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RESEARCH ARTICLE

PRODUCTION AND CHARACTERIZATION OF BIOCHAR OBTAINED THROUGH AN ARTISANAL REACTOR

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ABSTRACT

Background: This studyaims to produce and characterize biochar from four different feedstock biomasses using an artisanal reactor via slow pyrolysis at 300°C and 500°C. The primary objective is to evaluate the properties of biochar traditionally produced by farmers to assess its potential as a soil amendment for improving soil fertility and contributing to carbon sequestration. ***Methods:*** Biochar was produced from Vineyard (Vitis vinifera L.), Tomato (Solanum lycopersicum L.), Banana (Musa spp.), and Carnation (Dianthus caryophyllus L.) biomass. The biochar samples were characterized through proximate and ultimate analysis, pH, electrical conductivity (EC), cation exchange capacity (CEC), water-soluble nutrients, and scanning electron microscopy (SEM). Pyrolysis was conducted at two different temperatures, 300°C and 500°C, to examine the effects of temperature on biochar properties. ***Results:*** Proximate analysis showed a decrease in volatile matter content with increased pyrolysis temperature, with TB ranging from 30.87% to 19.86%, VB from 33.26% to 14.01%, BB from 37.13% to 17.38%, and CB from 38.66% to 22.55%. Higher ash content in biochar was associated with lower fixed carbon values. VB had the lowest ash content (5.39%; 8.93%) and the highest fixed carbon values (58.01%; 73.03%), while CB had the highest ash content (23.92%; 32.48%) and the lowest fixed carbon values (33.05%; 40.82%). Biochar pH ranged from 8.13 to 10.01, and EC values were higher at 500°C, with CB having the highest EC values (4.92; 6.23). Biochar at 500°C contained higher levels of water-soluble nutrients. ***Conclusion:*** The study concludes that biochar properties vary significantly with feedstock type and pyrolysis temperature. Biochar produced at 500°C generally exhibited enhanced chemical properties, making it a promising soil amendment for improving soil fertility and carbon sequestration potential.

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INTRODUCTION

Biochar, a carbonaceous substance produced through the pyrolysis of organic matter in oxygen-deprived environments, has garnered considerable interest in recent times due to its potential advantages in promoting sustainable agriculture (Jiang *et al.,* 2023). Individuals have acknowledged its capacity to augment soil fertility, enhance water retention, and boost agricultural yields. Biochar is recognized for its ability to sequester carbon, helping to ameliorate climate change by reducing greenhouse gas emissions (Lehmann *et al.,* 2015). Characterizing biochar is crucial for maximizing its effectiveness in agriculture due to the variability in its features such as porosity, surface area, and nutrient content, which are influenced by the feedstock and pyrolysis conditions (Lizundia *et al.,* 2022). The utilization of biochar in various developing regions, such as Ghana and Niger, still needs to be improved, despite its considerable potential (Jekayinfa, *et al.,* 2020). The absence of biochar manufacturing technologies that are both easily accessible and economical and specifically designed for local conditions presents a substantial obstacle (Wan *et al.,* 2020). Artisanal reactors, characterized by their simplicity and affordability, present a practical option for small-scale farmers to generate biochar utilizing biomass that is readily accessible in their local area (Illankoon et al., 2023). Nevertheless, the characteristics of biochar generated in these reactors, particularly its agricultural advantages, have yet to be thoroughly investigated (Gamay *et al.,* 2024). The lack of knowledge in this area prevents the efficient use of biochar as a soil supplement and restricts its wider implementation in sustainable farming methods (Withers et al., 2015). This work aims to fill this knowledge gap by creating and analyzing biochar from four distinct sources: vineyard (Vitis vinifera L.), tomato (Solanum lycopersicum L.), banana (Musa), and carnation (Dianthus caryophyllus L.). The biochar production will be carried out using an artisanal reactor. By studying the characteristics of biochars produced at different pyrolysis temperatures (300°C and 500°C), this research seeks to provide insights into the applicability of these biochars for boosting soil fertility and agricultural yield.

