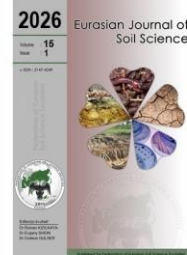




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Integrated physicochemical and structural characterization of date palm pit-derived biochar produced by slow pyrolysis

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Abstract

Biochar, a carbon-rich material produced via biomass pyrolysis, has attracted growing attention due to its diverse physicochemical properties and potential relevance in soil-related and environmental applications. In this study, biochar was produced from date palm (*Phoenix dactylifera* L.) pit residues, an abundant agro-industrial by-product, through slow pyrolysis at temperatures of 350 °C. The resulting material was systematically characterized to evaluate its physicochemical and structural attributes using proximate analysis, pH and cation exchange capacity (CEC) measurements, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis. The characterization results revealed that the produced biochar had a high yield of 75%, a low ash content (1.22%), and an acidic pH of 4.46. The biochar also exhibited a carbon-rich composition with a fixed carbon content of 27.3%, a measurable BET surface area of 18.22 m² g⁻¹, and a cation exchange capacity of 20.45 (cmol(+) kg⁻¹). These properties reflect the structural and chemical features of the biochar generated under the applied pyrolysis conditions. While no soil or biological performance was evaluated in this study, the measured physicochemical characteristics suggest potential relevance for future soil-based or environmental assessments. Overall, this work demonstrates the valorization of date palm pit residues into biochar with well-defined physicochemical and structural properties, contributing to waste management strategies and circular bioeconomy approaches. Further studies are recommended to assess the performance of this material under specific application conditions.

Keywords: Date palm pit biochar, slow pyrolysis, physicochemical properties, porous structure, cation exchange capacity, agro-industrial residue.

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Introduction

Rapid global population growth has increased the demand for agricultural products, leading to the generation of large volumes of agricultural waste that are often disposed of through landfilling, open dumping, or uncontrolled burning (Khan et al., 2024). Open burning of agricultural residues releases smoke and fine particulate matter rich in black carbon, resulting in nutrient losses, degradation of soil fertility, disruption of beneficial soil microbial communities, and deterioration of air quality with adverse effects on environmental and human health (Chakraborty et al., 2025; Saxena, 2025). Consequently, the valorization of agricultural waste into biochar has emerged as a sustainable strategy that links waste management with soil-relevant material production, supporting circular economy approaches while enabling the generation of biomass-derived materials with measurable physicochemical properties (Silva et al., 2025).



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Date palm (*Phoenix dactylifera* L.) trees are widely cultivated in arid and semi-arid regions because of their ability to adapt to environments with high temperatures for extended periods of time, limited rainfall, and low relative humidity (Kavvadias et al., 2024). Iraq is one of the world's leading date producers, with an annual production exceeding 800,000 tons, which translates into a large and continuous generation of date palm pit waste (Khalil and Jassim, 2024; Taha Abd et al., 2025). While date fruits represent an important food commodity, increasing attention has also been directed toward date palm pits, a major agro-industrial by-product generated during date processing. Date pits constitute approximately 10–20% of the total weight of the fruit, resulting in millions of tons of pit waste annually worldwide (Faia et al., 2022). Date palm pits are characterized by their lignocellulosic composition, rich in cellulose (26–42.5%), hemicellulose (12–28%), and lignin (7–11%), making them a suitable raw material for thermochemical conversion processes (Alkhoori et al., 2022). Despite this potential, date palm pits are commonly disposed of through landfilling or open burning in many date-producing regions, contributing to soil degradation, atmospheric pollution, greenhouse gas emissions, and associated health risks (Mahdi et al., 2015; Faia et al., 2022). Consequently, the sustainable management and valorization of date palm pit residues into value-added materials, such as biochar, represent an important strategy for mitigating environmental impacts while supporting circular economy and resource efficiency principles (Subhash et al., 2024).

Biochar is a solid, carbon-rich material produced by pyrolyzing organic biomass at temperatures ranging from 300 to 700 °C under oxygen-deficient conditions (Gunal et al., 2019; Dhar et al., 2022). Numerous studies and reviews have reported that biochar can provide environmental and agricultural benefits, such as carbon sequestration, mitigation of greenhouse gas emissions, and improvements in soil physical and chemical properties; however, these effects strongly depend on biochar properties, soil type, application rate, and environmental conditions (Shyam et al., 2025). The chemical composition of biochar, particularly its carbon (C), oxygen (O), and mineral element contents, is influenced by several factors, including feedstock type, pyrolysis temperature, and residence time (Ippolito et al., 2015). Among these factors, pyrolysis temperature is a primary determinant of biochar physicochemical characteristics, with increasing temperatures generally enhancing carbon content and structural stability while reducing oxygen-containing functional groups (Tomczyk et al., 2020). In general, biochars are characterized by a range of physical and chemical properties, such as fixed carbon content, ash content, surface area, porosity, cation exchange capacity, and pH, that vary widely with pyrolysis conditions and feedstock composition and should therefore be evaluated on a case-by-case basis (Akça and Namlı, 2015; Shyam et al., 2025; Sharma et al., 2025).

