



## Valorization of Agricultural Residues into Biochar in Pidie Regency, Indonesia: A Case Study on Feedstock-Dependent Physicochemical Properties

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### ABSTRACT

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*agricultural residues, waste valorization, biochar, Pidie Regency, characterization*

Agricultural-residue valorization into biochar offers a sustainable pathway for waste management and climate mitigation. This study produced and characterized biochars from three locally available feedstocks in Pidie Regency, Indonesia—young coconut waste (YCW), sugarcane bagasse (SCB), and corn cob (CCB)—via pyrolysis in a Kon-Tiki kiln. Pyrolysis experiments for each feedstock were conducted in triplicate to ensure reproducibility, and the resulting biochars were composited into representative samples prior to physicochemical characterization. The resulting biochars exhibited yields of 25–62% and strongly alkaline properties (pH > 11). Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM–EDX) analysis revealed porous carbon-rich structures with minor mineral constituents, while Fourier transform infrared (FTIR) confirmed the presence of oxygen-containing functional groups. Brunauer–Emmett–Teller (BET) analysis indicated high apparent surface areas (1145–3024 m<sup>2</sup>/g), although these values should be interpreted cautiously due to potential model limitations. Distinct physicochemical differences among feedstocks suggest feedstock-dependent structural development and surface functionality, providing insight into the suitability of locally derived biochars for targeted environmental applications, particularly in alkaline soil amendment and carbon stabilization.

## 1. INTRODUCTION

Organic waste generation continues to increase in line with population growth, particularly in developing countries such as Indonesia [1-3]. This waste generally originates from household, agricultural, and industrial activities. Approximately 6 million tons of organic waste are produced annually in Indonesia [4]. Inadequate management of organic residues poses significant environmental challenges, including the uncontrolled release of methane (CH<sub>4</sub>), a potent greenhouse gas contributing to global warming [5-9]. Therefore, sustainable waste management strategies are urgently needed, among which thermochemical conversion into biochar has emerged as a promising approach [10].

In regions such as Aceh Province, agricultural biomass residues are abundant yet underutilized and are often treated as waste. This creates an opportunity for valorization into value-added materials. In this context, this study focuses on selected feedstocks from Pidie Regency to evaluate their potential for biochar production and to investigate their physicochemical properties. Utilizing locally available

agricultural residues for biochar production offers a sustainable and cost-effective pathway for waste reduction and soil quality improvement [11, 12].

Biochar is a carbon-rich material obtained through pyrolysis under limited or no oxygen supply [13]. It has been widely recognized for its multifunctional benefits, including use as an adsorbent, soil amendment, water retention enhancer, and carbon sink [14-17]. Biochar improves soil properties such as porosity, aggregate stability, pH, and cation exchange capacity (CEC) while creating a favorable habitat for soil microorganisms [18-20]. In practice, biochar is often applied with organic fertilizers, synergistically enhancing crop yields [21]. In addition to agronomic benefits, biochar application contributes to greenhouse gas mitigation, with potential carbon sequestration estimated at 2.8 GtCO<sub>2</sub> annually [22, 23].

The properties of biochar depend strongly on feedstock type and pyrolysis conditions such as temperature and heating duration [13, 24]. Different agricultural residues, including cassava peels, sugarcane bagasse (SCB), rice husks, coconut shells, and wood, yield biochars with varying physicochemical characteristics, as reported in previous studies [25-28].

Characterization of biochar is therefore essential to determine its quality and suitability for specific applications in agricultural systems [26].

Several studies have investigated sustainable strategies for organic waste valorization in both global and Indonesian contexts. Manea et al. [29] reported that composting is a sustainable solution for municipal organic waste and highlighted recent innovations to improve composting efficiency. On the other hand, Jupesta and Permana [30] demonstrated the potential of the circular economy through Black Soldier Fly (BSF)-based treatment of organic waste in Tasikmalaya, Indonesia, which successfully converted waste into high-value products such as maggot and organic fertilizer [30]. Meanwhile, Farahdiba et al. [31] provided a national-level assessment of food waste management in Indonesia, identifying regulatory and technological gaps in achieving government targets for waste reduction. These studies highlight the growing interest in sustainable organic waste management. There is limited empirical evidence on the valorization of agricultural residues into biochar at the local or regional scale in Indonesia. In particular, studies focusing on rural agricultural regencies remain scarce, despite their high reliance on biomass and large quantities of underutilized residues.

In this context, Pidie Regency in Indonesia represents a relevant case study for agricultural waste management challenges and resource recovery opportunities. As one of the key agricultural production areas in Aceh, the region generates diverse lignocellulosic residues, particularly from corn cobs (CCB), young coconut waste (YCW), and sugarcane bagasse (SCB), which are among the dominant by-products of local farming activities. These biomass resources are largely underutilized and are commonly managed through open burning or uncontrolled disposal, contributing to greenhouse gas emissions, air pollution, and soil degradation.

Despite their continuous generation and potential as carbon-rich feedstocks, systematic studies evaluating their conversion into biochar under local conditions remain limited. Furthermore, differences in biomass composition among these residues may significantly influence the physicochemical properties of the resulting biochar, highlighting the need for comparative investigation. Therefore, this study focuses on these three representative feedstocks to assess their suitability for biochar production and to understand their property development. This approach supports sustainable waste valorization strategies and aligns with Indonesia's national waste reduction targets (Presidential Regulation No. 97/2017) [32] as well as global sustainability frameworks such as SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [33].

## 2. MATERIALS AND METHOD

### 2.1 Feedstock collections

Agricultural residues used in this study included CCB collected from Rinti Village, while YCW and SCB were obtained as waste from small-scale coconut water and sugarcane juice vendors in Jojo Village, Pidie Regency, Aceh Province, Indonesia. These sources were selected to represent commonly available agricultural and agro-processing residues in the region. Sampling was conducted over multiple time points to capture variability in feedstock availability. For each

type of biomass, at least three independent batches were collected from different collection events. Each batch consisted of approximately 5–25 kg of raw material. The collected batches were then combined, homogenized, and processed as composite samples to ensure representativeness prior to pyrolysis.

