


## RESEARCH ARTICLE OPEN ACCESS

# Baseline Characteristics of Pristine Agricultural Pods Biochar

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## ABSTRACT

The valorization of agricultural pod wastes into biochar offers a sustainable pathway for waste management and the development of functional carbonaceous materials. This study comparatively evaluates biochars produced from cocoa, flamboyant, and locust bean pods using an autothermal top-lit updraft gasifier with retort heating, a system designed to enhance efficiency in low-resource settings. The novelty of this work lies in providing the first comparative baseline data on unmodified pod-derived biochars synthesized under the same controlled gasification conditions. The results show that cocoa pod biochar exhibited the highest yield and superior textural properties, with a surface area exceeding 750 m<sup>2</sup>/g, while flamboyant and locust bean pod biochars displayed lower but comparable performance. Thermal analysis confirmed stability up to 250°C, while spectroscopic and microscopic characterizations revealed carbon-rich structures with oxygenated functional groups, porous morphology, and embedded mineral elements. These features suggest broad applicability in adsorption, soil amendment, and catalysis, although application trials remain a direction for future studies. In conclusion, this research establishes a reference for pod-based biochars and demonstrates the feasibility of simple, eco-friendly gasification systems for biomass valorization, contributing to the circular economy and sustainable materials development.

## 1 | Introduction

Global waste generation is increasing at an unprecedented rate as a result of population growth, rapid industrialization, urban expansion, and intensive agricultural production. The World Bank reported that 2.02 billion tons of solid waste were generated worldwide in 2016, and projections indicate a rise to 2.6 billion tons by 2025 and 3.4 billion tons by 2050 if current practices continue [1]. Agricultural residues constitute a significant fraction of this waste stream, accounting for nearly 998 million tons

annually [2]. These residues include crop stalks, husks, shells, and pods that are often treated as valueless materials. In many developing countries, the most common disposal methods are open dumping, uncontrolled burning, and landfilling, which contribute to greenhouse gas (GHG) emissions, soil degradation, leaching of contaminants into groundwater, and adverse effects on public health [2, 3]. Effective strategies for managing agricultural residues are therefore essential in the pursuit of global sustainability targets, including those outlined in the United Nations Sustainable Development Goals (SDGs).

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One promising approach for managing agricultural waste is its conversion into biochar, a carbon-rich solid material produced through thermochemical transformation of biomass in oxygen-limited environments [4–6]. Biochar has attracted significant research attention due to its wide range of applications in soil fertility improvement, wastewater treatment, carbon capture, energy storage, and catalysis [7, 8]. Its value lies in its physicochemical attributes, particularly high specific surface area, porosity, and chemical stability, which are determined by both feedstock type and conversion conditions [9–11]. Studies have shown that lignocellulosic feedstocks with high carbon and mineral content often produce biochars with enhanced adsorption and catalytic capacities [12–14]. Thus, the characterization of biochar is necessary to identify feedstocks that can be developed into effective functional materials.

Thermochemical processes for biochar production include pyrolysis, hydrothermal carbonization, torrefaction, and gasification [15–17]. Among these, gasification is increasingly favored because of its operational simplicity, higher energy recovery, and ability to simultaneously generate gaseous and solid products [18]. In particular, biofuel-powered top-lit updraft gasifiers (TUGs) with retort heating have gained interest as eco-friendly systems that operate without reliance on electricity, a critical factor for rural and off-grid regions in developing nations. These gasifiers achieve controlled heating through concentric combustion and retort design, enabling improved energy efficiency and by-product recovery [19]. However, their broader adoption is constrained by certain limitations, such as relatively low peak operating temperatures, short gasification durations, and selectivity of biofuels with sufficient thermal capacity [19, 20]. Because elevated temperatures and extended residence times are associated with higher surface area, greater fixed carbon content, and reduced volatile matter in biochar [19, 21], there is a strong case for optimizing feedstock selection and operational parameters in these systems.

Agricultural pods present a unique opportunity for biochar production. Pods are by-products of crops such as cocoa (*Theobroma cacao*), flamboyant (*Delonix regia*), and locust bean (*Parkia biglobosa*), which are abundant in tropical and subtropical regions. These residues are often discarded after seed extraction and lack competitive alternative uses, making them readily available feedstocks with minimal economic value [22–24]. The rationale for selecting cocoa, flamboyant, and locust bean pods lies in their regional abundance, limited commercial applications, and favorable chemical composition for thermochemical transformation. Cocoa pods are widely available in West Africa due to large-scale cocoa cultivation, yet most of them are left to decay or are incinerated, contributing to environmental pollution [25]. Flamboyant pods are generated seasonally in large quantities from ornamental trees, particularly in urban landscapes, and are typically treated as waste [26]. Locust bean pods are produced across sub-Saharan Africa, where their seeds are valued for food processing, but the husks are discarded in bulk [27]. The valorization of these wastes into biochar offers a dual benefit of environmental protection and resource recovery, consistent with the circular economy paradigm. From the literature, it was observed that there is no study on the comparative evaluation of the baseline properties of biochars derived from these three pods under identical gasification conditions.