Despite increasing interest in biochar derived from agricultural residues, detailed and integrated physicochemical and structural characterisation of biochar produced from date palm pit residues under low-temperature slow pyrolysis conditions is still limited. In particular, comprehensive material-level characterization combining proximate analysis, surface chemistry, morphology, crystallinity, and textural properties is still insufficiently reported for this feedstock. The objective of this study was therefore to produce biochar from date palm pits (*Phoenix dactylifera* L.) via slow pyrolysis at 350°C and to systematically characterize its physicochemical and structural properties using complementary analytical techniques, including proximate analysis, SEM–EDX, FTIR, XRD, and BET surface area analysis. This study supports the valorization of agro-industrial residues by providing a detailed material-level characterization of date palm pit-derived biochar. It also contributes to sustainable waste management and circular bioeconomy approaches, which may be relevant to the United Nations Sustainable Development Goals.

Material and Methods

Preparation and production of biochar from date palm pits

Date palm pits (*Phoenix dactylifera* L.) were collected from local farms in Diwaniyah Governorate, Iraq. The pits were thoroughly washed with distilled water to remove adhering impurities and oven-dried at 105 °C for 24 h to a constant weight, following standard biomass preparation procedures reported in previous biochar studies (Mahdi et al., 2015; Remmani et al., 2024). The initial moisture content of the raw pits was not determined separately prior to drying. The dried date palm pits were mechanically crushed using a laboratory grinder to reduce particle size prior to pyrolysis. The resulting material consisted of irregular pit fragments with an approximate size range of 0.25–1 mm, which were used directly as feedstock for biochar production (Rahmat, 2021). Biochar was produced through slow pyrolysis in a laboratory-scale tubular furnace (TF5/25|1250) under an inert nitrogen atmosphere. For each pyrolysis run, 20 g of dried pit material was placed in a cylindrical alumina crucible (length 80 mm, diameter 30 mm) and positioned at the center of the quartz reaction tube (inner diameter 50 mm) to ensure uniform heat exposure. To maintain oxygen-limited conditions, the furnace tube was continuously purged with 100 mL min⁻¹ of high-purity nitrogen. The biomass

was heated at a constant rate of $10^{\circ}\text{C min}^{-1}$ to a target temperature of 350°C and maintained for 4 hours. Following the pyrolysis process, the furnace was allowed to cool naturally to room temperature with continuous nitrogen flow. To ensure reproducibility, biochar was produced in three independent batches under the same conditions. The resulting biochar was mechanically ground with a mortar grinder and sieved through a stainless-steel mesh. Particles passing through a $100\text{ }\mu\text{m}$ sieve were collected for further analysis. Particle size distribution was not further quantified, and the reported particle size therefore refers to an upper cut-off value rather than a mean diameter (Mahdi et al., 2015).

Biochar yield was calculated on a dry-weight basis according to Eq. (1):

$$\text{Biochar yield (\%)} = (\text{mass of biochar} / \text{mass of dry feedstock}) \times 100 \quad (1)$$

Physicochemical characterization of biochar

Proximate analysis

Proximate analysis was conducted to determine moisture content, volatile matter, ash content, and fixed carbon following ASTM standard procedures. For each analysis, approximately 1.0 g of biochar sample was used. Moisture content was measured according to ASTM D3173 by oven-drying samples at 105°C until constant weight. Ash content was determined using ASTM D3174 by combusting samples at 650°C for 4 h in a muffle furnace (JSMF-14GT, JSR, Korea). Volatile matter was determined following ASTM D3175 by heating the sample at 950°C for 7 min under limited oxygen conditions. Fixed carbon content was calculated by difference using Eq. (2):

$$\text{Fixed carbon (\%)} = 100 - (\text{Moisture} + \text{Volatile matter} + \text{Ash}) \quad (2)$$

All proximate analysis measurements were performed in triplicate ($n=3$) using samples obtained from three independent biochar production batches, and results are reported as mean $\pm$ standard deviation (SD).

Biochar pH and electrical conductivity (EC) were measured using a 1:5 (w/v) biochar-to-deionized water suspension following the standardized protocol described by (Singh et al., 2017). For each measurement, 5.0 g of biochar was suspended in 25 mL of deionized water and equilibrated prior to analysis. pH was measured using a calibrated pH meter (SD300PH, Lovibond, Germany), while EC was measured using a conductivity meter (Cond 7110, WTW, Germany). Cation exchange capacity (CEC) was determined using the ammonium acetate saturation and extraction method as described by (Graber et al., 2017), with approximately 0.5 g of biochar used per determination. Bulk density was measured by filling a container of known volume with biochar and determining its mass, following (Blake, 1965).

All physicochemical measurements were conducted in triplicate ($n=3$) using samples from independent biochar production batches, and the results are expressed as mean $\pm$ standard deviation (SD).

