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Valorization of Date Palm Residues for Biochar Production:
Assessing Biochar Characteristics for Agricultural Application

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Highlights

- Optimized pyrolysis yields 44.95% biochar at 500°C from date palm residues.
- Structural and chemical analyses revealed porous biochar with the potential for enhancing soil health and productivity.
- Date palm biochar is suitable for enhancing soil fertility and offering a sustainable solution for waste management.

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Valorization of Date Palm Residues for Biochar Production: Assessing Biochar Characteristics for Agricultural Application

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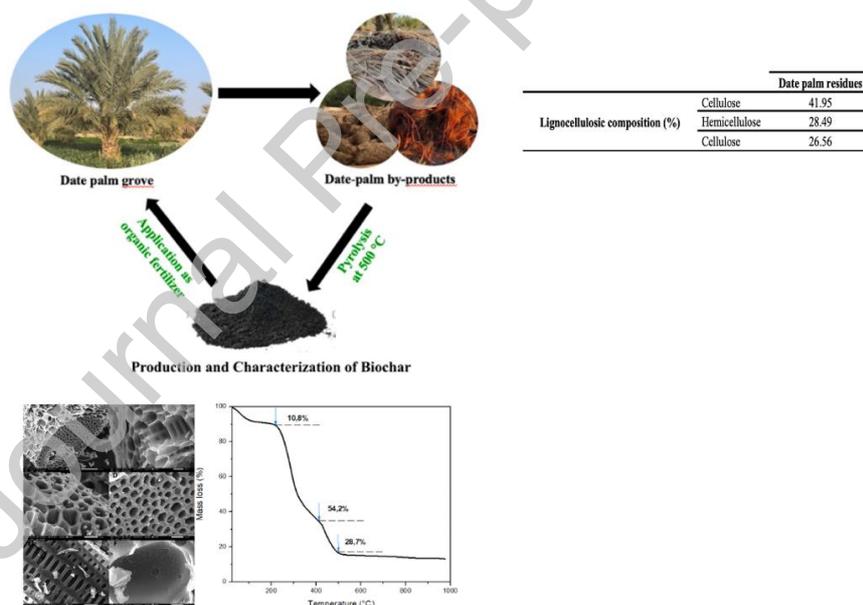
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Graphical Abstract



Abstract

Date palm residues are abundant in many arid and semi-arid regions, presenting both an environmental challenge and an opportunity for sustainable resource management. This study evaluates the valorization of date palm residues through slow pyrolysis at 500 °C to produce biochar suitable for agricultural soil enhancement. The date palm residues, which

consist of 41.95% cellulose, 28.49% hemicellulose, and 26.56% lignin, were processed to yield biochar with a production efficiency of 44.95%. The biochar's physicochemical properties were extensively analyzed, showing a fixed carbon content of 70.74%, a pH of 9.19, and a cation exchange capacity (CEC) of 68.05 cmol/kg. Elemental analysis revealed high carbon (71.9%) and low nitrogen (0.74%) content, indicating its stability and potential for long-term carbon sequestration. Thermogravimetric analysis (TGA) indicated thermal stability, while scanning electron microscopy (SEM) revealed a highly porous structure, beneficial for water retention and microbial colonization. These findings demonstrate that the slow pyrolysis process yields biochar with favorable properties, making it a promising amendment for soil fertilization. This study highlights the potential of biochar production in transforming date palm waste into valuable resources while mitigating the environmental impacts and costs associated with its disposal.

Keywords

Date palm wastes, pyrolysis, biochar, characterization, soil fertility, agricultural application.

1. Introduction

Date palm (*Phoenix dactylifera*) is one of the most widely cultivated trees globally, grown in various regions across the world (Alkhasha et al., 2020). It is primarily cultivated in North Africa and the Middle East, considered major production hubs. Additionally, date palm cultivation is prevalent in other arid and semi-arid regions, including Southern Africa, Pakistan, the USA, South America, Mexico, India, Australia, and several other countries (Sizirici et al., 2021). According to the latest statistics from the Food and Agriculture Organization (FAO) in 2021, the total harvested area for date palms was 1,235,601 hectares, producing 9,454,213 tons of dates (FAO, 2021). In Morocco alone, there are nearly 7 million palm trees spread over 61,332 hectares (FAO, 2021). The cultivation of date palms in Morocco is concentrated in the southeastern oases of the country, primarily in the regions of Draâ-Tafilalet, Sous-Massa, Oriental, and Guelmim-Oued Noun (Moujaoui et al., 2021).

Annually, palm trees generate large amounts of lignocellulosic residues, such as petioles, rachises, leaflets, fibrillium, bunches, thorns, and date stones, estimated to reach between 33 to 35 kg per tree (Makkawi et al., 2019). This biomass is primarily derived from the seasonal

pruning process, which is an essential agricultural practice (Fseha et al., 2022). Unfortunately, many farmers dispose of these organic residues by piling them in open fields, sending them to landfills, or burning them in the open air (El Janati et al., 2021). These inappropriate management options are not environmentally friendly and can lead to fire accidents, greenhouse gas emissions, infestation by pests, and environmental problems closely related to human health (Zubair et al., 2020). There are various ways to valorize DPR, including its use as biocombustible, animal feed, organic fertilizer through composting, or in the manufacturing of decorative objects (Bensidhom et al., 2018). Nevertheless, DPR has low nitrogen concentrations for composting and may produce final products carrying pathogens (Lepesteur, 2021).

The utilization of biomass offers a significant advantage in promoting a circular economy and sustainability. One of the key attractions of lignocellulosic biomass is its renewability, ensuring a continuous supply of resources without depletion (Ghodake et al., 2021). In this context, thermal pyrolysis has emerged as an innovative approach for converting lignocellulosic residues into valuable products (Sharma et al., 2022). This process enables the transformation of diverse waste materials, regardless of their complicated nature, feedstock composition, or pathogens contamination (Lee et al., 2021). By utilizing biomass resources and adopting thermal pyrolysis, organic residues such as DPR can be minimized and disinfected to produce high-value by-products, thus extending the lifecycle of resources, reducing environmental impacts, and creating economic value (Merlin, 2023).

Biochar can be defined as a black, solid carbonaceous material with a porous structure (Lehmann & Joseph, 2009). Due to its aromatic structure, biochar is more chemically and biologically stable than the initial feedstock (Ben Salem et al., 2021). Thermal pyrolysis involves the decomposition of organic substances at temperatures ranging from 300 to 1200 °C under oxygen-deficient conditions, resulting in three final products: bio-oil, pyrolysis gas, and biochar in varying proportions. The type of pyrolysis (slow, fast, or intermediate) depends on the associated process conditions (Joo et al., 2021). Slow pyrolysis, also known as carbonization, is characterized by a temperature typically around 500 °C, a longer residence time, and a slower heating rate of about 2, 5, or 10°C/min, favoring the formation of a significant portion of biochar (Yang et al., 2021).

Converting lignocellulosic biomass into biochar is a widely practiced method. The significant sources of lignocellulosic biomass are residues from agricultural activities and forest environments (Rangabhashiyam et al., 2019). In Morocco, a significant challenge that requires attention is the substantial residues generated from date palm production each year. This issue is particularly critical considering the country's prominent position in date palm cultivation. While several studies have utilized date palm residues as feedstock for pyrolysis, including those by (Hammani et al., 2020), (Makkawi et al., 2019), and (Giwa et al., 2019), limited research has been conducted on this aspect specifically in Morocco. However, Hammani et al. (2020) conducted a study dedicated to the valorization of date stone through pyrolysis, converting it into bio-oil and biochar using a fixed-bed reactor. From this perspective, this article presents the first investigation conducted in Morocco, focusing on the conversion of date palm residues into biochar using the slow pyrolysis process. The main objective of this research is to analyze and characterize the resulting biochar, with the aim of assessing its potential suitability for soil amendment purposes.