The characterization of biochar includes a complete investigation of its physical, chemical, and morphological properties, which are vital for understanding its usefulness as a soil supplement (Wang *et al.,* 2023). This research was motivated by the urgent need to establish sustainable agricultural techniques that are accessible to smallholder farmers. By thoroughly examining the potential of biochar created through traditional methods, this study will significantly enhance soil health and boost agricultural yields, particularly in regions where traditional fertilizers are too expensive or environmentally unsustainable (Njenga and Mendum, 2018). The findings are expected to educate policymakers and provide practical recommendations for integrating biochar into local agricultural systems, ultimately boosting food security and environmental sustainability.

METHODS AND MATERIALS

Feedstock preparation: In this study, biochar was produced from four distinct feedstocks: vineyard (Vitis vinifera L.), tomato (Solanum lycopersicum L.), banana (Musa spp.), and carnation (Dianthus caryophyllus L.). These feedstocks were selected due to their prevalence as agricultural residues in Antalya and its surrounding regions. Before biochar production, the feedstocks were chopped into 2 cm pieces and air-dried in the Physics Laboratory of the Faculty of Agriculture, Department of Soil Sciences and Plant Nutrition at Akdeniz University. The feedstocks were utilized in their natural state, without any modifications to their original composition.

Biochar production and preparation: Biochar production was conducted at the University of Applied Sciences in Isparta, within the Faculty of Agricultural Sciences and Technologies, Department of Soil Sciences and Plant Nutrition. The pyrolysis was carried out using an artisanal reactor (see Fig. 1) designed for slow pyrolysis at two peak temperatures: 300°C and 500°C. The reactor consists of two concentric cylinders. The smaller inner cylinder, which holds the biomass, is enclosed within a larger outer cylinder insulated with polystyrene foam. Biomass was placed in a smaller cylinder and sealed with a metal lid. Heat was provided by an external heater connected to an electrical resistance element situated within the outer cylinder, which supplies the necessary energy to heat the biomass chamber indirectly. The process utilized a heating rate of 20°C/min and a pyrolysis residence time of 12 hours. Temperature monitoring was performed using a digital temperature controller to ensure accurate temperature regulation throughout the experiment.

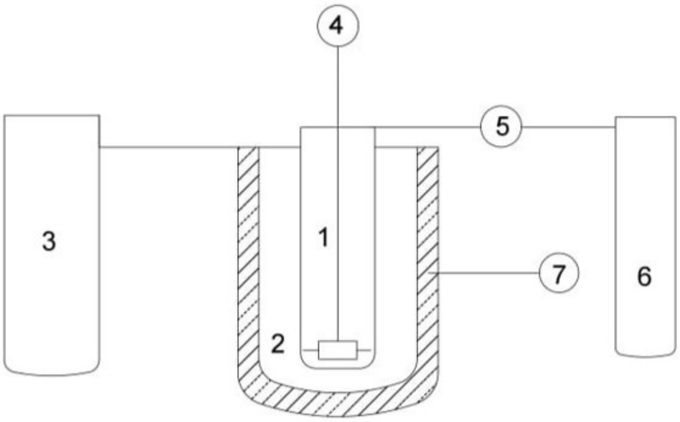

Fig. 1. Artisanal reactor system of pyrolysis: (1) Small cylinder, (2) Larger cylinder, (3) External heater, (4) Electrical resistance, (5) Digital temperature controller, (6) Oily product collecting vessel, (7) polystyrene used for isolating

