Journal of Agricultural Sciences
(Tarim Bilimleri Dergisi)

J Agr Sci-Tarim Bili
e-ISSN: 2148-9297
jas.ankara.edu.tr

JAS

Determination of Some Characteristic Properties of Biochar Obtained from Different Agricultural Wastes

Ebru Pınar Sayğan[a*], Ali Volkan Bilgili[b], Salih Aydemir[b], Osman Sönmez[c]

[a]*Izmir Olive Research Institute, İzmir, TÜRKİYE*

[b]*Harran University Soil Science and Plant Nutrition, Şanlıurfa, TÜRKİYE*

[c]*Erciyes University Soil Science and Plant Nutrition, Kayseri, TÜRKİYE*

ARTICLE INFO

Research Article

Corresponding Author: Ebru Pınar Sayğan, E-mail: ebrusaygan@hotmail.com

Received: 29 April 2024 / Revised: 20 December 2024 / Accepted: 01 February 2025 / Online: 29 July 2025

Cite this article

Sayğan E P, Bilgili A V, Aydemir S, Sönmez O (2025). Determination of Some Characteristic Properties of Biochar Obtained from Different Agricultural Wastes. *Journal of Agricultural Sciences (Tarim Bilimleri Dergisi),* 31(3):714-724. DOI: 10.15832/ankutbd.1475175

ABSTRACT

Recycling of post – harvest wastes, which do not have any input qualities, to biochar is of great importance. The use of biochar increases soil quality and crop yield. Biochars used in the study were produced from residues of the locally grown crops: corn cob (CC), cotton stalk (CS), tobacco stalk (TS), pistachio shells (PS), and olive pulp (pomace) (OP). The biochars were produced via the carbonization method at 300°C. Biochar materials were evaluated for their properties (pH, EC, total C, N, H/C ratio, C/N ratio) and mineral concentration (Ca, Na, Mg, K, Cu, Zn, Fe, Mn, B, Al, Ni, P, Pb) before and after biochar processes. Surface morphology properties were observed using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The conversion of crop biomass into biochar resulted in weight losses of between 42% and 69%. The pH of all biochars was alkaline (pH> 7). PS biochar exhibited the highest electrical conductivity (EC: 4.54 dS m^{-1}) compared to other biochar materials. Biochar total carbon levels ranged from 58.06% to 80.29%, with the highest carbon concentration found in biochar obtained from corn cobs. In terms of total nitrogen, biochar obtained from cotton straws had twice as much nitrogen compared to the other four biochars, resulting in the lowest C/N ratio. H/C ratio ranged between 0.04 and 0.09. The mineral concentration of the materials also increased following biochar conversion. SEM micrographs showed higher porosity in CSB, CCB, and TSB with well-structured pores, while in PSB and OMB, the pores were not well-developed. SEM-EDX analysis of mineral elements (e.g., K, Mg, Si, and P) showed significant results in the derived CCB. In conclusion, this study demonstrates the diverse properties and mineral concentration of biochars derived from various agricultural residues, highlighting their potential for sustainable soil improvement.

Keywords: Raw material, Surface morphology, Biochar, Carbonization

1. Introduction

Crop residues, which include leaves, stems, and straws left after harvest, have been a focal point of research since the 1970s for their potential as roughages. The total production of field crops across Turkey is 119.0 million tons, with a total waste of 46.2 million tons. Waste constitutes 38.9% of the produced field crops. The total production of horticulture crops in Turkey is 22.3 million tons, with a total waste of 4.03 million tons. Waste constitutes 18.1% of the produced horticulture crops (Ünlü et al. 2023). In the GAP region specifically, approximately 15 191 865 tons of waste are generated from a total area of 1 946 093 hectares of wheat, barley, corn, and cotton fields, highlighting the significant volume of crop residues available for utilization. Despite extensive studies, large-scale utilization of crop residues in developing countries remains limited (Akram & Fırıncıoğlu 2019). Techniques like biochar production are emerging as promising methods for enhancing their value and sustainability. Biochar can be produced from a variety of raw materials including energy crops (e.g., corn, wood pellets, and oilseed rape), agricultural wastes (e.g., wheat straw, rice husk, waste wood, pistachio, peanut, hazelnut shells, and manure) and other wastes including sewage sludge (Agrafioti et al. 2013; 2014; Inyang et al. 2014; Frišták et al. 2015).

Biochar is a charred organic material produced after the carbonization or pyrolysis process (under conditions without extremely low oxygen) from carbon (C)-based raw material. Biochar can also be used as a soil conditioner for the purpose of carbon sequestration and improving soil properties (Lehmann & Joseph 2009). Due to their abundant supply, low cost, and high carbon content, agricultural wastes are ideal feedstocks for producing biochar. Utilizing agricultural residues not only provides a sustainable method for waste management but also contributes to environmental conservation by reducing greenhouse gas emissions from decomposing organic matter. Furthermore, agricultural waste is often rich in minerals and nutrients, enhancing the quality of the produced biochar and its potential applications in soil improvement. By incorporating agricultural waste into biochar production, we can effectively address waste disposal challenges while simultaneously producing a valuable material that benefits soil health and fertility (Campos et al. 2020). In the region where this study is conducted, burning agricultural

residues is a common practice, which contributes to air pollution and environmental degradation (Bahşi et al. 2023; Yılmaz et al. 2024). By converting these residues into biochar instead of burning them, we not only mitigate pollution but also address soil degradation issues in an area where soils are in urgent need of organic matter (Bilgili et al. 2018). The resulting biochar improves soil health and fertility by enriching the soil with essential nutrients and enhancing its structure. Thus, utilizing agricultural waste for biochar production offers a more sustainable and environmentally friendly alternative to residue burning, benefiting both the local ecosystem and agricultural productivity. Characterizing biochar from different materials is crucial for understanding its properties and effectiveness, which significantly impacts its application in soil improvement and environmental management (Campos et al. 2020).

Various techniques, including SEM and SEM-EDX, have been employed to assess the characteristics of biochar (Mullen et al. 2010; Beesley & Marmiroli 2011; Chia et al. 2012; Parmila & Saraho 2013; Méndez et al. 2013; Xu et al. 2013). Numerous tests are employed to describe the characteristic structure of biochar. Among these, SEM and SEM-EDX are frequently utilized to examine the morphology and surface area of biochars (Jindo et al. 2014; Bouraoui et al. 2015). It is well understood that the microscopic structure of biochar significantly influences the physical conditions of the soil. The biochars obtained increase the water holding capacity of the existing surface areas and the soils where they are applied (Thies & Rillig 2009). The physical and chemical properties of biochar depend on the characteristics of the raw materials and pyrolysis temperature (Tan et al. 2014).