Addressing this gap is critical for understanding how feedstock composition influences yield, surface chemistry, and morphology in retort-based gasification systems.

The novelty of this study is threefold. First, it provides the first comparative analysis of biochars derived from cocoa, flamboyant, and locust bean pods using an autothermal TUG gasifier. Second, it establishes baseline physicochemical characteristics, including yield, thermal stability, surface area, pore volume, elemental composition, and morphology, using advanced analytical techniques such as BET, TGA, FTIR, SEM, and EDX. Third, it links feedstock-specific properties with potential application areas, thereby offering guidance for future research and practical implementation. The objective of this research is to characterize and compare biochars produced from cocoa, flamboyant, and locust bean pods under uniform autothermal gasification conditions. Specifically, the study seeks to determine the influence of pod feedstock on yield, stability, porosity, surface chemistry, and morphology. The results will serve as reference data for designing biochar-based materials for targeted applications in adsorption, soil improvement, catalysis, and energy storage. By addressing both waste management and material development, the study contributes to advancing resource-efficient strategies aligned with sustainable development and circular economy goals.

## 2 | Materials and Method

### 2.1 | Feedstock Collection and Preparation

The feedstocks, cocoa, flamboyant, and locust bean pod wastes were obtained from within the University of Ilorin premises. The as-collected pods were further screened and deseeded prior to washing with tap water to remove any dirt, including sand. Thereafter, the pods were washed with distilled water and oven-dried for approximately 6 h until constant weight was achieved. The pods were then manually chopped into pieces and kept for gasification.

### 2.2 | Biochar Production and Gasification Process

Biochar was produced from each of the pods' waste materials separately by a low-temperature autothermal top-lit updraft gasification system with retort heating. The diagrammatic look of the gasifier is displayed in Figure 1, and its design or configuration, as well as details of the mode of operation, can be found in earlier work by Ayanwusi [28] and Adeniyi's [19] research group. The gasifier was operated in an open ambient environment. The pods were loaded in the gasification chamber, covered, and placed in the center of the gasifier combustion chamber. Then, the gasifying biofuel was loaded concentrically around the gasification chamber in the combustion compartment of the gasifying system. The biofuel in the gasifying system was then lit from the top and allowed to burn for roughly 5 min, after which the gasifying system was enclosed with an end cap fitted to a fume exhaust pipe. A Cason, CA380, Singapore infrared thermometer was used to monitor the gasifier changes in thermal condition until the end of the operation. The temperature of the gasifier's center (C), top (T), middle (M), and base (B) was measured at

10-min intervals beginning when the initial 5 min of combustion (also referred to as 0 min) had passed [19]. The gasification operation lasted for about 120 min until reaching a peak temperature of 371°C. Afterward, the gasification chamber containing the formed biochar was unloaded, and the biochar yield was computed using the equation described by Adeniyi et al. [29]. The gasification process for each pod type was carried out once under controlled conditions. To ensure accuracy and reproducibility of thermal measurements, all temperature readings at the top, middle, base, and center of the gasifier were recorded in triplicate using an infrared thermometer at each interval.

### 2.3 | Material Characterization

The characterization techniques employed in this study are presented in Table 1, and the details of the procedure followed can be found in the previous related research work by Emenike et al. [30] and Adeniyi et al. [31].

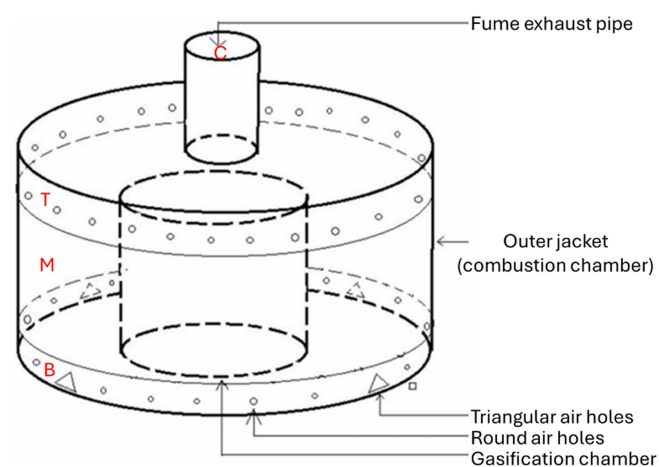


FIGURE 1 | The retort gasifier system.

