International Journal of Sustainable Energy and Environmental Research
2025 Vol. 14, No. 2 pp. 54-64
ISSN(e): 2306-6253
ISSN(p): 2312-5764
DOI: 10.18488/13.v14i2.4452

Effect of pyrolysis temperature on the physicochemical properties of biochar derived from spent coffee grounds

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Article History
Received: 28 July 2025
Revised: 5 September 2025
Accepted: 18 September 2025
Published: 3 October 2025

Keywords
Biochar
Coffee ground-derived biochar
Physiochemical characterization
Slow pyrolysis
Spent coffee grounds
Sustainable materials.

ABSTRACT
Biochar is a carbon-rich material widely recognized for its ability to enhance soil quality, adsorb heavy metals, and sequester carbon, thereby contributing to pollution mitigation and the reduction of greenhouse gas emissions. Spent coffee grounds (SCG), an abundant agricultural byproduct, represent a promising feedstock for biochar production. While coffee ground-derived biochar (CBC) supports waste reduction and aligns with sustainable development and circular economy principles, a significant volume of SCG remains underutilized globally, particularly in Vietnam, one of the world's leading coffee producers. Therefore, this study aims to investigate the influence of pyrolysis temperature on the physicochemical properties of CBC to identify optimal conditions for improving its environmental applications. SCG collected from coffee stores in Vietnam was subjected to slow pyrolysis under anoxic conditions at five different temperatures: 300°C, 350°C, 400°C, 450°C, and 500°C, with a fixed residence time of 2 hours. The obtained biochar samples were analyzed for yield, moisture content, ash content, pH, and surface functional groups. The findings revealed that increasing the pyrolysis temperature led to a decrease in both biochar yield and moisture content, while ash content and pH values increased accordingly. Fourier transform infrared analysis revealed significant differences in surface functional groups between SCG and CBC across different pyrolysis temperatures, highlighting the critical role of temperature in shaping biochar properties for adsorption and environmental remediation. The study contributes to a deeper understanding of how pyrolysis conditions influence the quality of SCG-derived biochar and offers a basis for optimizing production parameters to tailor its characteristics for specific applications.

Contribution/Originality: This study examines the impact of pyrolysis temperature on the physicochemical properties of biochar derived from spent coffee grounds. It aims to establish a foundation for optimizing its applications in environmental and agricultural contexts, thereby contributing to waste reduction and the advancement of sustainable materials.

1. INTRODUCTION

Biochar is a carbon-rich, porous solid material produced through the thermochemical conversion of biomass under anaerobic or oxygen-limited conditions, typically via pyrolysis. It possesses several notable physicochemical properties, including a high specific surface area, a well-developed pore structure, high carbon content, and abundant surface functional groups (e.g., –OH, –COOH). These characteristics make biochar a versatile material with a wide range of applications in agriculture and environmental remediation. Thanks to its superior physicochemical properties, biochar has found widespread applications in various fields. In soil amendment, biochar enhances water retention, supplies essential nutrients (N, P, K), regulates soil pH, and improves soil structure, while also stimulating beneficial microbial activity, thereby increasing crop productivity (Nguyễn & Cao, 2024; Pham, 2016). Its porous structure and abundant surface functional groups allow for the effective adsorption of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}) and organic pollutants such as pesticides, contributing to the mitigation of soil and water contamination (Atabani et al., 2019; Cao & Harris, 2010). Additionally, it is found that biochar has the capacity to sequester carbon dioxide (CO_2) and methane (CH_4) over long periods, thus reducing greenhouse gas emissions. When compressed into pellets, biochar exhibits a high calorific value (20–30 MJ/kg), making it a suitable renewable fuel substitute for coal in industrial applications. Moreover, biochar serves as a microbial carrier in sludge treatment processes and helps reduce ammonia emissions in livestock farming, thereby contributing to improved air quality (Khan et al., 2024; Lehmann et al., 2011). Biochar can be produced from a wide variety of organic biomass sources, including agricultural and forestry residues, as well as municipal and industrial waste. It is commonly derived from readily available feedstocks such as spent tea leaves, applewood, wheat straw, walnut shells, and rice husks. Forestry by-products, including sawdust and bark, are rich in lignin, contributing to the formation of structurally stable biochar. Animal manure, such as cattle and poultry waste, contains high levels of organic matter and yields nutrient-rich biochar with elevated potassium and phosphorus content (Glaser, Wiedner, Seelig, Schmidt, & Gerber, 2015). Kitchen waste is also a widely used precursor for biochar aimed at heavy metal adsorption (Ahmad et al., 2014). Current biochar production techniques are classified based on temperature, reaction atmosphere, and processing time, and include slow pyrolysis, fast pyrolysis, hydrothermal carbonization, and gasification.

