2020). Thermochemical processes can be used to process these environmental mixed waste materials. Low density Polyethylene (LDPE) is a plastic used for developing packaging bags and is a major constituent of the solid waste stream.

In recent years, plastic products have gained popularity for alternative uses such as packaging of edible products, water etc. Plastics like polyethylene, polystyrene and polypropylene find their applications in the food and beverage industry (Barnes, 2019). Plastics are long-chain organic polymers synthesized through chemical processes like polymerization and poly-condensation and are often preferred to other means of packaging due to their ease of production and versatility (Zalasiewicz, Gabbott, & Waters, 2019). Across Nigeria states including the FCT, the commoneset plastic pollutants is polyethylene sachets, which are used for packaging items like water (Ajala, Ighalo, Adeniyi, Ogunniyi, & Adeyanju, 2020; Nwachukwu, Obidi, & Odocha, 2010) and other common commodities for sale. Owing to the absence of efficient waste management systems and non-biodegradable nature, polyethylene wastes from packaged goods have become a nuisance to environment in Nigeria (Nwachukwu et al., 2010). The quest to find alternative means of reprocess polyethylene wastes cannot be overstressed (Olubanjo, 2019).

Co-carbonization is achieved when two different materials are carbonized together. Several pieces of research have been done on thermochemical conversion of two blends of material, usually done to improve the quality of the products. Cao, Yang, Li, Shi, and Li (2019) studied the preparation of porous carbon using co-carbonization of mesophase pitch and sawdust. Co-pyrolysis of sawdust and low-density polyethylene to produce bio-oil was done by Liu, Zhang, Yu, and Cai (2019). Another report (Reshad, Tiwari, & Goud, 2019) also studied the thermal and co-pyrolysis of rubber seed cake and polystyrene using a semi-batch reactor. Lang et al. (2019) co-hydrothermally carbonized corn stalk and animal manure (swine) to produce hydro-char. The potential of Pb(II) removal from aqueous solution by bio-char derived from corn stalk and polyethylene co-pyrolysis was also reported (Fan et al., 2020). Retort co-carbonization utilizes waste heat of biomass combustion for the carbonization process. This has been investigated for oil palm-LDPE (A. A. Adelodun, Adeniyi, Ighalo, Onifade, & Arowoyele, 2020), and sugarcane bagasse-LDPE (Adeniyi, Ighalo, Onifade, & Popoola, 2020)

The biomass and LDPE were target to serve as a typology of each of the two major constituents of MSW. Furthermore, waste leaves are readily available biomass in large quantity in Ilorin town in general and the University of Ilorin campus in particular. LDPE is one of the most utilised and versatile plastics and by consequence possess a large presence in MSW (Dahlbo, Poliakova, Mylläri, Sahimaa, & Anderson, 2018)

In this study, Elephant grass, Almond tree falling leaves, sugarcane baggase and oil palm fibres. Were each co-carbonised with low density polyethylene (LDPE) to produce hybrid biochar in a top-lit updraft biomass conversion reactor. In the method, an updraft gasifier with retort heating was used. The twin goals of the process are: firstly, the management of biomass-plastic wastes and is of supreme interest. Secondly is the energy conservation from the waste biomass usage as fuel and the readily available biomass-plastic wastes to produce valuable products.

II. MATERIALS AND METHODS

A. Materials

The biomass wastes were obtained on the University of Ilorin Farm sites (Table 1). The polyethylene water sachets were handpicked within the vicinity of the university. They were easily sourced due to the large consumption level of water sachets and absence of competitive alternative use. They were dried in the open air to remove any available moisture at atmospheric temperature. Different biomass wastes used in combination with four percentage water sachets were Elephant grass, Almond tree falling leaves, sugarcane baggase and oil palm fibres. The feed-fuel classification were made as presented in Table 1. A doping amount of four percent by weight (4 wt%) LDPE was used in each category of experiment.

Table 1: Biomass-Plastic Waste Combination

Feed-Fuel Code	**Biomass Type**	**Plastic Type**	**Plastic Percentage (%)**	**Fuel Type**
FF1	Elephant Grass	Waste Water Sachet (LDPE)	4	Dry bamboo (*Bambusa vulgaris*)
FF2	Almond (*Terminalia Catappa*) Leaves	Waste Water Sachet (LDPE)	4	Mimosa and neem stalk and stem
FF3	Sugarcane Bagasse	Waste Water Sachet (LDPE)	4	*African balsam (Daniella oliveri*)
FF4	Oil Palm Fiber	Waste Water Sachet (LDPE)	4	*African balsam (Daniella oliveri*)

The combustion fuels, Dry bamboo (*Bambusa vulgaris*), *African balsam (Daniella oliveri*), Mimosa and neem stalk and stem, were gathered in dried form and cut into relatively small sizes. Both fuel and feed will be dried in the open air to remove any available moisture at atmospheric temperature. The concept being explored is presented in Figure 1.