TABLE 1 | Applied characterization techniques for the biochar samples.

Techniques	Model	Wavelength/magnification	Purpose
BET	Quantachrome NovaWin 1994–2013, Quantachrome Instruments v11.03	—	To determine the specific surface area, pore volume, and pore diameter
TGA	PerkinElmer Thermal	—	To examine thermal stability and degradation, as well as track biomass mass loss
EDX	JSM-6510LV, England	—	To map out the distribution of elements and study the elemental composition and proportion
FTIR	Shimadzu FTIR-8400S, Japan	Wavelength: 400–4000 cm <sup>-1</sup>	To explore the functional groups and surface chemistry
SEM	Phenom ProX, Phenom-World BV, Netherlands	Magnification at 500×, 1000×, and 2000×	Investigate the morphology, pore structure, and topological framework

## 3 | Results and Discussion

### 3.1 | Temperature Profile and Biochar Yield Analysis

The retort gasification process is unique in that it is self-regulating and does not require temperature controls, depending on the kind of gasification biofuel. Therefore, it is necessary to monitor and assess the temperature profile in order to ascertain the system's functionality and efficiency. The biochar yield, peak temperatures, and process duration were used to assess the gasifier's performance. The temperature profile was used to explain the process time and peak temperatures. Figures 2–4 show the temperature profile of the retort gasification operation used to transform pods into biochar. The temperature rose gradually from ~25°C (ambient conditions) to the peak temperature (268°C for LPU after 30 min, 273°C and 279°C for FPU and CPU after 60 min) according to the readings at all gasifying system zones (a, b, c, and d). After that, the temperature gradually decreased up until the gasification biofuel was exhausted and ambient conditions were

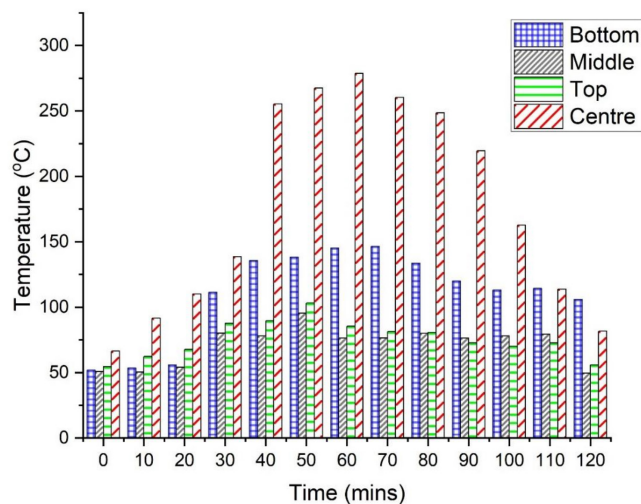
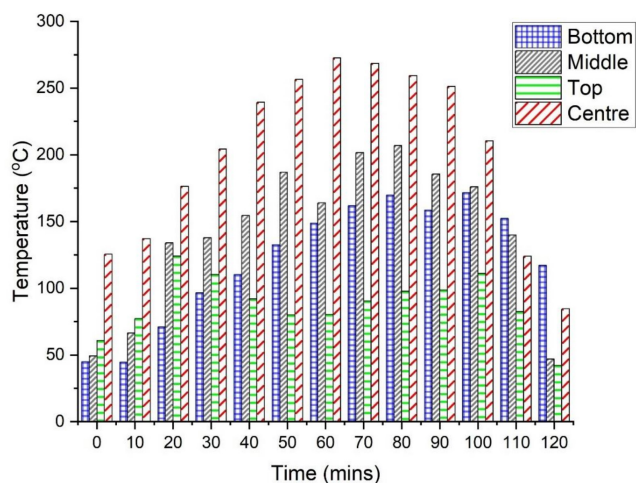
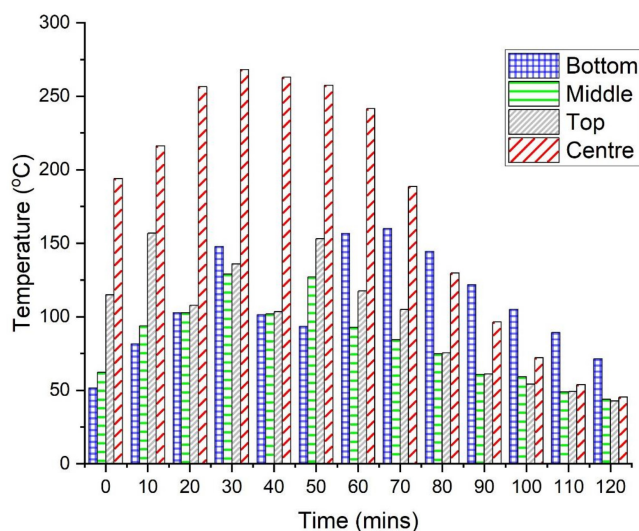


FIGURE 2 | Temperature profile of retort gasification process of cocoa pod into biochar.