Agriculture has long been a cornerstone of global economic development, particularly in developing countries such as Vietnam. However, alongside the increasing growth of agricultural production, a significant challenge persists concerning post-harvest agricultural residues such as rice straw, rice husks, coffee husks, banana stems, peanut shells, and cassava stalks. According to estimates by the General Statistics Office of Vietnam, by 2024, agricultural activities will generate over 159 million tons of agricultural by-products annually. Although often treated as waste, post-harvest agricultural residues can be considered valuable renewable resources when properly recovered and utilized as low-cost, eco-friendly materials. Their reuse offers both environmental and economic benefits, including the production of organic fertilizers, bioenergy, and green construction materials. This not only reduces agricultural waste and greenhouse gas emissions but also lowers production costs and adds value to the agricultural supply chain, contributing to circular and sustainable agriculture. Particularly, Vietnam, the second-largest coffee producer, generates a substantial amount of spent coffee grounds (SCG) as a by-product of coffee brewing and processing, especially in commercial beverage chains. Lacking direct reuse value, SCG is typically discarded, making it one of the major biomass wastes produced by the coffee industry. According to Atabani et al. (2019), SCG contains over one thousand organic compounds, including proteins, non-protein compounds, carbohydrates, tannins, dietary fiber, caffeine, cellulose, nitrogen, fatty acids, amino acids, polyphenols, minerals, lignin, and polysaccharides such as galactomannans and arabinogalactans, among which approximately 700 are volatile compounds. Due to its rich chemical composition and widespread availability, SCG holds great potential as a renewable and sustainable feedstock for the production of functional materials used in environmental remediation, bioenergy generation, and soil amendment in agriculture.

Despite the increasing global consumption of coffee, which leads to a continuous rise in SCG generation, the current management of SCG remains inadequate. It is apparent that improper disposal of SCG not only results in resource wastage but also contributes to greenhouse gas emissions, thereby exacerbating climate change impacts. Therefore, several treatment methods for SCG have been explored, including composting, biofuel production, and recycling into adsorbent materials. However, these approaches are still applied at a limited scale and have not yet gained widespread adoption (Campos-Vega, Loarca-Pina, Vergara-Castañeda, & Oomah, 2015). In addition, recycling and reuse strategies are still inconsistently implemented worldwide, especially in major coffee-producing countries. For example, in the context of Vietnam, most SCG is still handled using conventional practices such as crude composting or direct burning. These methods contribute to environmental issues, including air and soil pollution, which can negatively affect air quality and pose risks to public health. In Brazil and Colombia, some coffee processing facilities have experimented with composting SCG using additives to reduce phenolic and caffeine contents prior to application as fertilizer. Nevertheless, high operational costs and inconsistent outcomes have limited the widespread implementation of these methods (Inyang et al., 2015). In Europe, several countries have launched SCG collection programs from cafés for recycling into biofuels or adsorbent materials. Yet, the recycling rate remains low, accounting for only 10–15% of the total SCG generated (Mohan, Sarswat, Ok, & Pittman Jr, 2014). At the household level, SCG is often reused in simple applications such as natural deodorizers or cleaning agents; however, these uses are insufficient to address the large quantities of SCG generated by the coffee industry. The lack of supportive policies and advanced recycling technologies remains a key barrier to effective SCG management in many developing countries.

