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ORIGINAL PAPER

Innovative biochar production by co-carbonisation of plantain stalks with polyester fabric wastes

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Abstract

Agricultural and textile waste management presents significant environmental challenges globally. This study explores an innovative approach to biochar production through co-carbonization of plantain stalks with polyester fabric waste. Plantain stalks (90%) were combined with waste polyester fabric (10%) and processed using an auto-thermal carbonization reactor. The hybrid biochar demonstrated superior properties compared to plantain stalk-only biochar. The hybrid biochar achieved a 39.6% yield at 426.7 °C versus a 37.2% yield at 395.93 °C for the pristine biochar. Surface characterization revealed significant improvements: the hybrid biochar exhibited 29% greater surface area (492.172 m^2/g), 9% higher pore volume, and 15% larger pore diameter compared to the pristine biochar. The surface of the hybrid biochar was smoother and had clumps of particles, and the analysis of its elements showed it had more potassium than the regular biochar. Functional group analysis confirmed retention of key functional groups. These findings demonstrate the potential for converting dual waste streams into enhanced biochar products, supporting circular economy principles and sustainable waste management. The improved properties suggest applications in agriculture, environmental remediation, and material science. This research addresses the pressing need for innovative waste management solutions while creating value-added products from agricultural and textile waste.

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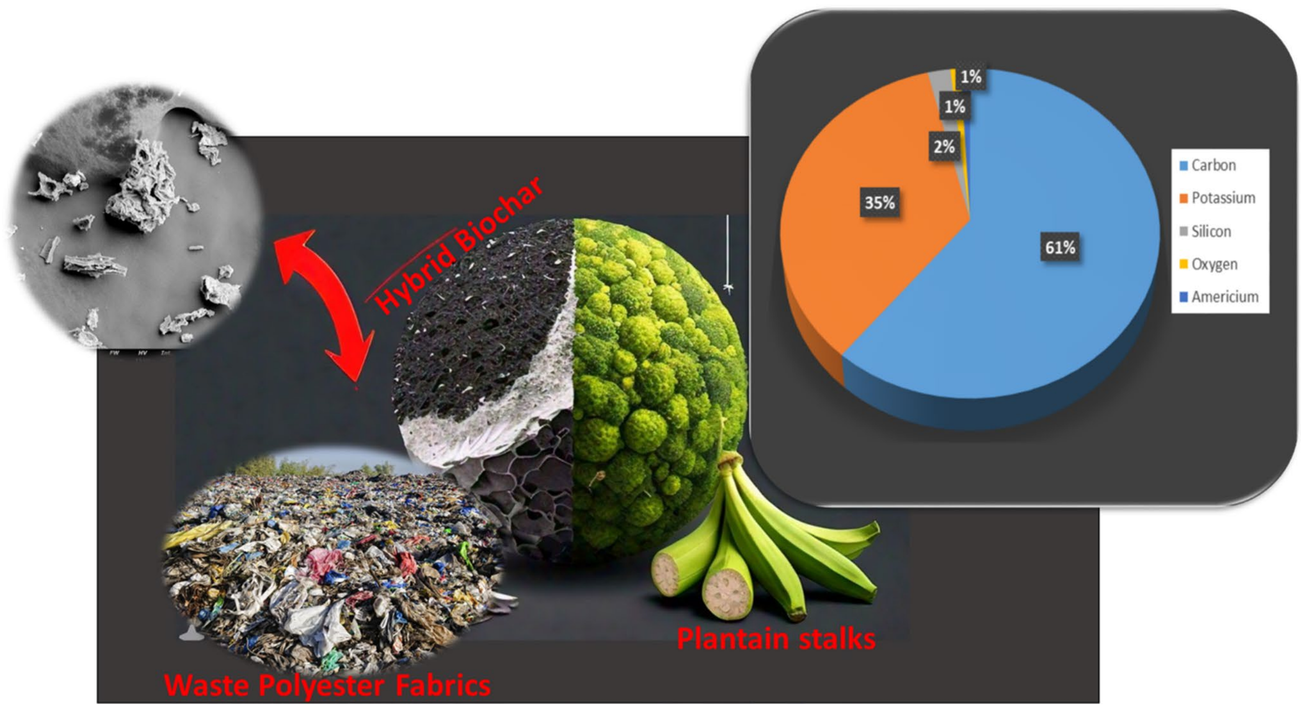
Graphical abstract



Keywords Carbonization · Circular economy · Environmental sustainability · Textile recycling · Waste management

Introduction

While plastics have significantly advanced sectors including transportation, communications, and healthcare since their widespread adoption in the twentieth century, their exceptional durability has consequently resulted in severe environmental pollution (Benson et al. 2021). Between 1950 and 2015, about 8.3 billion tonnes of plastic were produced globally, with 6.3 billion tonnes subsequently classified as waste. Unfortunately, 79% of this waste accumulates in landfills or natural environments, contributing to massive environmental plastic pollution (Gupta et al. 2024; Rhodes 2019). Polyester fabric waste represents a significant component of this plastic pollution crisis. As a synthetic polymer derived from petrochemical sources, polyester has become a textile industry staple due to its durability, cost-effectiveness, and versatility (Wang and Salmon 2022). However, the persistence of polyester in the environment is a growing concern. Once discarded, polyester fabric can remain in landfills for centuries, contributing to significant waste accumulation and the release of microplastics into ecosystems. These microplastics can infiltrate water sources and soil, posing risks to wildlife and human health (Mohammadi et al. 2023). Current polyester fabric recycling processes face several limitations: they often struggle with sorting and processing mixed-material textiles, the chemical recycling technologies required are complex and costly, and there is a lack of standardized guidelines and infrastructure for efficient recycling (Dissanayake and Weerasinghe 2021; Vadicherla et al. 2015). As a result, textile-to-textile recycling of polyester remains underdeveloped compared to more straightforward methods like those used for PET bottles (Shen et al. 2010). In response, waste management approaches such as landfilling and incineration have emerged as potential solutions, but they often fail to address the core issues associated with polyester waste (Loo et al. 2023). These methods can lead to environmental contamination and greenhouse gas emissions. Therefore, there is a pressing need to develop innovative repurposing methods that can transform polyester waste into valuable products, thus reducing its environmental footprint and advancing sustainability in waste management.