B. Reactor Description

Biomass Plastic Waste Conversion Reactor configuration is presented in Figure 2. The units involved were completely made up of stainless steel. The reactor consists of an outer and inner chamber, both cylindrical in shape (Figure 2). The outer chamber houses the combustion fuel, while the inner chamber holds the feed. The outer chamber consists of round and triangular holes at the bottom which allows the updraft of air through the heating gap. The inner chamber, which is the carbonization chamber, consists of four small air-holes at the bottom to prevent pyrolysis of the feed. The reactors are top-lit (the combustion fuel is

ignited at the top) and the fuel burns gradually downwards till all the fuel is used up (Adeniyi, Ighalo, & Onifade, 2019b). The heat from the combustion of the combustion fuel serves as a heat source for the carbonization of the feed. The outer chamber was fitted with a lid having a vertical exhaust pipe for capturing of carbon and minimal release of gases produced during combustion. T_a, T_b, T_c, and T_d are various points for temperature monitoring (as shown in **Figure 2**) at which the temperature were measured using a CASON CA380 infra-red Thermometer (Accuracy; ±0.1°C, Max; 380°C). This was to monitor the peak temperature obtained for each fuel biomass used.

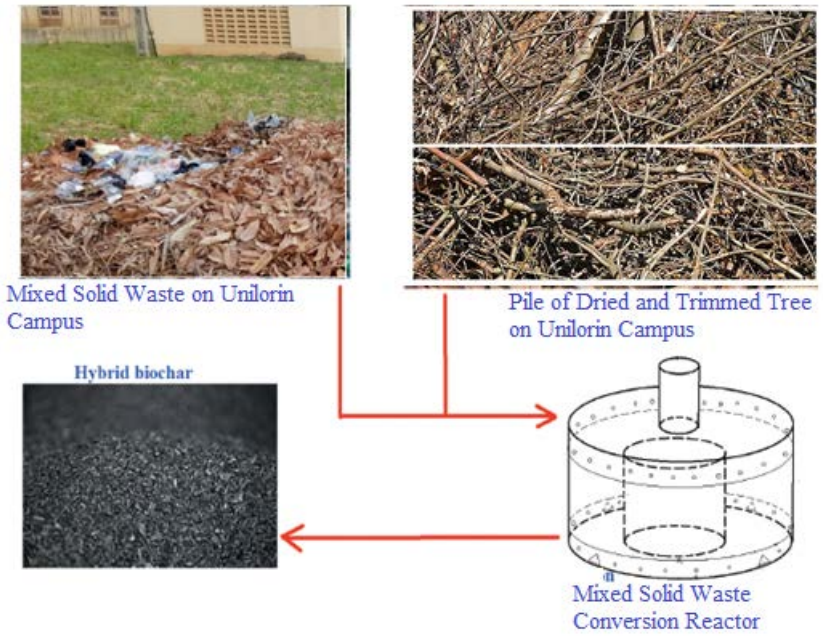

Fig. 1: The Overview of the Projected Process

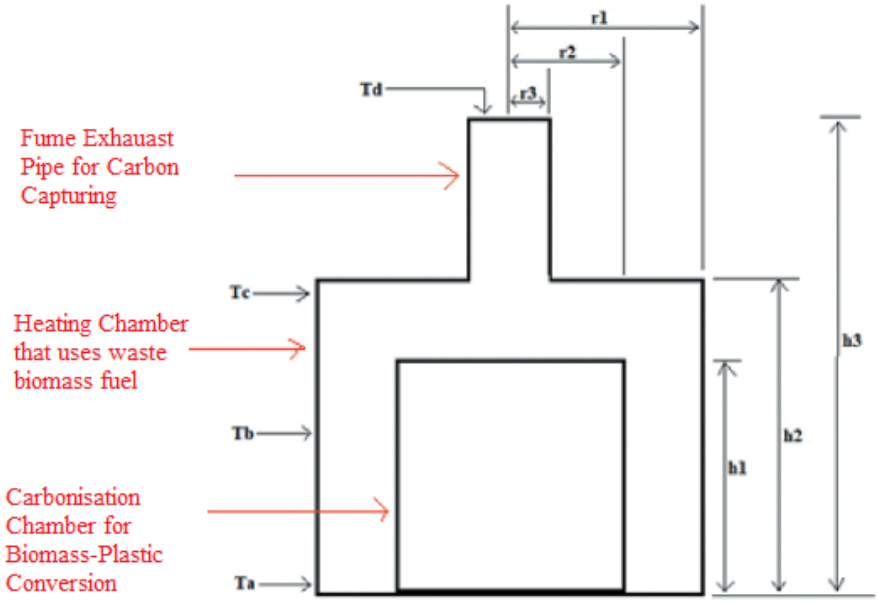

Fig. 2: 2D sketch of top-lit updraft fixed-bed conversion reactor

The entire process was repeated in each batch for the co-carbonization of the biomass and LDPE. Experiments were conducted in duplicates. The bio-char yield was computed using Eqn. 1 (Adeniyi, Ighalo, & Onifade, 2019a).

$$Yield_{Bio-char} = \frac{m_{Bio-char}}{m_{raw}} \times 100\% \quad (1)$$

C. Biochar Characterization

The (hybrid) biochar produced from each carbonization batch of biomass-plastic waste was characterized to ascertain some of its properties using Scanning Electron Microscopy-Energy Dispersive X-ray (SEM/EDX) and Branueur-Emmet-Teller (BET) analysis. The surface structure of the particles and elemental composition of the bio-char produced from both experimental runs were studied using Scanning Electron Microscopy-Energy