2. Material and methodology

2.1. Preparation of date palm biochar

The date palm residues (DPR) used in this study were collected from the Tafilalet date palm grove located in southeastern Morocco. The specific GPS coordinates of the collection site are 31.1344°N, 4.0155°W, which corresponds to the Erfoud area within the Tafilalet region. The selected site is known for its diverse cultivation of date palm varieties and high availability of agricultural residues. The residues primarily comprised a mixture of leaves, leaf stems, rachis, and free-fruit bunches. Upon collection, the DPR samples were sun-dried for two days under ambient conditions with a peak temperature of approximately 37 °C to reduce moisture content. Subsequently, the dried residues were oven-dried at 60 °C for 24 hours. The drying temperature of 60 °C was specifically chosen to prevent thermal deactivation of the biomass surface, as recommended by Abdelhafez et al. (2021). After drying, the DPR samples were manually chopped into smaller fragments to achieve a uniform particle size between 1–2 mm, ensuring consistency for pyrolysis. Pyrolysis of the DPR was carried out using a muffle furnace (DAIHAN LABTECH CO., LDT). The furnace was set to a heating rate of

10 °C/min, and the pyrolysis process was conducted at 500 °C for 4 hours under oxygen-limited conditions by placing the biomass in a porcelain crucible covered to restrict airflow. These pyrolysis parameters (500 °C for 4 hours, 10 °C/min heating rate) were chosen based on research by Keiluweit et al. (2010) and Singh et al. (2010), which indicates that this temperature and heating rate provide an optimal balance between biochar yield and quality. This combination enhances key properties such as surface area, porosity, and nutrient retention, which are crucial for agricultural applications (Yazhini et al., 2020). After pyrolysis, the mass of the DPR samples was recorded before and after the process to calculate the biochar yield. The biochar was left to cool inside the furnace overnight by free convection to avoid thermal shock. The cooled biochar was carefully transferred to an air-tight container to prevent moisture absorption until laboratory analysis.

2.2. Lignocellulose content determination

The DPR were analyzed for their hemicellulose, cellulose, and lignin content using the procedures outlined by Lee et al. (2017). The extractives were determined using a Soxhlet extractor on three sub-samples, each consisting of 1 g of biomass. Each of these 1 g biomass sub-samples was mixed with 60 mL of acetone and heated at 60°C for 6 hours. The resulting extract was dried in an oven at 110 °C and weighed. The content of extractives was calculated by weight difference. The hemicellulose content was determined through sodium hydroxide treatment, where 1 g of extractive-free feedstock was mixed with 150 mL of 0.5 M NaOH and agitated for 3.5 hours at 80 °C. The contents were filtered, washed, and dried to determine the hemicellulose weight. The lignin content was determined through a two-step acid hydrolysis process, where 300 mg of extractive-free biomass was mixed with 3 mL of 14M sulfuric acid and agitated for 2 hours. The solution was then diluted and autoclaved, cooled, filtered, and dried to determine the lignin weight. The cellulose content was finally calculated using equation (1), by subtracting the weights of the hemicellulose and lignin from the total feedstock weight.

$$\%W_{\text{cellulose}} = 100 - (\%W_{\text{hemicellulose}} + \%W_{\text{lignin}}) \quad (1)$$

Where %W is the weight percentage

2.3. Yield and proximate analyses of biochar

The yield of biochar production was calculated using equation (2) based on the initial mass of the DPR feedstock and the final mass of the produced biochar. The biochar yield was determined as follows:

$$\text{Biochar Yield (\%)} = (\text{Mass of Biochar (g)} / \text{Initial Mass of DPR (g)}) \times 100 \quad (2)$$

The pyrolysis experiments were conducted in triplicate to ensure reproducibility, and the results are expressed as mean values \pm standard deviation. The standard deviation (± 1.0) reflects the variability observed across the three replicates of the pyrolysis process.

The following proximate analyses: moisture, ash, and volatile matter of the DPR and the produced biochar were evaluated based on the ASTM D1762-84 standard method. Thus, the percentage of fixed carbon was determined by subtracting the contents of ash, volatile matter, and moisture from 100 (Schmidt et al., 2023).

The elemental composition of the ashes derived from date palm biochar was determined to assess its suitability for soil application. Ash composition plays a critical role in influencing soil properties, such as pH and nutrient availability. The biochar samples were subjected to wet digestion using concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) to break down the organic matrix and release the inorganic elements. After digestion, the samples were analyzed for essential macro- and micronutrients, including calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), and sodium (Na), using inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer Optima 4300 DV ICP-OES).

2.4. Ultimate analyses and elemental composition and heavy metals of biochar

The total C, H, N, and S content of the DPR and biochar samples were determined using an elemental analyzer (Thermo Scientific™ FlashSmart™). The difference was used as shown in equation (3) to estimate the percentage of oxygen content as follows:

$$\text{O (\%)} = 100 - (\text{C (\%)} + \text{H (\%)} + \text{N (\%)} + \text{S (\%)} + \text{ash (\%)})(3)$$

The biochar samples' soluble and total elemental composition of basic cations (Ca, Mg, Na, and K) were analyzed. The soluble cations (Ca, Mg, Na, and K) were determined in an aqueous extract (1:25), whereas the total elemental contents were determined using HNO_3 after wet

digestion (Imam & Capareda, 2012). The total and soluble concentrations of Na and K were measured using a flame photometer, while the total and soluble concentrations of Ca and Mg were measured using an inductively coupled plasma optical emission (ICP-OES) spectrometer (Perkin Elmer Optima 4300 DV ICP-OES).

Heavy metal concentrations in the biochar sample were determined using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), a standard method for quantifying trace elements in biochar and soil samples (Beesley et al., 2011; Uchimiya et al., 2011). Before analysis, the biochar was digested using a mixture of nitric and hydrochloric acids following established procedures for solid sample digestion (USEPA 3051A). The concentrations of lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), chromium (Cr), and zinc (Zn) were measured. The results were expressed in mg/L and compared against regulatory thresholds for agricultural applications, such as those set by the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI) (Lehmann & Joseph, 2015).

2.5. pH, Electrical conductivity, Cation exchange capacity, and Organic matter

The pH and electrical conductivity (EC) of the DPR and biochar samples were evaluated by shaking them in a uniform suspension with a 1:25 biochar-to-water ratio for 24 hours at 25°C. Digital pH and EC meters were used to measure the values of the homogeneous suspension and the aqueous extract (Aichour et al., 2022). The cation exchange capacity (CEC) was measured using the Na acetate solution method, followed by washing with alcohol. To determine the concentration of displaced Na, ammonium acetate was used and the concentrations were measured using a flame photometer (Alsewaileh et al., 2019). The organic matter content was measured by the Walkley-Black method (Walkley & Black, 1934).

2.6. Water retention capacity of biochar

To determine the water retention capacity of the produced biochar, the method described by (Gupta et al., 2018). was followed. Initially, 30 g of biochar was dried at 70°C for 24 hours to eliminate any moisture content. Three containers, containing 10 g of biochar and 100 g of distilled water were prepared and weighed. The containers were then sealed and left to stand for 48 hours. The resulting solutions were filtered through a cellulose filter under vacuum until no free water flow was observed. The weight of dry biochar was subtracted from the

weight of the soaked biochar to determine the amount of water absorbed (Al-Omran et al., 2019).

All the previous parameters were measured in triplicate to ensure precision and reliability.

2.7. Thermal stability

The thermal stability of isolated chemicals and weight change with temperature were investigated in this study using thermogravimetric analysis (TGA). A Linseis sta pt 1600 thermogravimetric analyzer was employed to analyze the feedstock and the produced biochar samples. Practically, 2 mg of the sample was placed in an aluminum crucible and heated at a rate of $10\text{ }^{\circ}\text{C min}^{-1}$ in an inert nitrogen gas atmosphere to a final temperature of $1000\text{ }^{\circ}\text{C}$. The resulting weight loss curves were analyzed to determine the temperature at which maximum weight loss occurred, and these values were used to generate a table representing the thermal degradation of lignocellulosic biomass (Suarez-riera et al., 2020).

2.8. SEM, FTIR, and XRD analyses of biochar

To investigate the surface morphology of the biochar, the samples were milled using a mortar and analyzed with a scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS). The SEM images were obtained using a JEOL IT500 HR microscope at an accelerating voltage ranging from 0.5 to 30 kV (Ben Salem et al., 2021). To characterize the functional groups of the feedstock and the biochar, Fourier transform infrared spectrometry (FTIR) was employed with a Bruker Vertex 80v to identify the different functional groups present in the samples, represented by their respective vibrational modes. The data were collected using the analytical tool MicroLab. In addition, X-ray diffraction (XRD) analysis of the biochar samples was conducted to identify the mineralogical phases. The analysis was performed using an XPERT-PRO instrument.

2.9. BET

To evaluate the surface area, pore volume, and pore size distribution of the biochar produced from date palm residues (DPR), the Brunauer-Emmett-Teller (BET) method was employed. The biochar samples were first degassed under vacuum at 150°C for 12 hours to remove any adsorbed moisture and impurities. The BET analysis was then conducted using nitrogen

adsorption-desorption isotherms at -196°C on a BET surface area analyzer (Micromeritics ASAP 2020) (Brunauer et al., 1938).