SEM images were examined in biochar samples obtained from various raw materials (Kim et al. 2012; Al-Wabel et al. 2013). When SEM images at a 4000-fold magnification of corn cob raw material and biochar obtained from different temperatures are observed, the raw material samples exhibit a non-porous structure. However, in the images of biochar forms obtained from different temperatures, it was observed that the original structure deteriorated and transformed into a rough and porous structure (Hao et al. 2013). When SEM images of pistachio shell materials and biochars obtained from different temperatures are examined, it is clearly seen that changes in surface morphology after biochar formation are observed depending on pyrolysis temperature. But in general, the porosity of biochar samples was found to be very low (Apaydin-Varol et al. 2007). When the images of biochar samples obtained at two different temperatures in olive pomace samples were compared, it was observed that the raw material sample had a solid surface structure. Different biochar materials have been found to have a rough and porous structure (Williams et al. 2020). When the SEM image of biochar materials obtained from *Mentha Arvensis* was examined, it revealed porous, rough, irregular structures. According to SEM-EDX analysis, it was observed that the carbon concentration ranged from 70% to 81%, while oxygen concentration ranged from 4% to 18%. Other elements such as Ca, K, Al, Mg, and Si were found in much smaller amounts in comparison to all other biochars.

The presence of Na, K, and Ca minerals in biochar materials, as nutrient elements, is very important for plant growth (Qian et al. 2013; Rivka et al. 2017). Additionally, biochar is significant due to its toxic metal concentration and its environmental impact. When the results of heavy metal analysis were examined according to the International Biochar Initiative (IBI 2012), it was determined that the levels were considerably lower than the maximum allowable threshold range for heavy metals. These findings suggest that biochar is suitable for a wide range of off-road applications (Nigam et al. 2018).

The European biochar certificate states that biochar must have an H/C ratio of less than 0.7 (The European Biochar Certificate 2014). Research suggests that optimal results in soil improvement and carbon sequestration are achieved when the H/C ratio is less than 0.6 and the O/C ratio is less than 0.4 (Schimmelpfennig & Glaser 2012).

While existing research has extensively investigated the potential of various plant residues for biochar conversion and evaluated the resultant properties, there remains a significant gap in the literature regarding the detailed characteristics of different biochar types, especially in specific agricultural contexts. In particular, the GAP region, known for its intensive crop and horticultural practices, generates substantial amounts of plant residues. By examining and comparing the biochar properties of diverse materials in this region, the study offers valuable information for improved soil management and environmental sustainability.

The aim of this study was to collect raw materials and subsequently produce biochar from five different sources. Specifically, the study aimed to compare thinning of SEM images for morphological and elemental composition values, SEM-EDX values, and determine the total C, N, alkali elements (Na, Mg, K, Ca), other essential elements (P, Fe), and heavy/toxic elements (Al, Cr, Cu, Mn, Mo, Ni, Zn) to reveal characteristic differences among the materials.

2. Material and Methods

2.1. Materials

Post harvesting residual materials of the commonly used agricultural products (Corn cob (CC), Cotton stalk (CS), Tobacco stalk (TS), Pistachio shells (PS) and Olive pulp (pomace) (OP)) in Southeast Anatolia Project (SAP) region were collected and used in the study as material.

The biochar was produced via the carbonization method at 300 °C using five different feedstocks (Ronsse et al. 2015; Seow et al. 2022). Biochars were produced by carbonization methods at a final temperature of 300 °C following 24 h of drying at 110 °C. Low pyrolysis results in higher efficiency as the raw material is partially burned. However, since it causes more biomass to burn at high speed, the efficiency of the resulting biochar decreases (Joseph et al. 2010; Angin 2013). For this reason, biochar was obtained at low speed.

2.2. Methods

The pH and electrical conductivity (EC) of the biochars were measured by preparing a 1:20 water suspension, according to Rajkovich et al. (2012). The total carbon (%), total nitrogen (%), and hydrogen (H) (%) concentration of both the raw materials and the biochar samples were determined using the Leco TruSpec® CHN-S Analyzer, following the standard methods ASTM D-5373 and ASTM D-4239 (Leco 2005). Macro and micro element concentration (Ca, Na, Mg, K, P, Cu, Zn, Fe, B, Mo and Mn) (mg kg^{-1}) were determined in ICP OES spectrophotometer (Inductively Couple Plasma spectrophotometer) (Perkin-Elmer, Optima 2100 DV, ICP/OES, Shelton, CT 06484-4794, USA) (Mertens 2005a after being subject to nitric acid-hydrojen peroxide (2:3) acid in a 40 bar pressure-resistant microweaving unit age burning (speedwave MWS-2 Berghof productts + Instruments Harresstr.1. 72800 Enien Gernmany) in 3 different steps (Step 1; 5 minutes of 75% microwave power at 145 ºC, Step 2; 10 minutes of 90% microwave power at 180 ºC, and Step 2; 10 minutes of 40% microwave power at 100 ºC (Mertens 2005a).

Biochar Yield (%): The conversion efficiency of biochar was calculated using the following equation:

$$Biochar\ yield\ (\%) = \frac{Weight\ of\ biochar}{Weight\ of\ feedstock\ used} * 100$$

Images were examined under a (ZEISS EVO 50) scanning electron microscope (SEM) (micron-sized) to analyze the morphological structural differences in the five different raw materials and the biochar samples obtained from them. The carbon percentage (C %), nitrogen percentage (N %), and percentage of other elements were determined using Scanning Energy Dispersive X-ray Spectroscopy (SEM-EDX).

3. Results and Discussion

3.1. Biochar yield

Feedstock type and its form significantly influence biochar yield, which ranged between 30.84% and 57.52% (Table 1). The maximum biochar yield (57.52%) was obtained from CSB, followed by OPB. The conversion of crop biomass into biochar resulted in weight loss. These losses occur rapidly between 200 °C to 300 °C, which is the temperature range (Bergman & Kiel 2005), with approximately 66% for CCB, 42% for CSB, 69% for TSB, 68% for PSB, and 49% for OPB of the initial mass. The variability in biochar yield can also be attributed to the presence of substances such as lignin, cellulose, and hemicelluloses in the feedstocks (Chandra & Bhattacharya 2019). The differences in our results are related to the use of different raw materials to obtain biochar.

Table 1- Biochar yield (%) values of different biochars

Biochar Samples	*Temperature at which the highest burning rate occurs*	*Total mass loss (%)*
CCB		34
CSB		57.52
PSB		31.97
TSB	<300 °C	30.84
OPB		50.71

* CCB: Corn cob biochar, CSB: Cotton stalks biochar, TSB: Tobacco stalks biochar, PSB: Pistachio shell biochar, OPB: Olive pulp (pomace) biochar.

3.2. Physical and chemical properties of the materials and biochars

The pH of all biochar samples was alkaline, ranging from 7.35 to 9.72. PSB exhibited the highest pH (9.72) and electrical conductivity (EC: 4.54 dS m^{-1}) compared to other biochar materials (Table 2). Biochar samples obtained from plants exhibit an alkaline structure, consistent with the results of our study (Akca et al. 2021). When examining the concentration properties of raw materials and biochar samples in Table 3, it is observed that the Total C increased after biochar production. Total C values ranged from 58.06% to 80.29%, and total N values ranged from 0.70% to 1.86%. The total C highest increase was observed in CCB. During biochar production, the oxygen concentration of the biochar reacts with carbon, leading to a decrease in oxygen concentration. This finding is consistent with the results of the study conducted by Quian et al. (2013). The O % content of the pure compound biochars was calculated by subtracting total C (%), H (%), N (%) and S (%) contents from unity (the conventional difference method) (Bakshi et al. 2020).