Dispersive X-ray (SEM Phenom ProX). The SEM analysis was done at a magnification of 500 to 1500 times with an acceleration voltage set at 15kV. Surface properties such as pore volume, surface area, and pore sizes were measured through the Branueur-Emmet-Teller (BET) analysis, using a NOVA Station BET analyzer. The Multipoint BET surface area and Dubinin-Radushkevic (DR) method for pore diameter and volume were used to determine the surface properties of the bio-char by Nitrogen adsorption at a temperature of 77 K.

III. RESULTS AND DISCUSSION

A. Peak Combustion Temperature, Carbonisation Time And Biochar Yield

The reactor performance was measured in terms of the peak combustion temperature, carbonisation time and biochar yield. In this work, different biomass wastes were used as fuel (Table 1) and their Peak temperature and carbonisation time profiles captured to elucidate their thermal capacity for biomass-plastic waste conversion to hybrid biochar. The controlled combustion in the outer chamber is exothermic and thermal emitting. The emitted heat was harnessed in the carbonisation chamber for biomass-LDPE to biochar conversion. The biomass fuel used for each turn of the experiment were Dry bamboo (*Bambusa vulgaris*), *African balsam (Daniella oliveri*), Mimosa and neem stalk and stem. Their combustion temperature and carbonisation time are presented in Table 2

Different runs of experiment were conducted and the rises in temperature were observed with time. These facilitate the information on the combustion time and the observed peak temperature for each run. In each of the experimental proceeding, the temperatures above 250 ^{o}C were sustained for more than 30 minutes. As presented in **Table 2**, the peak temperature ranged from 319 and 384 for all the carbonisation type. This confirms the process as capable of providing the thermal capacity above 250 ^{o}C sustained for over 30 minutes, a condition necessary for carbonisation (Adeniyi et al., 2019a, 2019b; Adewale George Adeniyi, Joshua O. Ighalo, & Damilola Victoria Onifade, 2020a)

Table 2: Reactor Performance Characteristics

Feed-Fuel Code	**Combustion Duration (Mins)**	**Peak Temperature (oC)**	**Biochar Yield (wt%)**
FF1	80	382	27.8
FF2	90	334	71.43
FF3	70	319	45.46
FF4	70	384	62.53