3. Results and discussion

3.1. Lignocellulosic components of the DPR

The lignocellulosic composition of the studied DPR sample is indicated in Table 1. It consists of 41.95 wt% cellulose, 28.49 wt% hemicellulose, and 26.56 wt% lignin. Accurate knowledge of the relative composition of these three biopolymers is crucial for conducting selective pyrolysis and predicting the expected fuel yield (Zadeh et al., 2020). Cellulose exhibits a greater capacity for generating bio-oil with enhanced organic content, reduced water content, and decreased solids content. In contrast, hemicellulose yields a higher volume of gas and produces a moderate amount of bio-oil characterized by higher water content and lower organic content (Yogalakshmi et al., 2022). Conversely, lignin generates a moderate level of bio-oil, a lower gas yield, and a considerably higher solids yield (Suresh et al., 2021). In the context of bio-oil and biochar production, lignocellulosic biomasses rich in cellulose are prioritized for bio-oil production, while biomasses abundant in lignin are preferred for biochar production (Wang et al., 2022). The lignocellulosic composition of the DPR resembles that reported in a study by Nasser et al. (2016) and that of Inayat et al. (2023). However, it differs from other lignocellulosic biomasses such as banana peel (cellulose:65%, hemicellulose: 8%, lignin: 10%) and aloe vera rind (cellulose:58%, hemicellulose: 16%, lignin: 14%), which have higher cellulose proportions and lower hemicellulose and lignin proportions banana peel and aloe vera rind (Lee et al., 2021). Considering the lignocellulosic composition of the DPR mixture, it demonstrates significant potential as a feedstock for pyrolysis to generate valuable biochar and various other pyrolysis products (Inayat et al., 2023; Sait et al., 2022)

Table 1. Proximate and ultimate analysis of date palm residues and their derived biochar

		Biomass	Biochar
Proximate analysis (Percentage weight dry basis)	Fixed carbon	26.03	70.74
	Volatile matter	66.3	9.01
	Ash	7.63	20.25
	Moisture	11.02	3.52

Ultimate analysis (Percentage weight dry basis)	Carbon (C)	45.02	71.9
	Hydrogen (H)	5.6	1.89
	Nitrogen (N)	0.36	0.74
	Sulphur (S)	0.24	0.68
	Oxygen (O)	48.78	28.74
	Phosphorus (P)	<0.01	0.2
	Potassium (K)	1.36	2.1
	Calcium (Ca)	2.49	5.51
	Magnesium (Mg)	0.59	2.03
Lignocellulosic composition (%)	Cellulose	41.95	-
	Hemicellulose	28.49	-
	Cellulose	26.56	-
Physicochemical analysis	pH	5.85	9.19
	EC (dS m ⁻¹)	2.89	7.92
	CEC (cmol kg ⁻¹)	41.57	68.05
Organic matter	OM (%)	90.91	30.83

2.10. Yield and proximate analyses of DPR and the produced biochar

In this study, a biochar yield of $44.95 \pm 1.0\%$ was obtained, calculated as the mean value from three replicate experiments. The variability ($\pm 1.0\%$) represents the standard deviation, demonstrating consistent results across all replicates. This yield was achieved under pyrolysis conditions of $500\text{ }^{\circ}\text{C}$ for 4 hours, with a heating rate of $10\text{ }^{\circ}\text{C}/\text{min}$, implying that the DPR were less resistant to higher temperatures, most likely due to weaker functional group bonds and the higher decomposability of its material and structure (Banitalebi et al., 2019). The increased loss of volatile materials and greater weight loss from biomass during pyrolysis under low oxygen circumstances can also explain the biochar production rate. This conclusion agrees with the findings of Al-Wabel et al. (2019), who reported a yield of $41.32 \pm 0.61\%$ at a pyrolysis temperature ($600\text{ }^{\circ}\text{C}$), a shorter pyrolysis period (3 hours), and a slower heating rate ($5\text{ }^{\circ}\text{C}/\text{min}$). The study by Elnour et al. (2019) reported a slightly lower yield of 35% using a similar pyrolysis temperature ($500\text{ }^{\circ}\text{C}$) but with a shorter pyrolysis time of 2 hours and the same heating rate ($10\text{ }^{\circ}\text{C}/\text{min}$). Another recent study by Alghamdi et al. (2023) found a yield of $35.47 \pm 3.25\%$ at $550\text{ }^{\circ}\text{C}$, 3 hours, and a heating rate of $10\text{ }^{\circ}\text{C}/\text{min}$, which is also lower than the observed yield. These comparative results suggest that the initial composition of the feedstock and the pyrolysis conditions, including temperature, residence time in the reactor, and heating rate can influence the biochar yield, with higher

temperatures generally leading to lower yields. However, further investigation and analysis are required to fully understand the factors affecting DP biochar yield under different pyrolysis conditions.

The proximate and ultimate analysis results of the biomass and the produced biochar are presented in Table 1. This study's proximate analysis of the biochar revealed a fixed carbon content of 70.74%, volatile matter of 9.01%, ash content of 20.25%, and moisture content of 3.52%. These characteristics have direct implications for soil applications.

The high fixed carbon content suggests that the biochar is highly stable and resistant to decomposition, making it a valuable long-term carbon sink in soils. Biochar with high fixed carbon content remains in the soil for longer periods, improving soil organic matter and aiding in carbon sequestration, which is critical for mitigating climate change (Lehmann & Joseph, 2009). Additionally, stable biochar increases soil aeration and enhances water retention, which are essential for improving soil structure and promoting plant growth (Obia et al., 2016).

The low volatile matter content (9.01%) also points to greater biochar stability. Low volatile matter means fewer volatile organic compounds are released from the biochar when applied to soil, reducing the risk of negative effects on plant growth or soil microorganisms. Biochar with low volatile matter contributes to improved microbial habitat in soils, promoting the activity of beneficial microorganisms (Qin et al., 2022). These microbes help in nutrient cycling, making essential nutrients like nitrogen and phosphorus more available to plants (Obia et al., 2016).

The biochar's moisture content (3.52%) is low, suggesting that it can absorb and retain water when applied to soils, improving the soil's water retention capacity. This is particularly beneficial in arid and semi-arid regions where water scarcity is a challenge. The porous structure of biochar allows it to retain moisture and provide a more consistent water supply to plants, improving drought resistance (Obia et al., 2016).

In terms of ash content, the analysis revealed that the date palm biochar contains 20.25% ash, which closely aligns with the findings of Sik et al. (2017) at 19.68%, though slightly lower than the values reported by Alkhasha et al. (2020) and Alghamdi et al. (2022), who observed

ash contents of 25.7%. The relatively high ash content suggests a substantial presence of essential minerals such as calcium, magnesium, potassium, and phosphorus, which are critical for plant growth and soil fertility (Wang et al., 2022). This is further confirmed by the detailed ash composition analysis mentioned in Table 2, which showed that potassium oxide (K_2O) was the most abundant component at 25.45%. Potassium is vital for root development, water regulation, and enhancing plant resilience, making biochar especially beneficial for potassium-deficient soils (Rehrah et al., 2015). Additionally, silicon dioxide (SiO_2) was found at 18.62%, a significant contributor to improving soil structure and enhancing plant resistance to environmental stressors, both biotic and abiotic (Wang et al., 2022). Calcium oxide (CaO), which comprised 12.78% of the ash, plays a crucial role in neutralizing soil acidity due to its liming effect and contributes to soil pH regulation, making nutrients more accessible to plants (Lehmann & Joseph, 2015). Magnesium oxide (MgO) at 7.33% is also essential for plant photosynthesis and soil buffering capacity. Phosphorus pentoxide (P_2O_5), though present at a lower concentration of 3.52%, is critical for root development and energy transfer in plants (Zhang et al., 2021). Iron oxide (Fe_2O_3) at 2.15% and sodium oxide (Na_2O) at 2.05%, while present in smaller amounts, also contribute to soil nutrient balance and structural integrity (Rees et al., 2014).

The high ash content and mineral composition suggest that date palm biochar has substantial potential as a soil amendment, particularly in nutrient-poor or acidic soils. The biochar's high potassium content positions it as an excellent slow-release fertilizer, while its calcium and magnesium levels enhance soil structure and buffering capacity, making it highly effective in managing acidic soils (Ahmad et al., 2014; Agegnehu et al., 2017). The relatively low sodium content ensures that the biochar can be used safely in a variety of soils without increasing the risk of salinity, which could otherwise negatively impact soil health and crop productivity (Rees et al., 2014). Additionally, the silicon content in the biochar may improve plant resistance to environmental stresses such as drought and pest infestations, making it particularly valuable in arid and semi-arid regions (Yongchao et al., 2015).

