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Original Research Article

Effect of Non-Thermal Plasma on Biochar Properties from Sugarcane Bagasse and Banana Peel

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Abstract

Biochar produced from agricultural waste, such as sugarcane bagasse and banana peel, has gained significant attention due to its potential environmental and industrial applications. This study aimed to enhance the physicochemical properties of biochar derived from these wastes using non-thermal plasma treatment. Biochar was produced via pyrolysis combined with non-thermal plasma treatment and then characterized to identify the differences. Characterization was performed using XRD (X-ray Diffraction), SEM (Scanning Electron Microscopy), FTIR (Fourier Transform Infrared Spectroscopy), and BET (Brunauer-Emmett-Teller) surface area analysis to evaluate changes in crystallinity, morphology, functional groups, and surface area. Non-thermal plasma treatment significantly altered the surface morphology of the biochar, increasing its porosity and surface area. The BET surface area of sugarcane bagasse waste was 0.061 m^2/g, which expanded to 87.50 m^2/g after changing to biochar, whereas banana peel waste had a BET surface area of 0.007 m^2/g, which increased to 427.2 m^2/g after changed to biochar. The pyrolysis process on both biochars also reduced OH (hydroxyl) transmittance, as evidenced by FTIR analysis, which indicated water evaporation. Non-thermal plasma treatment substantially improved the physical and chemical properties of biochar compared to untreated biomass.

Keywords: Biochar; non-thermal plasma; sugarcane bagasse; banana peel; surface area; crystallinity; functional groups

1. Introduction

Biochar, a carbon-rich material produced from the thermal decomposition of organic biomass in the absence of oxygen, has obtained significant attention in recent years for its environmental applications, particularly in pollutant adsorption, carbon sequestration, and soil improvement (Xue et al., 2023). The performance of biochar in these applications is highly dependent on its physical and chemical properties, including surface area, porosity, crystallinity, and functional groups. These properties vary considerably based on the feedstock used and the conditions under which the biochar is produced (Zhao et al., 2020).

The transformation of agricultural waste into biochar is economical due to its widespread availability globally. Annually, agricultural solid waste amounts to approximately 0.998 billion tons (Raut et al., 2023), with bagasse comprising 54% of this total (Raj and Tirkey, 2023). Sugarcane (Saccharum officinarum) is a viable source of bagasse, cultivated mainly in tropical countries such as Brazil, Mexico, China, Thailand, and Indonesia. In 2021, Indonesia produced 2,364,321 tons of sugarcane, generating approximately 756,582.72 tons of bagasse waste. From each ton of sugarcane, around 115 kg of sugar and 300 kg of bagasse are produced, along with other byproducts such as filter cake, molasses, and furnace ash (Taufani, 2023). East Java province leads sugarcane production in Indonesia, yielding approximately 14.7 million tons annually. Estimates indicate that sugarcane processing generates around 32% of its leftovers as bagasse (Kominfo Jatim, 2022).

However, the management of sugarcane bagasse residue is often inefficient due to equipment constraints during harvesting. As a result, farmers commonly resort to direct burning to reduce its volume, releasing particulate matter, carbon dioxide, and other harmful gases that negatively impact health and contribute to greenhouse gas emissions. The direct combustion method also generates fly ash, which may contaminate the soil and harm beneficial soil microorganisms (Machado et al., 2023). Sugarcane bagasse is rich in lignocellulosic content, consisting of approximately 42% cellulose, 25% hemicellulose, and 20% lignin. Its cellulose content, which contains carboxyl and hydroxyl groups, makes it highly effective for adsorbing pollutants in wastewater, particularly heavy metals (Machado et al., 2023). Transforming sugarcane bagasse into biochar supports a circular economy approach in Indonesia, enhancing both environmental sustainability and economic growth in rural areas.

In Indonesia, *Kepok* bananas are widely popular, especially for making fried bananas, a traditional dish. However, local governments struggle to manage agricultural waste, and promoting a sustainable economy remains among the most pressing challenges for the Indonesian government. Utilizing *Kepok* banana peel waste for biochar production not only reduces organic waste entering the environment but also enhances the economic value of banana peels. Biochar derived from *Kepok* banana peels has demonstrated promising potential in removing heavy metal contaminants from wastewater, achieving an adsorption efficiency of 52.14–99.27% at pH levels between 4 and 7 (Khairiyah et al., 2021). Moreover, using *Kepok* banana peels as activated carbon can reduce the concentration of contaminants such as Cu(II) by 94% and methylene blue dye by 92% (Hossain et al., 2012).