It can also be observed from **Table 2** that the biochar yield was 27.8 wt% 71.43 wt%, 45.46 wt% and 63.53 wt% at 382, 334, 319 and 3820^{o}C peak temperatures for FF1, FF2, FF3 and FF4 fuel-feed combinations respectively. The biochar yield for the biomass-plastic conversion of Almond (*Terminalia Catappa*) Leaves-LDPE is the highest, followed by the oil plam fibre-LDPE combination. The conversion with theleast biochar yield comes from elephant grass-LDPE combination. All of these are found higher than related works without LDPE addition (Adeniyi et al., 2019a, 2019b; Adeniyi, Ighalo, et al., 2020a). These notable biochar yields obtained from the biomass-plastic carbonisation is traceable to the presence of plastic in the mixed feed. This is due to the fact that the empirical elemental content of plastics composed mainly of carbon and hydrogen (Morét-Ferguson et al., 2010), and this is found higher than the biomass which empirically consists of carbon, oxygen and hydrogen (Vassilev, Baxter, Andersen, & Vassileva, 2010). In the carbonisation process without LDPE it is deduced that the higher oxygen in the system due to biomass leads to the synthesis of more oxidised conversion products (CO and CO_2). These oxidised products take up more carbon atoms with them consequently reducing the char yield. So when, LDPE is involved, the reverse is the case

B. Product Carbon Content

The composition of the products was determined using Energy Dispersive X-ray spectroscopy (EDS). Carbon content is specifically taken for proper understanding of the subject. From the results in **Table 3**, it can be observed that all the hybrid biochar are rich in carbon content, all in the measures above 75 % carbon content by weight. This is comparable with previous studies on carbonisation. (Adeniyi et al., 2019b; Adeniyi, Ighalo, et al., 2020a)

Table 3: Carbon Content

Feed-Fuel Code	**Element**	**Hybrid Biochar**	
		Atomic Conc.	**Weight Conc.**
FF1	Carbon	86.89	75.46
FF2	Carbon	88.25	78.95
FF3	Carbon	87.6	78.32
FF4	Carbon	86.9	79.49

C. Biochar Surface Morphology

The surface morphology of the products was determined using SEM. **Figures 3a-d** shows the SEM micrographs of the respectively. The surface characteristics of the biochar from FF1, FF2, FF3 and FF4 showed arrays of surface morphologies from amorphous nature to a regular of a hexagonal ring. They are largely of heterogeneous structures and noticeably porous.

From the FF1, the biochar showed a regular pattern of a hexagonal ring, while the FF2 features the globular structure and also observed to be heterogeneous surface morphology with small interstitial spaces and insignificant voids. FF3 is found having 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

FF4 is identified with the thin linings of carbon polymeric chain formations. This is traceable to the presence of the plastic molecules, well distributed homogeneously at the molecular level across the crux of the biochar. This is indicative of large surface area of the products with the hybrid char potentially having a higher surface area (Joshua O Ighalo & Adeniyi, 2020b). This inference was confirmed by the BET results.