Table 2. Ashes composition of date palm biochar

Component	Percentage (%)
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Potassium Oxide (K ₂ O)	25.45
Silicon Dioxide (SiO ₂)	18.62
Calcium Oxide (CaO)	12.78
Magnesium Oxide (MgO)	7.33
Phosphorus Pentoxide (P ₂ O ₅)	3.52
Iron Oxide (Fe ₂ O ₃)	2.15
Sodium Oxide (Na ₂ O)	2.05
Aluminum Oxide (Al ₂ O ₃)	1.87

2.11. Ultimate analyses and the organic matter of the produced biochar

The ultimate analysis of the biochar produced in this study revealed a carbon content of 71.9%, hydrogen content of 1.89%, nitrogen content of 0.74%, sulfur content of 0.68%, and oxygen content of 28.74%. Comparing these results with previous studies, it was found that the carbon content in the DP biochar (71.9%) was similar to the findings of Al-Wabel et al. (2019) for DP biochar (76.23%), but higher than the values reported by Jouiad et al. (2015) (60.9%) and Usman et al. (2015) (72.30%). The high carbon content (71.9%) of the produced biochar suggests that it is highly stable, meaning it will resist decomposition over time, making it suitable for long-term carbon sequestration in soils (Lehmann & Joseph, 2009). This high carbon content also indicates that the biochar has a strong potential to improve soil organic carbon levels, which can enhance soil structure, water retention, and microbial habitat (Obia et al., 2016). Additionally, the presence of recalcitrant carbon means that biochar can remain in the soil for years or even decades, contributing to the sustained enhancement of soil quality. The low hydrogen content (1.89%) is a sign of a more aromatic biochar structure, which further increases its soil stability. This is beneficial because biochars with low hydrogen content have a reduced tendency to break down and release gases into the soil environment (Qin et al., 2022). The nitrogen content (0.74%) of our biochar is comparable to previous findings by Jouiad et al. (2015) and Usman et al. (2015). Although the nitrogen content is low (as is common in biochars produced at higher temperatures), biochar can enhance nitrogen retention in soils by improving the soil's cation exchange capacity (CEC) and reducing nitrogen leaching (Qin et al., 2022). This makes

biochar particularly useful in agricultural systems where nitrogen loss is a concern. By acting as a nutrient reservoir, biochar can slow the release of nitrogen into the soil, ensuring its availability for plant uptake over a longer period.

The biochar's oxygen content (28.74%) is higher than that reported for other biochars such as corn stover (Mohan et al., 2018). Oxygen-rich biochars contain various functional groups (e.g., carboxyl and hydroxyl groups) that enhance nutrient retention and improve soil microbial activity, which are essential for nutrient cycling and soil fertility (Obia et al., 2016).

Biochar produced from date palm residues (DPR) exhibited significant concentrations of key nutrients, including calcium (Ca: 5.51%), magnesium (Mg: 2.03%), potassium (K: 2.1%), and phosphorus (P: 0.2%). These elements are essential for improving soil fertility and supporting plant growth. Calcium and magnesium play critical roles in enhancing soil structure, contributing to aggregate stability, increasing water retention, and reducing soil compaction (Usman et al., 2015). Such improvements in soil physical properties are crucial for optimizing root development and overall plant health in degraded soils (Radulov & Berbecea, 2024). The presence of calcium in particular indicates the potential for the biochar to act as a liming agent, effectively neutralizing acidic soils by raising the soil pH, a property that can improve nutrient availability in acidic conditions. Additionally, potassium is a crucial nutrient that regulates plant physiological processes such as water uptake and disease resistance, which enhances the biochar's value as a soil amendment in nutrient-poor soils (Wang et al., 2022). The relatively low concentration of phosphorus in the biochar may still provide sufficient amounts for root development and energy transfer, supporting overall plant growth (Rehrah et al., 2015).

The biochar produced in this study contained 30.83% organic matter, closely matching the findings of Alkhasha et al. (2020), who reported 30.32%. This organic matter is important for improving soil organic content, which is crucial for enhancing soil structure and water retention, particularly in arid and semi-arid regions where soil organic matter is typically low (Lehmann & Joseph, 2009). The organic matter in biochar also supports the microbial biomass in the soil, which further promotes soil health and nutrient availability (Obia et al., 2016). These variations in the ultimate analysis parameters, such as carbon, nitrogen, and

basic cations, highlight the influence of feedstock composition and pyrolysis conditions on the elemental composition of biochar (Kambo & Dutta, 2015).

The composition of the biochar produced in this study falls within the range of biochars commonly used for soil amendment. For example, Al-wabel et al. (2019) reported biochar produced from date palm leaflets with a similar carbon content (76.23%), which was highly effective in improving soil organic carbon content and promoting soil stability in sandy soils. Similarly, Qin et al. (2022) demonstrated that biochars with high fixed carbon and low volatile matter, similar to the values observed in this study, are associated with increased carbon sequestration and enhanced soil fertility by improving water retention and nutrient retention in agricultural soils.

Additionally, studies have shown that biochar produced from other lignocellulosic biomasses, such as corn stover biochar (Mohan et al., 2018), with comparable carbon and ash contents, has been successfully used to increase soil carbon storage and microbial activity, resulting in improved plant growth and crop yields. In the case of pine wood biochar, which has been reported to have a fixed carbon content of around 80.3% (Al-wabel et al., 2019), its application to soils significantly enhanced nutrient cycling and long-term soil productivity, making it a common choice for sustainable agriculture.

2.12. Physicochemical characteristics of the DPR and the produced biochar

The initial pH value of the feedstock was 5.85, whereas the resulting biochar exhibited an alkaline pH of 9.19. This increase in pH was primarily attributed to the rise in temperature during pyrolysis. Increasing the temperature during pyrolysis decreases acidic functional groups and increases basic functional groups, leading to an increased pH with a liming effect. The increase in ash content in the produced biochar is another factor contributing to its alkaline nature, as ash contains alkali salts that separate from organic compounds during pyrolysis (Banitalebi et al., 2019). In general, biochars produced through pyrolysis tend to display alkaline characteristics, typically falling within the pH range of 7.5 to 9.4 (Matos et al., 2021).

The alkaline pH of biochar is highly beneficial for soil amendment, particularly in acidic soils, where it can effectively neutralize soil acidity and create a more favorable environment for plant growth and microbial activity (Rehrah et al., 2015). Soils with higher pH levels often exhibit improved nutrient availability, especially for essential nutrients such as nitrogen, phosphorus, and potassium, which tend to be more accessible to plants in neutral to slightly alkaline soils (Sarfaraz et al., 2020). As such, the application of alkaline biochar can improve soil fertility, enhancing crop productivity while simultaneously promoting a healthier soil ecosystem (Alfattani et al., 2022).

In the present study, the DPR had a lower EC value (2.89 dS m^{-1}) compared to the obtained biochar (7.92 dS m^{-1}). This could be related to the accumulation of recalcitrant ionic species and the separation of soluble salts from the organic compounds during pyrolysis (Alghamdi, 2020). Soil amendment with biochars that possess adequate EC values can improve soil fertility by enhancing ion exchange and nutrient availability in soils, making it easier for plants to absorb essential nutrients like calcium, magnesium, and potassium (Sarfaraz et al., 2020). However, it's important to monitor EC values closely, as overly high EC levels could lead to salinity stress in sensitive plants. Consistently, CEC was calculated to be $68.05 \text{ cmol kg}^{-1}$ for date palm biochar, whereas DPR had a CEC of $41.57 \text{ cmol kg}^{-1}$. This increase in CEC can be attributed to the concentration of exchangeable cations during pyrolysis and the formation of carboxylic groups on the biochar surface, enhancing its ability to retain nutrients (Inyang et al., 2010; Bhat et al., 2022). High-CEC biochars like the one produced in this study are particularly effective in soils where nutrient leaching is a concern, as they can hold nutrients in the soil and release them slowly over time, improving the synchronization between nutrient availability and plant nutrient uptake (Wang et al., 2022). One of the positive effects of applying biochar produced at high temperatures ($\geq 500^\circ\text{C}$) is the improvement of the soil's CEC due to the biochar's high surface area and charge density, making it a useful tool for long-term nutrient management in soils (Rehrah et al., 2015). High-CEC biochars can serve as slow-release amendments, maintaining nutrient availability in the soil and supporting sustained plant growth.