Thermochemical conversion processes are crucial in transforming waste materials into a range of valuable products, including biochar, bio-oil, and biogas, among others (Pocha et al. 2023). The major thermochemical conversion processes include pyrolysis, hydrothermal carbonization, torrefaction, and gasification (Papadopoulou et al. 2025; Senapati et al. 2025). Biochar is a stable, carbon-rich material created through the thermochemical conversion of biomass under limited oxygen conditions (da Silva et al. 2022).

Historically, biochar has its roots in ancient agricultural practices, with the pre-Columbian Amazonian civilizations who used it to enhance soil fertility in the form of "Terra Preta," or "black earth" (Danesh et al. 2022). This ancient practice of enriching soil with biochar contributed to its long-term fertility and sustainability. Today, biochar is valued for its ability to improve soil health by enhancing water retention, nutrient availability, and microbial activity (Adekiya et al. 2020). Beyond agriculture, biochar is also utilized in water filtration, waste management, and as a potential material for construction and energy storage applications (Wang et al. 2023). A recent innovation for biochar production involves integrating plastics into biomass at specific percentages for biochar production, which enhances recycling and material quality. This method optimizes the properties of the hybrid biochar, repurposes waste plastics and biomass, and addresses the challenges of waste management and environmental sustainability. For instance, polypropylene-based facemask were combined with almond leaves in a 10% plastic to 90% biomass ratio to produce biochar (Emenike et al. 2022). Despite these advancements, the application of this technique to textiles or other biomass types remains largely unexplored.

Previous studies have focused on rigid plastics (PET bottles, polystyrene containers) rather than flexible textile materials. Polyester fabric waste presents unique challenges and opportunities due to its fibrous structure, different thermal behaviour, and potential for enhanced biochar properties. This study addresses this gap by specifically investigating textile polyester waste co-carbonization with agricultural biomass. The aim of this study is to investigate the carbonization of waste polyester fabric and plantain stalks to produce hybrid biochar. This research seeks to explore the synergistic effects of combining both synthetic and natural waste materials, addressing waste management challenges while creating a sustainable product. Plantain stalks, which are the fibrous remnants left after harvesting plantains, are often regarded as agricultural waste (Nwabueze et al. 2024). These stalks are typically discarded or burned, which not only wastes a potentially valuable resource but also contributes to environmental pollution (Matchum et al. 2024). The disposal of plantain stalks through burning releases greenhouse gases and particulate matter, exacerbating air pollution. Plantain stalks were chosen for this study due to their abundance as an agricultural waste product (Ajala et al. 2024). Utilizing plantain stalks can help address the issue of waste disposal in plantain farming, offering a sustainable solution that adds value to an otherwise discarded material. This study represents the first investigation of textile polyester fabric waste co-carbonization with plantain stalks, distinguishing it from previous research that primarily focused on rigid plastic waste. The innovation lies in utilizing flexible textile waste, which presents different thermal decomposition characteristics and potentially unique property enhancement mechanisms compared to conventional plastic-biomass combinations. The significance of this study lies in its potential to provide a sustainable solution for managing waste polyester fabric and plantain stalks, turning them into valuable biochar for various purposes. The justification for the study is based on the need to reduce environmental pollution from synthetic and agricultural waste while exploring innovative recycling methods that contribute to resource efficiency and sustainability. The experimental work was conducted at the Department of Chemical Engineering, University of Ilorin, Nigeria, from March 2024 to August 2024.

Materials and methods

Materials

The polyester fabric was obtained as a fabric offcut or waste piece from a tailoring/sewing shop in Oke-Odo, Tanke, within the Ilorin metropolis of Kwara State, Nigeria. The plantain stalks were sourced from Ganmo Market in Ilorin, while the *Delonix regia* stems used were collected from the premises of the University of Ilorin.

Biochar/hybrid biochar production

Two biochar samples were produced in this study: (1) biochar from 100% plantain stalks (PSO) and (2) hybrid biochar from 90% plantain stalks and 10% waste polyester fabric (PSPE). The 90:10 ratio was selected based on previous studies demonstrating optimal property enhancement at 10% polymer content (Emenike et al. 2022). This ratio ensures sufficient polymer integration while maintaining the biomass-dominated character of the biochar. The carbonization temperature was process-controlled rather than pre-set, allowing natural thermal progression to optimize biochar formation under the specific reactor conditions.

Feedstock carbonization was performed using an autothermal carbonization reactor operated in an open environment, utilizing waste biomass as the thermal energy source. This reactor design has been described in detail in previous studies (Iwuozor et al. 2023). This reactor is particularly efficient in areas with inconsistent electricity supply. The reactor consists of two main components: the inner chamber and the outer chamber. The feedstocks were placed in the inner chamber, which was properly sealed and positioned at the centre of the outer chamber. The biomass fuel (*Delonix regia* stems) was then arranged concentrically around and on top of the inner chamber within the outer chamber until the outer chamber was filled.

The biomass fuel was then ignited with a lighter and allowed to burn in open air for about five minutes.

Subsequently, the outer chamber was enclosed with a cover attached to a fume exhaust. The temperature of the reactor was monitored using an infrared thermometer gun (Cason, CA380, Singapore) at four distinct regions: the base, middle, top, and centre points of the reactor, from the onset until the temperature of the reactor equilibrated with the environment. At this equilibrium point, the reactor was opened, and the produced biochar/hybrid biochar was recovered and weighed to determine the percentage yield of the product (Iwuozor et al. 2023). In addition, the temperature of the systems was computed to produce a graph of temperature versus time.