Table 2- pH, EC, C/N, H/C, O/C values of different biochars

	CCB	*CSB*	*PSB*	*TSB*	*OPB*
pH	8.46	7.35	9.72	7.52	9.24
EC (dSm^{-1})	0.88	1.06	4.54	0.54	1.06
C/N	107.05	40.32	108.49	37.44	36.51
H/C	0.04	0.09	0.04	0.06	0.07
O/C	0.2	0.61	0.27	0.46	0.37

* CCB: Corn cob biochar, CSB: Cotton stalks biochar, TSB: Tobacco stalks biochar, PSB: Pistachio shell biochar, OPB: Olive pulp (pomace) biochar.

Table 3- Total C and N (%) concentration of different raw and biochar materials concentration

	CCR	*CCB*	*CSR*	*CSB*	*TSR*	*TSB*	*PSR*	*PSB*	*OPR*	*OPB*
					%					
Total C	44.19	80.29	44.98	58.06	45.02	64.4	42.97	75.94	50.00	67.91
Total N	0.27	0.75	0.56	1.44	0.75	1.72	0.58	0.70	1.19	1.86
Total H	6.08	3.30	6.03	4.94	6.18	4.11	6.20	2.70	6.16	4.97
Total O	49.46	15.66	48.43	35.56	48.50	29.77	50.25	20.66	42.65	25.26

*CCR: Corn Cob raw material, CCB: Corn cob biochar, CSR: Cotton stalks raw material, CSB: Cotton stalks biochar, TSR: Tobacco stalks raw material, TSB: Tobacco stalks biochar, PSR: Pistachio shell raw material, PSB: Pistachio shell biochar, OPR: Olive pulp (pomace) raw material, OPB: Olive pulp (pomace) biochar.

C/N ratio ranged from 36.51 to 108.49 for biochar materials. As it can be seen that C/N ratio decreased after biochar materials were converted into biochar, which is also suitable in terms of uptake of nutrients by plant which prefer low C/N ratio (20-30). In general except for pistachio shell C/N ratio of all other materials had a lower C/N ratio after they were converted into biochar. The values of C/N ratio may change depending upon the conditions where biochars were obtained such as temperature and also duration of carbonization period obtain biochar (Watson et al. 2002; Howell 2005**).** In the case of biochar, a critical C/N ratio ranging between 20 and 32 for biochar (Nguyen et al. 2017). The main components of lignocellulosic substances are organic components such as lignin, cellulose, and hemicellulose. The reason why biochar produced from lignocellulosic substances has different properties is due to the difference in basic components. In corn cobs, the deterioration temperatures of high amounts of cellulose and lignin in the raw material are between 240-350 ºC and 280-500 ºC (Demirbas 2004). Therefore, in our study, CCB was found to be higher due to this degradation. It was determined that the H/C ratios in the biochar materials ranged between 0.04 and 0.09, while the O/C ratios ranged between 0.20 and 0.61. According to the European Biochar Certificate, the H/C ratio, as a measure of biochar stability for agricultural use, should be less than 0.7 (The European Biochar Certificate 2014). It has been suggested that the best conditions for carbon sequestration and soil remediation can be achieved when the O/C ratio of biocarbons is 0.4 and the H/C ratio is less than 0.6 (Schimmelpfennig & Glaser 2012). Upon examination of our results, it was observed that the H/C ratio was below 0.7 for all five different biochars. Therefore, it can be inferred that these materials would be suitable for use to agricultural inputs such as soil improvers. Comparing the O/C ratio with our results, it is suggested that the CCB, PSB, and OPB forms would be suitable for use as soil improvers and agricultural inputs, in line with the findings of Schimmelpfennig and Glaser (2012). In the biochar samples obtained from corn cobs at 400 °C. Carbon (C) 80.50 %, N 0.87 %, H/C ratio 0.52, and O/C ratio 0.08 were obtained (Drané et al. 2024). Compared to our study results; Similar results were obtained for the C % value, but a higher value was obtained for the N % value. A lower value for the H/C ratio and a higher value for the O/C ratio was obtained. In the biochar samples obtained from cotton stalk at 300 °C, values of C 47.13%, N 1.09 %, H/C 1.14 and O/C 0.75 were obtained. In our study, C (%), N (%) and O/C values are similar. A higher value was obtained in H/C value. In the biochar samples obtained from tobacco stem at 350 °C, C 37.1 % and N 2.54 % were obtained (Chen et al. 20016). In our study results, the C value is higher and the N value is lower. In biochar samples obtained from cotton stalk at 300 C, values of C 51.56%, N 1.40%, H/C 1.09 O/C 0.51 were obtained (Liu et al. 2018). In our study, C (%), N (%) and O/C values are similar. A lower value was obtained in H/C value. In biochar samples obtained from cotton stalk at 300 °C, values of C 54.41%, N 1.35%, H/C 0.91 O/C 0.41 were obtained (Khalid et al. 2024). In our study, C, N and O/C values are similar. H/C price had reached lower value. Reference information for this is given in Table 4.

Based on the analysis of alkaline elements (Na, Mg, K, Ca), other essential elements (P, Fe), and heavy/toxic elements (Al, Cr, Cu, Mn, Mo, Ni, Zn) detected in the ICP analysis of raw material and biochar samples, it can be concluded that they can serve as soil improvers. The concentrations of these three classes of elements are presented in Table 5. The highest concentrations are found in the alkaline element class, followed by essential elements and toxic elements. According to raw materials and biochars results of the ICP analysis, the concentrations of alkaline elements varied as follows: Raw materials (Na (339.00-715.00 mg kg^{-1}), K (12050-52170 mg kg^{-1}), Mg (3454-7256 mg kg^{-1}), and Ca (10660-28870 mg kg^{-1}). For other essential elements, the concentrations were: P (2355-13510 mg kg^{-1}) and Fe (135-735 mg kg^{-1}). Regarding heavy/toxic elements, the concentrations were: Al (100.00-803.60 mg kg^{-1}), B (68.00-113.00 mg kg^{-1}), Cu (9.90-38.70 mg kg^{-1}), Mn (42.70-153.80 mg kg^{-1}), Pb (3.50-7.10 mg kg^{-1}), Ni (0.80-3.70 mg kg^{-1}), and Zn (193-651 mg kg^{-1}). Biochar materials (Na (611.00-821.00 mg kg^{-1}), K (11780-26590 mg kg^{-1}), Mg (4007-7935 mg kg^{-1}) and Ca (16210-52520 mg kg^{-1}). For other essential elements, the concentrations were: P (3727-11570 mg kg^{-1}) and Fe (279-797 mg kg^{-1}). Regarding heavy/toxic elements, the concentrations were: Al (213.40-966.10 mg kg^{-1}), B (58.70-90.60 mg kg^{-1}), Cu (11.00-61.90 mg kg^{-1}), Mn (52.70-167.70 mg kg^{-1}), Pb (6.50-10.50 mg kg^{-1}), Ni (0.80-

3.80 mg kg^{-1}) and Zn (197-547 mg kg^{-1})). When the results of the analysis were examined, it was observed that the Na concentration increased in all biochar samples compared to the raw materials. CCB samples exhibited higher Mg concentration compared to other materials, while CSB samples showed a notable increase in Fe concentration. OPB samples showed significant increases in P, B, Ca, Cu, and Zn concentration. Additionally, CCB samples had the highest Al concentration, while CCB samples had the highest Ni concentration. Lead values increased for all materials except CSB. Pb value increases with the production of biochar. However, the opposite situation was detected in CCB sample.