**FIGURE 3** | Temperature profile of retort gasification process of flamboyant pod into biochar.



**FIGURE 4** | Temperature profile of retort gasification process of locust bean pods into biochar.

reached. Comparable temperature profiles have been reported for retort gasification of onion peels–chicken feathers [29], groundnut shell [28], and *D. regia* pod [32].

Ighalo et al. [32] gave an empirically logical reason for this type of temperature profile trend. According to the authors [32], it is normal for the temperature to rise at the start of the operation because heat is transferred into the gasification chamber from the controlled combustion in the combustion gap. To keep the process going, air naturally convects upward from the base air openings into the regulated combustion zone (updraft). The heating biofuel in the gap was gradually consumed by this combustion zone, which moved from the higher area down the gasifying system's base. Without any new oxygen supply, the pod feedstock undergoes thermal conversion in the gasification chamber. The gasification chamber's partially burned exhaust, which is still high in carbon monoxide, escapes into the combustion gap. As soon as it reaches the combustion gap, this is burnt, releasing more thermal energy into the process. This

additional burning of the gaseous product that escaped from the gasification chamber is called the process's "retort." It is imperative to mention that the retort heating assists the gasifier in reaching high temperatures for an extended period using only a very small amount of biofuel. Moreover, the cylindrical type of gasifier employed in this current work facilitates a synergistic heating effect on the central gasification chamber [24, 33], and all of these points to an improved efficiency.

Furthermore, unlike cocoa and flamboyant pods that have inherently higher bulk density and low volatile content, locust bean pod has higher volatile content, lower bulk density, and is very light. Thus, locust bean pod can combust more rapidly, causing it to hit its peak at an earlier time, but not sustain the temperature. On the other hand, cocoa pod is more compact, and this makes it take longer to heat through, but it retains and accumulates more heat, resulting in a higher final temperature over a longer time frame.

The temperature profile behavior and impact of the inherent bulk density also reflect in the final yield. Specifically, as can be seen from the yield result presented in Table 2, cocoa pod gave the highest biochar yield of 41% compared with LPU (~38%) and FPU (~31%). This research outcome also corroborates the claim of Adeniyi et al. [19] that elevated temperatures and longer gasification times often produce biochar with enhanced qualities, including higher carbon, better yield, and lower volatile composition [19]. Additionally, from the research findings on the temperature profile and yield analysis, it can be inferred that TUG is more efficient for CPU.

### 3.2 | Thermal Stability and Degradation Characteristics

The phase transformations and thermal behavior of the three pod BC materials were studied using DTA/TGA, and the results are presented in Figures S1–S3. First of all, it is noted that the BCs have comparable thermal properties, with the CPU looking more stable, possibly due to its inherent compact structure. Secondly, we observed the inception of substantial mass loss between 250°C and 300°C. Thereafter, a pyrolytic degradation was noticed till around 500°C–600°C. This indicates that a sustained minimum retort gasification peak temperature between 260°C and 280°C will successfully degrade the pod precursors, considering both the temperature effect and the synergistic influence of air updraft and circulation within the gasifying system.

Furthermore, the TGA profiles show three distinct zones. Specifically, in both the first (around 23°C to between 250°C

**TABLE 2** | Yield and textural profile of the biochar samples.

Pod-derived biochar	Yield (%)	Surface area (m <sup>2</sup> /g)	Pore volume (cc/g)	Pore diameter (nm)
CPU	41.00	776.13	2.45	3.02
FPU	30.80	636.39	2.10	3.04
LPU	37.87	565.52	2.11	2.80

and 300°C) and third (around > 500°C–883°C) zones, there was only a very small weight loss. The weight loss in the first zone can be ascribed to the loss of moisture content [34–36], while in the third zone, decomposition for all the samples is considered finished, and the functional groups become stable [34, 37]. On the other hand, in the second zone (between the 1st and the 3rd zone), a sharp weight loss was noticed, which can be ascribed to full-scale degradation and decomposition instigated by a combination of heat breakdown and oxidation [35, 36]. Also, according to the DTG result of both BCs in Figures S1–S3, the highest thermal degradation temperature for the FPU and LPU is approximately 400°C, while that of CPU is > 400°C but < 500°C. This suggests that the CPU is more thermally stable.

Although it is subject to the kind of application, in the grand scheme of things, it can be inferred that these BC materials, especially CPU, would remain stable and exhibit no significant deterioration at temperatures lower than 250°C.