Among the various potential applications of SCG, one of the most promising is the production of biochar through pyrolysis under oxygen-limited conditions at temperatures ranging from 300 to 700°C (Inyang et al., 2015). Coffee ground-derived biochar (CBC) typically exhibits a porous structure, a high specific surface area (up to 500 m^2/g), and a range of surface functional groups such as –OH and –COOH (Mohan et al., 2014). These characteristics make CBC highly effective in wastewater treatment, where it has demonstrated notable adsorption capacity for heavy metal ions and synthetic dyes. Moreover, CBC has also been shown to effectively remove hazardous organic contaminants such as pesticides and pharmaceutical residues from aqueous solutions, achieving removal efficiencies of up to 90% under optimized conditions. Several studies have focused on the preparation of CBC and investigated its various applications Oliveira, Gevaerd, Mangrich, Marcolino-Junior, and Bergamini (2021) demonstrated that pyrolysis temperature (200- 700 °C) significantly affects the physicochemical properties of CBC, including surface area, adsorption capacity, and chemical composition. Similarly, Souza et al. (2023) found that increasing the temperature from 300 °C to 600 °C enhances pH, surface area, thermal stability, and the content of elements such as K, P, Ca, and Mg. Notably, caffeine was detected in biochar extracts at 300 °C, while aromatic compounds appeared above 400°C. In Vietnam, several studies have also explored the production and application of CBC. Tran et al. (2020) synthesized CBC via slow pyrolysis at 500°C for varying durations (0.5, 1.5, and 3 hours) and applied it to treat livestock wastewater. The results showed that pyrolysis duration significantly influenced biochar yield and pollutant adsorption efficiency. Similarly, Trinh and Vu (2015) produced CBC at 500°C for 7 hours and demonstrated its potential for removing contaminants from wastewater, highlighting a sustainable approach to biomass waste utilization. Vo and Trieu (2019) investigated the use of CBC to adsorb antibiotics such as norfloxacin and tetracycline, with maximum adsorption capacities of approximately 70 mg/g and 39 mg/g, respectively. Their findings also indicated that pyrolysis temperature affected the formation of organic compounds within the biochar structure.

Although it is evident that pyrolysis temperature influences the formation of organic compounds within the biochar structure, studies examining its impact on the quality and physicochemical properties of CBC remain relatively limited, particularly in Vietnam, where substantial amounts of SCG are generated. Therefore, this study aims to evaluate the physicochemical properties of CBC, including yield, moisture content, ash content, pH, and surface functional groups. The CBC was produced from SCG collected at Highlands Coffee stores in Da Nang, Vietnam, via pyrolysis under oxygen-limited conditions at varying temperatures (300 °C to 500 °C) with a fixed residence time of 2 hours. The findings of this study are expected to clarify the relationship between pyrolysis temperature and the physicochemical properties of CBC, thereby contributing valuable experimental data for biochar research in Vietnam and beyond. Furthermore, the study aims to support the optimization of biochar production from SCG, promoting its application in environmental remediation and the development of sustainable materials.

2. MATERIALS AND METHODS

2.1. Materials

SCG was collected from Highlands Coffee stores in Da Nang, Vietnam. Upon collection, the SCG samples were rinsed twice with tap water and once with distilled water to remove impurities. The cleaned samples were then evenly spread on aluminum trays and oven-dried at 105°C for 12 hours. After drying, the SCG (Figure 1) was stored in zipper-sealed plastic bags and kept in a refrigerator for later use.

Figure 1. Dried SCG sample after oven-drying at 105 °C for 12 hours.

2.2. Methods

2.2.1. Biochar Preparation

Following the drying process, SCG were placed in ceramic crucibles and sealed with aluminum foil punctured with small random holes to allow gas release during pyrolysis. Pyrolysis under oxygen-limited conditions was conducted at different target temperatures of 300°C, 350°C, 400°C, 450°C, and 500°C. The heating rate was set at 10°C/min, and the samples were held at the target temperature for 2 hours to ensure the production of stable biochar. Upon completion of the pyrolysis process, the obtained biochar samples were allowed to cool naturally to room temperature and subsequently stored in labeled zipper-sealed plastic bags according to their respective pyrolysis temperatures. The pyrolysis was carried out using a laboratory muffle furnace (Carbolite, Model AAF 11/7).

2.2.2. Biochar Characterization

2.2.2.1. Determination of Biochar Yield

The mass of SCG and CBC was determined using a gravimetric method. The determination of biochar yield was conducted in triplicate, and the mean values along with standard deviations were calculated to ensure the reliability of the results.

The biochar yield was calculated using Equation (1) as follows:

$$\text{Biochar yield (\%)} = \frac{WCBC}{WSCG}\ 100 \quad (1)$$

Where: WCBC (g) is the mass of biochar obtained after pyrolysis, WSCG (g) is the initial mass of spent coffee grounds prior to pyrolysis.