Surface elemental composition (SEM-EDX)

Surface morphology and elemental composition of the biochar were analyzed using a field-emission scanning electron microscope (FEI Quanta 200) equipped with an energy-dispersive X-ray spectroscopy (EDX) detector (Bruker, Germany). Prior to analysis, samples were mounted on aluminum stubs and coated with a thin conductive layer. SEM imaging was performed under high vacuum conditions at appropriate accelerating voltage to examine surface morphology and pore structure. EDX analysis was employed to determine the surface elemental composition of the biochar. The technique provides semi-quantitative information on major and minor elements present on the biochar surface and does not represent a complete bulk elemental (CHNS/O) analysis.

Fourier transform infrared spectroscopy (FTIR)

FTIR analysis was conducted using a Thermo Nicolet Avatar 370 spectrometer (USA) equipped with an attenuated total reflectance (ATR) accessory to identify surface functional groups present in the biochar. Spectra were recorded over the wavenumber range of $4000\text{--}400\text{ cm}^{-1}$ at a spectral resolution of 4 cm^{-1} , with 32 scans accumulated for each sample. All spectra were baseline-corrected and processed using OMNIC software (Thermo Scientific) prior to interpretation. FTIR analysis was used to qualitatively identify characteristic functional groups associated with biochar produced under the applied slow pyrolysis conditions.

X-ray diffraction (XRD)

X-ray diffraction patterns were collected using a BRUKER XRD diffractometer (Germany) to investigate the crystalline and mineral phases present in the biochar. Measurements were conducted over a suitable 2θ range

using Cu K α radiation. XRD patterns were interpreted to identify mineral constituents and to evaluate the structural ordering of the carbon matrix formed during pyrolysis.

Brunauer–Emmett–Teller (BET) surface area

Specific surface area and textural properties of the biochar were determined using nitrogen adsorption–desorption analysis with a BELSORP MINI II analyzer. Prior to measurement, biochar samples were degassed at 200°C for 12 h under vacuum to remove adsorbed moisture and gases. Nitrogen (N₂) was used as the adsorptive gas, and adsorption–desorption isotherms were recorded at 77 K. The specific surface area was calculated using the Brunauer–Emmett–Teller (BET) equation over a relative pressure (p/p_0) range of 0.05–0.30. Total pore volume was estimated from the amount of nitrogen adsorbed at $p/p_0 \approx 0.99$. Pore size distribution was derived from the adsorption branch of the isotherm using the Barrett–Joyner–Halenda (BJH) model, which is applicable to the mesopore range (2–50 nm).

Results

Proximate analysis and key physicochemical properties of palm pit-derived biochar

Proximate analysis provides fundamental information on the compositional and physicochemical characteristics of biochar, which are essential for understanding its material properties and behavior under different application contexts. The proximate analysis and selected physicochemical properties of biochar derived from date palm pits are summarized in Table 1.

Table 1. Proximate analysis and physicochemical properties of biochar derived from date palm pits.

Property	Value
Biochar yield (%)	75.00
Moisture content (%)	2.79
Ash content (%)	1.22
Volatile matter (%)	68.70
Fixed Carbon (%)	27.30
pH	4.46
EC (dS m ⁻¹)	1.86
CEC (cmol(+) kg ⁻¹)	20.45
Bulk density (g cm ⁻³)	0.50
Particle density (g cm ⁻³)	1.00
Porosity (%)	50.00

The biochar yield of 75% calculated on a dry-weight basis (Eq. (1)), indicates a high solid conversion efficiency of date palm pits under the applied slow pyrolysis conditions at 350°C, consistent with previous reports for low-temperature pyrolysis of lignocellulosic biomass (Mahdi et al., 2015). The low moisture content (2.79%) reflects effective drying and thermal conversion, which is favorable for storage stability. The ash content (1.22%) suggests a relatively low inorganic fraction, typical of biochars produced from woody or seed-based biomass. The volatile matter content (68.7%) indicates the presence of thermally labile organic fractions, which is characteristic of biochars produced at relatively low pyrolysis temperatures (Bureq and Davidson, 2023). In contrast, the fixed carbon content (27.3%) reflects the formation of a partially carbonized matrix, which is expected to increase with increasing pyrolysis temperature. These results are consistent with the thermal decomposition behavior of lignocellulosic feedstocks reported in the literature. The measured pH value (4.46) indicates that the produced biochar is acidic in nature, which is attributable to the retention of oxygen-containing functional groups formed during low-temperature pyrolysis. Electrical conductivity (1.86 dS m⁻¹) reflects the presence of soluble ionic species on the biochar surface, while the measured cation exchange capacity (20.45) (cmol(+) kg⁻¹) indicates the presence of surface functional groups capable of participating in ion exchange processes. Bulk density (0.50 g cm⁻³) and particle density (1.00 g cm⁻³) were used to calculate porosity. The porosity was determined according to the following Eq. (3):

$$\text{Porosity (\%)} = [1 - (\text{BD}/\text{PD})] \times 100 \quad (3)$$

Based on these values, the calculated porosity was 50%. The bulk density, particle density, and porosity values all indicate a moderately porous material structure, which is due to the release of volatile compounds during the thermal conversion process (Tahir et al., 2022).