Various modification techniques have been explored to enhance the performance of biochar, with non-thermal plasma treatment emerging as a promising approach. This low-temperature plasma process can introduce new functional groups, increase surface area, and alter the surface morphology of materials (Kang et al., 2020). Non-thermal plasma creates an electric discharge that converts electrical energy into thermal energy. This process ionizes plasma gas, creating conductors and promoting molecular disintegration through energization, separation, bonding, and atomic relocation (Sanito et al., 2020). During the procedure, materials disintegrate into their elemental components under anoxic environment due to the intense heat (Hrabovsky and Van der Walt, 2018). In comparison to traditional non-contact heating methods, plasma technology offers advantages such as rapid and direct heating, greater heat levels, a streamlined system footprint, and a broader range of chemical conversion (Kang et al., 2020).

Recent studies have demonstrated that plasma treatment can enhance the adsorption capacity and chemical reactivity of biochar by modifying its surface chemistry. However, the specific effects of non-thermal plasma on biochar derived from agricultural residues, such as sugarcane bagasse and banana peel, remain underexplored.

As far as the author is aware, no studies have been carried out to investigate the specific effects of non-thermal plasma on biochar quality derived from agricultural residues for broad environmental applications. This study aims to examine the effects of non-thermal plasma treatment on the morphology, crystallinity, functional groups, and surface area of biochar. The focus is on biochar derived from sugarcane bagasse (SB), an abundant byproduct of the sugarcane industry, and *Kepok* banana peel (BP), a common agricultural waste. This research seeks to improve the characteristics of biochar and analyze its effectiveness in sustainability solutions, particularly in pollutant removal and soil remediation.

2. Methods

2.1. Biomass Waste Samples Preparation

SB was obtained from a sugar mill in the Sidoarjo Regency, East Java Province, Indonesia. Then, *Kepok* BP waste was sourced from the fruit market waste collection in Surabaya City, East Java Province, Indonesia. First, the gathered raw materials were thoroughly cleaned. Then, the samples were boiled in water. Subsequently, both the SB and BP are finely cut into tiny pieces using a grinding machine (Rong Tsong, 0–2B, Taiwan) at 30,000 rpm and subjected to drying in an oven (Drying Oven DO45, DENG YNG, Taiwan) at 80°C for 4 hours. After drying, the samples underwent to put into a ball mill (PM100 Restsch) at a rotation speed of 570 rpm for 10 minutes to crush and screened with a 100-mesh sieve (Scheufele *et al*2015).

2.2 Biochar Production

The biochar production followed the previous research by Dermawan, 2022 with temperature-generated consideration for the best pyrolysis for both samples. The prepared samples were first placed into the crucible to begin the pyrolysis process. Then, the crucible is inserted into a quartz tube located in the microwave propagation path, as shown in Figure 1. Two independent gas flow channels, each set to 9 L/min for 5 minutes, were used to activate the plasma. The process was conducted with a microwave input power of 1.2 kW, a nitrogen gas pressure of 30 psi, and a temperature of 300°C. The pyrolysis temperature is indirectly determined using a thermocouple connected by wire, and a rod is installed on the bottom of the outer side. To avoid potential degradation or contamination, the produced biochar was kept in airtight containers(Dermawan *et al*2022).