Table 4- Studies conducted with different biochar samples

Biochar material	*Pyrolysis Temperature*	*Elemental Composition*									*Reference*
		C (%)	*N(%)*	*H(%)*	*O(%)*	*S(%)*	*H/C*	*O/C*	*pH*	*EC(dS/m)*	
Corn Cobs (CC)	500 °C	71.49	0.85	3.06	10.26	0.03	-	-	8.59	1.34	Rattanaphaiboon et al. 2021
	600 °C	79.5	0.8	2.2	17.4	0.1	0.33	0.16	-	-	Wang et al. 2022
	400 °C	80.50	0.87	3.53	9.03	0.12	0.52	0.88	-	-	Drané et al. 2024
	450 °C	82.20	0.75	3.17	6.81	0.17	0.46	0.06	-	-	
	500 °C	84.60	0.88	2.80	4.98	0.11	0.39	0.04	-	-	
	550 °C	87.00	0.79	2.33	3.02	0.11	0.32	0.25	-	-	
	600 °C	87.30	0.86	1.82	2.64	0.13	0.03	0.02	-	-	
	300 °C	42.39	0.82	6.49	48.04	-	-	-	7.08	-	Adekanye et al. 2022
	400 °C	54.36	0.63	4.32	39.02	-	-	-	7.69	-	
	500 °C	59.48	0.42	2.70	38.96	-	-	-	7.07	-	
	300 °C	55.31	1.78	-	-	-	-	-	6.38	0.21	Ali et al. 2021
	400 °C	61.87	2.93	-	-	-	-	-	7.88	1.23	
Cotton Stalks (CS)	300 °C	47.13	1.09	4.51	47.17	0.1	1.14	0.75	-	-	Afif et al. 2020
	400 °C	58.8	1.49	3.47	36.11	0.14	0.70	0.46	-	-	
	300 °C	54.41	1.35	4.16	29.41	-	0.91	0.41	6.53	-	Khalid et al. 2024
	400 °C	62.41	1.45	3.13	20.31	-	0.60	0.26	6.67	-	
	500 °C	69.36	1.32	2.45	11.66	-	0.42	0.14	6.87	-	
	300 °C	51.56	1.40	4.70	35.36	0.59	1.09	0.51	-	-	Liu et al. 2018
	400 °C	63.69	1.34	3.59	17.86	0.65	0.68	0.21	-	-	
	500 °C	69.1	1.01	2.57	13.71	0.68	0.45	0.15	-	-	
Tobacco stalk (TS)	350 °C	37.1	2.54	3.09	14.99	-	-	-	-	-	Chen et al. 2016
	450 °C	35.95	2.33	2.14	12.03	-	-	-	-	-	
Pistachio shell (PS)	300 °C	66.67	0.34	4.16	29	-	-	-	4.96	1.37	Komnitsas et al. 2015
	350 °C	69.98	0.23	3.31	26	-	-	-	5.11	2.15	
	400 °C	74.83	0.35	3.36	15.50	-	0.55	0.13	7.89	-	Schmidt et al. 2023
	600 °C	88.55	0.32	1.74	11.20	-	0.29	0.04	9.19	-	
Olive pulp (OP)	400 °C	65.3	1.72	3.82	25.5	-	0.35	0.37	-		Lustosa Filho et al. 2024
	500 °C	73.3	1.79	2.37	11.5	-	0.06	0.17	-	-	
Olive mill waste (OMW)	300 °C	68.1	1.13	-	-	-	1.12	-	8.53	0.82	Marra et al. 2018
	500 °C	72.7	0.37	-	-	-	0.19	-	8.98	5.06	

Table 5- Concentrations of alkaline elements (Na, Mg, K, Ca), other essential elements (P, Fe) and heavy/toxic elements (Al, Cr, Cu, Mn, Mo, Ni, Zn) of different raw and biochar materials

	CCR	***CCB***	***CSR***	***CSB***	***TSR***	***TSB***	***PSR***	***PSB***	***OPR***	***OPB***
					Alkaline elements (mg kg^{-1})					
Na	357.00	615.00	693.00	812.00	594.00	807.00	715.00	611.00	339.00	821.00
K	22450	13020	12050	26590	52170	17800	18780	21138	27720	11780
Mg	5203	7935	3454	5654	5713	4007	7256	6012	5525	6445
Ca	14360	26900	12590	17870	10660	16210	28870	41232	25010	52520
					Other essential elements (mg kg^{-1})					
P	3213	5228	2355	3727	13510	3902	5950	7230	5358	11570
Fe	464	619	358	797	735	279	280	412	135	485
					Heavy/toxic elements (mg kg^{-1})					
Al	803.60	816.00	457,20	966.10	468.90	213.40	174.70	521.30	100.00	251.50
B	75.60	67.90	68.00	58.70	113.00	58.70	77.60	71.00	86.10	90.60
Cu	19.90	13.50	9.90	14.80	38.70	11.00	17.10	21.40	31.40	61.90
Mn	42.70	82.40	45.00	53.00	153.80	52.70	88.80	123.00	90.10	167.70
Pb	5.40	10.50	6.90	6.50	3.50	7.80	7.10	9.30	4.60	7.70
Ni	3.70	3.80	2.20	1.50	2.10	0.80	0.80	1.50	1.60	2.90
Zn	193	227	239	197	651	221	376	530	291	547

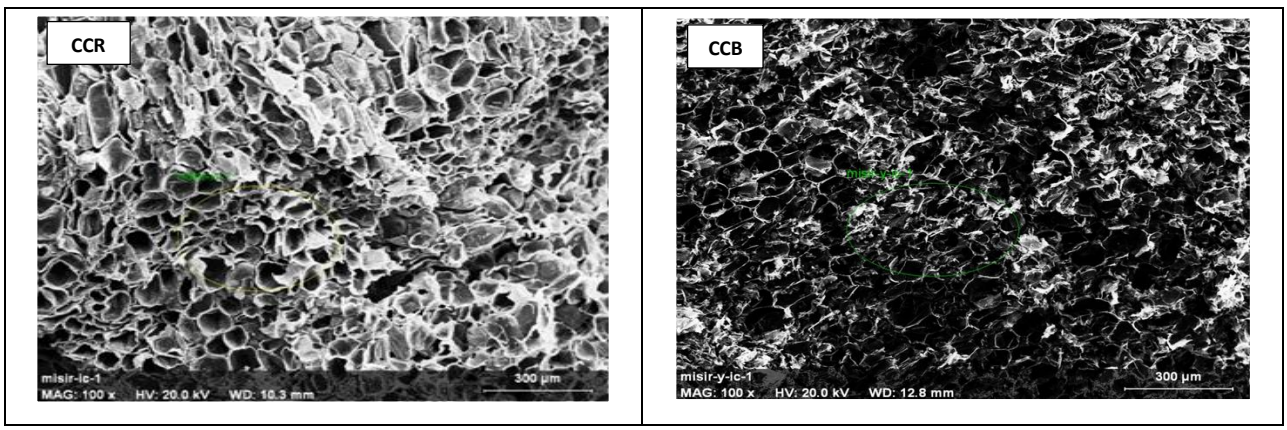
*CCR: Corn Cob raw material, CCB: Corn cob biochar, CSR: Cotton stalks raw material, CSB: Cotton stalks biochar, TSR: Tobacco stalks raw material, TSB: Tobacco stalks biochar, PSR: Pistachio shell raw material, PSB: Pistachio shell biochar, OPR: Olive pulp (pomace) raw material, OPB: Olive pulp (pomace) biochar.