The biochar yield was estimated as the proportion of solid product to the original biomass (wt/wt). The produced biochar was finely ground using a pestle and mortar, sieved through a 1 mm mesh, and stored in sealed plastic boxes to prevent moisture absorption. The mass percentage of biochar yield was calculated by Eqn (1):

$$\text{Biochar yield (\%)} = \frac{W}{W0} \times 100 \qquad (1)$$

W0 = Initial mass (g); W = Mass of biochar after pyrolysis

Biomass and biochar characterization

Biomass characterization: Before analysis, the biomass residues were milled and strongly homogenized using a vibratory sieve shaker for 5 min. Biomass parameters such as proximate analysis and structural analysis have been evaluated. Proximate analysis was performed to identify moisture content (M), ash, volatile matter (VM), and fixed carbon (FC) contents. The moisture content was determined using the oven dry method following ASTM D3173-03, samples were dried in an oven at 105°C for 2 hours. The VM was determined following ASTM D3175-07, samples were combusted at 950±20°C in a muffle furnace for 7min. The ash content was determined following ASTM D3174-02, samples were furnacing at 500°C for 1h, then the furnace temperature was raised to 750°C, and samples were placed for 2h. Fixed carbon content was determined by difference (ASTM D3172-07a) using the following equation 2:

$$\text{Fixed Carbon (\%)} = 100 - (\text{\%moisture} + \text{\%ash} + \text{\%volatile matter}) \qquad (2)$$

Structural analysis was also performed to determine cellulose, hemicellulose, lignin, and extractive contents of the biomass feedstocks following ASTM D1107-96.

Biochar characterization: Effective characterization of biochar is crucial for optimizing its applications. Various analytical methods were employed to assess its properties: The pH of biochar was determined by mixing a 1:10 (W/V) ratio of biochar with distilled water, followed by agitation for 2 hours. After mixing, the pH was measured using a calibrated pH meter, following the procedure described by Jindo *et al.,* (2014). The EC was measured in a 1:10 (W/V) ratio of biochar to distilled water. The mixture was shaken for 2 hours, allowed to stand for 30 minutes, and then analyzed using a pre-calibrated EC meter. The CEC was determined using the washing displacement method as outlined by Holmgren *et al.* (1977). This method involves displacing cations from the biochar and measuring their concentration in the wash solution. **Proximate Analysis** which includes moisture, volatile matter, and ash content, was performed according to ASTM standards: ASTM D3173-03 (moisture), ASTM D3175-07 (volatile matter), and ASTM D3174-02 (ash content). Fixed carbon content was calculated by difference, following ASTM D3172-07a. **Ultimate Analysis which** focused on the elemental composition of biochar, including Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O), and Sulfur (S). Elemental analysis was conducted using the CHNS-932 LECO Elemental Analyzer at the Scientific and Technological Research Laboratory of Inonu University. C, H, and S were determined by infrared absorption, N by thermal conductivity, and O by difference.

The Concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were measured using inductively coupled plasma atomic emission spectrometry (ICP-AES). **Scanning Electron Microscopy (SEM);** the surface morphology of the biochar was analyzed using a Quanta 200 FEG scanning electron microscope. The **High Heating Value (HHV)** was calculated based on the results of the ultimate analysis, providing insight into the energy content of the biochar. These methods collectively offer a comprehensive assessment of biochar's physicochemical properties, crucial for evaluating its suitability for various applications such as soil amendment and carbon sequestration.

Statistical analyses: Statistical analyses of the data were conducted using R software for Windows 14.0. To evaluate differences among the various values of the tested variables, an analysis of variance (ANOVA) was performed with a significance level set at 5% ($p < 0.05$). GraphPad Prism for detailed data visualization and further statistical analysis.