### 3.3 | Textural Properties and Pore Profile Analysis

The textural and porous properties of the BC, such as pore diameter, pore volume, and surface area, were evaluated using various models of analysis, including BET and BJH. The results are summarily presented in Table 2. Interestingly, among the three unmodified pod BCs, CPU has the best surface area of 776 m<sup>2</sup>/g and pore volume of 2.4 cc/g compared with FPU and LPU, with a surface area of 636 and 565 m<sup>2</sup>/g as well as a pore volume of 2.10 and 2.11 cc/g, respectively. These are part of the key features that dictate how well the biochar can function as an adsorbent or catalyst [32, 38, 39]. More explicitly, material with high pore volume (CPU in this case) has the capacity to accommodate more adsorbate when used as an adsorbent for pollutant removal or separation processes. Likewise, materials with large surface areas can interact well with light and/or adsorbate when employed in adsorption or photocatalytic operations [40]. In future research work, these aforementioned potential areas of application should be explored to further confirm/establish the applicability of the BCs.

Furthermore, it is worth mentioning that the superior textural properties of CPU can be corroborated by the temperature profile analysis. In that, elevated temperatures and longer gasification times often produce biochar with enhanced qualities like better surface area [19]. Moreover, on a logical note, CPU having a large surface area is not surprising, owing to the fact that cocoa pod has an inherently larger surface area when compared with flamboyant and locust bean pods visually before being converted to biochar. As for the pore diameter, the three BCs can be characterized as mesoporous materials ( $\geq 2$  nm to  $\leq 50$  nm pore diameter). However, LPU has the smallest pore diameter, while CPU and FPU have approximately the same pore diameter, as can be seen in Table 2.

### 3.4 | Elemental Composition Analysis

The elemental composition of the BC materials was determined using the EDX analytical spectroscopic technique. The

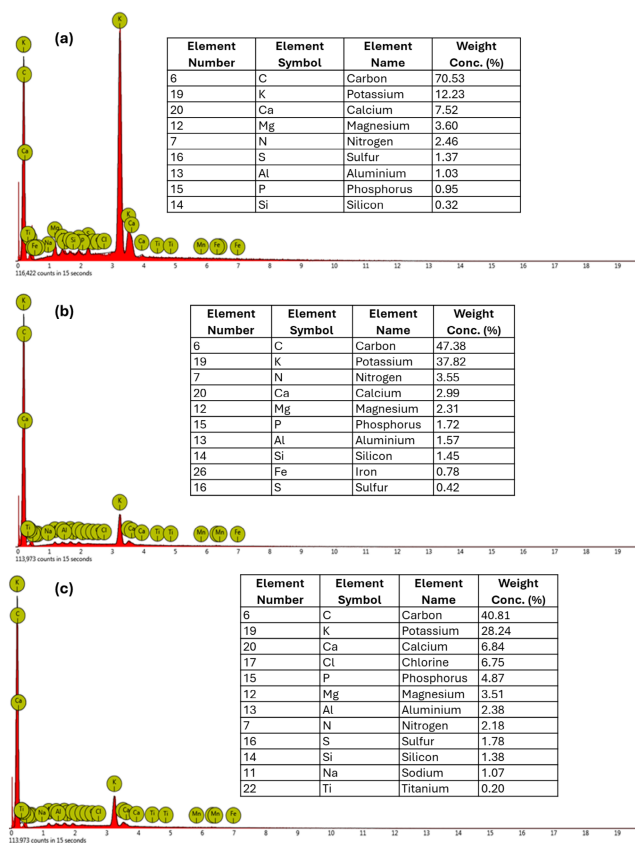


FIGURE 5 | EDX analysis of (a) CPU, (b) FPU, and (c) LPU.

elemental mapping and weight concentration of the elements present in each BC material are displayed in Figure 5. As expected from BC, a carbon-rich product, the result displayed in Figure 5 shows carbon as the major element in all three BC materials, with CPU leading the chart (70.53%) followed by FPU (47.38%) and LPU (40.81%). The carbon content is also higher than other elements in other related studies [41–43]. The high BC carbon content is not surprising, as plant biomass has been confirmed to predominantly contain lignin and hemicellulose/cellulose [44, 45]. However, in the case of the CPU, the carbon content is higher than that reported in other studies [41, 42, 46], and this means that the used retort gasifier enhances or preserves the BC carbon composition.