### 2.2 Biochar production

Biochar was produced from three agricultural residues: CCB, YCW, and SCB. The process was carried out using a Kontiki kiln [34], a conical metal reactor designed to facilitate pyrolysis under limited oxygen conditions. The kiln was fabricated from steel plates with a top diameter of 1.50 m, a depth of 0.90 m, and a wall inclination angle of 63.5°, enabling efficient air circulation and stable combustion during operation.

Prior to pyrolysis, all feedstocks were sun-dried under direct sunlight for approximately 2–3 days until no further noticeable weight reduction was observed, indicating near-equilibrium moisture content. The dried mass was used as the reference for yield calculation; however, the moisture content was not quantitatively determined. The dried materials were manually reduced in size to approximately 5–10 cm to facilitate uniform heating during pyrolysis.

Pyrolysis was conducted under self-sustained combustion conditions following previously reported procedures [35]. The Kontiki kiln operates as an open pyrolysis system with limited temperature control; therefore, temperature was monitored qualitatively based on process observation (flame intensity and combustion behavior) but was not continuously or systematically recorded. Based on the typical operation of Kontiki kilns, the temperature is expected to be within the range of 400–600 °C, although this was not directly verified using thermocouple measurements. The biomass was initially ignited, and once a stable flame was established, additional feedstock was added periodically (approximately every 5–10 minutes) to maintain continuous pyrolysis while minimizing complete oxidation. Occasional manual stirring was performed to promote uniform carbonization.

The total pyrolysis duration for each batch was approximately 1.5–2 h, depending on feedstock type and loading conditions. Upon completion, the process was terminated by quenching with water (approximately 10–20 L, applied by sprinkling) to extinguish the flame and stabilize the biochar. The resulting biochar was allowed to cool, then sun-dried, ground, and sieved through a 100-mesh sieve prior to storage in airtight containers for subsequent analyses. Biochar yield was calculated based on the mass of feedstock after air-drying prior to pyrolysis and the mass of biochar after post-production drying using the following equation:

$$Yield(\%) = \frac{m_{biochar}}{m_{dry\ feedstock}} \times 100 \quad (1)$$

where,  $m_{biochar}$  is the mass of the produced biochar after post-pyrolysis drying, and  $m_{dry\ feedstock}$  is the mass of the feedstock after sun-drying prior to pyrolysis. Moisture content was not quantitatively determined; therefore, the yield does not represent a strictly dry-basis value and may introduce minor variability.

Pyrolysis experiments for each feedstock were conducted in triplicate. The resulting biochars were composited prior to characterization, and unless otherwise stated, analyses were

performed on representative samples without independent replication. This approach was adopted to improve sample representativeness under the operational variability of the Kontiki kiln.

### 2.3 Biochar characterizations

Biochar pH was determined by suspending 5 g of biochar in 25 mL of deionized water (1:5 ratio). The suspension was stirred at 200 rpm for 1 h at 25 °C, allowed to settle for 30 min, and then measured with a calibrated pH meter (pH meter Probe, Italy) [36], with slight modifications. Functional groups of biochar were identified using Fourier transform infrared (FTIR).

FTIR spectra were recorded using an FTIR spectrometer (IR Prestige-21, Shimadzu, Japan) within the wavenumber range of 4000–400  $\text{cm}^{-1}$  [37]. The analysis was performed using the attenuated total reflectance (ATR) method under standard instrument settings, with a spectral resolution of 4  $\text{cm}^{-1}$  and 32 scans per sample. Baseline correction was applied automatically by the instrument software prior to analysis.

The surface morphology of raw materials and biochars was examined using a scanning electron microscope (SEM) (JEOL JSM-6510LV, Japan) operated at an accelerating voltage of 10 kV and a magnification of 1000 $\times$  [38]. Prior to imaging, samples were coated with a thin layer of gold to improve conductivity. Elemental composition was analyzed using an integrated energy-dispersive X-ray (EDX) detector. Elemental data were collected from multiple representative areas (at least three spots per sample), and results are reported in atomic percentage (At%) using the instrument's standardless quantification method.

The specific surface area of the biochar samples was determined using the Brunauer–Emmett–Teller (BET) method with a Quantachrome NovaWin analyzer (Anton Paar QuantaTec, Version 11.06, USA) [39, 40]. Nitrogen ( $\text{N}_2$ ) adsorption–desorption isotherms were measured at 77 K. Prior to analysis, samples were degassed under vacuum at 200 °C for 6 h to remove moisture and adsorbed gases. The specific surface area was calculated using the multipoint BET method within the relative pressure range of  $P/P_0 = 0.05\text{--}0.30$ . The BET fitting exhibited a high correlation coefficient ( $R^2 = 0.997$ ), indicating good linearity. The instrument report indicated that degassing conditions were not recorded during analysis; therefore, the pre-treatment conditions may not have been fully controlled, which could influence the adsorption results. Measurements were conducted on representative samples.