Biochar/hybrid biochar characterization

Material characterization followed the process outlined by Adeniyi et al. (2021).

Fourier transform infrared (FTIR) spectroscopy

The biochar and hybrid biochar samples were analyzed using a Fourier transform infrared spectrophotometer (Shimadzu, FTIR-8400 s, Japan) to identify functional groups. Samples were prepared using the KBr pellet method, with spectra recorded in the range of 4000–400 cm^{-1}. This analysis was essential to understand how polyester addition affects the chemical structure of the resulting biochar.

Surface area and porosity analysis

A Brunauer–Emmett–Teller (BET) analyzer (Quantachrome NovaWin Instruments v11.03) was used to determine surface area and porosity characteristics. Samples were degassed at 300 °C for 3 h before analysis. Pore volumes and pore diameters were determined using the Barrett-Joyner-Halenda (BJH) adsorption method to provide comprehensive porosity characterization.

Scanning electron microscopy and energy dispersive X-ray spectroscopy

Surface morphology and elemental composition were analyzed using SEM–EDX (Phenom-World BV, Netherlands) at various magnifications (×600, ×800, ×1000). This multi-scale analysis provided insights into the surface texture changes and elemental distribution resulting from polyester fabric integration.

Results and discussion

Temperature profile and biochar yield

The heat progression within the reactor was carefully monitored throughout the process by measuring temperatures at the bottom, middle, top, and centre of the reactor. The temperature profiles for these specific sections for the product prepared with plantain stalk only (PSO) and the one prepared with 90% plantain stalk and 10% polyester fabrics (PSPE) are shown in Figs. 1 and 2, respectively. This profile was obtained by plotting the average temperature recorded at each section every 10 min. The temperatures at the bottom, middle, and top indicate the movement of the combustion zone from the base to the top of the reactor, while the temperature at the centre provides an accurate representation of the internal reactor conditions. The carbonization process for the plantain stalk alone (PSO), composed of 100% plantain stalk, lasted 170 min.

The carbonization temperature (Fig. 1) recorded across all segments gradually increased from the start of the process, reaching a peak before progressively decreasing until the end of the carbonization process. Specifically, the temperature at the bottom, middle, and top of the reactor rose continuously from 0 to 80 min and then began to decline until the end of

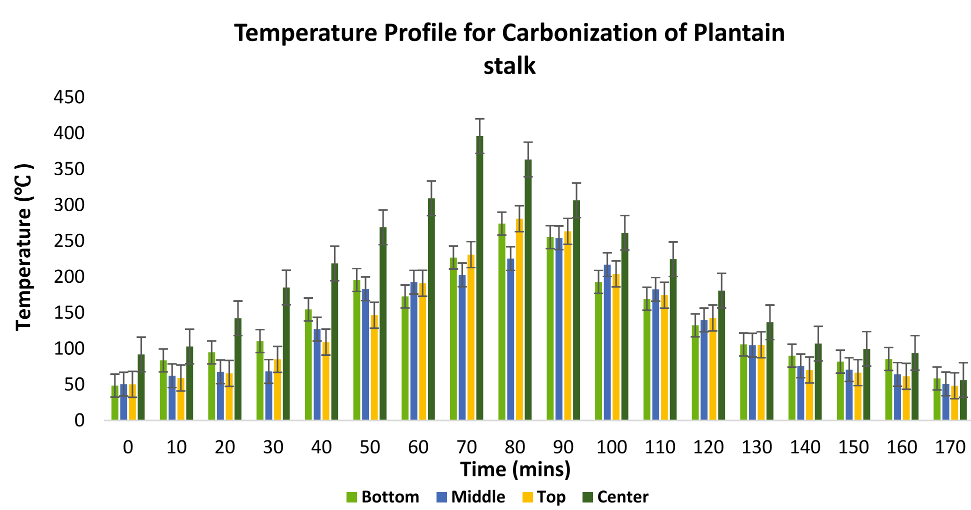


Fig. 1 Temperature profile during carbonization of PSO (100% plantain stalks) showing thermal progression at different reactor positions

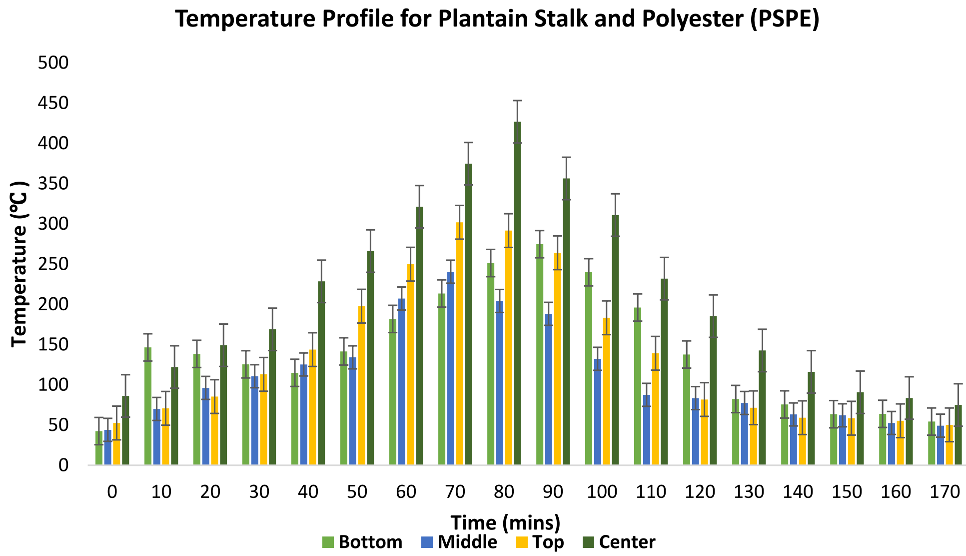


Fig. 2 Temperature profile during co-carbonization of PSPE (90% plantain stalks + 10% polyester fabric), illustrating extended thermal processing and higher peak temperature compared to biomass-only carbonization

carbonization. But while the temperature at the centre of the reactor also followed this pattern, the progressive decrease in carbonization started 10 min earlier. The peak temperatures of 274.03 °C, 225.38 °C, and 280.93 °C were recorded at the bottom, middle, and top of the reactor, respectively, at the 80-min mark. In contrast, the centre of the reactor reached its peak temperature of 395.93 °C at 70 min, marking the highest temperature observed. In addition, the highest peak temperatures were also recorded at the centre of the reactor during the carbonization of almond waste (Iwuozor et al. 2023), which utilized similar reactor types.