RESULTS AND DISCUSSION

Feedstocks analysis: The physicochemical properties of the feedstocks, as assessed through proximate and structural analyses, reveal significant variations that influence their suitability for biochar production. The moisture content across all feedstocks ranged from 5% to 6%, with tomato feedstock showing the lowest moisture at 5.15% and carnation biomass the highest at 6.82%. These values are below the 10% threshold typically recommended for effective thermochemical conversion (Braga *et al.,* 2014), indicating that all feedstocks are suitable for the pyrolysis process. Vineyard biomass exhibited the highest volatile matter content at 71.83%, aligning closely with the 70.79% reported by Rosas *et al.* (2015). Conversely, banana biomass had the lowest volatile matter at 66.54%, which is consistent with the values reported by Tahir *et al.* (2019) and Kabenge *et al.* (2018) for banana peels. The high volatile matter in vineyard biomass suggests a greater potential for gas production during pyrolysis, whereas banana biomass's lower volatile content indicates a higher proportion of fixed carbon. The ash content serves as an indicator of the mineral elements present in the biomass. Vineyard biomass had a lower ash content (4.08%) compared to the 9% reported by Rosas *et al.,* 2015. In contrast, banana biomass had a higher ash content (13.12%), which aligns with findings by Kabenge *et al.* (2018). and Abdullah *et al.* (2014). for banana peels and pseudo-stems. Higher ash content in banana biomass may affect the biochar's mineral composition and its role as a soil amendment. The fixed carbon content varied among feedstocks, with vineyard biomass exhibiting the highest value at 18.57%, slightly differing from the FC values in vineyard residues reported by Rosas *et al.,* 2015. The fixed carbon content for other feedstocks was 12.89% for carnation, 15.09% for bananas, and 16.76% for tomatoes. The higher fixed carbon content in vineyard biomass suggests it may produce a biochar with better carbon sequestration potential. Structural analysis showed varying levels of extractive substances, cellulose, lignin, and hemicellulose. Carnation had the highest extractive content (16.81%), while cellulose was most abundant in clover (40.87%). Vineyard biomass had the highest lignin content (27.41%), indicating its potential for structural reinforcement in biochar. Banana biomass had the highest hemicellulose content (40.77%), aligning with the values reported by Kabenge *et al.* (2018) for banana peels. The lower cellulose, lignin, and hemicellulose values in the vineyard and other biomasses indicate different structural compositions that can impact biochar properties. In summary, the analysis underscores the diverse characteristics of the feedstocks, influencing their biochar production potential and end-use applications. Each feedstock offers distinct benefits and limitations based on its chemical and physical properties, which should be considered when selecting materials for biochar production.

Table 1. Physicochemical properties of biochar feedstocks

Feedstocks	Proximate analysis %				Structural analysis %			
	M	VM	Ash	FC	Cellulose	Lignin	Hemicellulose	Extractives
Vineyard	5.52	71.83	4.08	18.57	39.07 ±0.23	27.41 ±0.19	29.44 ±0.43	5.30 ±0.01
Tomato	5.15	65.57	12.52	16.76	35.26 ±0.18	11.56 ±0.04	40.66 ±0.21	14.07 ±0.01
Banana	5.24	66.54	13.12	15.09	31.16 ±0.06	14.94 ±0.03	40.77 ±0.15	12.06 ±0.004
Carnation	6.82	69.78	10.51	12.89	40.87 ±0.060	11.58 ±0.01	37.04 ±0.15	16.81 ±0.01

M: moisture; VM: volatile matter; FC: fixed carbon

The characteristics of biochar: The physicochemical properties of biochars produced from various feedstocks at two different pyrolysis temperatures (300°C and 500°C) reveal notable trends and differences. The yield of biochar varied with pyrolysis temperature and feedstock type. At 300°C, the yield increased in the following order: banana biochar (BB) (39%) < vineyard biochar (VB) (44%) < carnation biochar (CB) (46%) < tomato biochar (TB) (47%). This pattern is attributed to the lower extent of aliphatic compound condensation and minimal losses of gases like CH4, H2, and CO (Amonette and Joseph, 2009). Conversely, at 500°C, the yield decreased in the order: of TB (34%) > BB (33%) > CB (32%) > VB (30%). This reduction is due to the increased dehydration of hydroxyl groups and thermal degradation of lingo-cellulosic components (Antal and Grønli, 2003). Notably, TB demonstrated the highest yield at both temperatures, whereas BB and VB showed the lowest.