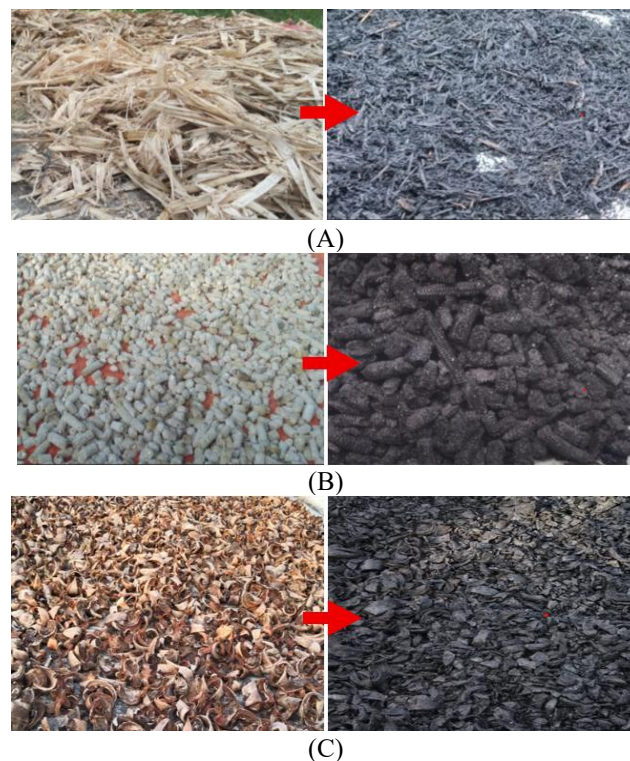
## 3. RESULTS AND DISCUSSION

### 3.1 Visual of biochars

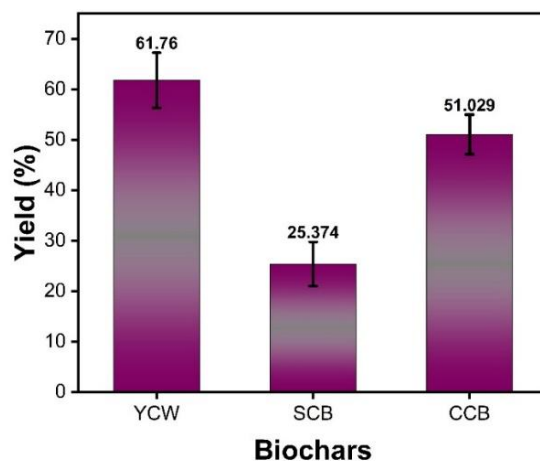
Figure 1 presents the visual photographs of the raw material and biochars obtained after pyrolysis. The raw material exhibits a fibrous and heterogeneous appearance, characteristic of lignocellulosic biomass with visible structural rigidity. After carbonization, the color changes markedly to black, indicating organic matter's decomposition and carbon-rich structures' formation. The reduction in size and increase in fragility of the biochars compared to the raw biomass suggest the breakdown of cellulose, hemicellulose, and lignin during pyrolysis, leaving behind a porous carbon matrix.

Figure 2 presents the biochar yields obtained from various

agricultural residues. The highest yield was achieved from YCW (61.76%), followed by CCB (51.03%). The relatively high yield of biochar from YCW can be attributed to its higher lignin [41] as well as a lower fraction of volatile compounds, which undergo less degradation during pyrolysis, leaving behind a more stable carbon fraction. CCBs also produced relatively high yields, likely due to their significant lignin and silica contents, which contribute to the structural stability of the carbon matrix during thermal decomposition.



**Figure 1.** Raw materials (left) and biochar-derived agriculture wastes (right): (A) sugarcane bagasse (SCB), (B) corn cob (CCB), and (C) young coconut waste (YCW)

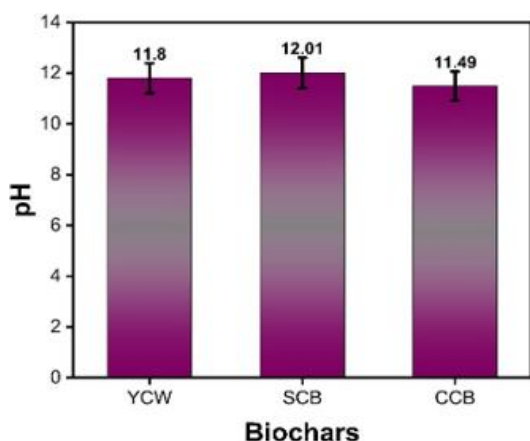


**Figure 2.** Yield of biochars obtained from different agricultural residues

The lowest yield was observed in SCB (25.37%). Its high cellulose and hemicellulose content and relatively low lignin fraction can explain this finding [42]. Since holocellulose is more thermally labile, its decomposition during pyrolysis reduces residual carbon fraction, leaving only a small portion of the biomass converted into biochar. Overall, the variation

in biochar yields across different agricultural residues is strongly influenced by their chemical composition, particularly the balance between lignin, cellulose, and hemicellulose. Biomass with higher lignin and mineral content tends to yield more biochar, as these components are more resistant to thermal degradation, while feedstocks rich in holocellulose produce lower yields. These findings highlight the importance of feedstock selection in developing biochar production strategies for agricultural waste valorization, particularly in optimizing production efficiency and tailoring biochar properties for soil amendment applications.