A closer examination of the temperature profile (Fig. 2) of the product prepared with 90% plantain stalk and 10% polyester (PSPE) revealed a slightly different pattern compared to the carbonization of 100% plantain stalk. The temperatures at the middle, top, and centre of the reactor also showed a gradual increase up to a certain point, followed by a progressive decrease until the end of the reaction time. However, the temperature at the bottom of the reactor did not follow this trend. Instead, there was a rise in temperature at the bottom at 10 min, which then decreased until 40 min before increasing again from 50 to 90 min, reaching a peak of 274.65 °C. Afterward, the temperature steadily decreased until the end of the carbonization process.

Similar to PSO, the highest peak temperature for PSPE was also observed at the centre of the reactor. However, while the peak temperature for PSO occurred at 395.93 °C after 70 min of reaction time, the peak for PSPE was reached at a higher temperature and duration, specifically 426.7 °C at 80 min. A similar trend was noted in a study that carbonized and co-carbonized *Terminalia ivorensis* leaves and *Terminalia ivorensis* leaves with Coca-Cola PVC. In the study, the highest peak temperature at the centre occurred at 40 min when only *Terminalia ivorensis* leaves were carbonized and at 80 min when they were co-carbonized with PVC (Adeniyi et al. 2022). Based on these observations and previous reports, it can be concluded that the addition of polymers to biomass extended the time at which the highest peak temperature is reached. It is also noteworthy that the peak temperatures at the top and middle of the reactor for PSPE were observed 10 min before the highest peak temperature at the centre, which is the opposite of what occurred with PSO. In the case of PSO, all other segments of the reactor reached their peak temperatures 10 min after the highest peak temperature at the centre.

Biochar yields were 37.2% for PSO (peak temperature: 395.93 °C) and 39.6% for PSPE (peak temperature: 426.7 °C), representing a 2.4% yield increase with polyester addition. This improvement is in line with enhanced carbon retention from the synthetic polymer component. The yield obtained by Barrezueta-Unda et al. (2019) for plantain stalk biochar was 29.38%, which was 7.9% lower than was observed for the plantain stalk in this study. The yield recorded by Jabar et al. (2023) for plantain stalk biochar was 26.85%, which was 10.35% less than what was obtained for PSO in this study and was 2.45% less than what Barrezueta-Unda et al. (2019) obtained. Adeniyi et al. (2021) obtained a yield of 6.98% from a biochar prepared from plantain fibre. The authors' result was far lower than what was obtained for PSO in this study, and the difference in the result obtained might be due to the variation in process variables. Olawale and Ogunsuyi (2020) obtained a yield of 58.40%, 82.93%, and 58.80% for biochar produced from plantain flowers, plantain stems, and plantain leaves, respectively. These results were higher than the yield obtained in this study, and the difference may be due to a slight difference in feedstock differences, sources, as well as process variables utilized.

The observed yield increase is in line with previous co-carbonization studies. Adeniyi et al. (2022) also observed the same trend of increase in the yield of biochar that was prepared with 100% *Terminalia ivorensis* and 90% *Terminalia ivorensis* leaves with 10% PVC. Specifically, a biochar yield of 45.20% was obtained for *Terminalia ivorensis* leaves biochar, while 45.60% was obtained for the sample mixed with PVC. Comparing the biochar yield of PSPE recorded in this study with the authors' obtained for the biochar prepared with 90% *Terminalia ivorensis* leaves and 10% PVC, it was observed that the yield was more than was obtained in this study. The yield of the biochar sample with ten percent facemask and ninety percent almond leaves (Iwuozor et al. 2023) and that of the sample with 90% *Terminalia ivorensis* leaves and 10% PVC (Adeniyi et al. 2022) were comparable but were both more than that which was obtained in this study. The reason may be as a result of different biomass feedstock and polymer employed, as plantain stalk was used in this study in comparison to the leaves employed in their study. In summary, the addition of the polymer resulted in an increase in biochar yield, from 37.2% during the carbonization of PSO to 39.6% when PSPE was co-carbonized. This rise could be attributed to the higher carbon content found in polyester fabrics, which significantly enhanced the material's yield (Iwuozor et al. 2023).

Surface area and porosity analysis (BET)

The surface areas of the two samples were measured using BET (Brunauer–Emmett–Teller) analysis, while the pore volumes and pore diameters were determined using the BJH (Barrett-Joyner-Halenda) adsorption method. The biochar produced from plantain stalk only (PSO) had a surface area of 381.762 m^2/g, a pore volume of 0.25 cc/g, and a pore diameter of 1.853 nm. In comparison, the biochar sample produced from 90% plantain stalk and 10% polyester fabric (PSPE) had a surface area of 492.172 m^2/g, a pore volume of 0.273 cc/g, and a pore diameter of 2.123 nm. Polyester addition enhanced surface properties significantly: surface area increased by 110.41 m^2/g (29% improvement), pore volume by 0.023 cc/g (9% increase), and pore diameter by 0.27 nm (15% enlargement).