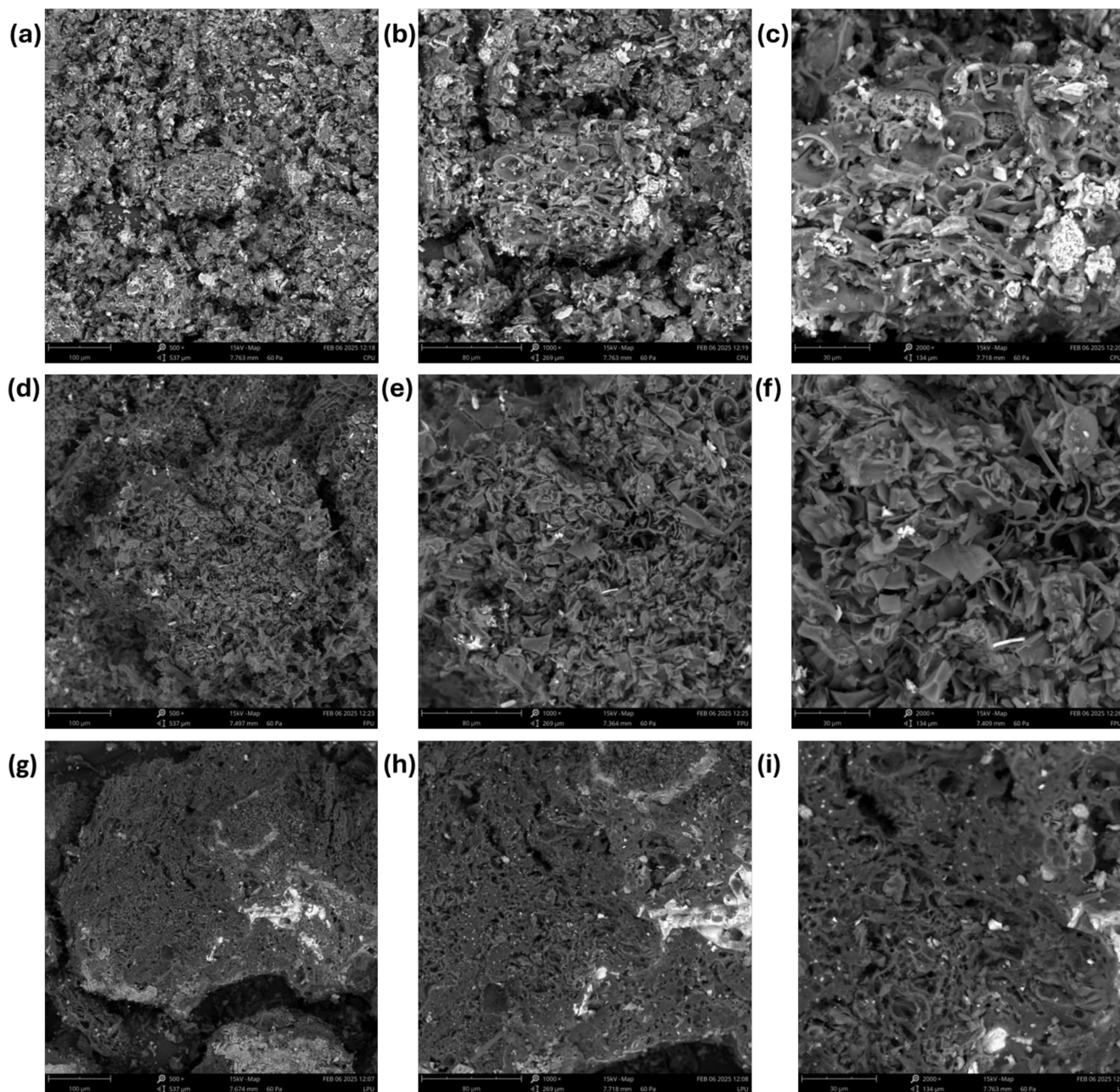
Furthermore, for all the materials, potassium and calcium are the second and third largest elements present, except for FPU, where nitrogen slightly surpasses calcium. Tsai et al. [42] also recorded a high presence of potassium among the non-carbon elements. Other important elements present in trace amounts include aluminum, silicon, chlorine, phosphorus, sodium, titanium, and iron. Though these elements are present in small quantities, they can boost the properties of BC materials when ion exchange or complexation mechanisms are required in a remediation process, especially in heavy metal and dye adsorption. Also, the presence of chlorine as the fourth abundant element in LPU could be applied for water remediation. Beyond water remediation, with the presence of potassium, phosphorus, and nitrogen, the BC materials will be good for soil fortification/amendments because these are essential fertilizer components and macronutrients needed in large amounts by plants.

Additionally, the presence of these minor elements can as well fortify the BC materials with better electrical and thermal properties to enhance their application spectrum, but should not be employed in boilers because potassium and sodium can cause slagging or fouling if care is not taken [42, 43].