### 3.2 pH profile of biochars



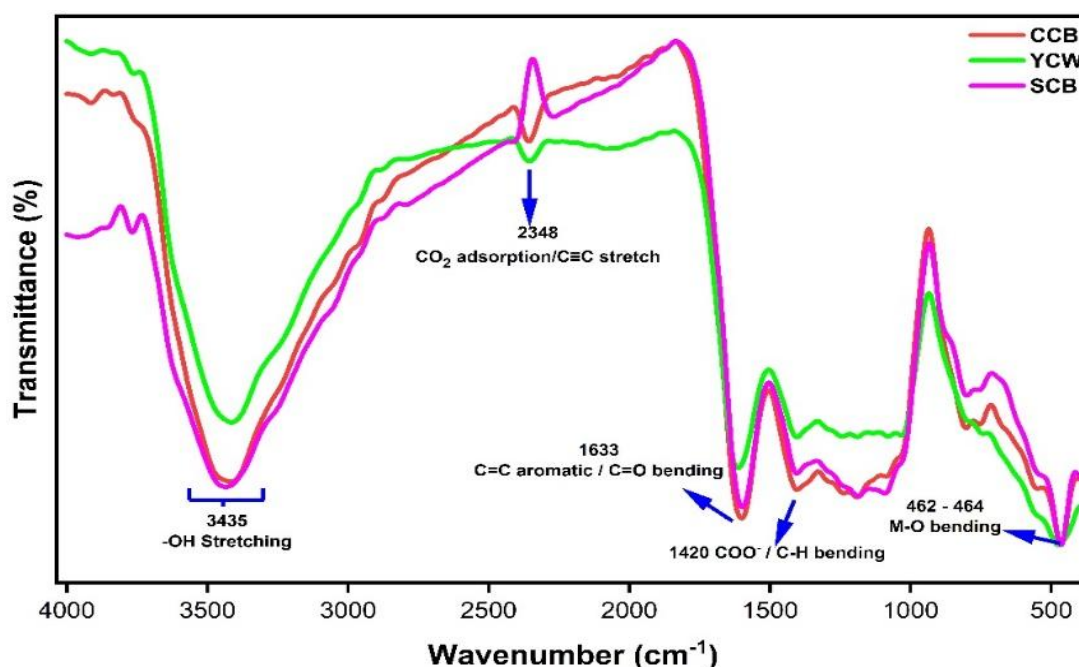
**Figure 3.** pH profile of biochars from different agricultural waste biomass

Figure 3 presents the pH values of biochars derived from different feedstocks, showing a highly alkaline range (pH > 11) for SCB, CCB, and YCW biochars. This strong alkalinity is primarily attributed to the accumulation of inorganic ash components, including alkaline metal oxides and carbonates formed during pyrolysis. Such high pH values indicate that these biochars may be beneficial for application in acidic soils,

where they can contribute to pH neutralization, enhance nutrient availability, and support microbial activity. However, these benefits are highly dependent on soil conditions and application rates.

In contrast, the application of highly alkaline biochar to neutral or alkaline soils may lead to adverse effects, including reduced availability of micronutrients (e.g., Fe, Mn, Zn, and P), increased salinity, and potential phytotoxicity. Excessive biochar application has also been reported to clog soil pores and adsorb essential nutrients, thereby limiting water and nutrient exchange and inhibiting plant growth [43]. Therefore, the use of high-pH biochar should be carefully managed. It is more suitable for acidic soils (pH < 6), with moderate application rates (e.g., 1–5% w/w or 10–30 t/ha) depending on soil characteristics and crop requirements. These findings highlight the importance of matching biochar properties with soil conditions to optimize agronomic benefits while minimizing potential risks.

The present findings align well with previous studies on biochar alkalinity. Agricultural residues generally yield alkaline biochars, particularly when pyrolyzed at elevated temperatures. For instance, wheat straw and pine sawdust biochars exhibited pH values of 10.2 and 10.5, respectively, when produced at 500 °C [44]. Similarly, biochar produced at higher pyrolysis temperatures generally exhibits an alkaline pH, which is significantly higher than that of the raw biomass, confirming its strong liming potential for acidic soils. This behavior is influenced by feedstock type and processing conditions, as reported by Murtaza et al. [45]. These results are comparable to the high pH (> 11) observed in biochars in this study, emphasizing the general tendency of lignocellulosic residues to generate strongly alkaline products. Taken together, the comparison underscores that both feedstock origin and pyrolysis temperature are decisive factors determining biochar pH. The highly alkaline biochars identified in this study (SCB, CCB, and YCW) are thus well-suited for acidic soil remediation.



**Figure 4.** Fourier transform infrared (FTIR) spectra of corn cob (CCB), young coconut waste (YCW), and sugarcane bagasse (SCB) biochars

**Table 1.** Interpretation of functional groups of biochars from Fourier transform infrared (FTIR) spectra

Wavenumber (cm <sup>-1</sup> )	Functional Groups	Chemical Indications	Descriptions
3435	O–H stretching (hydroxyl)	Free or bound –OH (water, phenol, alcohol, carboxylate)	Commonly derived from polar groups on the biochar surface. Different intensities indicate varying levels of oxygen-containing functional groups.
2348	CO <sub>2</sub> -related band / possible C≡C stretching (tentative assignment)	Possible CO <sub>2</sub> -related signal, atmospheric CO <sub>2</sub> , or residual functional groups (e.g., alkyne/isocyanate)	May arise from atmospheric CO <sub>2</sub> or instrument background; interpretation should be made with caution.
1633	C=O stretching/C=C aromatic stretch/C=C bend/H–O–H bending	Aromatic structures, carbonyl, or bound water	A common peak in biochar indicates aromatic ring structures or conjugated carbon groups.
1420	COO <sup>-</sup> symmetric/C–H bending (methyl/methylene)	Carboxylate salts or aromatic compounds	Generally originates from residual carboxylate groups or lignin/hemicellulose compounds.

### 3.3 Fourier transform infrared analysis

FTIR spectroscopy is a widely used technique for biochar characterization. Through FTIR analysis, the functional groups present on the biochar surface can be identified. The study compared the FTIR spectral peaks of different biochar types. The spectra from FTIR analysis reflect the presence of residual organic and inorganic compounds from pyrolysis, which significantly influence the surface chemical properties of biochar and its potential applications in agriculture and environmental remediation. The FTIR spectra of the analyzed biochars are shown in Figure 4, with their corresponding interpretations summarized in Table 1.

The FTIR spectra presented in Figure 4 reveal a broad absorption band around 3435 cm<sup>-1</sup> that appears across all samples. This band corresponds to hydroxyl (–OH) groups, which may originate from bound water or polar functional groups such as alcohols, phenols, and carboxylates in the biochars. The most intense and broad peaks were observed in samples of CCB, indicating that these biochars contain the highest abundance of polar functional groups. The presence of hydroxyl groups is particularly important, as it reflects the hydrophilic–hydrophobic balance of the biochar surface and directly influences adsorption capacity for water, nutrients, and other polar molecules. Zhao et al. [46] reported that biochars with pronounced O–H bands generally exhibit strong affinity for soil ions and nutrients due to surface complexation mechanisms.