The water retention capacity of the biochar, expressed as the amount of water absorbed per gram of dry biochar, was found to be 2.17 grams of water per gram of dry biochar, consistent

with the results documented by Suarez-Riera et al. (2020). Biochars with high water retention capacity can significantly improve the water-holding capacity of soils, particularly in arid and semi-arid regions, where water availability is a limiting factor for plant growth. By improving soil moisture retention, biochar can reduce the need for frequent irrigation, making it a valuable amendment in water-scarce environments (Lehmann & Joseph, 2009).

2.13. Heavy metals assessment

The analysis of heavy metals in date palm biochar, as shown in Table 3, suggests that it is safe for agricultural use based on international safety standards, such as those outlined by the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC). According to these standards, the permissible thresholds for heavy metals in biochar intended for soil application are as follows: arsenic (As) ≤ 13 mg/kg, cadmium (Cd) ≤ 1.5 mg/kg, chromium (Cr) ≤ 90 mg/kg, lead (Pb) ≤ 120 mg/kg, and mercury (Hg) ≤ 1 mg/kg (IBI, 2015; EBC, 2020). The concentrations of heavy metals in the biochar produced in this study are well below these limits, ensuring its suitability for agricultural applications. The lead concentration was measured at 0.0374 mg/L, significantly below the European Biochar Certificate (EBC) limit of 120 mg/kg. Lead is a concern in biochar due to its potential to accumulate in soil and crops. Still, the low concentration observed in DPBC suggests a minimal risk of contamination in agricultural settings. Similar findings regarding low lead concentrations in biochar from plant residues have been reported in other studies (Beesley et al., 2011; Cao et al., 2009).

Cadmium, another heavy metal of concern due to its high toxicity even at low concentrations, was present at 0.0437 mg/L. This is well within the acceptable limits established by the International Biochar Initiative (IBI), which allows cadmium concentrations up to 1 mg/kg. The low cadmium content ensures that DPBC will not contribute to harmful accumulation in soils or plants, which is essential for maintaining food safety. Research has similarly indicated that biochar derived from plant residues generally has low cadmium concentrations (Khan et al., 2017). Nickel was found at undetectable levels (<0.01 mg/L), which is beneficial for agricultural biochar as excessive nickel can hinder plant growth and microbial activity in the soil. The absence of detectable nickel further supports the safety of DPBC for use in soil amendment. These findings align with previous studies on biochar, which report minimal

nickel content in plant-based biochars (Lehmann & Joseph, 2015). Similarly, arsenic, a toxic and carcinogenic element, was also undetectable in DPBC. The absence of arsenic confirms that this biochar will not introduce a significant risk of soil or water contamination, which is crucial for long-term agricultural sustainability. Arsenic is often found in trace amounts in biochars derived from contaminated biomass, but plant-based biochar typically has very low or undetectable levels (Beesley et al., 2011). Chromium was measured at 0.0334 mg/L, a concentration well below the EBC's threshold of 90 mg/kg. While certain forms of chromium, such as hexavalent chromium (Cr(VI)), can be highly toxic, the total chromium levels in DPBC are low, ensuring that it does not pose a risk to soil health or crop safety. Studies on biochar produced from agricultural residues, such as date palm, have demonstrated similarly low chromium levels (Ronsse et al., 2013). Zinc, an essential micronutrient for plants, was present at 0.0183 mg/L in DPBC. This concentration is low, but it may contribute positively to soil fertility by providing a small amount of zinc, which is beneficial for plant growth. At these low concentrations, zinc is unlikely to reach toxic levels in soils amended with DPBC biochar. Similar low levels of zinc in biochar derived from plant-based residues have been discussed in previous literature (Soria et al., 2020).

Table 3. Heavy Metal Composition and Risk Assessment of Date Palm Biochar Compared to EBC/IBI Safety Limits

Heavy Metal	Concentration (mg/L)	EBC/IBI Limit (mg/kg)	Risk Level
Lead (Pb)	0.0374	120	Minimal
Cadmium (Cd)	0.0437	1	Low
Nickel (Ni)	<0.01	-	None
Arsenic (As)	Undetectable	-	None
Chromium (Cr)	0.0334	90	Low
Zinc (Zn)	0.0183	-	Beneficial (low conc.)

2.14. Scanning electron microscopy

Scanning Electron Microscopy (SEM) is a highly accurate technique for examining the surface morphology of biochar. In Figure 1, SEM images reveal a highly porous structure with various pore shapes, including micropores (<2 nm), mesopores (2-50 nm), and macropores (>50 nm) (Zubair et al., 2020). The biochar surface morphology displayed different types of pores, such as cylindrical and polygonal pores, interspersed with several large pores. These well-developed pores are arranged in a honeycomb-like pattern. The formation of pores can be attributed to the volatilization of organic materials like hydrogen, carbon monoxide, and methane during pyrolysis. The variation in pore volume is due to chemical changes that occurred during pyrolysis (Saremi et al., 2020). The pore structure of biochar plays a crucial role in improving soil physical properties when incorporated into soils. Macropores (>50 nm) are particularly important for facilitating essential soil functions, including aeration, hydraulic conductivity, and root expansion, which are critical for supporting plant growth and water movement through the soil (Obia et al., 2016). These large pores provide habitats for soil microorganisms, such as bacteria, fungi, and actinomycetes, which range in size from 0.5 to 5 μm . These microbes are essential for nutrient cycling, organic matter decomposition, and enhancing soil fertility (Samoraj et al., 2022).

Mesopores and micropores in biochar are equally beneficial. Mesopores (2-50 nm) help in water retention and nutrient storage, ensuring that plants have access to moisture during periods of drought. Micropores (<2 nm), on the other hand, significantly increase the surface area of biochar, enhancing its capacity to adsorb nutrients such as nitrogen, phosphorus, and potassium, which prevents nutrient leaching and promotes their gradual release back into the soil (Yang et al., 2021). This increased surface area also fosters microbial colonization, creating favorable environments for beneficial microbial communities that enhance plant nutrient uptake and improve soil health. The honeycomb-like porous structure observed in the SEM images can introduce new pore spaces into soils, improving the soil structure and providing aeration and water retention capacity. Soils with biochar amendments exhibit better water storage, which is particularly beneficial in arid and semi-arid regions where water scarcity can limit plant productivity (Horák et al., 2020). The pores also provide physical protection for microbial communities, allowing them to thrive and function more effectively in nutrient cycling and organic matter breakdown (Obia et al., 2016).