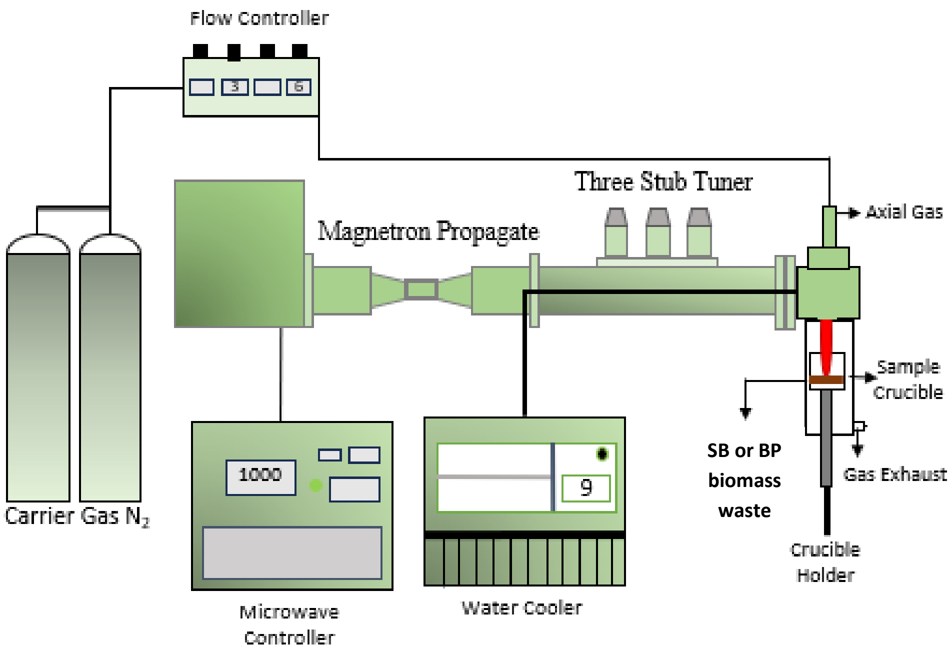

Figure 1. Schematic diagram of experimental setup

2.3 Characterization Techniques

Characterization of the samples, both before and after pyrolysis, was conducted using four different tests. First, Scanning Electron Microscopy (SEM) was performed to observe changes in surface morphology, with the hypothesis that each process would introduce more structural damage (Ahmadi et al.,2016). X-ray Diffraction (XRD) was utilized on biomass and biochar to evaluate changes in crystallinity and phase structure (Dermawan *et al*2022). Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify and analyze functional groups (Setiawan *et al*2022). Finally, Brunauer-Emmett-

Teller (BET) analysis was conducted to measure changes in surface area and porosity in the treated samples.

3. Result and Discussion

3.1 SEM

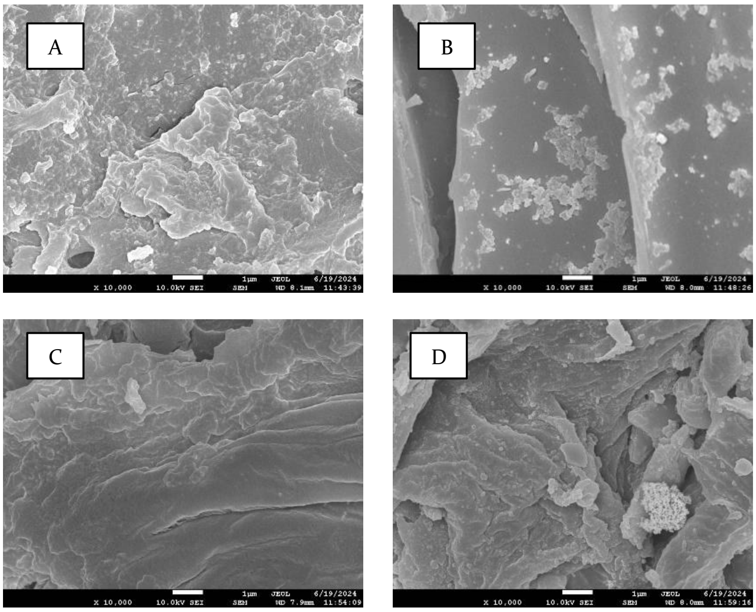

Figure 2. SEM of sugarcane bagasse and banana peels
(A) SB Biomass; (B) SB Biochar; (C) BP Biomass; (D) BP Biochar

Figure 2 showed surface morphology before and after plasma treatment. The morphological comparison between treated and untreated biochar samples revealed significant changes in surface structure due to pyrolysis and additional treatments. The untreated SB biomass (A) showed a rough surface with minimal porosity, which was characteristic of natural organic material. Post-pyrolysis, SB biochar (B) became more fragmented, with increased surface roughness and visible pores due to carbonization. Similarly, after treatment, untreated BP biomass (C) exhibits a compact surface, which became more porous and irregular in BP biochar (D), indicating thermal degradation.