The pH of biochar generally increases with pyrolysis temperature. At 300°C, the pH values were: VB (8.13) < BB (8.72) < TB (8.92) < CB (9.56). At 500°C, pH values rose to: VB (9.19) < TB (9.67) < CB (9.82) < BB (10.01). The increase in pH with higher temperatures is attributed to the concentration of non-pyrolyzed inorganic elements and the hydrolysis of salts such as Ca, K, and Mg (Gaskin *et al.,* 2008; Novak *et al.,* 2009). This trend aligns with previous studies indicating that higher-temperature biochar tends to have higher pH values (Lehmann *et al.,* 2011; Mukherjee *et al.,* 2011; Yuan *et al.,* 2011). The EC values were higher at 500°C than at 300°C, reflecting the increased ion concentration in the biochar. At 500°C, the EC values were: VB (0.56) < BB (3.64) < TB (4.44) < CB (6.23). At 300°C, the values were: VB (0.29) < BB (3.41) < TB (4.41) < CB (4.92). CB consistently had the highest EC, while VB had the lowest. These findings are consistent with the broad range of EC values reported in the literature (Rajkovich *et al.,* 2012; Smider and Singh, 2014). CEC values generally increased with temperature, except for BB. At 300°C, CEC values were: TB (199.3 cmol/kg) < VB (207.15 cmol/kg) < BB (316.25 cmol/kg) < CB (858 cmol/kg). At 500°C, CEC values were: BB (191.45 cmol/kg) < CB (1305 cmol/kg) < VB (1314.5 cmol/kg) < TB (1315 cmol/kg). This increase in CEC with higher temperatures, except for BB, aligns with the findings of Yuan and Xu R. (2011), which indicate that biochars at higher temperatures typically have higher CEC values. The concentration of macro and micronutrients in biochar generally increased with pyrolysis temperature. At 300°C, the highest macronutrient values were found in TB, CB, CB, and BB for P, K, Ca, and Mg, respectively. At 500°C, the highest values were observed in TB, CB, BB, and BB. For micronutrients, the maximum values at 300°C were found in TB (Fe), CB (Mn), CB (Zn), and CB (Cu). At 500°C, the highest values were found in TB (Fe), BB (Mn), CB (Zn), and TB (Cu). The increase in nutrient concentrations with temperature is attributed to the loss of biomass mass and the concentration effect of remaining elements. Overall, these results highlight the impact of feedstock type and pyrolysis temperature on the properties of biochar. Variations in yield, pH, EC, CEC, and nutrient content underscore the need to select appropriate feedstocks and pyrolysis conditions to optimize biochar for specific applications, such as soil amendment and carbon sequestration.

Table 2. Physiochemical characteristics of biochars

	Biochar							
	VB		TB		BB		CB	
Pyrolisis temp (°C)	300	500	300	500	300	500	300	500
Yield (%)	44	30	47	34	39	33	46	32
pH	8.13 ±0.03	9.18 ±0.01	8.92 ±0.01	9.67 ±0.00	8.72 ±0.01	10.01 ±0.03	9.82 ±0.01	9.56 ±0.01
EC (dS/m)	0.29 ±0.01	0.56 ±0.02	4.41 ±0.18	4.44 ±1.51	3.41 ±0.03	3.64 ±0.08	4.92 ±0.01	6.23 ±0.08
CEC (cmol kg^{-1})	207.15	1314.5	199.3	1315.00	316.25	191.45	858.00	1305.00
P (mg/kg^{-1})	2600	2700	6200	8300	1400	3300	4100	4800
K (mg/kg^{-1})	11700	11900	52300	65200	35600	38800	62300	88000
Ca (mg/kg^{-1})	13100	20000	24800	26200	29500	46300	32500	4400
Mg (mg/kg^{-1})	1700	2500	4800	5200	9100	12600	3300	6000
Fe (mg/kg^{-1})	817.7	1041	2378	3067	288.6	1755	608.9	1332
Mn (mg/kg^{-1})	61.7	63.4	109.2	145.7	213.9	434.6	342.8	412
Zn (mg/kg^{-1})	32.8	78.9	123.8	163	47.3	48.1	182.3	158
Cu (mg/kg^{-1})	26.2	24.1	36.1	39.7	17.2	21.00	44.2	26.2