Concentrations of these elements in the biochars should meet the following the International Biochar Initiative (IBI) : Cu <6000 mg kg^{-1}, Mo <75 mg kg^{-1}, Ni <420 mg kg^{-1}, Zn <7800 mg kg^{-1}, As <100 mg kg^{-1}, Cd <39 mg kg^{-1}, Cr <1200 mg kg^{-1}, Co <100 mg kg^{-1}, Pb <300 mg kg^{-1}, and Se < 200 mg kg^{-1} in order to avoid toxicity, and Na <1200 mg kg^{-1} to avoid salinity (IBI 2015).

When the results of ICP heavy metal analysis, according to the International Biochar Initiative (IBI), were reviewed, all specified values were found to be significantly lower than the maximum allowable threshold range for these metals. These findings are consistent with the results reported by Nigam et al. 2018.

3.3. Morphological analysis

Corn cob (CC), cotton stalk (CS), tobacco stalk (TS), pistachio shells (PS), and olive pulp (pomace) (OP) raw material and biochar samples were examined using a scanning electron microscope (SEM), and Scanning Electron Microscope – Energy Dispersive X-Ray Spectroscopy (SEM-EDX) spectrum values were obtained for use in the study (Figure 1 and 2).



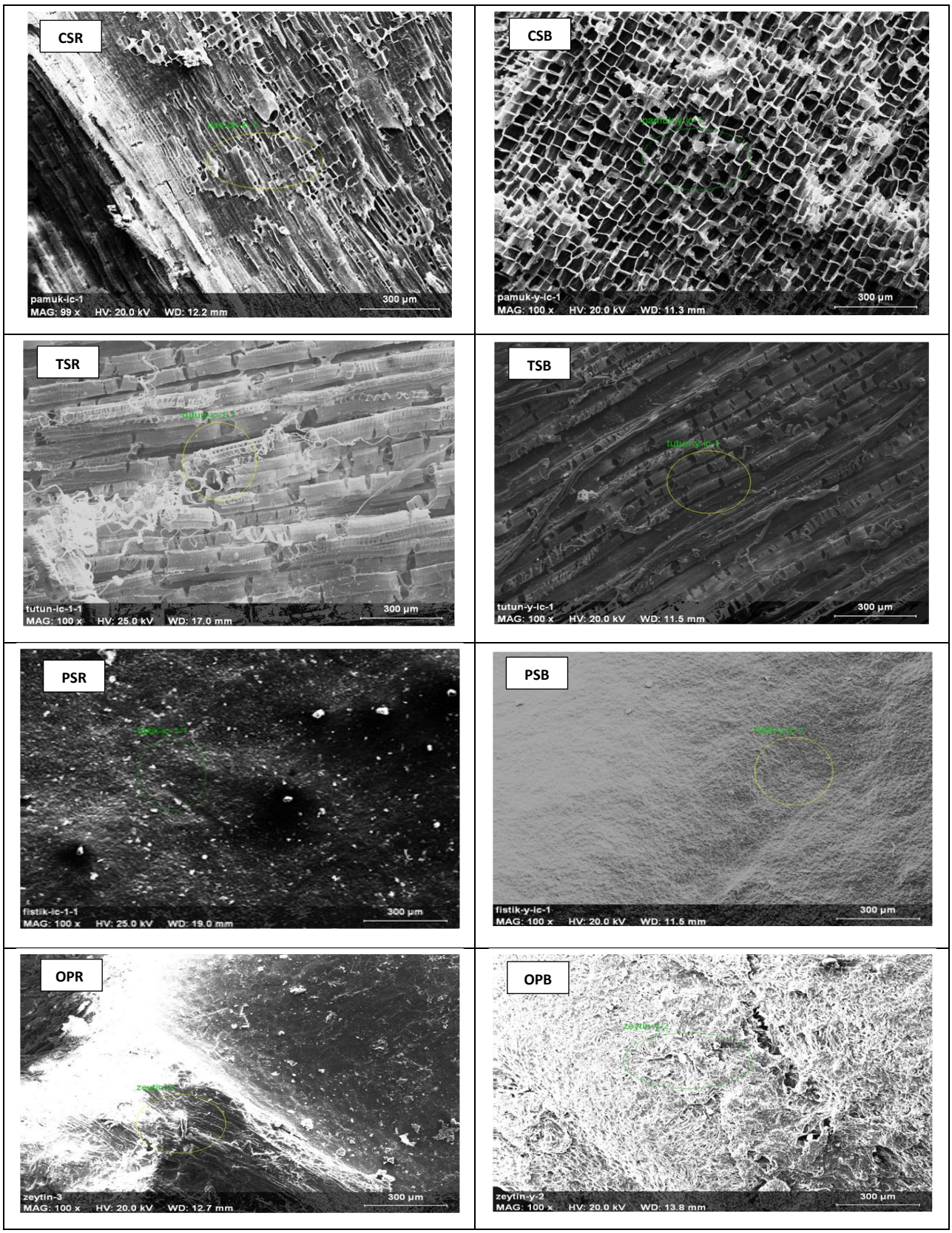


Figure 1- SEM image of raw material and biochar samples

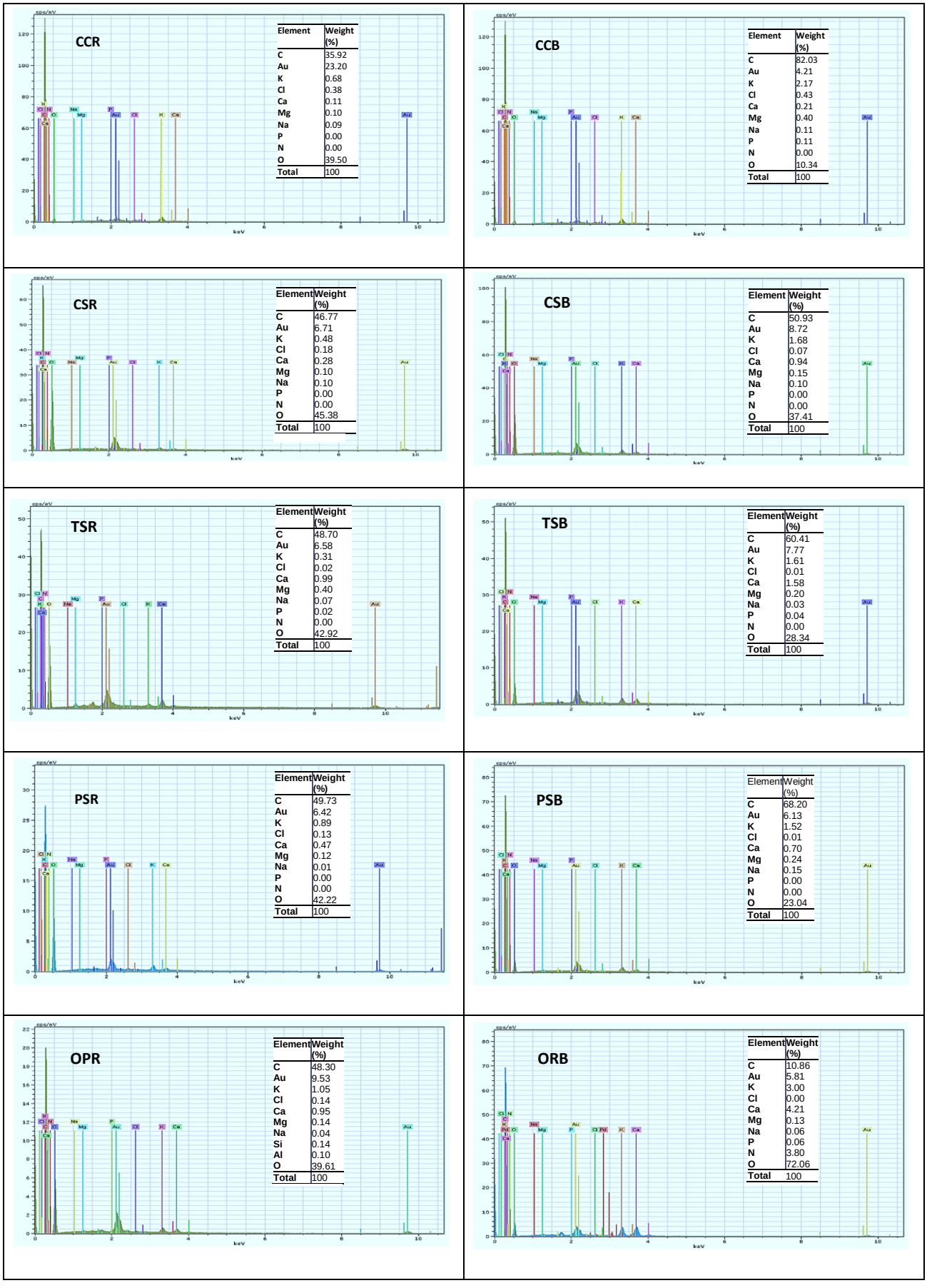


Figure 2- SEM-EDX spectrum of raw material and biochar samples

SEM methods are widely used to display and determine the surface area of biochar. SEM images of biochar obtained from different raw materials showed that surface area and porous structures increased after raw materials were converted into biochar form. The morphological properties of biochar are also very important for its use as a soil improver. When Scanning Electron Microscope – Energy Dispersive X-Ray Spectroscopy (SEM-EDX) analysis results are examined, cotton stalk biochar has been shown to have the best pore development (better defined pores), within the other materials, and the biochar of pistachio shell and olive pulp have a smaller porous structure. TS biochar has more developed pores compared to the four biochar materials and CCB and CSB have a more visible regular, rough and small pore structure than other samples. The study results of CCB materials are similar to those of Hao et al. 2013. Pores are unclear in the PSB and OPB. After the conversion of raw material into biochar, a difference in porous structure was observed. Morphologically a deformation occurs and accordingly, it is noteworthy that there is a noticeable increase in the surface area in total, especially in the internal structure. PSB samples are similar to the results of the study conducted by Apaydin-Varol et al. 2007 and OPB samples by Williams et al. 2020. The pore area of CCB is considerably increased compared to other samples. According to Thies & Rilling 2009, the large pore area provides a habitat for microorganisms and helps improve soil quality. According to Fuertes et al. 2010 and Akhtar et al. 2014, the presence of a large pore area increases the potential for use as a soil improver.