2.2.2.2. Determination of Biochar Moisture Content

The moisture content of the sample, expressed as a percentage of mass, was calculated using Equation (2) as follows:

$$\text{Moisture content (\%)} = \frac{m1 - m2}{m1} 100 \quad (2)$$

Where: m1 (g) is the mass of the crucible containing the sample before drying, m2 (g) is the mass of the crucible containing the sample after drying (at 100 °C for 4 hours).

The determination of biochar moisture content was conducted in triplicate, and the mean values along with standard deviations were calculated to ensure the reliability of the results.

2.2.2.3. Determination of Biochar Ash Content

The ash content of the biochar sample, expressed as a percentage of mass, was calculated using Equation (3) as follows:

$$\text{Ash content (\%)} = \frac{m2 - m}{m1 - m} 100 \quad (3)$$

Where: m (g) is the mass of the empty porcelain crucible, m1 (g) is the mass of the crucible containing the sample before ashing, m2 (g) is the mass of the crucible containing the sample after ashing (at 650 °C for 2 hours).

The determination of biochar ash content was conducted in triplicate, and the mean values along with standard deviations were calculated to ensure the reliability of the results.

2.2.2.4. pH Measurement of Biochar

To measure pH, 10 g of biochar was mixed with 200 mL of distilled water (1:20 w/v) in a 250 mL Erlenmeyer flask. The mixture was agitated for 20 minutes and filtered. The pH of the filtrate was measured using a HI 2211 pH/ORP meter.

2.2.2.5. Analysis of Surface Functional Groups

Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the surface functional groups present in the raw SCG and biochar samples. All samples were finely ground using a mortar and pestle and sieved to obtain uniform particle size. Spectral measurements were performed using a JASCO FT/IR-6800 spectrometer (JASCO Analytical Instruments, USA) in the range of 4000 - 500 cm^{-1}, using four consecutive scans after background correction. The FTIR data provided insight into the chemical bonding and structural features of the biochar surface.

3. RESULTS AND DISCUSSIONS

3.1. The Yield of Biochar

The yield of CBC was determined using Equation (1) and is presented in Table 1. The results indicate a decreasing trend in biochar yield with increasing pyrolysis temperature, from 48.516 ± 0.011% at 300°C to 19.049 ± 0.008% at 500°C. The findings of this study are consistent with previous literature, which has shown that both the yield and properties of biochar are significantly influenced by the physicochemical characteristics of the raw biomass and the applied pyrolysis temperature. For example, Zhang et al. (2020) used SCG as a biomass feedstock for biochar production and reported a decrease in yield with increasing pyrolysis temperature, from 59.7% at 300 °C to 28.6% at 500 °C. Similarly, Islam, Parvin, Dada, Kumar, and Antunes (2024) observed that raising the temperature led to a gradual reduction in biochar production from SCG, with a yield of 23.5% at 500°C and 21.8% at 1000°C. In another study by Kan, Strezov, and Evans (2016), SCG pyrolyzed at 400°C and 700°C produced biochar with yields of 43% and 26%, respectively. This trend can be explained by the fact that at lower pyrolysis temperatures (300 - 400°C), the decomposition of lignocellulosic biomass is predominant. As the temperature increases, the structural breakdown of the material intensifies, promoting the release of volatile compounds, enhanced dehydrogenation and dehydration reactions, and further conversion of organics into gases, thereby resulting in reduced solid yield.

Table 1. The yields of biochar.

Pyrolysis temperature (°C)	Yield (%) Mean ± S.D.
300°C	48.516 ± 0.011
350°C	37.051 ± 0.010
400°C	33.271 ± 0.012
450°C	23.153 ± 0.008
500°C	19.049 ± 0.008

Note: S.D.: standard deviation.

Overall, our findings reinforce the inverse relationship between pyrolysis temperature and biochar yield, as consistently reported in the literature. Therefore, selecting a lower pyrolysis temperature may be a viable strategy to optimize biochar yield and reduce energy consumption during thermal processing. However, it is worth noting that higher pyrolysis temperatures tend to increase the carbon content in biochar while reducing the hydrogen and oxygen content. This reflects a higher degree of carbonization and a more condensed aromatic carbon structure in the resulting material. Consequently, the selection of an appropriate pyrolysis temperature should be based on the intended application of the biochar, striking a balance between production efficiency and the desired material properties.