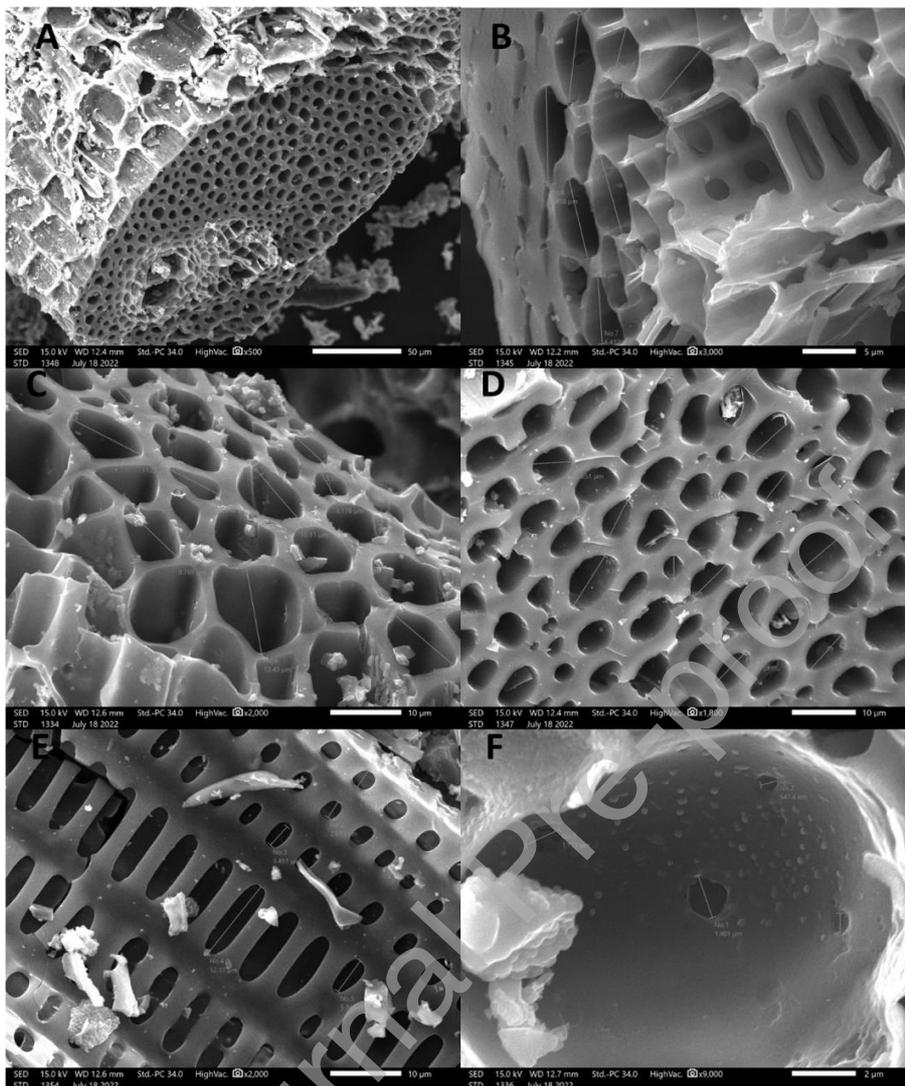


Figure 1. Scanning Electron Microscopy (SEM) images of date palm biochar illustrating its structural features at varying magnifications: (A) overview of the macroporous architecture, (B) detailed image of pore walls and cavities, (C) micro-scale porosity promoting adsorption, (D) uniform honeycomb-like pores, (E) elongated and irregular macrochannels, and (F) intact cross-sectional view of a biochar particle. These structures contribute to enhanced soil aeration, water retention, and microbial colonization.

2.15. Thermogravimetric analysis of DPR

To assess the bioenergy potential of the feedstock, it is necessary to obtain reaction kinetics from the thermal degradation process. This can be achieved by analyzing the thermogravimetric (TG) curve, which shows the mass loss at increasing temperatures and a fixed heating rate (Lee et al., 2017). In this study, the effect of heating on the percentage of mass loss of DPR was investigated at a fixed heating rate of $10\text{ }^{\circ}\text{C min}^{-1}$ in an N_2 atmosphere over a temperature range of approximately 1000°C , and the results are shown in Figure 2. The TG curves obtained during the pyrolysis process of the DPR indicate the degradation stages of the main organic compounds in the feedstock, namely hemicellulose, cellulose, and lignin (Karampinis et al., 2012).

Three distinct stages were observed in the TG curves. The first stage showed an initial mass reduction of 10.8% from ambient temperature to around 224°C , attributed to the release of moisture and light volatiles, which can be classified as the drying phase. The second stage, occurring from 224°C to approximately 512°C , was characterized by significant mass degradation of 54.2% and is considered the key pyrolysis stage. The third stage, between 400°C and 512°C , showed a mass loss of 28.7%, corresponding to the decomposition of lignin. Lignin degradation starts at temperatures above 420°C and continues up to 512°C . The most critical devolatilization of the feedstock was observed between 180°C and 500°C , known as the active pyrolysis zone (Müsellim et al., 2018). This temperature range includes the degradation of hemicellulose, cellulose, and lignin, with distinct zones for each component. The low-temperature zone (224°C to 336°C) is where hemicellulose degradation occurs, while the medium-temperature zone (336°C to 420°C) corresponds to cellulose degradation. Lignin decomposition starts at temperatures above 420°C and continues up to 512°C . The final stage, referred to as the passive zone, starts after 512°C when devolatilization stops, and carbon and ash remain as the final solid residue.

The results obtained in this study align with previous research on date palm residues. Makkawi, El, et al. (2019) reported a temperature range for major devolatilization between $200\text{-}525^{\circ}\text{C}$, and Ben Salem et al. (2021) found a similar range of $210\text{-}520^{\circ}\text{C}$. In this study, the range for devolatilization was observed between $224\text{-}512^{\circ}\text{C}$, which is consistent with findings by Nasser et al. (2016). The thermogravimetric analysis (TG) results provide

valuable insights into the stability and carbon content of the biochar produced at different pyrolysis stages. The temperatures at which hemicellulose, cellulose, and lignin degrade influence the biochar's chemical composition and its effectiveness as a soil amendment. For example, biochars produced in the active pyrolysis zone (180°C-500°C) tend to have a higher fixed carbon content, which makes them more stable when applied to soils, contributing to long-term carbon sequestration and improving soil organic matter (Lehmann & Joseph, 2009).

The decomposition of lignin at higher temperatures (above 420°C) results in biochars with high recalcitrant carbon content, enhancing their ability to persist in soils for extended periods without rapid decomposition. This characteristic is essential for soils that require long-term fertility management and carbon storage (Mohan et al., 2006). Moreover, biochars produced at higher temperatures tend to have better adsorption properties, which can improve nutrient retention in soils, particularly in preventing the leaching of critical nutrients such as nitrogen, phosphorus, and potassium (Pariyar et al., 2020). The final carbon and ash residues produced after the passive zone (512°C and above) contain essential minerals such as calcium, magnesium, and potassium, which are critical for soil fertility. The ash fraction can act as a liming agent, helping to neutralize soil acidity and improve nutrient availability (He et al., 2022). Soils that are acidic or nutrient-deficient can benefit from biochars rich in these basic cations, enhancing plant growth and crop yields (Yadav et al., 2024). The reaction kinetics derived from the TG curve also provide insights into the biochar's energy potential, which can be leveraged in bioenergy applications. However, for soil applications, the focus is on the biochar's ability to improve soil physical and chemical properties, particularly its role in enhancing soil structure, increasing water retention, and fostering microbial activity, which contributes to sustainable agricultural practices (Murtaza et al., 2021).

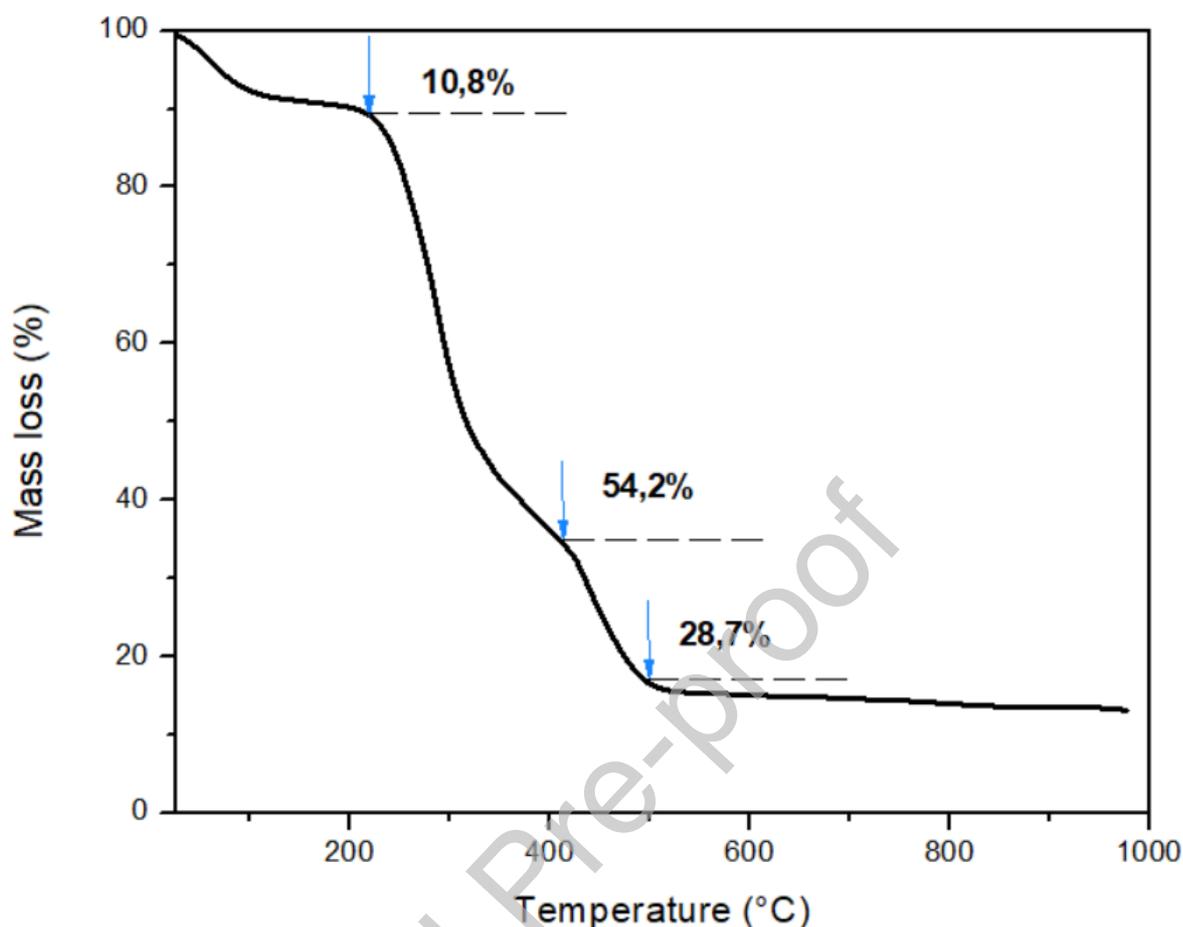


Figure 2. Thermogravimetric analysis of biochar produced from Date Palm Residues (DPR), showing mass loss (%) at different temperature stages: moisture evaporation (10.8% below 200°C), decomposition of hemicellulose and cellulose (54.2% between 200–400°C), and lignin degradation (28.7% between 400–600°C).