### 3.5 | SEM Morphological Analysis

The SEM images for the BC materials at different magnifications (500 $\times$ , 1000 $\times$ , and 2000 $\times$ ) are presented in Figure 6. This analysis provides the material topology, morphology, as well as pore structures [47]. Moreover, it visually helps assess the presence of pores, which could dictate the material's reaction/adsorption/catalytic sites and how they interact with other substances. Across the board, the SEM analysis revealed that the

BC materials have a heterogeneous collection of particles with different sizes, irregular shapes like rectangles and spheres, rough surfaces, cavities, and pore networks that are likely to be suitable for improved adsorption processes, wastewater treatment, carbon capture, soil amendment, biomolecule separation, and catalysis. However, FPU looks flakier. A little whitish appearance observed (which is more prominent in CPU and LPU), similar to what was seen in chicken feathers–*D. regia* hybrid biochar [23] can be ascribed to the presence of crystalline mineral metals or oxides [33, 41] and this is in very good agreement with the EDX findings above. The presence of elements like magnesium, potassium, and kalcinite has been reported in other studies on similar pod biochar prepared using other methods [24, 41, 42, 48]. Furthermore, these BC materials will be good for soil nutrient and water retention capacity enhancement if put to trial [33].



**FIGURE 6** | SEM image of CPU at 500–2000 $\times$  (a–c), FPU at 500–2000 $\times$  (d–f), and LPU at 500–2000 $\times$  (g–i).

### 3.6 | Functional Groups Analysis

The presence of various functional groups in the BC materials was determined using an FTIR spectrophotometer. This is an important analysis in suspecting the areas of application of a particular material prior to a real trial [47, 49]. The FTIR results of CPU, FPU, and LPU are presented in Figure S4, and the spectra cover from 4000 to 650  $\text{cm}^{-1}$  wavelength. It can be observed that the BC materials all have non-sharp characteristic bands in the functional group region. Conversely, the characteristic band in the fingerprint region appears sharp and somewhat broad. This is suspected to be due to overlapping bands from complex aromatic networks and the presence of minerals (usually inorganic), as suggested by the SEM and EDX analysis.

Notably, the existence of the OH functional group can be seen at characteristic bands around 3589.4 (CPU), 3630.4 (FPU), and 3593.2/3403.1 (LPU)  $\text{cm}^{-1}$ . These OH signals could have probably emerged from cellulose present in the pods and can be attributed to phenol, water, or alcohol [49]. Ighalo et al. [50] observed the presence of this signal at 3677  $\text{cm}^{-1}$ . The characteristic band at 3131.0  $\text{cm}^{-1}$  can be ascribed to OH of R-COOH. The band at 2922.2  $\text{cm}^{-1}$  can be ascribed to C-H stretching vibrations [24, 43, 51] and aldehyde. The characteristic bands at 2117.1 and 2105.9  $\text{cm}^{-1}$  which are sharper for FPU and LPU compared with CPU can be attributed to the existence of the alkyne functional group as well as  $\text{C}\equiv\text{N}$  [24, 52]. The presence of  $\text{C}=\text{C}$  of the aromatic ring, R-COOH, N-O, and nitramine-containing functional groups was confirmed by the existence of sharp characteristic signals at 1576, 1576.7, 1561.8, and 1408.9  $\text{cm}^{-1}$  [24, 49, 53, 54]. The sharp bands at 1394 and 1371.7  $\text{cm}^{-1}$  for CPU, FPU, and LPU, respectively, can be assigned to alcohol C-OH bending vibrations, while the stretching version can be ascribed to the non-sharp characteristic signal at 1248.7  $\text{cm}^{-1}$  for FPU, which can also be attributed to the C-O functional group [49, 50, 54].

The characteristic signals at 1006.4 and 1036.2  $\text{cm}^{-1}$  can be assigned to the symmetric C-O stretching of inherent typical hemicellulose, lignin, and cellulose present in the pods. Lastly, the existence of a band at 868.5, 872.2, and others at around 752.9–697.0  $\text{cm}^{-1}$  can be attributed to out-of-plane alkene or aromatic carbons in -CH [24, 49]. The existence of carbon-oxygenated functional groups suggests that the BC materials likely contain graphitic structures [55], which are known for networks of pores and carbon structures, and this corroborates the SEM, BET, and EDX analysis.