3.2. The Moisture Content of Biochar

The moisture content of the CBC samples is presented in Table 2. The results demonstrate a clear decreasing trend in moisture as the pyrolysis temperature increases, reflecting a strong inverse correlation between thermal treatment intensity and the residual water content in the final biochar product. At 300°C, the highest moisture content was recorded at 7.762 ± 0.022%, indicating the persistence of water and some volatile compounds that were not fully removed at lower pyrolysis temperatures. As the temperature increased to 350°C and 400°C, the moisture content declined to 6.871 ± 0.014% and 6.128 ± 0.007%, respectively. This reduction is primarily attributed to the progressive evaporation of water and partial decomposition of volatile organic matter. Notably, at 450°C and 500°C, the moisture content further decreased to 5.991 ± 0.012% and 5.185 ± 0.003%, respectively. The lowest moisture value at 500°C suggests that most of the water content was removed at this elevated temperature, resulting in a structurally stable carbon material with minimal residual moisture.

Table 2. The moisture content of biochar.

Pyrolysis temperature (°C)	Moisture content (%) Mean ± S.D.
300°C	7.762 ± 0.022
350°C	6.871 ± 0.014
400°C	6.128 ± 0.007
450°C	5.991 ± 0.012
500°C	5.185 ± 0.003

Note: S.D.: Standard deviation.

When compared with previous studies, Tangmankongworakoon (2019) reported a moisture content of 4.16% for biochar pyrolyzed at 500°C, which is only slightly lower than the value obtained at the same temperature in the present study. Similarly, the study by Kiggundu and Sittamukyoto (2019), who produced biochar from coffee husks through slow pyrolysis at temperatures ranging from 350°C to 550°C with a residence time of 30–60 minutes, reported that moisture content decreased with increasing pyrolysis temperature. The lowest moisture content, approximately 4.77%, was observed at 550°C for 30 minutes, which is comparable to the values observed at 400 - 500°C in the present study. These findings indicate that the moisture contents of the biochars produced in this work, ranging from 5.485% to 7.762%, as the pyrolysis temperature decreased from 500°C to 300°C, align well with previously published data. This consistency reinforces the conclusion that pyrolysis temperature is a critical factor influencing the moisture characteristics of biochar. In summary, the results clearly demonstrate that pyrolysis temperature plays a decisive role in determining the moisture retention capacity of biochar. Higher temperatures result in drier and more structurally stable products, making them more suitable for long-term storage or for applications requiring low moisture content. Therefore, selecting an appropriate pyrolysis temperature is essential for optimizing the performance of biochar in various applications, such as soil amendment, wastewater treatment, or biofuel production.

3.3. The Ash Content of Biochar

The results presented in Table 3 indicate that the ash content of CBC is significantly influenced by the pyrolysis temperature. Specifically, the ash content decreased sharply from 32.211 ± 0.078% at 300°C to its lowest value of 14.154 ± 0.036% at 350°C. However, starting from 400°C, the ash content showed a continuous increase, reaching a maximum of 48.618 ± 0.233% at 500°C.

Table 3. The ash content of biochar.

Pyrolysis temperature (°C)	Ash content (%) Mean ± S.D.
300°C	32.211 ± 0.078
350°C	14.154 ± 0.036
400°C	41.608 ± 0.345
450°C	44.432 ± 0.112
500°C	48.618 ± 0.233

Note: S.D.: standard deviation.

The reduction in ash content observed at 350°C may be attributed to the effective removal of volatile inorganic compounds at this temperature, prior to the stabilization and accumulation of more thermally resistant minerals. At higher temperatures (≥ 400°C), the increase in ash content reflects the accumulation of refractory inorganic constituents, while the progressive decomposition of organic matter contributes to a higher proportion of ash relative to the remaining biochar mass. These findings suggest that pyrolysis temperature not only alters the chemical composition but also significantly affects the proportion of residual inorganic material, thereby influencing key properties such as adsorption capacity and chemical stability. The increase in ash content with rising pyrolysis temperature is due to the accumulation of non-volatile and non-combustible compounds in the biochar. As the pyrolysis temperature increases, the content of carbon and inorganic matter becomes more concentrated, while the proportion of volatile substances decreases, resulting in a higher ash yield. In the study by Tran et al. (2020), biochar pyrolyzed at 500°C for various durations showed a progressive increase in ash content, with the highest value reaching 31.25% after 6 hours of pyrolysis. Similarly, Al-Awadhi, Pradhan, McKay, Al-Ansari, and Mackey (2022) reported that increasing the pyrolysis temperature from 300°C to 450°C led to an approximate 5% increase in ash content. Consistent with this trend, Jeníček, Tunklová, Malaťák, Neškudla, and Velebil (2022) observed an increase in ash content from 1.98% at 250°C to 6.95% at 550°C in their study.