2.16. Fourier transform infrared spectroscopy

The biochar produced from DPR was analyzed using FTIR spectroscopy to identify the chemical groups present in the material. The FTIR spectra demonstrated that the pyrolysis of date palm residues significantly altered their chemical composition. As shown in Figure 3, the devolatilization effect was evident, with peaks observed between 2855 and 2926 cm^{-1} , 1438 and 1443 cm^{-1} , and at 721 cm^{-1} , attributed to C–H stretching, CH_2 and CH_3 deformation, and C–H rocking of alkane groups, respectively (Coates, 2006). This indicates that bond cleavage of alkane groups, likely from hemicellulose, cellulose, and lignin, occurred

during pyrolysis (Leng et al., 2011). Peaks corresponding to aromatic compounds (884 and 1593 cm^{-1}) and carboxylic acids (1581 cm^{-1} and 1579 cm^{-1}) were also present in the biochar, signifying the formation of these compounds as a result of pyrolysis.

When compared with biochars derived from other feedstocks, such as rice husk and wood residues, this study identified unique intensities at 721 cm^{-1} for alkane-related functional groups. Volli et al. (2021) reported similar transformations, but the prominence of alkane peaks in date palm biochar highlights its distinct lignocellulosic profile. Studies that focused specifically on date palm residues, such as Hammani et al. (2020) and Jouiad et al. (2015), also identified carboxyl and aromatic groups in biochars, but the variation in alkane intensities in this study suggests that feedstock composition and pyrolysis conditions significantly influence the resulting chemical structures. The FTIR spectra in this work are consistent with Makkawi et al. (2019), who observed similar aromatic peaks in date palm-derived biochars. However, the presence of a more prominent alkane peak (721 cm^{-1}) in this study highlights the distinct chemical signature of biochar produced from a mixture of date palm residues.

Overall, the FTIR analysis revealed structural changes in various chemical groups, such as alkanes, alcohols, alkyl halides, carboxylic acids, and aromatic compounds. These findings align with the observed changes in elemental atomic ratios, indicating increased carbonization due to cracking and the reconstruction of aromatic rings (Bavariani et al., 2019).

The functional groups identified in the biochar, such as carboxyl, carbonyl, and amine groups, are crucial for soil applications as they serve as chelating agents, enhancing the ion-exchange capacity (CEC) of the biochar. These groups are capable of forming bonds with essential nutrients and metals, which prevents their leaching and promotes their gradual release into the soil. This process ensures that plants have access to critical nutrients, such as potassium, calcium, and magnesium, over extended periods (Silvestre et al., 2018). In this way, the application of biochar improves nutrient retention and soil fertility, making it a valuable amendment in sustainable agriculture.

The presence of carboxyl and hydroxyl groups also enhances the CEC and EC of biochar, contributing to its ability to bind and hold cations, which improves soil structure and fertility (Hossain et al., 2020). For instance, soils with biochar amendments have been shown to better retain water and nutrients, particularly in acidic or nutrient-poor soils, thereby increasing crop productivity (Ramamoorthy et al., 2024). These functional groups also promote soil microbial activity by providing stable surfaces for microbial colonization, which is essential for nutrient cycling and improving overall soil health (Pan et al., 2021).

The surface chemistry of biochar, as evidenced by the FTIR spectra, plays a critical role in chemical interactions between biochar and soil. The presence of aromatic compounds and carboxylic acids suggests that this biochar can enhance soil organic carbon and improve long-term soil fertility, particularly in soils with low organic matter content (Silvestre et al., 2018). Additionally, biochar's ability to chelate heavy metals and other contaminants makes it an effective tool for soil remediation, further improving soil quality and productivity (Ahmad et al., 2014).

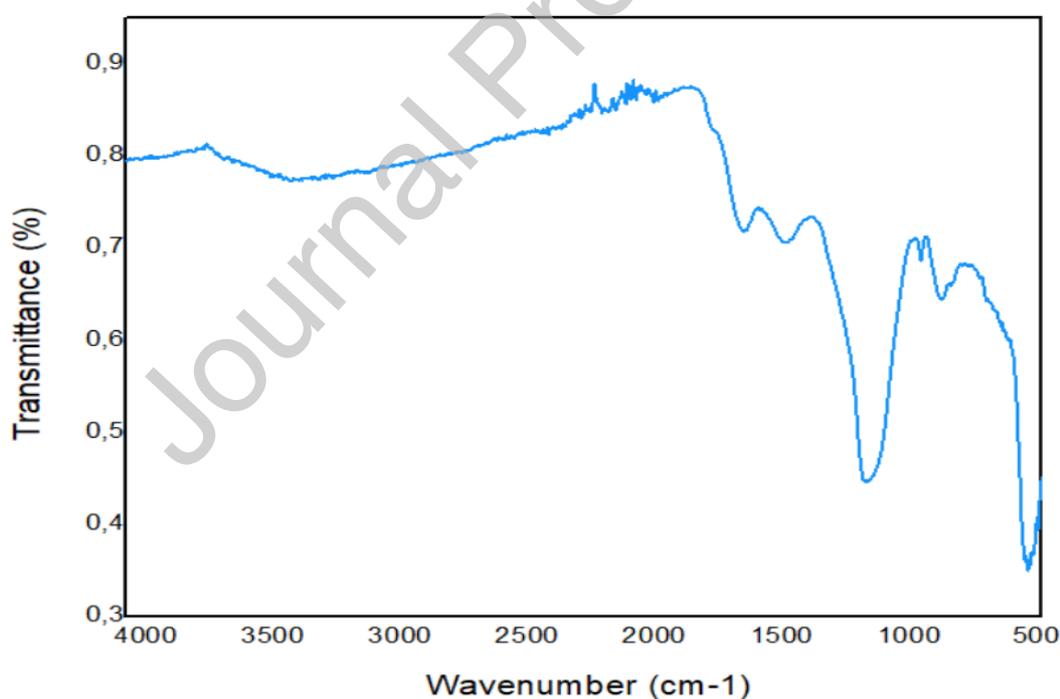


Figure 3. FTIR spectrum of biochar produced from Date Palm Residues (DPR), showing key functional groups: broad O-H stretching vibrations around 3400 cm^{-1} , C-H

stretching near 2900 cm^{-1} , C=O stretching of carbonyl groups at $\sim 1700\text{ cm}^{-1}$, aromatic C=C stretching around 1600 cm^{-1} , and C-O stretching vibrations near $1000\text{--}1100\text{ cm}^{-1}$. These functional groups highlight the biochar's potential for nutrient retention and soil interaction.

2.17. X-ray diffraction

The X-ray diffraction (XRD) analysis of the biochar produced from date palm residues (DPR) reveals that its structure is primarily amorphous, as indicated by the broad, diffuse background observed in the spectra. This amorphous nature is typical of biochar and results from the disordered arrangement of carbon atoms, which occurs during the pyrolysis process (Downie et al., 2012). Despite this overall amorphous structure, the XRD spectra also display several well-defined peaks, suggesting the presence of localized crystalline structures within the biochar (Figure 4). These crystalline structures are often attributed to the presence of inorganic minerals such as calcite and quartz, which persist through the pyrolysis process and contribute to the biochar's soil-amending properties (Zhao et al., 2014, Tang et al., 2020).