In a study by Adeniyi et al. (2021) on the production of biochar from plantain fibre, a surface area of 424.8 m^2/g and a pore volume of 0.1636 cc/g were reported. The surface area reported by the authors was higher than that of PSO in this study but 67.372 m^2/g lower than the surface area of PSPE biochar in this study. The pore volume reported by Adeniyi et al. (2021) was lower than both results obtained in this study. The differences between the authors' results and those of PSO in this study could be due to slight differences in biomass feedstock source. The difference between Adeniyi et al. (2021) results and those for PSPE could be attributed to both the variation in feedstock source and the addition of 10% polyester fabric in this study. The BET surface area, pore diameter, and pore volume reported by Iwuozor et al. (2023), which centered on the co-carbonization of waste facemasks and almond leaves, were all lower than those found for PSPE in this study. These discrepancies in results can likely be attributed to the different types of biomass feedstock and polymer materials used.

The study by Zhou et al. (2022) on the pyrolysis and adsorption behaviour of activated carbon derived solely from waste polyester textiles reported a BET surface area of 548.89 m^2/g, a pore volume of 0.213 cc/g, and a pore diameter of 1.55 nm. While the BET surface area was higher than the result obtained for PSPE in this study, the pore volume and pore diameter were lower. This difference can be attributed to the fact that the activated carbon was produced exclusively from polyester material without the incorporation of any biomass. The BET surface area and pore volume of a biochar produced from polyester cotton blended fabric, with and without modification, were reported as 1605.481 m^2/g and 0.70 cc/g and 5.26 m^2/g and 0.0076 cc/g, respectively (Zhong et al. 2022). The author's findings for the unmodified biochar were significantly lower than the results reported for PSPE in this study. However, the surface area and pore volume after $ZnCl_2$ modification were considerably higher than what was observed for PSPE in the current study, which were also higher than what Zhou et al. (2022) obtained.

In summary, the surface area of PSPE is about 29% greater than that of PSO. The pore volume of PSPE is approximately 9% greater than that of PSO, and the pore diameter of PSPE is around 15% greater than that of PSO. The pore diameter of the biochar sample derived solely from plantain stalk (PSO) is less than 2 nm, indicating a microporous structure (Zhong et al. 2022). In contrast, the PSPE biochar sample has a pore diameter ranging between 2 and 50 nm, classifying it as mesoporous, which makes it suitable for applications in energy conversion, photocatalysis, adsorption, and energy storage (Jawad and Surip 2022).

Surface morphology analysis (SEM)

The scanning electron microscope (SEM) micrographs of biochar prepared from 100% plantain stalk (PSO) and from a mixture of 90% plantain stalk and 10% polyester fabrics (PSPE) are shown in Fig. 3. Each sample was analyzed using three magnification levels: ×600, ×800, and ×1000. The SEM image of PSO biochar at magnifications of ×600, ×800, and ×1000 is presented in Fig. 3a, b, and c, respectively, while the SEM image of PSPE is presented in Fig. 3d, e, and f. SEM analysis revealed irregularly sized and shaped particles distributed across the material surface. Particle morphologies included elongated and plate-like structures, with some overlapping clusters and isolated individual particles. The surface texture of the sample was relatively rough and attributed to the distribution of these irregular particles across the surface. Additionally, voids were observed in the