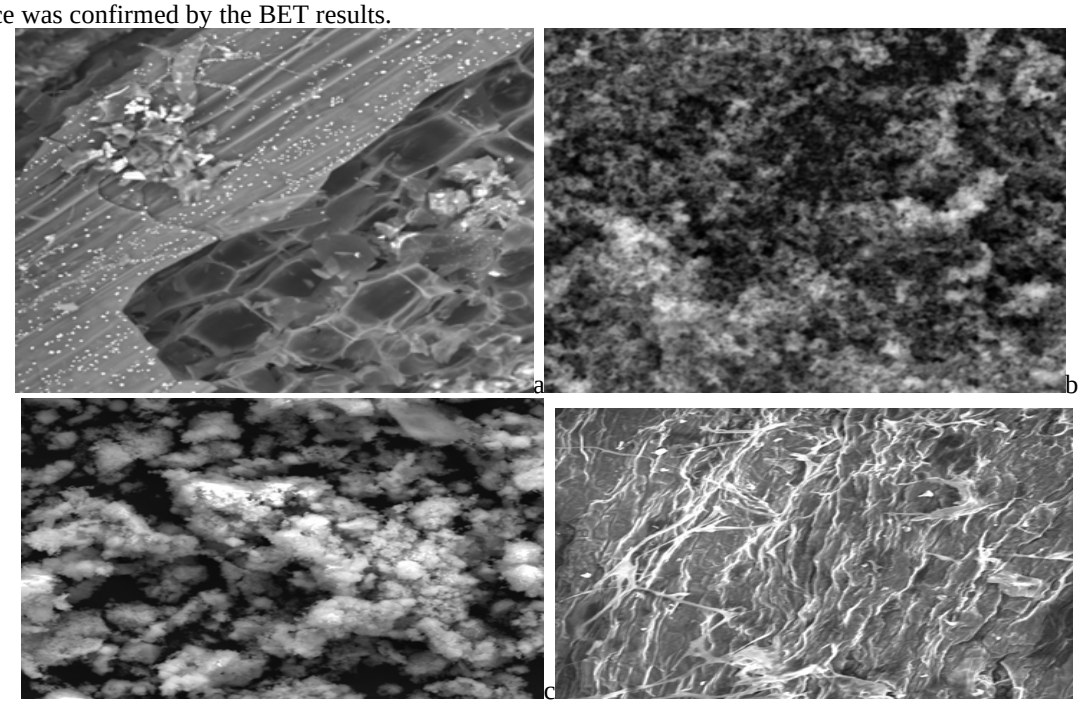

Fig. 3: The surface characteristics of the biochar from FF1, FF2, FF3 and FF4

D. Biochar Porous Properties

The results of the Branueur–Emmett–Teller (BET) analysis of the FF1, FF2, FF3 and FF4 processes biochar are summarised in **Table 4**. It can be observed that all specific surface area are above 300 m^2/g except from FF2 process. This makes Sugarcan Baggass-LDPE biochar the highest in surface area. This is relatively high for a biochar sample obtained without the use of any chemical or physical activation process. This further highlights the usefulness of these hybrid 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. All samples had similar pore volumes except product obtained from FF2.

Table 4: Summary of Textural Properties of the Products

Properties	**FF1**	**FF2**	**FF3**	**FF4**
BET surface area $(m^2/g)^a$	427.2	296.8	510.5	392.5
Micropore volume $(m^3/g)^b$	0.152	n/a	n/a	0.1502
Total pore volume $(m^3/g)^c$	0.217	0.078	0.2317	0.2201
Pore diameter $(nm)^c$	2.105	5.448	3.684	2.128

E. Justification Of The Study Approach

In this section, the major intents of exploring this are elucidated. An attempt to co-carbonise biomass-plastic waste was carried out with focus of practical implementation of the process in waste management in the upcoming economies like Africa where stable and affordable electricity is still a challenge. As earlier observed, Duru, Ikpeama, and Ibekwe (2019), the major components of a typical municipal solid waste stream in Nigeria is about 55% biomass (albeit food waste), 19% plastics, 11% paper (also biomass) with the rest being, textile, metals and glass. The choice of feed stocks was made in such a way that a typology of biomass and of plastic are represented with the biomass having a far greater proportion in the feed and of different types. From the study, it was observed that the quantity of yield and quality of product (in terms of carbon content and specific surface area) is higher for the hybrid conversion process than for the biomass conversion alone. This is a very positive result previously published in the open literature (Adeniyi et al., 2019a, 2019b; Adeniyi, Ighalo, et al., 2020a)

A second key justification is the use of a retort heating technique. Here, thermal energy evolved from the controlled combustion of biomass is used for the carbonisation process. The temperature profile shows that the process is self-regulating and inherently safe (Adedeji A. Adelodun, Adeniyi, Ighalo, Onifade, & Arowoyele). Despite the fact that very high temperatures are not achieved, this is quite favourable since the product of interest is the biochar, and was produced within the limit of thermal capacity obtainable from the biomass employed. Furthermore, an important implication of retort heating is the lack of electrical power requirement for the process (Adewale George Adeniyi, Joshua O Ighalo, & Damilola Victoria Onifade, 2020b). This significantly mitigates cost, and makes the design more enticing to potential investors especially in developing African countries (like Nigeria) where steady power supply is still not yet achieved. Retort heating also underlines the usability of the process even in remote locations or in on-site applications (Joshua O Ighalo & Adeniyi, 2020a).

IV. CONCLUSION

The co-conversion of Biomass-LDPE tagged FF1, FF2, FF3 and FF4 were successfully achieved in an updraft biomass reactor with retort heating and there was significant improvement in char quality with the process. The range of the reactor yield was 27.8 wt% to 71.43 wt%, which is higher than convention biochar yield without LDPE doping for the hybrid co-conversion and an improvement on similar processing without LDPE was evident. The specific surface areas of the hybrid biochar were all above 300 m^2/g save one. Furthermore, the retort heating techniques ensures low cost, high biochar yield and no electrical and mechanical power requirement. The study has been able to successfully achieve the co-conversion of biomass and plastics (as typologies of MSW major components in Nigeria) to valuable products with a twin goal of waste management and product development.

V. DISCLOSURE STATEMENTS

Conflict of Interest: The authors declare that there are no conflicts of interest.

Funding: There was no external funding for the study.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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