A distinct absorption band at 2348 cm<sup>-1</sup> was observed, particularly in SCB biochar. This band may be attributed to CO<sub>2</sub>-related signals; however, it can also arise from atmospheric CO<sub>2</sub>, background interference, or residual functional groups formed during pyrolysis, such as alkyne or isocyanate species. Therefore, this peak should be interpreted with caution and not considered definitive evidence of CO<sub>2</sub> adsorption.

Although the presence of this band may suggest potential interactions with gaseous species, no direct gas adsorption measurements were conducted in this study. As such, any implication regarding CO<sub>2</sub> adsorption capacity remains preliminary. The observed feature may instead reflect the complex surface chemistry and possible microporous characteristics of the biochar [47, 48], which warrant further investigation through dedicated adsorption analyses.

The FTIR analysis presented in Figure 4 also reveals an absorption band at 1633 cm<sup>-1</sup>, which corresponds to aromatic C=C stretching, C=O stretching, or H–O–H bending. This peak is generally present across all spectra. It indicates the existence of aromatic structures characteristic of conjugated

carbon systems and phenolic rings, as well as possible carbonyl groups derived from ketones, aldehydes, or carboxylic acids in the biochar. The relatively strong intensity observed in biochar YCW suggests lignin residues or natural phenolic compounds that were not completely decomposed during pyrolysis. This spectrum confirms that these biochars retain part of their complex aromatic structures, essential for thermal stability and surface characteristics. Previous studies have reported that aromatic structures contribute significantly to the long-term chemical stability of biochar and enhance its adsorption capacity for aromatic organic contaminants [49, 50].

Furthermore, the FTIR spectra display a characteristic absorption band at 1420 cm<sup>-1</sup>, closely associated with COO<sup>-</sup> vibrations from carboxylate groups and C–H bending of methyl or methylene groups. This band appears prominently in biochars YCW, suggesting the persistence of polar compounds such as hemicellulose or lignin that were not fully degraded during pyrolysis. The presence of carboxylate groups enhances the surface polarity of biochar and underlines its relevance for adsorbing negatively charged organic compounds. Previous research has indicated that COO<sup>-</sup> groups can participate in ion exchange and complexation with inorganic pollutants [51]. In addition, the FTIR spectra in Figure 4 display a band at 462–464 cm<sup>-1</sup>, corresponding to metal–oxygen bending vibrations (M–O). This feature is particularly prominent in all samples, reflecting the vibrational characteristics of metal–oxygen groups, particularly Si–O, Fe–O, or Al–O.

The diversity of FTIR spectra across the three biochars analyzed demonstrates their unique chemical characteristics and provides valuable insights into the functional potential of each material. Biochars SCB, which exhibit strong bands at 3435 cm<sup>-1</sup>, 2348 cm<sup>-1</sup>, and 1420 cm<sup>-1</sup>, can be considered as possessing the most active polar functional groups, making them highly suitable candidates for sustainable agricultural applications, particularly in enhancing adsorption capacity and interactions with organic and ionic compounds in soil.

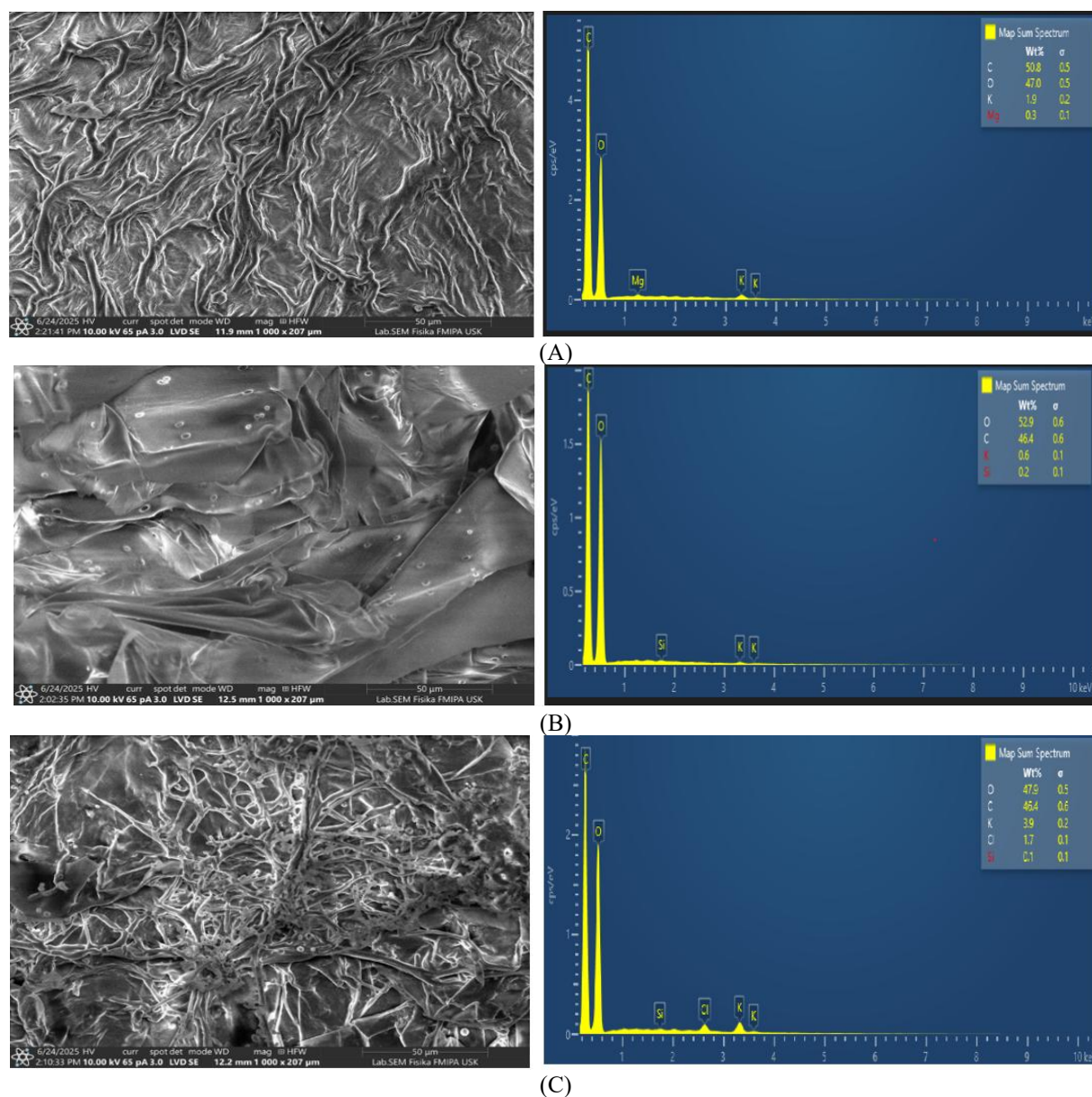
### 3.4 Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy analysis of raw materials