According to the SEM-EDX analysis results, the sample with the highest carbon concentration and the lowest oxygen concentration is CCB. This result can be explained by the physical properties of the raw materials. It is manifested by an increase in the carbon composition of biochar and a decrease in the oxygen composition. In SEM-EDX analysis, carbon is the predominant element, accompanied by oxygen and a much lower proportion of other elements (such as Ca, K, Al, Mg, and traces of Si). Nigam et al. 2018 obtained similar results at three different temperatures (450 °C, 650 °C, and 850 °C). The findings of the study regarding low-temperature biochar samples were comparable to our study results. When determining the concentration properties of biochar samples, it is considered crucial for their use as soil improvers. Corn cobs was put in a muffle furnace and pyrolyzed at 300 °C. The SEM results for biochar produced at 300 °C showed a smaller pore size. The present study presented the physico chemical properties of corn cob biochar 47–50 %. SEM-EDX analysis demonstrated the elemental composition of biochar (Ali et al. 2021). SEM results have small pores. SEM-EDX results are similar to C analysis results.

4. Conclusions

By evaluating both the H/C and O/C biochar ratios in this study, it was found that the H/C ratio supports the suitability of all the biochar forms examined for agricultural use, while the O/C ratio indicates that only CCB, PSB, and OPB are particularly well-suited for carbon sequestration and soil improvement. Regarding C/N ratios, biochars derived from CSB and OPB displayed the lowest C/N values, and, except for PSB, the C/N ratio of all materials decreased after conversion into biochar.

The presence of essential nutrient elements such as Na, K, Ca, Mg, Mn, Zn, P, Fe, and N in biochar is crucial for plant growth. Specifically, the analysis revealed that Na concentration increased in all biochar samples compared to the raw materials, with CCB samples showing higher Mg levels, CSB samples exhibiting a notable increase in Fe, and OPB samples displaying significant increases in P, B, Ca, Cu, and Zn concentrations, all of which contribute to improved soil fertility and plant nutrition.

The porous structure of biochar significantly influences the physical, chemical, and biological properties of soil. It enhances the soil's water retention capacity, provides a habitat for microorganisms, and improves various soil characteristics, particularly the carbon content. SEM-EDX analysis in this study revealed that CCB and CSB biochars have a more porous structure compared to TSB, PSB, and OPB.

Given the combined properties of CCB, including its higher elemental concentration and more porous structure, it is concluded that CCB holds greater potential for agricultural applications and is likely to be more effective in enhancing soil fertility and boosting crop production compared to the other biochar types.