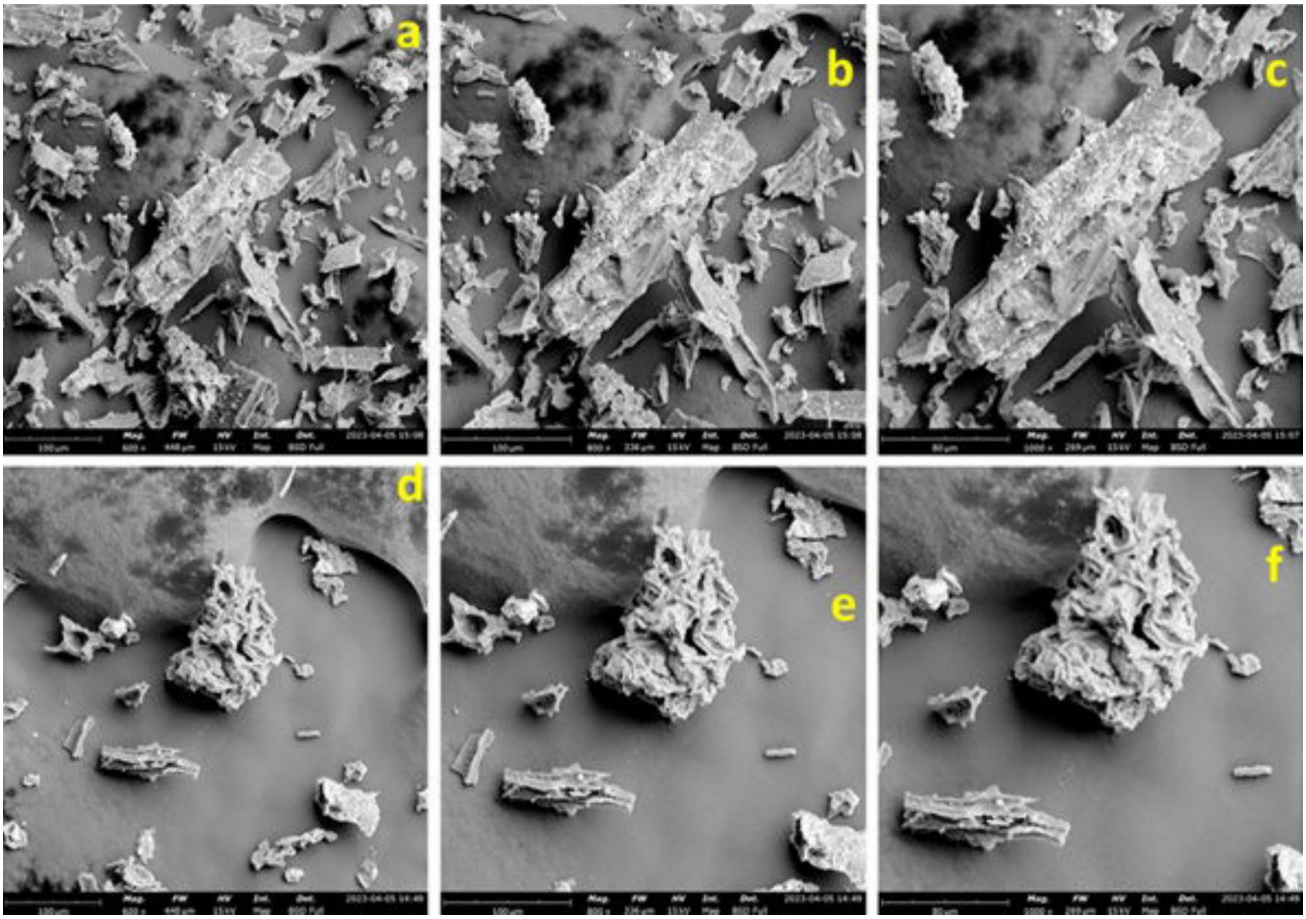


Fig. 3 Scanning electron microscopy images showing surface morphology of biochar samples at different magnifications. **a–c** PSO biochar derived from 100% plantain stalks at ×600, ×800, and ×1000 magnification, respectively. **d–f** PSPE hybrid biochar from 90% plantain stalks and 10% polyester fabric at ×600, ×800, and ×1000 magnification, respectively

upper left region of the sample, further contributing to the heterogeneous surface morphology.

The SEM images of the PSPE sample, examined at different magnification levels, showed some differences in particle size and distribution. At 600× magnification, smaller particles were observed compared to those seen at 800×, while the particles observed at 1000× were larger than those at 800×. A prominent feature at the centre of the PSPE sample was a cluster of aggregated particles, likely resulting from the binding effect of the polyester fabric. Surrounding this central cluster, smaller particles of varying sizes and shapes were dispersed across the surface. In comparison to the PSO sample, the SEM image of the PSPE sample exhibited a finer and smoother surface, with fewer scattered particles. This suggests that the addition of 10% polyester to the plantain stalk may have facilitated particle aggregation, leading to the smoother surface texture observed in the PSPE biochar. The smoother appearance is likely due to the influence of the polyester fabric during the carbonization process. Additionally, a cavity present in both the PSO and PSPE images was observed in the upper right portion of the PSPE sample. However, in the PSPE biochar, this cavity appeared broader but less pronounced compared to the one in the PSO biochar. The overall surface texture of the PSPE biochar was also less rough, further indicating the impact of polyester addition on the morphological characteristics of the biochar.

Comparing the SEM images obtained in this study with those reported in previous research, Onifade et al. (2020) observed a smooth surface with the presence of small microparticles on a composite material prepared from polystyrene and plantain fibre biochar. While this observation aligns with the smooth surface seen in the PSPE biochar in this study, the particles on the surface of the PSPE biochar were notably larger than the microparticles reported by Onifade et al. (2020). The disparity in particle size may be attributed to the different feedstocks used; Onifade et al. (2020) utilized waste polystyrene and plantain fibre, whereas this study employed polyester fabrics and plantain stalks for biochar production. Similarly, the SEM image of biochar prepared from a mixture of cotton and polyester, as reported by Hanoğlu et al.

(2019), also exhibited a smooth surface akin to the PSPE biochar in this study. However, the PSPE biochar differed in that it displayed a cluster of agglomerated particles, in contrast to the elongated, thread-like particles observed on the surface of the biochar by Hanoğlu et al. (2019).

In contrast to the hybrid biochar analyzed in this study, Emenike et al. (2022) documented a rough surface with small crevices and scattered white particles of varying sizes on a hybrid biochar prepared from *Daniella oliveri* leaves and disposable face masks. A similar rough texture was reported by Adeniyi et al. (2023) for a hybrid biochar derived from *Daniellia oliveri* leaves and polyethylene terephthalate (PET). The differences in surface morphology across these studies likely stem from the variation in biomass feedstocks and polymer additives used. In conclusion, the PSPE biochar exhibited a less rough surface with fewer but clustered whitish particles compared to the PSO biochar, which showed a rougher surface with more dispersed particles. This suggests that even a small amount of polymer added to biomass can significantly influence the microstructural characteristics of the resulting biochar.

Functional group analysis (FTIR)

The identification of the functional group inherent in the PSO and PSPE biochar samples was carried out using Fourier transform infrared (FTIR) spectroscopy. The analysis was carried out separately on each sample, and the experiment was done to determine the influence the addition of 10% polyester fabrics to plantain stalks had on the functional group of the resulting biochar. The FTIR analysis of PSO is shown in Fig. 4a, while the FTIR analysis of PSPE is presented in Fig. 4b. FTIR spectral comparison revealed fewer bands in PSPE compared to PSO, attributed to polyester fabric incorporation. Only the 1565.5 cm^{-1} band, associated with C=C stretching in aromatic lignin structures, appeared in both samples. This band is associated with the C=C stretching of the aromatic skeletal mode of lignin (Abdullah et al. 2023). The band at 3142.1 cm^{-1}, corresponding to the C-H stretching vibration in hemicellulose (Abdullah et al. 2023), was present in PSO but absent in PSPE. Additionally, the peak at 1736.9 cm^{-1} may be attributed to the C=O stretching mode, observed in PSO, which was also absent in PSPE. This absence is believed to be caused by the addition of polyester fabric in PSPE.