VB: Vineyard Biochar; TB: Tomatoes Biochar; BB: Banana Biochar; CB: Carnation Biochar.

Table 3. Overview of the tested properties of the biochar from different feedstocks at different temperatures

Biochars	Pyrolysis temp	Proximate analysis (%)				Ultimate analysis (%)							Heating value
	(°C)	M	VM	Ash	FC	C	H	N	S	O	O/C	H/C	(MJ·kg^{-1})
Vinyard	300°C	3.34 ±0.60	33.26 ±0.73	5.39 ±0.21	58.01 ±0.07	63.57	4.53	1.37	-	30.53	0.48	0.07	22.84
	500°C	4.03 ±0.10	14.01 ±1.08	8.93 ±0.28	73.03 ±1.52	54.75	2.62	0.86	-	41.77	0.76	0.05	15.51
Tomatoes	300°C	4.9 ±0.10	30.87 ±0.25	23.82 ±0.11	40.42 ±0.32	60.00	3.77	1.78	0.31	34.15	0.57	0.06	19.94
	500°C	3.01 ±0.04	19.86 ±1.16	30.62 ±0.28	46.51 ±0.73	51.62	2.28	1.39	0.44	44.27	0.86	0.04	13.52
Banana	300°C	3.79 ±0.3	37.13 ±1.15	17.65 ±0.12	41.42 ±0.86	51.75	3.96	0.67	0.14	43.48	0.84	0.08	16.18
	500°C	2.72 ±0.1	17.38 ±1.17	25.55±0.51	54.35 ±0.50	47.69	1.92	1.04	0.17	49.18	1.03	0.04	10.99
Carnation	300°C	4.38 ±0.11	38.66 ±0.26	23.92±0.52	33.05 ±0.99	54.00	4.55	3.22	0.13	38.11	0.71	0.08	18.23
	500°C	4.15 ±1.01	22.55 ±0.04	32.48±0.26	40.82 ±0.69	49.93	1.88	2.49	0.28	45.42	0.91	0.04	12.04

M: Moisture; VM: Volatile Matter; FC: Fixed Carbon; - not detectable

The physicochemical characteristics of biochar, detailed in Table 3, reveal several key trends based on feedstock type and pyrolysis temperature. Biochar moisture contents varied slightly with temperature. At 300°C, the moisture contents were 3.34% for Vineyard biochar (VB), 4.03% for Tomato biochar (TB), 4.90% for Banana biochar (BB), and 4.38% for Carnation biochar (CB). At 500°C, these values were 4.03% (VB), 3.01% (TB), 2.72% (BB), and 4.15% (CB). The slight variation suggests that while moisture content decreases with temperature, it remains relatively stable across different feedstocks. The volatile matter content of biochar decreased as pyrolysis temperature increased.