Non-thermal plasma treatment further modified the biochar's surface. Plasma treatments etched the surface, increasing roughness, porosity, and functional groups that enhance reactivity and pollutant interaction. In summary, untreated biomass samples exhibited smooth, compact surfaces with minimal porosity, whereas treated biochar samples displayed increased roughness and porosity due to interaction with the thermal process. During this process, microwave plasma at atmospheric pressure generated an electric discharge that converted electrical energy into thermodynamic power. Subsequently, charge separation transformed the plasma gas into conductive materials, inducing Fragmentation, energy excitation, bond detachment, molecular attachment, and both atomic and molecular transfer—all contributing to component decomposition. The presence of more chemically active species and biomass within the plasma apparatus further expanded the surface area of the biochar, thereby increasing its roughness and porosity (Sanito *et al* 2020). Non-thermal plasma typically etches biochar, improving its porosity and reactivity, though these effects may not be visually evident in this comparison (Dermawan *et al* 2022). Better visualization requires higher magnification and resolution, which can be achieved using TEM (Transmission Electron Microscopy) or HR-TEM (High-Resolution Transmission Electron Microscopy) (Zhang *et al*., 2001).

3.2 XRD

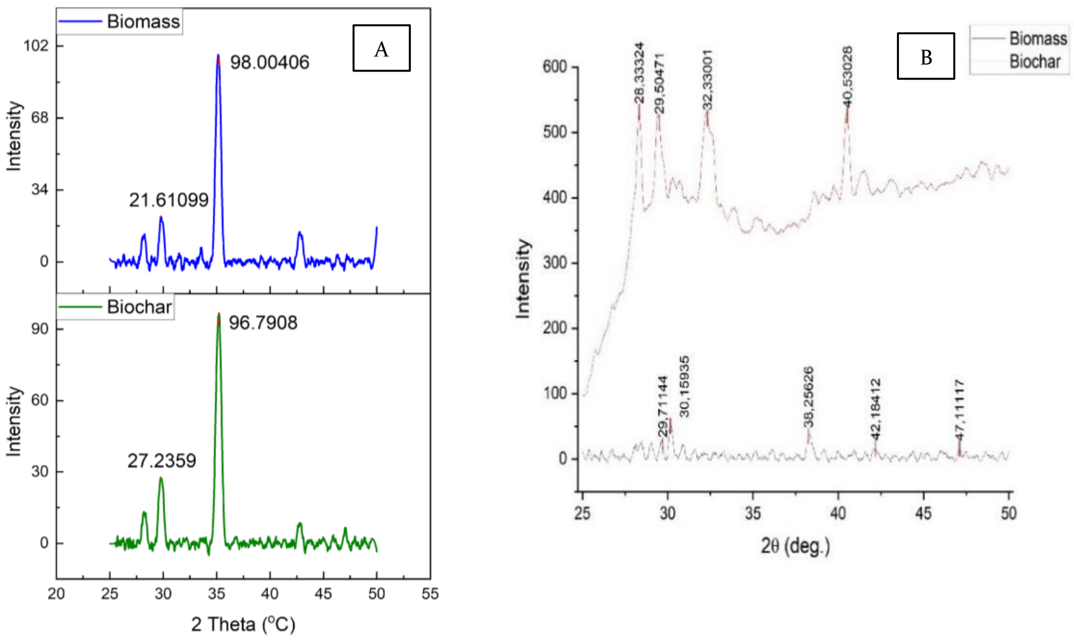

Figure 3. Sugarcane bagasse and banana peel biomass and biochar XRD test results (A) SB biomass and biochar (B) BP biomass and biochar

Tabel 1 SB and BP biomass and biochar crystallinity index and size

Sample	2θ (Main Reflection)	Crystallinity Index (%)	Crystal size (nm)
SB Biomass	35.1289	77.94%	166.68
SB Biochar	35.2276	71.88%	198.673
BP Biomass	24.46°	66.94%	58.86
BP Biochar	26.103°	59.62%	89.98

Figure 3 shows the crystalline phases of the biochar. Peak intensity, width, and position comparisons that indicate changes in crystallinity. The XRD diffractogram pattern of SB biomass and biochar was obtained through the plasma process, with a spectrum comparing the structural properties. The peak intensity of the biomass crystals was recorded at 98.00406, while the biochar was lower at 96.7908, signaling structural changes during conversion (Torres *et al*2020). The XRD pattern test results for BP show differences between the BP biomass and biochar. XRD analysis revealed that both samples had different amorphous structures, with crystal sizes of 21.86 nm for the biomass and 39.98 nm for the biochar, respectively. For biomass and biochar, further analysis of the peak patterns was conducted using the Joint Committee for Powder Diffraction Standards (JCPDS) 50-2241.