These crystalline structures are associated with inorganic elements present in the biochar, particularly minerals that survived the pyrolysis process. The dominant peaks observed at $2\theta = 29.61^\circ$, 35.73° , and 40.69° are attributed to calcite (CaCO_3), a common mineral found in biochar that contributes to its liming effect and ability to neutralize acidic soils (Fseha et al., 2022). Additionally, a peak at $2\theta = 25.48^\circ$ corresponds to quartz (SiO_2), which indicates the presence of silicate materials, likely originating from the original feedstock. Smaller peaks observed at 43.33° and 72.14° correspond to other inorganic fractions present in the biochar, including elements like magnesium (Mg), sodium (Na), potassium (K), and chlorine (Cl). These elements are often found in biochar as residual minerals after the organic material undergoes thermal decomposition during pyrolysis (Zubair et al., 2020).

The amorphous carbon structure of the biochar contributes to its stability in soil, making it an effective material for long-term carbon sequestration. Biochars with such a structure can persist in soils for extended periods, gradually enhancing soil organic matter (Lehmann & Joseph, 2015). In addition, the presence of crystalline minerals such as calcite and quartz

enhances the biochar's functionality as a soil amendment. Calcite (CaCO_3), for example, provides a liming effect, which helps to neutralize acidic soils, improving soil pH and making nutrients more available to plants. Soils that are too acidic tend to limit the availability of essential nutrients and inhibit microbial activity; the addition of biochar rich in calcite can correct this imbalance, making nutrients more accessible to plants and fostering microbial diversity (Novak et al., 2009). The quartz (SiO_2), on the other hand, can contribute to soil structure improvement by increasing soil aeration and drainage, particularly in clay soils that tend to retain excessive water (Manu et al., 2014). Biochar with crystalline components like quartz can provide stable surfaces for microbial colonization, which is essential for nutrient cycling and maintaining soil fertility (Lehmann et al., 2011; Sun et al., 2014).

Additionally, the presence of inorganic fractions, such as magnesium (Mg), potassium (K), and sodium (Na), can enhance the nutrient content of soils, particularly in nutrient-poor environments. These elements are vital for plant health and play critical roles in various physiological processes, such as photosynthesis, enzyme activation, and osmotic regulation. The release of these elements from biochar over time provides a slow-release nutrient source, ensuring sustained soil fertility and improved crop productivity (Lehmann et al., 2006; Major et al., 2010).

The combination of amorphous and crystalline structures in the biochar provides long-term stability in soils, which is beneficial for carbon sequestration. The carbon in biochar is highly recalcitrant, meaning it persists in soils for extended periods, improving soil organic matter and contributing to long-term soil health (Lehmann & Joseph, 2015). As a result, the XRD results highlight biochar's potential to improve soil pH, enhance nutrient availability, and support sustainable agricultural practices.

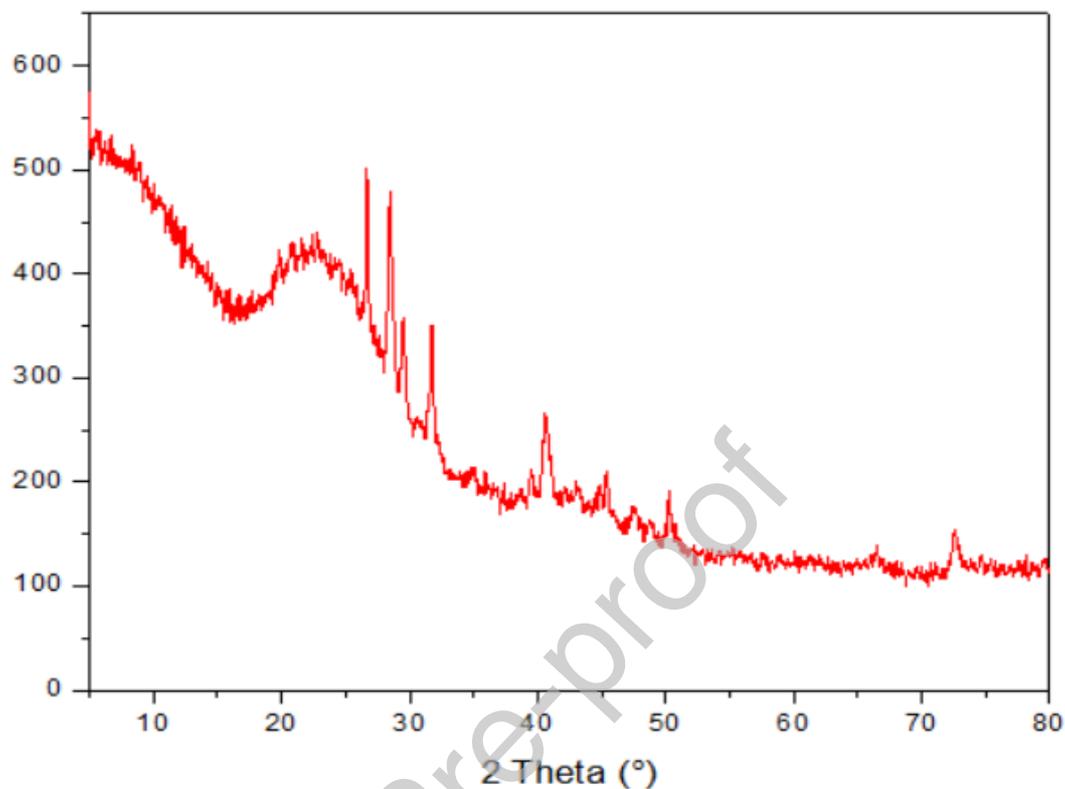


Figure 4. XRD pattern of biochar produced from date palm waste mixture, showing broad diffraction peaks around 20° – 30° (2θ), indicative of amorphous carbon, and sharp peaks corresponding to crystalline mineral phases such as potassium, calcium, and silicon compounds. These features highlight the biochar's structural characteristics and potential for soil improvement.

2.18. BET

The BET surface area of the DPR biochar produced at 500°C for 4 hours with a heating rate of $10^{\circ}\text{C}/\text{min}$ was approximately $125\text{ m}^2/\text{g}$, which is within the range commonly reported in the literature for biochar derived from date palm residues under similar conditions. For instance, Al-Wabel et al. (2019) reported a BET surface area of $103\text{ m}^2/\text{g}$ for biochar produced from date palm leaflets at 500°C , while Qambrani et al. (2017) noted a range of 50 – $150\text{ m}^2/\text{g}$ for date palm biochar produced under similar pyrolysis conditions. This relatively high surface area is a critical indicator of the biochar's potential to improve soil properties.

The well-developed pore structure, including micropores and mesopores, significantly enhances the biochar's capacity to adsorb nutrients, such as nitrogen, phosphorus, and potassium, preventing their leaching and promoting their gradual release into the soil (Atkinson et al., 2010; Downie et al., 2012). This improves the nutrient retention capacity of soils, making the biochar a valuable amendment for improving soil fertility over extended periods. Additionally, the porous structure contributes to the biochar's ability to retain water, which is particularly beneficial in arid and semi-arid regions where water availability is limited (Atkinson et al., 2010). The increased water-holding capacity reduces the need for frequent irrigation, making the biochar suitable for improving water efficiency in agricultural practices (Laird et al., 2010). Furthermore, the high surface area of biochar provides habitats for soil microorganisms, promoting microbial activity, which is essential for nutrient cycling and overall soil health (Biederman & Harpole, 2013). The combination of high surface area and porosity also enhances soil aeration and root penetration, leading to improved soil structure and increased crop productivity (Sohi et al., 2010).

3. Conclusion

Converting DPR into biochar through slow pyrolysis at 500 °C addresses two key challenges: sustainable organic waste management and the enhancement of soil fertility in oasis ecosystems. The resulting DPR biochar exhibits a stable structure, high thermal stability, significant porosity, and low concentrations of heavy metals, making it a promising soil amendment for agricultural use. This biochar promotes microbial activity, while its functional groups (carboxyl, hydroxyl) aid in nutrient retention and gradual release, thus supporting long-term soil fertility. Furthermore, its amorphous structure and crystalline components contribute to regulating soil pH and improving nutrient dynamics. Additionally, its high surface area enhances water retention and aeration, further benefiting soil health. Following these results, we recommend conducting trials under controlled conditions and in field experiments to assess the agronomic potential of this DPR biochar.

Author Contributions

REHALI Mariyem, BOUAMRI Rachid, EL GHACHTOULI Naïma contributed to the study conception and design. Material preparation, and data collection were performed by REHALI Mariyem and the analysis was performed by all authors. The first draft of the manuscript was written by REHALI Mariyem and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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