At 300°C, the volatile matter was highest in CB (38.66%) and lowest in TB (30.87%). At 500°C, the order remained similar, with CB (22.55%) and TB (19.86%) showing the greatest and smallest reductions, respectively. This trend aligns with literature indicating that higher pyrolysis temperatures reduce volatile content as aliphatic compounds and gases like CH4, H2, and CO are lost (Enders *et al.,* 2012; Angin, 2013). Ash content increased with temperature, showing a positive correlation with fixed carbon content. For instance, Vineyard biochar had the lowest ash content at both temperatures (5.39% at 300°C and 8.93% at 500°C), while CB had the highest (23.92% at 300°C and 32.48% at 500°C). Conversely, Vineyard biochar exhibited the highest fixed carbon values (58.01% at 300°C and 73.03% at 500°C), whereas CB had the lowest (33.05% at 300°C and 40.82% at 500°C) (Spokas, 2010; Lee et al., 2010; Yargicoglu, *et al.,* 2015). The elemental analysis revealed that carbon (C) and oxygen (O) were the dominant elements across all biochars, with hydrogen (H), nitrogen (N), and sulfur (S) present in minor amounts. The carbon content ranged from 47.69% to 63.57%, consistent with values reported by Yargicoglu et al. (2015). The oxygen content varied between 30.53% and 49.18%, reflecting the initial composition of the feedstocks. The H/C and O/C ratios were lower than the reference values due to the loss of volatile compounds and the increase in fixed carbon during pyrolysis (Ronsse et al., 2013; Rutherford *et al.,* 2012). The Higher Heating Value (HHV) of biochar decreased with increasing pyrolysis temperature, ranging from 16.18 MJ/kg at 300°C to 10.99 MJ/kg at 500°C. The highest HHV was observed for Vineyard biochar (22.84 MJ/kg at 300°C and 15.51 MJ/kg at 500°C), while the lowest was for Banana biochar (16.18 MJ/kg at 300°C and 10.99 MJ/kg at 500°C). These values indicate a reduction in energy content with higher pyrolysis temperatures, consistent with the findings of Mehmood *et al.* (2017) and Ahmad *et al.* (2017). Scanning Electron Microscopy (SEM) images (Fig. 2) reveal significant structural differences among the biochar. The surfaces of the biochar displayed various irregular cracks and textures, illustrating the heterogeneous nature of biochar produced from different feedstocks. In summary, these results highlight the impact of feedstock type and pyrolysis temperature on the properties of biochar, influencing its potential applications and effectiveness as a soil amendment.