Surface elemental composition by SEM–EDX

The surface elemental composition of palm pit-derived biochar was examined using SEM–EDX analysis, and the results are presented in Table 2. It should be noted that EDX provides semi-quantitative information on surface elemental composition and does not represent a complete bulk elemental (CHNS/O) analysis.

Table 2. Surface elemental composition of biochar derived from date palm pits determined by SEM–EDX.

Element	Wt%	At%
Carbon (C)	63.26	74.67
Oxygen (O)	21.16	18.75
Potassium (K)	6.20	2.25
Phosphorus (P)	2.39	1.09
Calcium (Ca)	2.24	0.79
Sulfur (S)	1.85	0.82
Sodium (Na)	1.59	0.98
Magnesium (Mg)	0.69	0.40

Wt% = weight percentage; At% = atomic percentage. The values represent the mean surface composition determined by SEM-EDX analysis of five different areas on the biochar surface.

The surface elemental composition of palm pit-derived biochar was analyzed using SEM-EDX, and the results presented in Table 2 represent mean values obtained from five different analyzed areas on the biochar surface. It should be noted that SEM-EDX only provides semi-quantitative data on surface elemental composition and does not include bulk elemental (CHNS/O) analysis. Carbon was the dominant surface element, reflecting the carbon-rich nature of the biochar matrix formed during pyrolysis. The presence of oxygen indicates the retention of oxygen-containing functional groups on the biochar surface, which is typical for biochars produced at low to intermediate temperatures. In addition, minor inorganic elements such as potassium, calcium, phosphorus, and magnesium were detected, originating from the mineral constituents of the original biomass. These elements are commonly reported in biomass-derived biochars and reflect feedstock composition rather than functional performance. The relatively low sodium content suggests limited accumulation of soluble salts on the biochar surface.

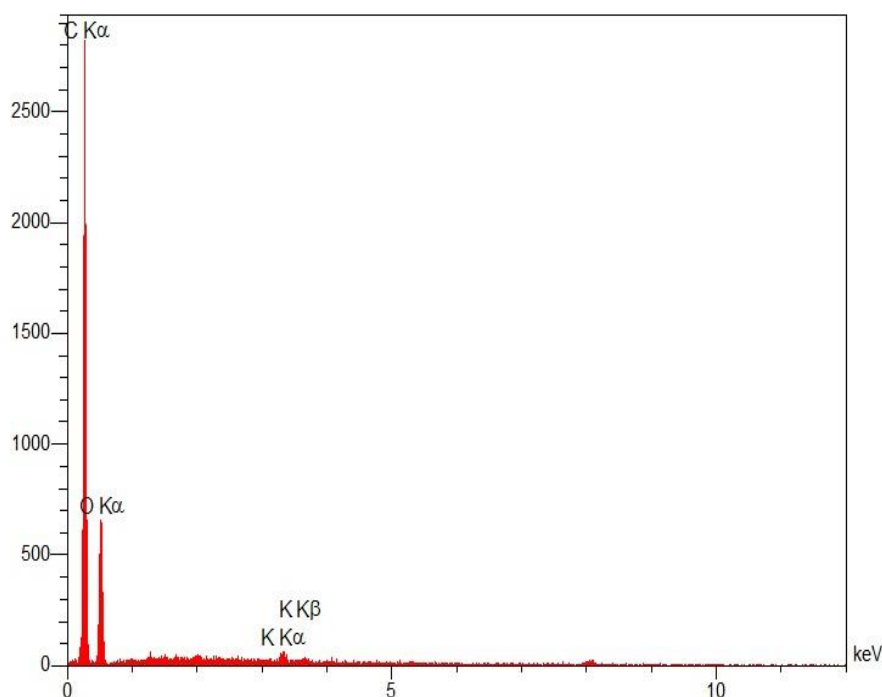


Figure 1. Representative SEM–EDX spectra illustrating the distribution of major and minor elements detected on the surface of date palm pit–derived biochar.

Surface morphology and pore structure (SEM)

Scanning electron microscopy was employed to examine the surface morphology and pore structure of the biochar produced from date palm pits. Representative SEM micrographs are shown in Figure 2. The images reveal a heterogeneous surface morphology characterized by irregular pores and voids of varying sizes, which formed as a result of volatile release during the pyrolysis process. The observed pore network reflects the anatomical structure of the original biomass and the applied thermal treatment conditions. The presence of micro- and meso-scale pores is typical for biochars produced from lignocellulosic materials at low pyrolysis temperatures. Such morphological features contribute to the overall textural properties of the biochar and are consistent with previously reported SEM observations for seed- and pit-derived biochars. The SEM results confirm the development of a porous carbon matrix but do not, by themselves, indicate specific soil or biological performance outcomes.