3.4. The pH of Biochar

The pH values of biochar samples produced at different pyrolysis temperatures are presented in Table 4. The results indicate a clear increasing trend in pH with rising pyrolysis temperature, ranging from 6.78 at 300°C to 9.86

at 500°C. This trend is consistent with findings from Al-Awadhi et al. (2022), who reported that the pH of biochar increased with temperature in the range of 350–600°C. Similarly, Islam et al. (2024) found that biochar derived from SCG at 300°C had a pH of 6.5, while that produced at 600°C exhibited a pH of 9.8, which aligns closely with the pH values obtained in the current study. The increase in pH with pyrolysis temperature is primarily attributed to the thermal degradation of acidic compounds and the enrichment of basic species in the final biochar product. During pyrolysis, acidic organic compounds such as organic acids and cellulose are decomposed into gases (e.g., CO_2, CO, CH_4) and volatile byproducts, leading to a reduction in acidic functional groups (e.g., –COOH, –OH) on the biochar surface and thereby raising the overall pH. Moreover, at elevated temperatures, alkali and alkaline earth metal ions (e.g., K^+, Na^+, Ca^{2+}, Mg^{2+}) originating from the raw biomass become concentrated in the biochar, further contributing to its basicity. It is worth noting that pH plays a crucial role in regulating surface charge, the ionization degree of adsorbates, and the dissociation behavior of various functional groups on the adsorbent surface (Konneh, Wandera, Murunga, & Raude, 2021).

Table 4. pH of biochar.

Pyrolysis temperature (°C)	pH
300°C	6.78
350°C	7.27
400°C	8.91
450°C	9.08
500°C	9.86

3.5. Presence of Functional Group

The FTIR method was employed to identify the characteristic functional groups present in SCG before and after thermal treatment. Figure 2 displays the FTIR spectra of the raw SCG sample and the thermally treated samples at different pyrolysis temperatures (300°C, 350°C, 400°C, 450°C, and 500°C). The FTIR spectrum of the raw SCG sample exhibited several characteristic absorption peaks, including a peak at 1632.45 cm^{-1}, which corresponds to the C=C stretching vibration typically associated with hemicellulose. There was also a peak at 2922.59 cm^{-1}, corresponding to the C–H stretching of –CH_2 and –CH_3 groups. Additionally, a peak at 2358.52 cm^{-1} was observed, likely associated with physically adsorbed carbon dioxide or the stretching of carbon–nitrogen triple bonds (C≡N bonds).

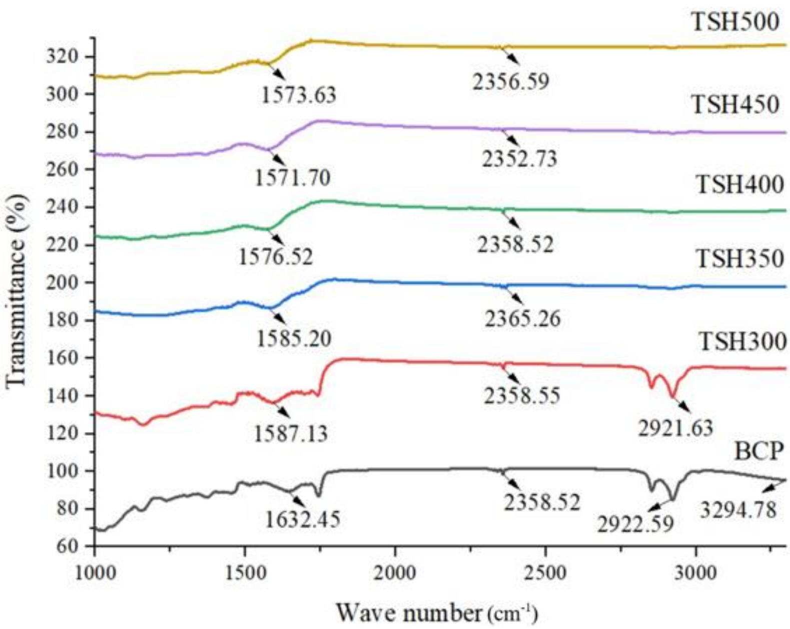

Figure 2. FTIR spectra of SCG and biochar samples produced at different pyrolysis temperatures.