The SEM–EDX analysis revealed the surface morphology and elemental composition of three agricultural residues used as biochar feedstocks (Figure 5). The results demonstrated significant variations in texture, structural arrangement, and mineral composition among different biomass types, which are closely related to their lignocellulosic structure and inorganic content.

The CCB (Figure 5(A)) displayed a highly irregular and fibrous structure, characterized by elongated fibrils stacked in a disordered fashion. This morphology is typical of raw lignocellulosic biomass consisting of cellulose, hemicellulose, and lignin. EDX analysis detected 50.8% C, 47% O, 1.9% K, and 0.3% Mg. These results agree with earlier reports identifying abundant fibrillar structures interwoven with natural binding components such as lignin and hemicellulose [52, 53]. The presence of these residual polymers explains the compact yet irregular surface, which is expected to undergo significant decomposition and porosity development during pyrolysis, thus enhancing the suitability of CCB biochar for adsorption and soil fertility improvement. SCB (Figure 5(B)) presented a layered surface with relatively smooth morphology and minor cracks. The intact lignocellulosic network indicates cellulose, hemicellulose, and lignin remain strongly bound within the plant cell wall matrix. EDX analysis showed O (52.9%), C (46.4%), and K (0.6%). These findings highlight the dominance of polar functional groups from carbohydrate polymers, consistent with previous SEM–EDX studies [54–57]. Moreover, its microfibrillar structure, often described as web-like cellulose

fibers interwoven with lignin, provides a basis for developing a complex carbon framework upon pyrolysis. This morphological feature enhances the potential of SCB as a promising feedstock for producing biochar with a large surface area and high adsorption performance.

The SEM image of YCW (Figure 5(C)) showed a complex fibrous morphology with irregularly aligned lignocellulosic fibrils. These fibers intersected randomly, forming a network reinforced by lignin and hemicellulose. EDX analysis indicated O (47.9%), C (46.4%), K (3.9%), and Cl (1.7%). The high carbon and oxygen contents reflect its organic nature. At the same time, mineral elements such as K and Cl may enhance the agronomic value of the resulting biochar as a soil amendment. Similar observations were reported by Suman and Gautam [58] and Basu et al. [59], who described coconut fibers as elongated cellulose microfibrils with cracks, voids, and globular protrusions associated with waxy and fatty impurities. Such features suggest that coconut-derived biochar can develop a porous and reactive surface after pyrolysis, offering potential for both environmental and agricultural applications.



**Figure 5.** Scanning electron microscope (SEM) morphology and energy-dispersive X-ray (EDX) elemental composition of raw materials: (A) corn cob (CCB), (B) sugarcane bagasse (SCB), and (C) young coconut waste (YCW)