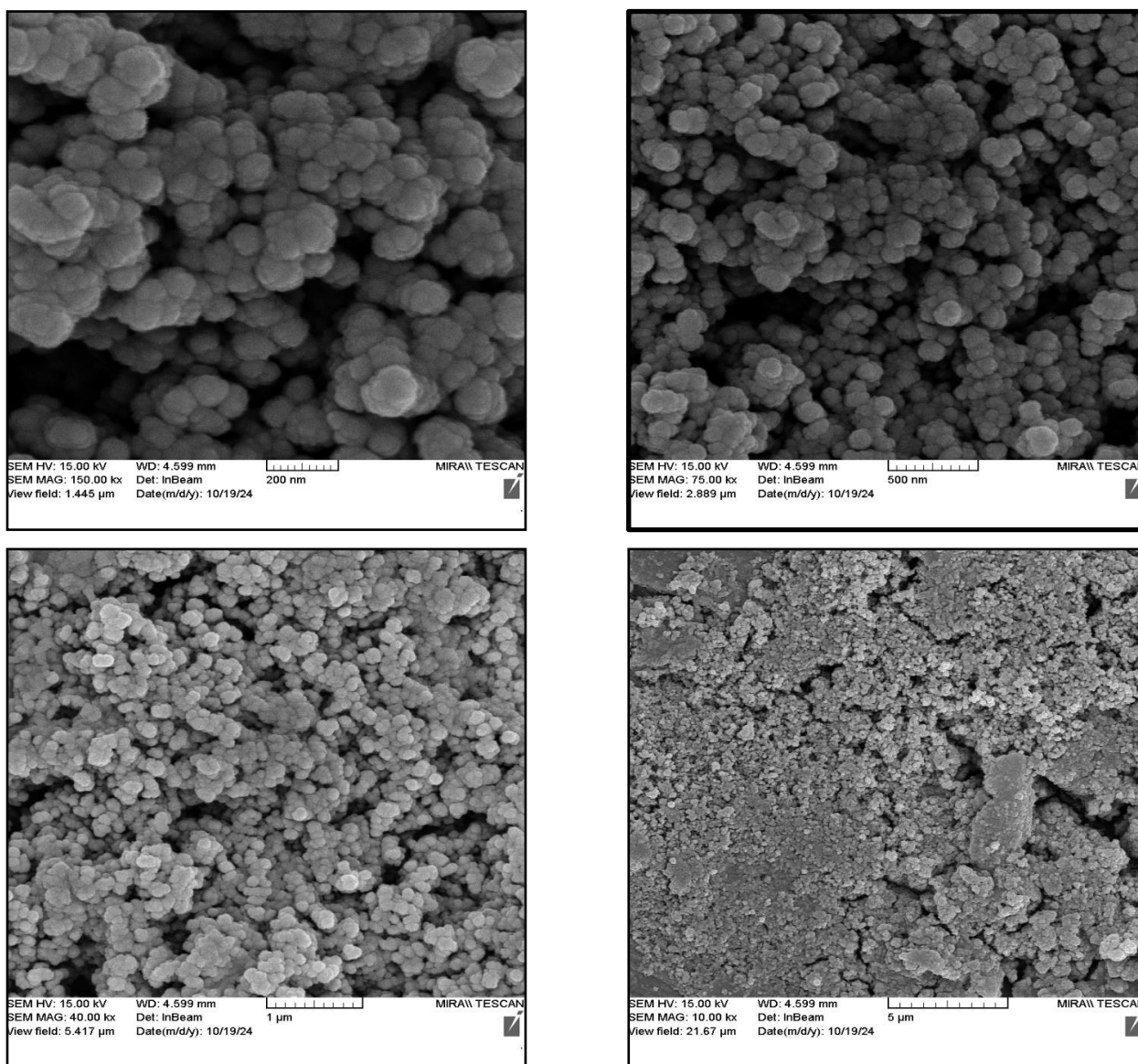


Figure 2. Scanning electron microscopy (SEM) micrographs of biochar derived from date palm pits produced by slow pyrolysis at 350 °C, illustrating the surface morphology and pore structure developed during low-temperature thermal conversion.

FTIR of palm pit-derived biochar

The FTIR spectrum of date palm pit-derived biochar was examined to determine the primary surface functional groups formed during slow pyrolysis at 350°C. The principal absorption bands observed in the FTIR spectrum and their tentative functional group assignments are summarized in Table 3.

Table 3. Main absorption bands observed in the FTIR spectrum of date palm pit-derived biochar and their tentative functional group assignments.

Peak (cm ⁻¹)	Transmittance (%T)	Functional Group Assignment	Possible Bond Type
3699.02	97.56	O-H Stretching	Free or weakly hydrogen-bonded hydroxyl groups (surface -OH or adsorbed moisture)
3301.22	96.51	O-H stretching	Hydrogen-bonded hydroxyl groups (phenolic -OH or adsorbed water)
2925.31	87.21	C-H stretching (aliphatic)	Asymmetric stretching of CH ₂ groups
2854.92	92.35	C-H stretching (aliphatic)	Symmetric stretching of CH ₂ groups
1745.59	88.27	C=O stretching	Carbonyl groups (carboxylic acids, ketones, or esters)
1458.48	90.95	C-H bending	Methyl and methylene deformation
1158.29	87.17	C-O stretching	Alcohols, phenols, ethers, or esters
806.53	94.13	Aromatic C-H out-of-plane bending	Substituted aromatic rings

Note: Functional group assignments are tentative and based on comparison with reported FTIR spectra of biochars produced at low to intermediate pyrolysis temperatures.