Table 1 reveals that plasma treatment processes lead to a reduction in the crystallinity of the material. For both SB and BP samples, the crystallinity index of the biochar calculated by the Segal method was lower than that of the corresponding biomass. Specifically, the crystallinity of SB biomass decreased from 77.94% to 71.88% in SB biochar, while BP biomass decreased from 64.94% to 58.62% in BP biochar. This reduction in crystallinity could be attributed to the thermal and oxidative effects of the plasma treatment and biochar formation, which tended to disrupt the ordered arrangement of carbon atoms. Plasma treatment typically causes surface and bulk structure changes, leading to partial degradation or disorder in the crystalline regions. The increase in the size of the crystals and the amorphous content of biochar can increase the adsorption capacity and mechanical stability, making it more effective at absorbing contaminants (Dermawan *et al*2022). A decrease in crystallinity often correlates with changes in material properties, particularly mechanical strength and thermal stability. Materials with higher crystallinity usually exhibit greater mechanical strength, as the regular atomic structure provides rigidity and resistance to deformation. Therefore, the lower crystallinity in biochar suggests a reduction in mechanical strength compared to the original biomass. Similarly, high crystallinity is often associated with enhanced thermal stability, as ordered structures resist thermal breakdown more effectively. The reduced crystallinity in biochar indicates it may be less thermally stable than biomass, although it should retain some stability due to its carbon-rich composition (Kurniati *et al*2017). For instance, studies have shown that biochar can enhance the thermal stability of polymer composites, acting as a nucleating agent and accelerating the overall rate of crystallization (Alghyamah *et al*2021). Due to plasma pyrolysis temperature, the plasma treatment process may also affect the formation or degradation of specific crystalline phases, such as graphitic carbon or metal oxides. While the decrease in crystallinity implies that graphitic structures were either not fully formed or partially disrupted, the potential presence of metal oxides (if minerals were present in the biomass) could also influence the crystalline structure (Atinafu *et al.*,2025). Overall, plasma treatment alters the crystalline structure of biochar, impacting its mechanical and thermal properties (Sanito *et al*2020).

3.3 FTIR

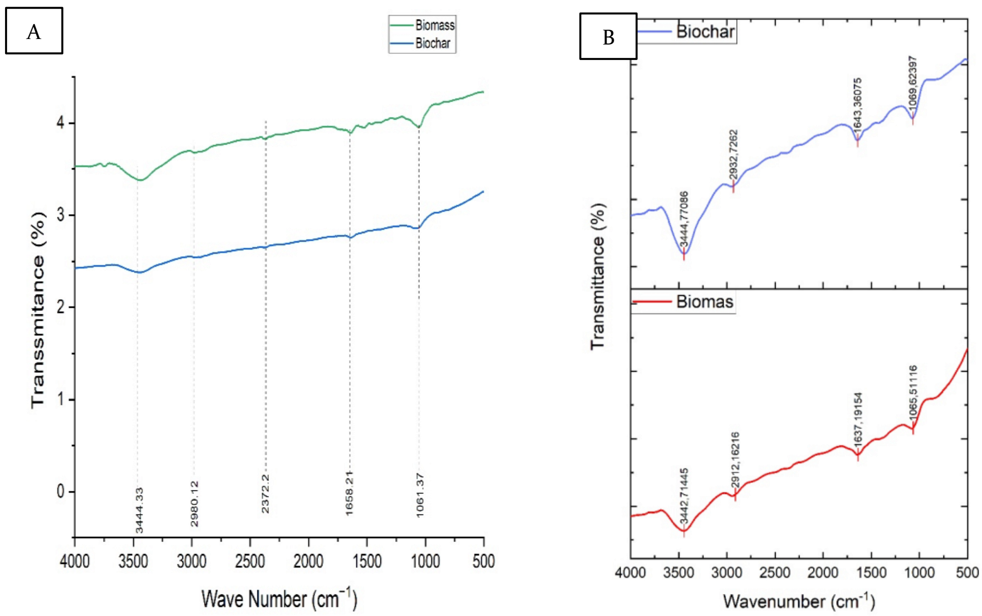

Figure 4 SB and BP biomass and biochar FTIR test results
(A) SB biomass and biochar (B) BP biomass and biochar