After thermal treatment at 300°C, notable spectral changes were observed. The peak at 1632.45 cm^{-1}, attributed to C=C stretching in hemicellulose, disappeared, indicating the degradation or removal of hemicellulose during thermal treatment. A new peak emerged at 1587.13 cm^{-1}, which can be assigned to the stretching vibrations of aromatic C=C or imine C=N bonds, suggesting the formation of more thermally stable conjugated structures. While the C–H peak at 2921.63 cm^{-1} remained, its reduced intensity reflects partial degradation of aliphatic structures. The persistent presence of the 2358.55 cm^{-1} peak suggests that physically adsorbed carbon dioxide remained entrapped within the biochar matrix. Following this, at a pyrolysis temperature of 350°C, the FTIR spectrum showed a further reduction in absorption bands. The C–H stretching band in the 2920 - 2930 cm^{-1} region was no longer detectable, implying the complete decomposition of hydrocarbon chains. The peak at 1585.20 cm^{-1} remained, indicating the relative stability of unsaturated functional groups such as aromatic C=C bonds. Notably, the absorption band at 1741.41 cm^{-1}, originally attributed to carbonyl (C=O) stretching in the raw SCG, was absent, confirming the thermal breakdown of carbonyl-containing structures during pyrolysis. As the pyrolysis temperature increased to higher levels (400°C, 450°C, and 500°C), the FTIR spectra exhibited a continued decline in both the intensity and number of absorption bands, indicating the progressive thermal degradation of organic constituents. At 400°C, characteristic peaks were observed at 1576.52 cm^{-1} and 2358.52 cm^{-1}; at 450°C, peaks appeared at 1570 cm^{-1} and 2352.73 cm^{-1}; and at 500°C, peaks were recorded at 1573.63 cm^{-1} and 2356.59 cm^{-1}.

The consistent presence of absorption bands within the 1570 - 1587 cm^{-1} region across all thermally treated biochar samples suggests the thermal stability of double-bond-containing functional groups such as aromatic or olefinic C=C. Conversely, the disappearance or significant reduction of absorption bands associated with –OH, C–H, and C=O stretching vibrations indicates the elimination of thermally labile functional groups during pyrolysis. Overall, the FTIR analysis confirms that thermal treatment induced substantial changes in the chemical composition and molecular structure of SCG. Labile functional groups such as hydroxyl, carbonyl, and aliphatic hydrocarbons were largely decomposed, while thermally stable moieties, including aromatic structures and possibly adsorbed carbon dioxide, remained. These transformations highlight the effectiveness of pyrolysis in modifying the chemical framework of SCG, contributing to the development of new physicochemical properties in the resulting biochar.

4. CONCLUSION

The study successfully produced biochar from SCG through slow pyrolysis at various temperatures (300°C, 350°C, 400°C, 450°C, and 500°C). The physicochemical characteristics of the resulting biochar were analyzed, revealing that pyrolysis temperature significantly influenced the biochar yield, moisture content, ash content, pH, and surface functional groups. Specifically, the biochar yield decreased from 59.7% to 28.6% as the pyrolysis temperature increased from 300°C to 500°C. The pH of the biochar also increased progressively with temperature, ranging from 6.78 to 9.86, with the highest value recorded at 500°C. Moreover, moisture content showed a declining trend, reaching the lowest value of 5.485 ± 0.003% at 500°C, while ash content increased significantly, peaking at 48.618% at the same temperature. FTIR analysis revealed the gradual disappearance or complete loss of functional groups such as –OH, C–H, C=O, and C–O with increasing pyrolysis temperature from 300°C to 500°C, indicating the decomposition of organic structures and the formation of a more stable carbon framework. This study provides valuable insights into the influence of pyrolysis temperature on the physicochemical characteristics of biochar from SCG, thereby establishing a basis for optimizing production parameters tailored to environmental applications. However, the scope of the current research is limited by the use of a single biomass feedstock and constant pyrolysis residence time. Future investigations should consider a broader range of feedstocks and process conditions, as well as conduct performance-based evaluations targeting specific applications such as contaminant adsorption, soil amendment, or carbon sequestration.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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