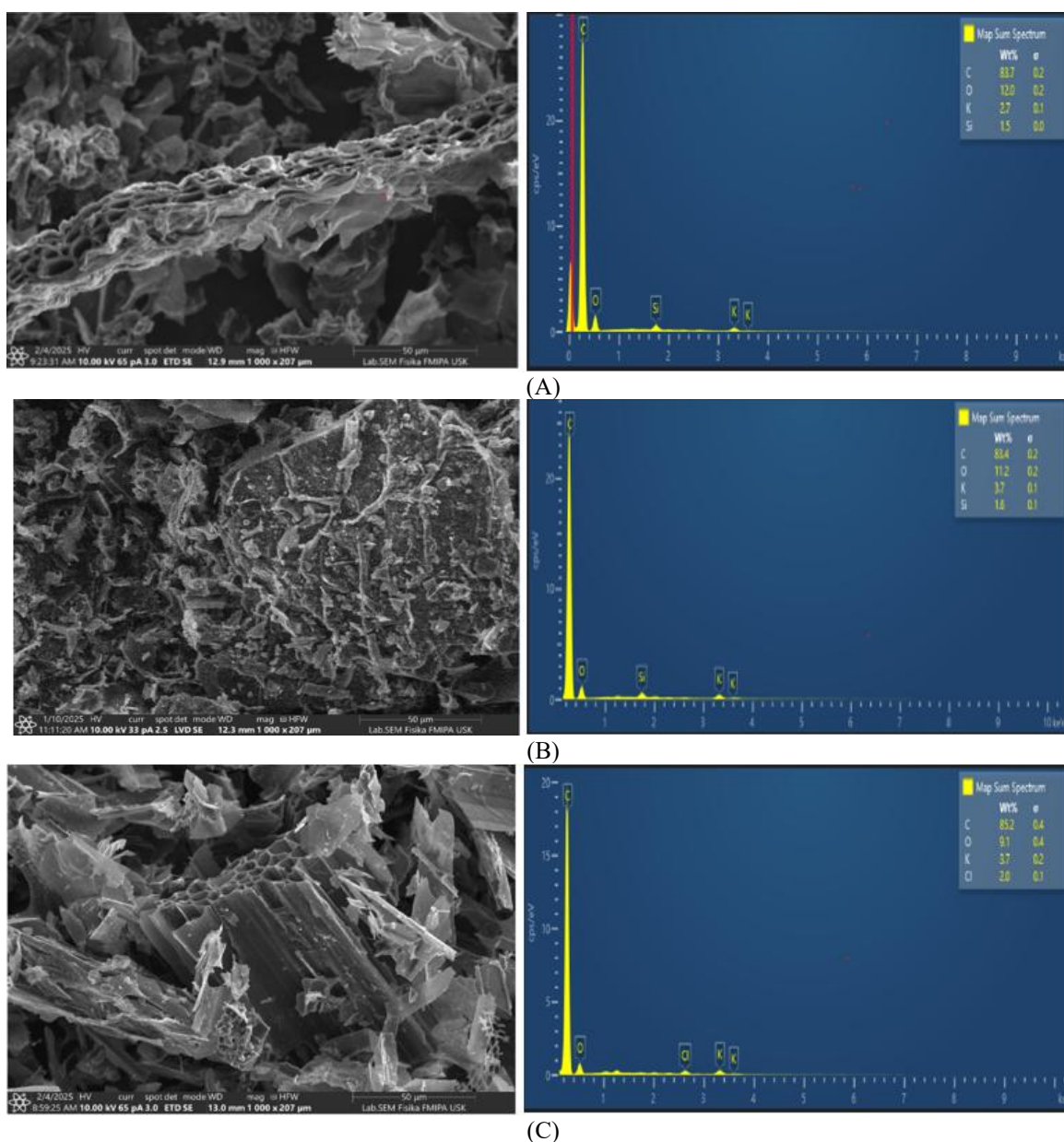
Overall, the SEM–EDX analysis highlights the diverse morphological and compositional characteristics of agricultural residues in Pidie District. CCB, SCB, and YCW exhibit typical lignocellulosic features favorable for biochar production in sustainable farming systems. These differences underline the importance of feedstock selection in tailoring biochar properties for targeted applications.

### 3.5 Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy analysis of biochar

SEM examined the morphological and elemental characteristics of biochars—EDX to evaluate surface structure and elemental distribution after pyrolysis. Surface morphology plays a key role in determining adsorption capacity, chemical reactivity, and long-term stability of biochars in environmental and agricultural applications. Representative SEM micrographs (magnification 1000×) and EDX spectra are presented in Figure 6. All biochars generally exhibited heterogeneous surfaces with porous structures, microscopic cracks, and remnants of plant cell tissues. Such porous and irregular structures are typical of pyrolyzed

biomass and are strongly influenced by feedstock type and pyrolysis conditions. These findings are consistent with earlier studies reporting that pore structures are formed due to the release of volatile compounds during pyrolysis, with each biomass yielding a distinctive morphology [60].

Biochar derived from CCB (Figure 6(A)) displayed relatively smooth surfaces with oval-shaped and irregular pores. Its elemental composition was dominated by C (83.7%), O (12.0%), and K (2.7%). The high carbon content and reduced oxygen indicate efficient volatilization during pyrolysis, yielding a stable carbonaceous framework. Open and irregular pores promote diffusion and adsorption processes, enhancing its potential as an adsorbent. Similar porous and elongated cylindrical structures were also described in neem wood biochar, which showed favorable adsorption properties [61]. Compared with the raw cob (Figure 5(A)), the carbon fraction increased markedly from 50.8% to 83.7%, corresponding to an increase of approximately 64.8%, while oxygen decreased, confirming the successful conversion of volatile components into stable carbon structures.



**Figure 6.** Scanning electron microscope (SEM) morphology and energy-dispersive X-ray (EDX) elemental composition of biochars (A) corn cob (CCB), (B) sugarcane bagasse (SCB), and (C) young coconut waste (YCW)

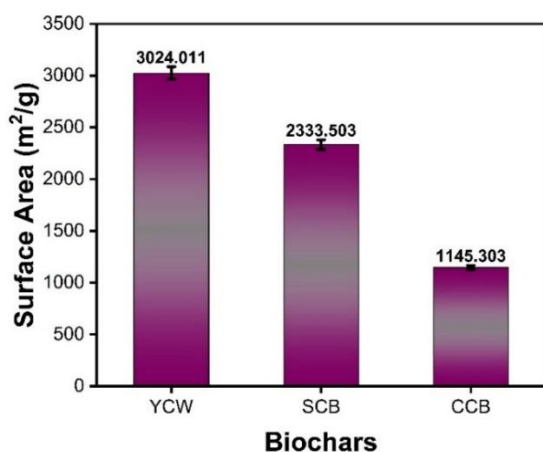
SCB (Figure 6(B)) exhibited cellular morphology with large open pores, reflecting the fibrous nature of the feedstock. While the raw material showed smooth and compact cell walls (Figure 5(B)), pyrolysis resulted in well-developed porosity. EDX results showed a high carbon content (83.4%) alongside O (11.2%) and K (3.7%). Such carbon enrichment indicates effective pyrolysis, while the relatively high K suggests potential nutrient contribution when applied as a soil amendment. These features support its use in CO<sub>2</sub> adsorption, consistent with FTIR evidence at 2348 cm<sup>-1</sup>. Similar mesoporous structures (~8 nm pore size) were also reported in other agro-residue biochars, which exhibited enhanced adsorption of metal ions and organics [28].