Figure 4, Table 2, and Table 3 show various functional groups of biomass and biochar. FTIR analysis of SB and BP reveals changes in functional groups after biochar formation, which is crucial for understanding its reactivity and potential applications. In biochar SB, functional groups such as OH, C-H, CO_2, and C=C remained unchanged from the biomass, indicating that oxygen-containing groups were preserved, enhancing biochar hydrophilicity and interaction with polar substances (Chen *et al.*, 2008; Yargiç *et al.*, 2015; Schott *et al.*, 2021; Qureashi *et al.*, 2023). A new Fe-O bond was detected at 1061 cm^{-1} in biochar SB, potentially increasing its capacity to adsorb heavy metals such as chromium or iron due to additional binding sites. This makes biochar SB potentially valuable for applications such as water purification and catalysis, where metal ion interactions are critical (Zafeer *et al.*, 2024).

The introduction of NH bonds at 1638 cm^{-1} in BP biochar indicated nitrogen incorporation, which could enhance its ability to adsorb heavy metals or organic contaminants through nitrogen-based interactions (Sarbon et al.,2014). Additional chemical groups, including hydroxyl (OH) and carbonyl (C=O), remained present, contributing to hydrophilic properties and adsorption capacity (Vinoth *et al.*,2021). The CH bonds in BP biochar remained stable, contributing to the material's structural integrity. These chemical features suggested that both biochars can be effective in adsorption due to their polar functional groups (Wiliana et a*l.*,2022). In contrast, nitrogen in BP biochar and iron in SB biochar added specificity to their applications in metal ion removal or catalysis. Additionally, the retention of aromatic structures in both biochars indicated long-term stability, making them valuable for soil amendments by improving water retention and nutrient availability (Shyam *et al.*,2025).

Table 2 Functional groups of SB biomass and biochar

Wave Number (cm^{-1})		**Functional Groups**	**Reference**
SB Biomass	**SB Biochar**		
3444.33	3444.33	O–H	(Chen, et al.,2008)
2980.12	2980.12	CH_2	(Schott et al.,2021)
2372.20	2372.20	CO_2	(Schott et al.,2021)
1658.21	1658.21	C=O	(De Muñiz et al.,2013)
1526.76	1526.76	C=C	(Yargiç et al.,2015)
-	-	C–H	(Qureashi et al.,2023)
1061.37	1061.37	C–O	(Qureashi et al.,2023)

Table 3 Functional groups of BP biomass and biochar

Wave Number (cm^{-1})		**Functional Groups**	**Reference**
BP Biomass	**BP Biochar**		
3447.02	3442.71	O–H	(Vinoth et al.,2021)
1485.52	1485.52	CO_3	(Vinoth et al.,2021)
1636.57	1638.73	N-H	(Sarbon et al.,2014)
1636.57	1638.73	C=C	(Chaliserry,2018)
2400.46	2376.72	C–H	(Wiliana et al.,2022)
1485.53	1345.50	Fe–O	(Vinoth et al.,2021)

3.4 Surface Area and Porosity

Table 4 BET surface area of SB and BP biomass and biochar

Material	Surface Area (m^2/g)	Pore size (nm)	Pore volume (cm^3/g)
SB Biomass	0.06	131.20 nm	0.002 cm^3/g
SB Biochar	87.5	2.94 nm	0.001 cm^3/g
BP Biomass	0.01	374.36 nm	0.06 cm^3/g
BP Biochar	5.24	12.68 nm	0.02 cm^3/g

The surface area data reveals substantial changes in material properties before and after plasma treatment. Untreated biomass samples, such as SB and BP, exhibit minimal surface areas, with SB biomass at 0.061 m^2/g and BP biomass at 0.007 m^2/g. However, plasma treatment significantly enhances the permeability and exposed surface of the biochar samples. Subsequent to process, SB biochar's surface area increases to 87.50 m^2/g, while BP biochar demonstrates a remarkable rise to 427.2 m^2/g.