Acknowledgements

This study was financially supported by TÜBİTAK (The Scientific and Technological Research Council of Turkey) (Project No:112R005)

References

Adekanye T, Dada O & Kolapo J (2022). Pyrolysis of maize cob at different temperatures for biochar production: Proximate, ultimate and spectroscopic characterization. *Research in Agricultural Engineering* 68(1): 27–34. https://doi.org/10.17221/106/2020-RAE

Afif R A, Anayah S S & Pfeifer C (2020). Batch pyrolysis of cotton stalks for evaluation of biochar energy potential. *Renewable Energy* 147: 2250-2258. https://doi.org/10.1016/j.renene.2019.09.146

Agrafioti E, Bouras G, Kalderis D & Diamadopoulos E (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis* 101: 72–78. https://doi.org/10.1016/j.jaap.2013.02.010

Agrafioti E, Kalderis D & Diamadopoulos E (2014). Arsenic and chromium removal from water using biochars derived from rice husk, organic solid wastes and sewage sludge. *Journal of Environment Management* 133: 309–314. http://dx.doi.org/10.1016/j.jenvman.2013.12.007

Akca M O, Sozudoğru Ok S, Denız K, Mohammedelnour A & Kibar M (2021). Spectroscopic Characterisation and Elemental Composition of Biochars Obtained from Different Agricultural Wastes, *Journal of Agricultural Sciences* (*Tarim Bilimleri Dergisi*) 27(4): 426-435. https://doi.org/10.15832/ankutbd.623876

Akhtar S S, Li G T, Andersen M N & Liu F L (2014). Biochar enhances yield and quality of tomato under reduced irrigation. *Agricultural Water Management* 138: 37–44. https://doi.org/10.1016/j.agwat.2014.02.016

Akram M Z & Yaman Fırıncıoğlu S (2019). The Use of Agricultural Crop Residues as Alternatives to Conventional Feedstuffs for Ruminants. *Eurasian Journal of Agricultural Research* 3(2): 58-66

Ali L, Manzoor N, Li X, Naveed M, Nadeem S M, Waqas M R, Khalid M, Abbas A, Ahmed T & Li B (2021). Impact of Corn Cob-Derived Biochar in Altering Soil Quality, Biochemical Status and Improving Maize Growth under Drought Stress. *Agronomy* 11, 2300. https://doi.org/10.3390/agronomy11112300

Al-Wabel M I A, Al-Omran A H, El-Naggar A M, Nadeem M & Usman A R A (2013). Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology* 131: 374–379. http://dx.doi.org/10.1016/j.biortech.2012.12.165

Angin D (2013). Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Biores. Tech*. *128*: 593–597. https://dx.doi.org/10.1016/j.biortech.2012.10.150

Apaydin-Varol E, Pütün E & Pütün A E (2007). Slow pyrolysis of pistachio shell, Science Direct, *Fuel* 86: 1892–1899. http://doi:10.1016/j.fuel.2006.11.041

Bahşi K, Ustaoğlu B, Aksoy S & Sertel E (2023). Estimation of emissions from crop residue burning in Türkiye using remotely sensed data and the Google Earth Engine platform, *Geocarto Internatıonal* 38(1): 2157052. https://doi.org/10.1080/10106049.2022.2157052

Bakshi S, Banik C & Laird D A (2020). Estimating the organic oxygen content of biochar. Scientific Reports 10: 13082. https://doi.org/10.1038/s41598-020-69798-y

Beesley L & Marmiroli M (2011). The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. *Environmental Pollution*, 159(2): 474–480. http://dx.doi.org/10.1016/j.envpol.2010.10.016

Bilgili A V, Yeşilnacar İ, Akihiko K, Nagano T, Aydemir A, Hızlı H S & Bilgili A (2018). Post-irrigation degradation of land and environmental resources in the Harran plain, southeastern Turkey, *Environ Monit Assess* 190: 660. https://doi.org/10.1007/s10661-018-7019-2

Bouraoui Z, Jeguirim M, Guizani C, Limousy L, Dupont C & Gadiou R (2015). Thermogravimetric study on the influence of structural, textural and chemical properties of biomass chars on CO_2 gasification reactivity. *Energy* pp. 703-710. http://dx.doi.org/10.1016/j.energy.2015.05.100

Campos P, Miller A Z, Knicker H, Costa-Pereirac M F, Merino A & Rosaa J M D (2020). Chemical, physical and morphological properties of biochars produced from agricultural residues: Implications for their use as soil amendment, *Waste Management* 105: 256-267. https://doi.org/10.1016/j.wasman.2020.02.013

Chandra S & Bhattacharya J (2019). Influence of temperature and duration of pyrolysis on the property heterogeneity of rice straw biochar and optimization of pyrolysis conditions for its application in soils. *J. Clean. Prod.* 215: 1123–1139. https://doi.org/10.1016/j.jclepro.2019.01.079

Chen H, Lin G, Wang X, Chen Y, Liu Y, Yang H & Shao J (2016). Physicochemical properties and hygroscopicity of tobacco stem biochar pyrolyzed at different temperatures, *Journal of Renewable and Sustaınable Energy 8,* 013112. https://doi.org/10.1063/1.4942784

Chia C H, Gong B, Joseph S D, Marjo C E, Munroe P & Rich A M (2012). Imaging of mineral-enriched biochar by FTIR, Raman and SEM–EDX. *Vibrational Spectroscopy* 62: 248–257. https://doi.org/10.1016/j.vibspec.2012.06.006

Demirbas A (2004). Effects of Temperature and Particle Size on Bio-Char Yield from Pyrolysis of Agricultural Residues, *Journal of Analytical and Applied Pyrolysis* 72: 243-248. https://doi:10.1016/j.jaap.2004.07.003

Drané M, Zbair M, Hajjar-Garreau S, Josien L, Michelin L, Bennici S & Limousy L (2024). Unveiling the Potential of Corn Cob Biochar: Analysis of Microstructure and Composition with Emphasis on Interaction with NO_2. *Materials 17*, 159. https://doi.org/10.3390/ma17010159

Frišták V, Pipíška M, Lesný J, Soja G, Friesl-Hanl W & Packová A (2015). Utilization of biochar sorbents for Cd^{2+}, Zn^{2+}, and Cu^{2+} ions separation from aqueous solutions: comparative study. *Environ. Monit. Assess* 187, 4093. https://doi: 10.1007/s10661-014-4093-y

Fuertes A B, Arbestain M C, Sevilla M, Maciá-Agulló J A, Fiol S, López R, Smernik R J, Aitkenhead W P, Arce F & Macias F (2010). Chemical and structural properties of carbonaceous products obtained by pyrolysis and hydrothermal carbonisation of corn stover, *Australian Journal of Soil Research* 48: 618-626. https://doi:10.1071/SR10010

Hao F, Zhao X, Ouyang W, Lin C, Chen S, Shan Y & Lai X (2013). Molecular Structure of Corncob-Derived Biochars and the Mechanism of Atrazine Sorption. *Agronomy Journal* 105: 773-782. https://doi.org/10.2134/agronj2012.0311

Howell J (2005). Organic Matter: Key to Soil Management. Available at http://www.hort.uconn.edu/ipm/veg/croptalk/croptalk1_4/page8.html. [verified 1.19.11]

IBI (2012). Standardized product definition and product testing guidelines for biochar that is used in soil. Int. Biochar Initiat. 22. doi:http://www.biochar-international.org/ characterizationstandard

Inyang M, Gao B, Zimmerman A, Zhang M & Chen H (2014). Synthesis, characterization, and dye sorption ability of carbon nanotube- biochar nanocomposites. *Chemical Engineering Journal* 236: 39–46. https://doi.org/10.1016/j.cej.2013.09.074

Jindo K, Mizumoto H, Sawada Y, Sanchez-Monedero M & Sonoki T (2014). Physical and chemical characterization of biochars derived from different agricultural residues., *Biogeosciences* 11: 6613-6621. https://doi:10.5194/bg-11-6613-2014