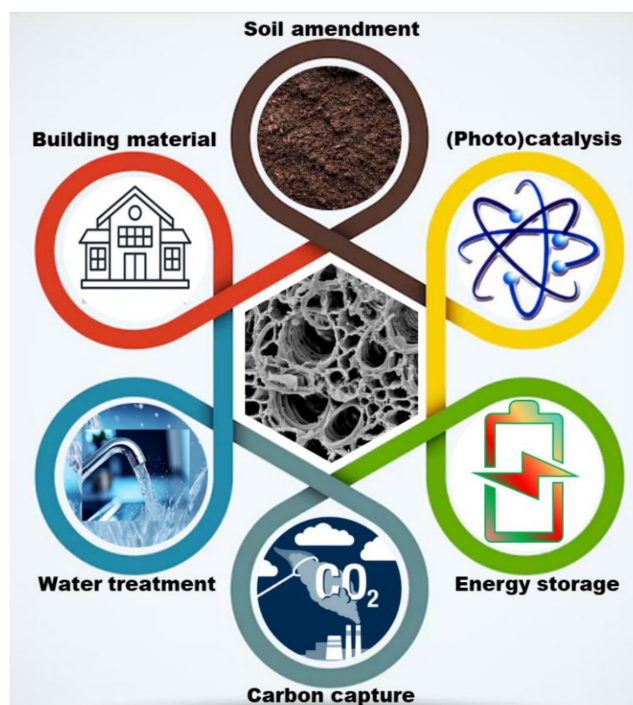
### 3.7 | Study Significance and Potential Applications

This study holds significant relevance for several key reasons, particularly in the areas of environmental sustainability and materials science. First of all, the conversion of locally sourced biomass waste to functional biochar material points to the potential grassroots valorization of readily available waste materials into value-added products, which are better than synthetic feedstocks such as synthetic polymers. Moreover, the use of locally sourced biomass waste over synthetic feedstocks reduces costs and mitigates environmental pollution impacts associated

with the indiscriminate disposal of these wastes, especially in countries where there is no proper waste management system.

The profiling of the inherent properties of the biochar materials using avant-garde techniques such as BET, TGA, EDX, FTIR, and SEM provided insight into the porosity, chemical makeup, elemental composition, surface morphology, and topology. These discoveries expand the body of knowledge on the chemistry of biochar and material science research generally. Furthermore, the low-temperature autothermal top-lit updraft gasification technique employed in this work also expands the horizon of advanced eco-friendly gasification technology for more efficient biomass conversion with less carbon emissions, in contrast to the traditional carbonization strategy or mere incineration. Furthermore, this technique can be adapted for small-scale, rural, or industrial installations, including point-of-use systems, owing to the simple reactor design.

Also, give the properties of the biochars produced in the work; these materials can find application in water treatment via adsorption and other areas presented in Figure 7. Moreover, with the presence of potassium, phosphorus, and nitrogen, the BC materials can be employed for soil fortification/amendments because these are crucial fertilizer components and macronutrients required in large amounts by plants. Thus, it is recommended that researchers explore the applications of these biochar materials in future studies. Additionally, in the future, AI researchers can explore building an intelligent algorithm using existing datasets to monitor temperature profiles, biochar yield, and characteristics for advanced retort gasification technology, as well as biochar application screening [29]. Ultimately, this research also holds practical relevance in the area of United Nations SDGs advancement, circular economy promotion, zero carbon economy pursuit, and resource utilization, especially in resource-limited nations.



**FIGURE 7** | Potential application of CPU, FPU, and LPU biochar materials.

## 4 | Conclusion

This study compared biochars from cocoa, flamboyant, and locust bean pods produced in an autothermal TUG with re-tort heating. The work is the first to provide baseline data on these biochars under uniform conditions. Cocoa pod biochar gave the highest yield and the best surface and pore properties. Flamboyant and locust bean pod biochars showed lower but still useful performance. The results confirm that feedstock strongly affects product quality in this system. The properties found point to practical uses. The high surface area of cocoa pod biochar supports its use in adsorption and water treatment. The presence of potassium, phosphorus, and calcium in all three biochars indicates value for soil amendment and nutrient recovery. Their thermal stability below 250°C suggests they are suited for applications in moderate temperature environments. Despite these encouraging outcomes, certain limitations must be acknowledged. This work focused on laboratory-scale gasification without replication of the full conversion process, which restricts statistical validation of yield data. Application trials were not conducted, and the performance of pod biochars in real environmental systems remains to be tested. Furthermore, while the autothermal gasifier demonstrated efficiency under controlled conditions, questions of scalability, feedstock supply logistics, and long-term operational stability require further evaluation before industrial deployment. This study shows that pod wastes are suitable feedstocks for biochar production and offers reference data for their development as carbon-based materials. It shows the potential of simple autothermal gasification systems as low-cost tools for waste management and resource recovery.

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### Ethics Statement

The authors have nothing to report.

### Consent

The authors have unanimously decided that this manuscript be sent for possible publication.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** TGA/DTG analysis of CPU. **Figure S2:** TGA/DTG analysis of FPU. **Figure S3:** TGA/DTG analysis of LPU. **Figure S4:** FTIR spectrum for (a) CPU, (b) FPU, and (c) LPU.