The FTIR spectrum of palm pit-derived biochar (Figure 3) reveals several absorption bands that are commonly found in biochars produced at low to intermediate pyrolysis temperatures. Broad bands in the 3700-3300 cm^{-1} region are attributed to O-H stretching vibrations associated with hydroxyl or phenolic groups, and/or adsorbed moisture, which may persist in biochars produced at relatively low temperatures (Kritikaki et al., 2025). The presence of aliphatic C-H stretching bands at approximately 2925 and 2855 cm^{-1} suggests incomplete thermal decomposition of aliphatic biomass components, which is consistent with the applied pyrolysis temperature of 350 °C. The absorption band at 1746 cm^{-1} corresponds to C=O stretching vibrations of carbonyl-containing functional groups, such as carboxylic acids or esters, indicating the presence of oxygen-containing functionalities (Kritikaki et al., 2025; Sathyabama and Firdous, 2025). It should be emphasized that FTIR analysis provides qualitative information on functional group presence, and the observed bands should be interpreted as indicative of surface chemical characteristics rather than direct evidence of specific functional performance.

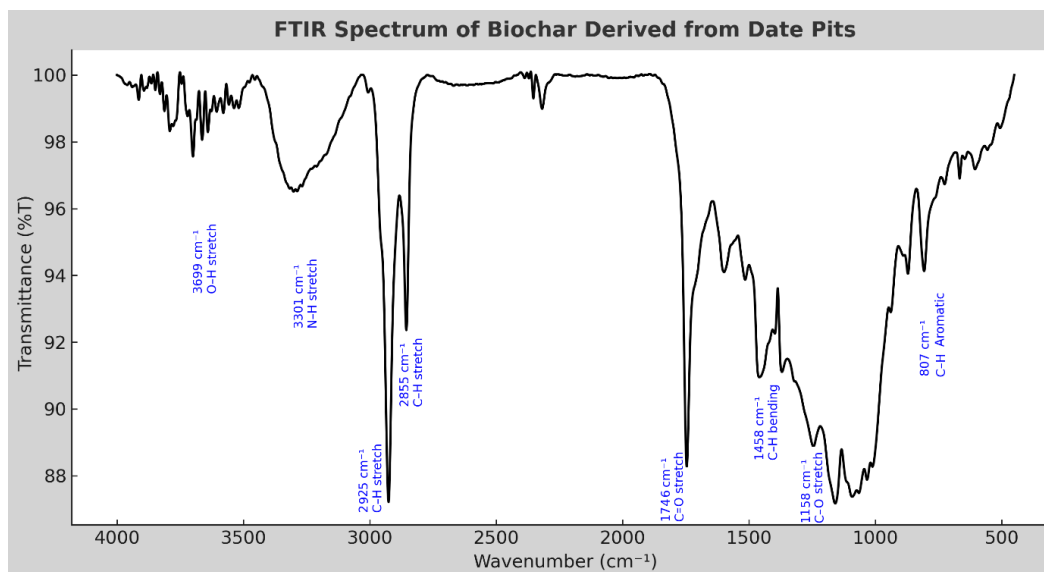


Figure 3. FTIR spectrum of date palm pit-derived biochar produced at 350 °C, showing characteristic absorption bands associated with oxygen-containing, aliphatic, and aromatic functional groups.

X-ray diffraction (XRD) analysis of biochar derived from palm pits

X-ray diffraction (XRD) analysis was used to investigate the structural ordering and mineral phases found in palm pit-derived biochar. The XRD pattern (Figure 4) is dominated by a broad diffraction band centred in the 2θ range of approximately 20-30°. This is commonly assigned to the (002) reflection of turbostratic or disordered carbon in biomass-derived biochars produced at low pyrolysis temperatures.