These drastic improvements in surface area are attributed to the energization, separation, bonding, and atomic relocation occurring during the plasma pyrolysis process. These processes contribute to the decomposition of biomass components, creating more reactive species within the plasma apparatus, thereby improving the porosity and surface area of the resulting biochar (Sanito et al., 2020; Dermawan et al., 2022).

The increased surface area directly impacts the material's performance, particularly in environmental applications such as adsorption and pollutant removal. A larger surface area provides more active sites for adsorption, thereby enhancing the biochar's effectiveness in capturing contaminants from water, air, or soil (Leng et al., 2021). For instance, BP biochar, with its large surface area of 427.2 m^2/g, is expected to outperform its biomass precursor in removing heavy metals or organic pollutants. The enhanced surface area facilitates greater contact between the adsorbent and contaminants, resulting in improved efficiency in remediation processes (Satyam & Patra, 2024).

3.5 The potential for environmental application

The morphological structure of both biochars after plasma pyrolysis showed increased fragmentation, enhanced surface roughness, and higher porosity, with more distinct pores than their original biomass. While the crystallinity index of biochar was lower than that of the corresponding biomass, the crystalline size was notably larger. This increase in crystal size and amorphous content is beneficial for improving adsorption capacity and mechanical stability, thereby enhancing the biochar's effectiveness in pollutant absorption (Dermawan et al., 2022; Zafeer et al., 2024).

The existence of functional groups like OH, C-H, CO_2, and C=C in biochar is critical for understanding its reactivity and potential applications. The detection of Fe-O bonds in sugarcane bagasse (SB) biochar suggests an improved capacity to adsorb heavy metals by providing additional binding sites (Zafeer et al., 2024). SB biochar shows promise for applications such as adsorption and catalysis, where interactions with metal ions are essential. The introduction of NH bonds could further enhance its ability to adsorb heavy metals or organic contaminants through nitrogen-based interactions (Sarbon et al., 2014).

Functional groups like OH and C=O contribute to increased hydrophilicity and adsorption capacity (Chen et al., 2008; Qureashi et al., 2023). The presence of CH bonds in banana peel (BP) biochar adds structural stability, improving the material's overall integrity. The chemical properties indicate that both biochars could serve as effective adsorbents due to their polar functional groups (Wiliana et al., 2022). Additionally, the nitrogen content in BP biochar and iron presence in SB biochar enhance their efficiency for metal ion removal and catalytic applications (Sarbon et al., 2014).

Furthermore, the conservation of aromatic structures in both biochars suggests long-term stability, making them advantageous for soil amendments by improving water retention and nutrient availability (Shyam et al., 2025). The increase in biochar's surface area through plasma treatment significantly improves its efficiency, especially in environmental applications like adsorption and pollutant removal. Biochar with enhanced surface area contributes to more adsorption-active sites, thereby improving its ability to capture contaminants from water, air, or soil (Leng et al., 2021; Satyam & Patra, 2024).

This study highlights the potential environmental applications of biochar produced through atmospheric pressure microwave plasma treatment as an effective adsorbent, catalyst, or soil amendment. Its enhanced morphology, crystallinity, functional groups, and surface area offer promising opportunities for various practical applications.

4. Conclusions

The application of non-thermal plasma significantly altered the morphology, crystallinity, and surface area of biochar derived from sugarcane bagasse and banana peel, as demonstrated by SEM, XRD, FTIR, and BET characterization results. Plasma treatment enhanced porosity and surface area, resulting in both biochars exhibiting surface areas approximately 100 times greater than their original biomass, thereby rendering the biochar more amorphous. In conclusion, this study demonstrates that non-thermal plasma treatment effectively enhances the morphological, chemical, and physical properties of biochar derived from sugarcane bagasse and banana peel. The plasma treatment process significantly increased surface area and introduced beneficial functional groups, which suggests great potential for environmental applications such as pollutant removal, soil amendment, and catalysis. While these findings are promising, further research is needed to optimize treatment parameters and assess the long-term stability of the modified biochar in practical applications. This study contributes to the understanding of biomass modification techniques and opens new pathways for developing high-performance materials from agricultural waste.

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