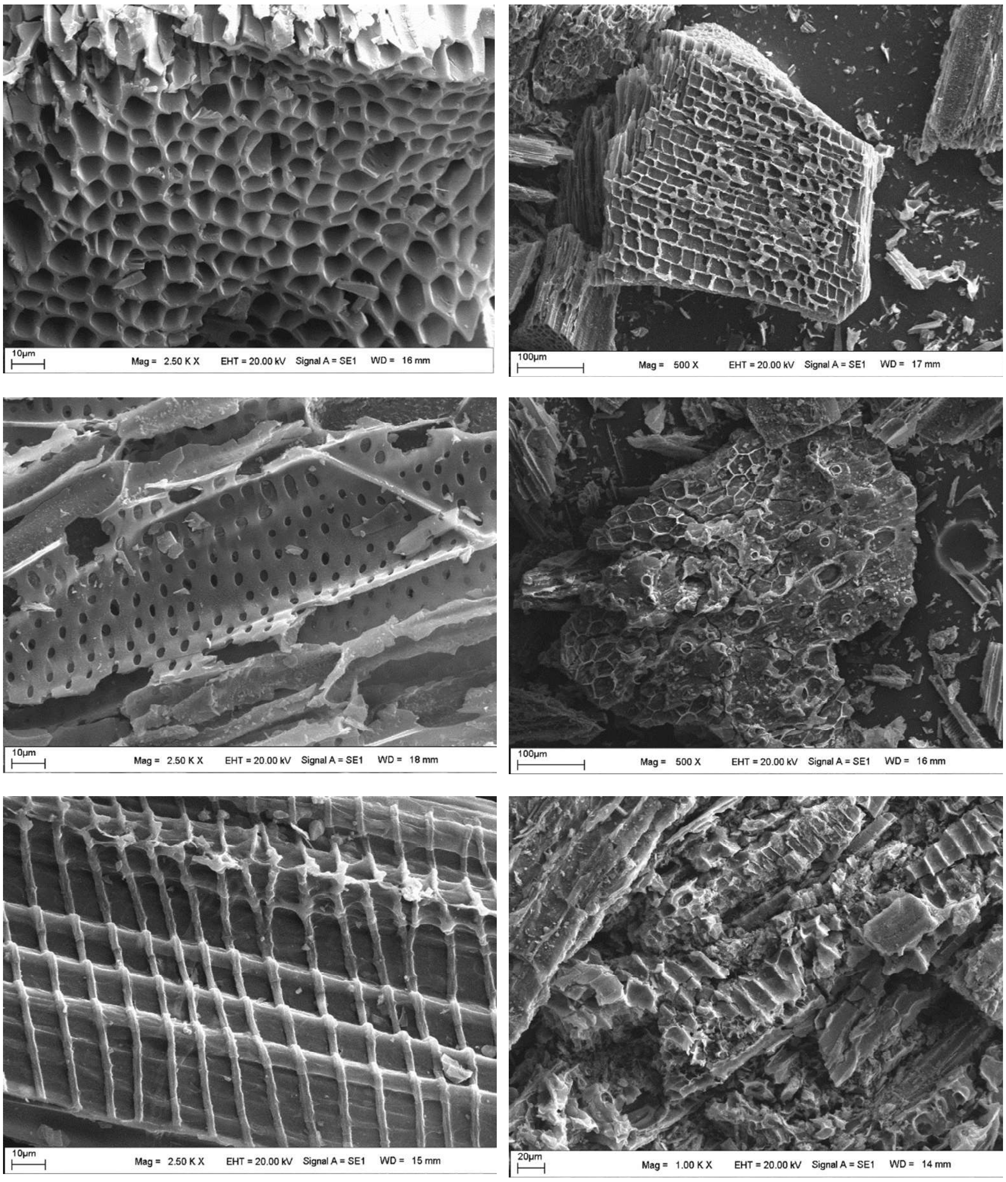

Fig. 2. SEM images of A. vineyard biochar at 300°C, bar= 10µm, B. vineyard biochar at 500°C, bar=100µm, C. tomatoes biochar at 300°C, bar=10µm, D. tomatoes biochar at 500°C, bar=100µm, E. banana biochar at 300°C, bar=10µm, F. banana biochar at 500°C, bar=20µm, G. carnation biochar at 300°C, bar=10µm, H. carnation biochar at 500°C, bar=20µm

CONCLUSION

The physical and chemical properties of biochar derived from four different types of biomass (vineyard waste, tomato plants, banana peels, and carnation plants) were examined using an artisanal pyrolysis reactor. The biochar displayed significant variations in characteristics, which were affected by the biomass type and the conditions of the pyrolysis process. The biochar exhibited unique properties based on the source of the biomass and the pyrolysis temperature. These differences underscore the importance of feedstock selection and temperature control in biochar production. The biochar produced demonstrated promising potential to enhance soil fertility through pH buffering, nutrient enrichment, soil aggregation, and moisture retention. Such improvements are crucial for sustainable agriculture and soil health. The study highlights that biochar technology can be successfully implemented at the farm level. Farmers can produce high-quality biochar using simple, artisanal methods, contributing to improved soil fertility and increased crop yields. Overall, this research supports the viability of biochar as a sustainable soil amendment, offering practical benefits for agricultural productivity and environmental sustainability. Future studies could focus on field trials to further validate these findings and optimize biochar application strategies.

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Data Availability: The datasets generated during and/or analyzed during the current study are available within the paper.

Key-points

- Biochar yield was positively related to the pyrolysis temperature.
- Volatile matter content decreased with increasing pyrolysis temperature.
- Biochar pH values were alkaline.
- Carbon and oxygen were the major elements components.
- High temperature and heating rate produced more prominent porous biochar.

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