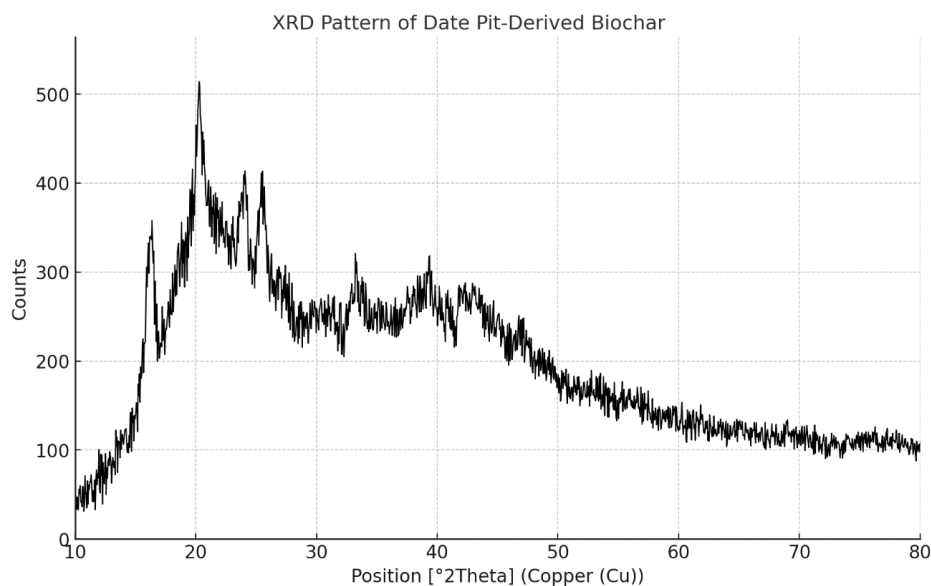


Figure 4. XRD pattern of date palm pit-derived biochar produced at 350°C, showing a broad diffraction band in the 2θ range of 20–30° attributed to the (002) reflection of turbostratic/disordered carbon, along with weak reflections associated with minor inorganic mineral phases.

The absence of sharp and well-defined graphite reflections indicates that the carbon matrix lacks long-range crystalline order and remains predominantly amorphous, as complete graphitization is not expected under the applied pyrolysis temperature of 350°C. Such broad diffraction features are typical of lignocellulosic biochars produced below 500°C. In addition to the carbon-related features, weak diffraction peaks were observed at specific 2θ positions, which are tentatively attributed to residual inorganic mineral phases inherited from the feedstock. These include peaks near $2\theta \approx 26.6^\circ$, likely associated with silica-based minerals such as quartz, and minor calcium-containing phases at higher angles. The identification of these mineral phases is considered tentative and reflects the inherent mineral composition of date palm pits rather than post-pyrolysis functional behavior. Overall, the XRD results confirm the predominantly amorphous nature of the carbon matrix with a turbostratic carbon structure and the presence of minor crystalline mineral constituents, consistent with the applied pyrolysis conditions and biomass origin.

BET surface area and porosity analysis of biochar derived from palm pits

Nitrogen adsorption-desorption analysis was used to determine the surface area and textural properties of the palm pit-derived biochar. The Brunauer–Emmett–Teller (BET) parameters obtained from nitrogen adsorption data are summarized in Table 4, and the corresponding BET transform plot used for surface area determination is shown in Figure 5.

Table 4. BET surface area and textural properties of palm pit-derived biochar determined by nitrogen adsorption.

Parameter	Value	Unit
Specific surface area, a_s	18.223	$\text{m}^2 \text{g}^{-1}$
Monolayer adsorption capacity, V_m	4.1867	$\text{cm}^3(\text{STP}) \text{g}^{-1}$
BET Constant (C)	82.729	-
Total Pore Volume	0.0087541	$\text{cm}^3 \text{g}^{-1}$
Average Pore Diameter	1.9216	nm

a_s = BET specific surface area; V_m = monolayer adsorption capacity derived from BET analysis.

The measured BET specific surface area ($18.22 \text{ m}^2 \text{g}^{-1}$) indicates a moderately developed porous structure, which is typical of biochars produced at relatively low pyrolysis temperatures without chemical or physical activation. The total pore volume ($0.0088 \text{ cm}^3 \text{g}^{-1}$), estimated at a relative pressure of $p/p_0 \approx 0.99$, reflects the cumulative pore space accessible to nitrogen molecules. The average pore diameter of approximately 1.92 nm indicates a micropore-dominant pore system located near the micro-mesopore boundary ($\approx 2 \text{ nm}$), which is consistent with the textural characteristics of carbonaceous materials produced at low pyrolysis temperatures. The BET constant ($C = 82.73$) provides qualitative information on the interaction strength between nitrogen molecules and the biochar surface during adsorption and is commonly used as an indicator of adsorption energetics under measurement conditions. It should be emphasized that BET parameters describe physical textural properties only, and no adsorption or removal performance was evaluated in this study.

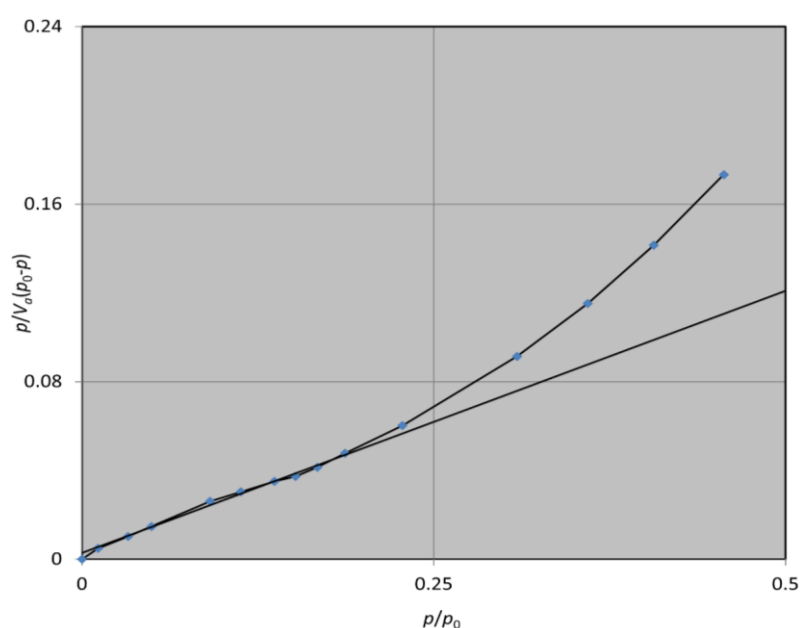


Figure 5. BET transform plot $[p/V_a(p_0-p)]$ versus p/p_0 derived from nitrogen adsorption data of palm pit-derived biochar, used for determination of the BET specific surface area.