The peak, 2113.4 cm^{-1} in PSO, shifted to 2117.1 cm^{-1} in PSPE. These peaks are attributed to C≡C stretching of alkynes. The band at 1364.2 cm^{-1} in PSO shifted to 1375.4 cm^{-1} in PSPE, and they corresponded to C=C (Liu et al. 2022). The pattern of peak shifts between PSO and PSPE is inconsistent, with some peaks increasing while others decrease. For instance, the peak at 760.4 cm^{-1} observed in PSO shifted to 745.5 cm^{-1} in PSPE, whereas the bands at 801.4 cm^{-1} and 879.7 cm^{-1} in PSO shifted to 820.0 cm^{-1} and 883.4 cm^{-1}, respectively, in PSPE. The bands are attributed to C–H bending. The peak at 1878.6 cm^{-1} in the PSO biochar sample was observed at a lower intensity of 1871.1 cm^{-1} in the PSPE sample, and they were linked to C=O stretch (Onifade et al. 2020). The peaks at 1114.5 cm^{-1} in PSO and 1110.7 cm^{-1} in PSPE were attributed to C–O stretches, and this signified the presence of cellulose, lignin, and hemicellulose (Adeniyi et al. 2021). In general, it was noted that the addition of polyester caused the reduction in the number of significant peaks in PSPE compared to PSO samples. The FTIR spectra of the biochar revealed that the functional groups, which include C=C stretching of the aromatic skeletal mode of lignin, C≡C stretching of alkynes, O–H, C–H stretching vibrations in hemicellulose, and C–O, were observed to be identical.

Elemental composition analysis (EDX)

Energy dispersive X-ray spectroscopy (EDX) was employed to analyze both PSO and PSPE biochar samples, providing insights into the inorganic elements present. In the PSO sample, three elements were identified: carbon, potassium, and silicon, with weight percentages of 74.11 wt%, 19.12 wt%, and 6.77 wt%, respectively. In contrast, five elements were detected in the PSPE sample. The two elements that are present in PSPE but not in PSO are oxygen and americium. However, these additional elements were detected in minimal concentrations, with oxygen at 0.92 wt% and americium at 0.88 wt%. The presence of oxygen in PSPE is attributed to the incorporation of polyester fabrics, as the ester groups in synthetic polymers are known to contribute to elevated oxygen levels (Moltó et al. 2006). The detection of americium in the PSPE biochar requires careful interpretation. Americium is a transuranic element that does not naturally occur in the environment (Jiménez-Reyes et al. 2021). Its apparent presence may indicate analytical interference or contamination during sample preparation, misidentification of spectral peaks due to overlapping signals, or contamination during the manufacturing process of the polyester fabric. The unusual nature of this detection depicts the importance of comprehensive quality control in hybrid biochar production and the need for rigorous analytical verification when unexpected elements are detected. The inclusion of polyester fabric in the PSPE biochar likely introduced these elements, highlighting the impact of synthetic additives on the elemental composition of biochar.

Similar to the trend observed in the PSO sample, carbon remained the most abundant element in the PSPE biochar, followed by potassium and silicon. Specifically, the PSPE sample contained 60.98 wt% carbon, 35.13 wt% potassium, and 2.10 wt% silicon. A comparative analysis of the two samples showed that the inclusion of polyester fabric led to