Biochar from YCW (Figure 6(C)) showed a coarse and irregular fibrous surface with visible wood-like textures. EDX analysis indicated the highest carbon concentration among all samples (85.2%), along with O (9.1%), K (3.7%) and Cl (2%). This exceptionally high carbon fraction reflects highly efficient pyrolysis and a stable aromatic structure, suggesting strong thermal and chemical stability. The fibrous and porous morphology makes this biochar suitable for long-term applications such as adsorbents, microbial carriers, or reinforcing agents in composites. These observations are consistent with reports of woody biochars, which typically exhibit coarse textures, intact fibers, and high structural stability [62].

SEM-EDX analysis confirmed that pyrolysis significantly transformed the raw biomass morphology into porous carbon structures with enriched carbon fractions. Biochars from CCB, bagasse, and coconut waste demonstrated enhanced carbonization and pore development, favouring their use in adsorption, soil improvement, and environmental remediation.

### 3.6 Brunauer–Emmett–Teller analysis

BET analysis was conducted to characterize the porous structure of biochars, including BET specific surface area ( $S_{BET}$ , m<sup>2</sup>/g). These parameters are critical for understanding the adsorption potential of biochar toward nutrients, water retention, pollutant immobilization, and the provision of microhabitats for soil microorganisms. The results of the BET analysis are presented in Figure 7.



**Figure 7.** BET specific surface area ( $S_{BET}$ ) analysis of biochars from various agricultural waste biomass

Among the tested samples, biochar from YCW exhibited the highest surface area (3024 m<sup>2</sup>/g), followed by SCB (2333

m<sup>2</sup>/g) and CCB (1145 m<sup>2</sup>/g). These values are considerably higher than those typically reported for conventional biochars and even exceed the range commonly associated with activated carbons. Such unusually high surface area values should be interpreted with caution. It is well recognized that the BET method may overestimate surface area in highly microporous carbon materials, particularly when the selected relative pressure range is not fully optimized for micropore-dominated systems. Under these conditions, multilayer adsorption assumptions inherent in the BET model may not be entirely valid, leading to inflated surface area values.

Therefore, the reported values in this study are more appropriately considered as apparent BET surface areas rather than absolute surface areas. While the results suggest the formation of a highly developed porous structure, further analysis using complementary methods such as t-plot or non-local density functional theory (NLDFT) is necessary to more accurately resolve micropore contributions.

For comparison, previous studies have reported significantly lower surface areas for biochars derived from various feedstocks, such as walnut shell (292 m<sup>2</sup>/g) [63], palm kernel shell (300 m<sup>2</sup>/g) [64], and wood-based biochars (2–734 m<sup>2</sup>/g) depending on feedstock and pyrolysis conditions [65, 66]. Similarly, agricultural residues such as sugarcane waste (712 m<sup>2</sup>/g), CCB (222 m<sup>2</sup>/g), bamboo (248 m<sup>2</sup>/g), and rice straw (222 m<sup>2</sup>/g) have shown substantially lower values [67]. These discrepancies highlight the importance of careful interpretation of BET-derived surface areas, particularly for materials with potentially complex pore structures. In addition, uncertainty in sample pre-treatment (degassing conditions) may contribute to the observed high surface area values. The original BET reports are provided in the Supplementary Information.

The adoption of a conventional, low-cost production strategy substantially strengthens the practical relevance of this study. Kontiki kiln-based pyrolysis not only produced materials with enhanced physicochemical properties relative to previously reported systems, but also preserved operational simplicity and scalability. Such characteristics make this approach particularly suitable for sustainable organic waste management in resource-constrained settings. Taken together, these findings suggest that their application could be particularly effective in improving soil fertility, water management, and pollutant remediation.

The Kontiki kiln operates as an open pyrolysis system with limited control over temperature and oxygen availability, which may result in temporal and spatial temperature fluctuations during operation. Such variability can potentially influence biochar yield and structural properties. In this study, temperature was monitored qualitatively to ensure stable combustion conditions; however, it was not continuously recorded or used as a controlled parameter. To mitigate the potential impact of process variability, pyrolysis experiments for each feedstock were conducted in triplicate, and the resulting biochars were composited prior to characterization to obtain representative samples.

The relatively consistent yield range observed across repeated experiments suggests that, despite the inherent variability of the system, the process remained sufficiently stable for comparative evaluation. Nevertheless, the results should be interpreted with consideration of this limitation, and future studies incorporating real-time temperature monitoring are recommended to further improve process control and reproducibility.

#### 4. CONCLUSIONS

This study demonstrates that feedstock type strongly influences the physicochemical properties of biochar produced using a Kontiki kiln. Biochar yields ranged from 25 to 62%, and all samples exhibited strongly alkaline characteristics (pH > 11). Significant variation in textural properties was observed among feedstocks, with specific surface areas of 3024 m<sup>2</sup>/g for YCW, 2333 m<sup>2</sup>/g for SCB, and 1145 m<sup>2</sup>/g for CCB, indicating substantial differences in pore development. Among the evaluated materials, YCW and SCB biochars exhibited superior textural properties, particularly in terms of higher specific surface area and more developed porous structures compared to CCB. However, these values should be interpreted with caution due to potential overestimation associated with microporous characteristics and limitations of the BET method.

These findings highlight the importance of feedstock selection for tailoring biochar properties for specific applications. The results suggest potential for the use of these materials in soil-related and environmental applications, particularly in acidic soil amendment; however, their roles in greenhouse gas mitigation and carbon sequestration remain preliminary and require further validation through dedicated assessments of carbon stability and soil–biochar interactions. Overall, this study provides empirical insight into the valorization of locally available agricultural residues in Pidie Regency, Indonesia, demonstrating their potential as sustainable biochar feedstocks while emphasizing the need for further application-specific evaluation.

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