Discussions

The integrated physicochemical and structural characterisation results show that slow pyrolysis of date palm pits at 350 °C yields a carbonaceous material whose properties are strongly influenced by feedstock composition and low-temperature thermal conditions. The 75% biochar yield observed in this study is consistent with yields reported for pit- and seed-derived biomasses pyrolysed below 400 °C, which typically retain a large fraction of solid carbon due to their dense structure and relatively high lignin content (Enders and Lehmann, 2017; Bureq and Davidson, 2023). The low ash content (1.22%) and moderate fixed carbon content (27.3%) reflect the organic nature of date palm pits, as well as the limited mineral concentration during thermal conversion. Comparable ash contents (<2–3%) and fixed carbon values have been reported for date pit and nutshell biochars produced at similar temperatures, whereas higher pyrolysis temperatures generally result in increased fixed carbon and reduced volatile matter (Amin et al., 2016; Santos et al., 2024). The acidic pH (4.46) of the produced biochar contrasts with the alkaline character often reported for biochars generated at higher temperatures or from mineral-rich feedstocks. Similar acidic pH values have been documented for low-temperature biochars derived from palm residues and seed-based materials, where oxygen-containing functional groups are retained due to incomplete deoxygenation (Singh et al., 2017; Mihoub et al., 2024).

SEM-EDX analysis confirmed carbon and oxygen as the dominant surface elements, with minor contributions from potassium, calcium, phosphorus, and magnesium. These inorganic elements are commonly inherited from the original biomass and have been found at comparable levels in pit-derived and agricultural residue biochars, indicating feedstock mineral composition rather than functional performance (Bird et al., 2017; Nzediegwu et al., 2021). FTIR analysis revealed the presence of hydroxyl, carbonyl, aliphatic, and aromatic functional groups, indicating that cellulose, hemicellulose, and lignin underwent partial thermal decomposition at low pyrolysis temperatures. Similar FTIR features have been reported for pit- and seed-derived biochars produced at 300–400 °C, with oxygenated surface functionalities remaining prominent (Țucureanu et al., 2016; Remmani et al., 2024). The XRD results showed a predominantly amorphous carbon structure with a broad (002) diffraction band associated with turbostratic carbon, as is typical of biochars produced below 500°C. The absence of sharp graphite reflections confirms that complete graphitisation did not occur under the conditions used, which is consistent with previous research on lignocellulosic biochars (Keiluweit et al., 2010; Singh and Raven, 2017). Textural analysis showed a moderate BET specific surface area (18.22 m² g⁻¹) and an average pore diameter of approximately 1.9 nm, indicating a micropore-dominant pore system near the micro–mesopore boundary. These values fall within the range reported for low-temperature, non-activated biochars derived from agricultural residues and are primarily attributed to pore development through volatile release rather than chemical activation (Lehmann and Joseph, 2015; Remmani et al., 2024). Overall, the measured physicochemical and structural properties of the produced biochar fall within the range reported for seed- and pit-derived biochars produced at similar pyrolysis temperatures. While no application-specific performance was assessed in this study, the findings provide a well-defined material baseline for future studies into specific soil or environmental functions under controlled conditions.

Conclusion

This study demonstrates that slow pyrolysis of date palm pits (*Phoenix dactylifera* L.) at 350 °C produces biochar with distinct and quantifiable physicochemical and structural properties governed by feedstock composition and low-temperature thermal conditions. The produced biochar exhibited a high yield (75%), low ash content (1.22%), moderate fixed carbon content (27.3%), and an acidic pH (4.46), reflecting incomplete carbonization and retention of oxygen-containing functional groups. Textural and surface analyses revealed a measurable BET specific surface area of 18.22 m² g⁻¹, an average pore diameter of approximately 1.9 nm indicative of micropore-dominant porosity near the micro–mesopore boundary, and a cation exchange capacity of 20.45 cmol(+) kg⁻¹. SEM–EDX, FTIR, and XRD analyses confirmed a carbon-rich surface chemistry with diverse oxygenated functional groups and a predominantly amorphous, turbostratic carbon structure. Overall, the findings provide a detailed material-level analysis of palm pit-derived biochar produced using low-temperature slow pyrolysis. While this study did not assess application-specific soil or environmental performance, the measured properties are consistent with those reported for lignocellulosic biochars, indicating that date palm pit residues are a viable feedstock for biochar production within sustainable waste management and circular bioeconomy frameworks. Future studies should focus on assessing performance under controlled application conditions.

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