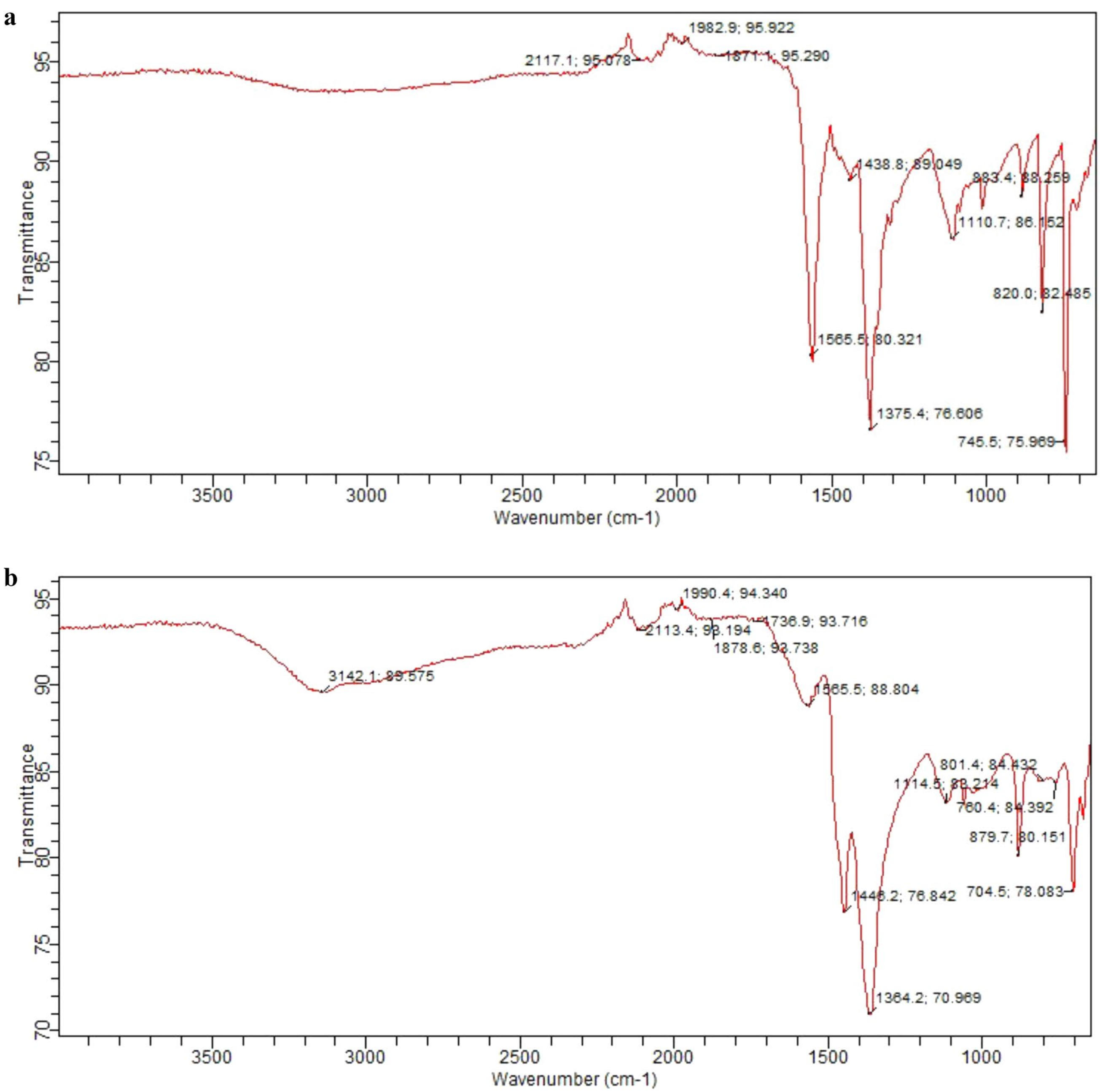


Fig. 4 **a**: FTIR spectrum of PSO biochar derived from 100% plantain stalks, displaying characteristic peaks for lignin, hemicellulose, and cellulose components. **b**: FTIR spectrum of PSPE hybrid biochar from plantain stalks and polyester fabric mixture, showing reduced peak intensity and shifts attributed to polyester integration effects on biomass functional groups

a reduction in carbon and silicon concentrations by 13.13 wt% and 4.67 wt%, respectively, while potassium increased by 16.02 wt% (Table 1). This suggests that the incorporation of polyester fabric influenced the elemental composition, decreasing the levels of carbon and silicon while increasing potassium content. This observation is consistent with findings reported by Iwuozor et al. (2023), who studied the production of hybrid biochar from almond leaves and waste facemasks. In their study, the almond leaf biochar initially contained 61.16 wt% carbon and 3.69 wt% silicon. However, upon producing hybrid biochar with 10% waste facemask and 90% almond leaves, both carbon and silicon levels decreased to 57.21 wt% and 0.80 wt%, respectively. Similarly, Adeniyi et al. (2023) observed a decrease in carbon content when producing hybrid biochar from *Daniella oliveri* leaves and polyethylene terephthalate (PET), where carbon content dropped from 67.8 wt% in the pure biomass biochar to 33.8 wt% in the hybrid biochar. However,

Table 1 Comparative properties of PSO and PSPE biochar samples showing the impact of polyester fabric addition

Property	PSO	PSPE	Improvement (%)
Yield (%)	37.2	39.6	+ 6.5
BET surface area (m^2/g)	381.762	492.172	+ 29.0
Pore volume (cc/g)	0.25	0.273	+ 9.2
Pore diameter (nm)	1.853	2.123	+ 14.6
Peak temperature (°C)	395.93	426.7	+ 7.8
Carbon content (wt%)	74.11	60.98	-17.7
Potassium content (wt%)	19.12	35.13	+ 83.7
Silicon content (wt%)	6.77	2.10	-69.0

unlike the findings in Iwuozor et al. (2023) and the present study, Adeniyi et al. (2023) reported an increase in silicon concentration in their hybrid biochar. These discrepancies may be attributed to variations in the biomass and polymer feedstocks used across the different studies, highlighting the complex interactions between different materials during biochar production. In conclusion, the PSPE sample is recommended for applications requiring high potassium content, such as in agriculture for use as fertilizer and feed supplements and in the chemical industry for potassium-based chemicals.

Environmental and safety considerations

The integration of polyester fabric into biochar production raises important considerations regarding potential environmental and safety implications. While the analysis shows improved physical properties, the long-term environmental impact of polyester-derived biochar requires careful evaluation. Key considerations include:

- Microplastic Formation: The potential for microplastic release during biochar application needs investigation through leaching studies and field trials.
- Chemical Safety: Comprehensive toxicity assessment is required before agricultural applications to ensure no harmful compounds are present.
- Long-term Stability: The stability of hybrid biochar in soil systems over extended periods requires monitoring.
- Application Guidelines: Specific guidelines for safe application rates and suitable end-uses need development.

Future research should prioritize comprehensive environmental impact assessment and establish safety protocols for hybrid biochar applications. This includes conducting standardized leaching tests, soil microcosm studies, and plant uptake trials to validate the safety profile of polyester-derived biochar.

Conclusion

This study has successfully investigated the production and characterization of biochar from plantain stalks and the production of hybrid biochar from a mixture of 90% plantain stalks and 10% waste polyester fabric. The plantain stalk biochar yielded 37.2% at a peak temperature of 395.93 °C, while the hybrid biochar yielded 39.6% at a peak temperature of 426.7 °C. The BET analysis showed that the value of BET surface area, pore volume, and diameter for PSPE were all higher than what was obtained for PSO; specifically, the PSPE biochar had a 29% greater surface area, a 9% higher pore volume, and a 15% larger pore diameter compared to the PSO biochar. FTIR spectra revealed that the functional groups, including C=C stretching in the aromatic skeletal mode of lignin, C≡C stretching of alkynes, O–H, C–H stretching vibrations in hemicellulose, and C–O, were identical in both biochars. SEM analysis showed that PSPE had a smoother surface texture with fewer but clustered whitish particles, in contrast to the rougher surface with scattered particles observed in PSO. EDX analysis identified five elements in PSPE, compared to three in PSO, with PSO containing higher concentrations of carbon and silicon, while PSPE had a higher potassium content. The resulting hybrid biochar shows significant improvements in key properties, making it suitable for various applications: The increased surface area and porosity, combined with higher potassium content, suggest potential as a soil amendment for nutrient retention and plant growth enhancement. The mesoporous structure and enhanced surface properties indicate suitability for contaminant adsorption and water treatment applications. The improved physical properties may enable use in filtration systems, catalyst supports, and energy storage applications. However, comprehensive safety assessment and environmental impact studies are essential before practical implementation, particularly regarding potential microplastic release and long-term stability. Future research should focus on optimizing processing parameters, conducting toxicity assessments, and scaling up production for industrial applications.

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Declarations

Compliance with ethical standards This article does not contain any studies involving human or animal subjects.

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

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