Joseph S D, Camps-Arbestain M, Lin Y, Munroe P, Chia C H, Hook J, Van Zwieten L, Kimber S, Cowie A & Singh B P (2010). An investigation into the reactions of biochar in soil. *Soil Research* 48: 501–515

Khalid U & Inam M A (2024). The Influence of Pyrolysis Temperature on the Performance of Cotton Stalk Biochar for Hexavalent Chromium Removal from Wastewater, *Water Air Soil Pollut* 235: 114. https://doi.org/10.1007/s11270-024-06922-y

Kim K H, J, Kim Jae-Young, Cho Tae-Su & Choi J W (2012). Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (*Pinus rigida*). *Bioresource Technology* 118: 158–162. http://dx.doi.org/10.1016/j.biortech.2012.04.094

Komnitsas K, Zaharaki D, Pyliotis I, Vamvuka D & Bartzas G (2015). Assessment of pistachio shell biochar quality and its potential for adsorption of heavy metals, Waste Biomass Valor 6: 805–816 https://doi.10.1007/s12649-015-9364-5

Kostas E T, Durán-Jiménez G, Shepherd B J, Meredith W, Stevens L A, Williams O S A, Lye G J & Robinson J P (2020). Microwave pyrolysis of olive pomace for bio-oil and bio-char production. *Chemical Engineering Journal* 387: 123404. https://doi.org/10.1016/j.cej.2019.123404

Leco (2005). Carbon, Hydrogen and Nitrogen in Flour and Plant Tissue LECO Corporation 3000 Lakeview Avenue.

Lehmann J & Joseph S (2009). Biochar for environmental management: science and technology. Sterling, VA: Earthscan.

Liu Z, Niu W, Chu H, Zhou T & Niu Z (2018). Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues. *BioResources* 13: 3429-3446

Lustosa Filho J F, da Silva A P F, Costa S T, Gomes H T, de Figueiredo T, Hernández Z (2024). Biochars Derived from Olive Mill Byproducts: Typology, Characterization, and Eco-Efficient Application in Agriculture—A Systematic Review. *Sustainability, 16,* 5004. https://doi.org/10.3390/su16125004

Marra R, Vinale F, Cesarano G, Lombardi N, d'Errico G & Crasto A (2018). Biochars from olive mill waste have contrasting effects on plants, fungi and phytoparasitic nematodes. *PLoS ONE 13* (6): e0198728. https://doi.org/10.1371/journal.pone.0198728

Méndez A, Terradillos M & Gascó G (2013). Physicochemical and agronomic properties of biochar from sewage sludge pyrolysed at different temperatures. *Journal of Analytical and Applied Pyrolysis* 102: 124–130. https://doi.org/10.1016/j.jaap.2013.03.006

Mertens D (2005a). AOAC Official Method 922.02. Plants Preparation of Laboratuary Sample. Official Methods of Analysis, 18th edn. Horwitz, W., and G.W. Latimer, (Eds). Chapter 3, pp1-2, AOAC-International Suite 500, 481. North Frederick Avenue, Gaitherburg, Maryland 20877-2417, USA.

Mullen C A, Boateng A A, Goldberg N M, Lima I M, Laird D A & Hicks K B (2010). Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. *Biomass and Bioenergy 34*: 67–74. https://doi.org/10.1016/j.biombioe.2009.09.012.

Nguyen T T N, Xu Cheng-Yuan, Tahmasbian I, Che R, Xu Z, Zhou X, Wallace H M, Bai S H (2017). Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. *Geoderma 288*: 79–96. https://doi.org/10.1016/j.geoderma.2016.11.004

Nigam N, Shanker K, & Khare P (2018). Valorisation of Residue of Mentha arvensis by Pyrolysis: Evaluation of Agronomic and Environmental Benefits. *Waste Biomass Valor* 9: 1909–1919. https://doi.org/ 10.1007/s12649-017-9928-7

Parmila D & Saraho A K (2013). Effect of temperature on biochar properties during paper mill sludge pyrolysis. *International Journal of Chemtech Research* 5(2): 682–687

Qian K, Kumar A, Patil K, Bellmer D, Wang D, Yuan W & Huhnke R L (2013). Effects of biomass feedstocks and gasification conditions on the physiochemical properties of char, *Energies 6*: 3972-3986. https://doi.org/10.3390/en6083972.

Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman, A R & Lehmann J (2012). Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils* 48: 271-284. https://doi.org/10.1007/s00374-011 0624-7

Rattanaphaiboon P, Homdoung N & Tippay N (2021). Production and Characterization of Corncob Biochar for Agricultural Use, *3rd International Conference on Energy and Power, ICEP2021* AIP Conf. Proc. 2681, 020034-1–020034-6; https://doi.org/10.1063/5.0117160

Rivka B, Laird D, Thompson M L & Lawrinenko M (2017). Characterization and quantification of biochar alkalinity. *Chemosphere* 167: 367-373. http://dx.doi.org/10.1016/j.chemosphere.2016.09.151

Ronsse F, Nachenius R W & Prins W (2015). Carbonization of Biomass, *Recent Advances in Thermo-Chemical Conversion of Biomass* 293-324. https://doi.org/10.1016/B978-0-444-63289-0.00011-9

Schimmelpfennig S & Glaser B (2012). One step forward toward characterization: some important material properties to distinguish biochars. *Journal of Environment Quality*, 41: 1001-1013. https://doi.org/10.2134/jeq2011.0146

Schmidt M P, Ashworth D J, Celis N & Ibekwe A M (2023). Optimizing date palm leaf and pistachio shell biochar properties for antibiotic adsorption by varying pyrolysis temperature, *Bioresource Technology Reports 21,* 101325. https://doi.org/10.1016/j.biteb.2022.101325

Seow Y X, Tan Y H, Mubarak N M, Kansedo J, Khalid M, Ibrahim M L & Ghasemi M (2022). A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications, *Journal of Environmental Chemical Engineering*, 10, 107017. https://doi.org/10.1016/j.jece.2021.107017

Tan C, Yaxin Z, Hongtao W, Wenjing L, Zeyu Z, Yuancheng Z & Lulu R (2014). Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage. *Bioresource Technology 164*: 47–54. http://dx.doi.org/10.1016/j.biortech.2014.04.048

The European Biochar Certificate (2014). www.biochar-international.org

Thies J E & Rillig M C (2009). Characteristics of biochar: Biological properties. *In Biochar for Environmental Management* pp. 85–105

Ünlü A, Arslan Z F, Arslan R & Ceylan F (2023). Amount of herbal waste in Türkiye at national and regional scale. *Journal of Agriculture Faculty of Duzce University 1*(1):26-37.

Wang L, Olsen M N P, Moni C, Dieguez-Alonso A, Rosa J M, Stenrød M, Liu X & Mao L (2022). Comparison of properties of biochar produced from different types of lignocellulosic biomass by slow pyrolysis at 600 ◦C, *Applications in Energy and Combustion Science 12*: 100090. https://doi.org/10.1016/j.jaecs.2022.100090

Watson C A, Atkinson D, Gosling P, Jackson L R & Rayns F W (2002). Managing soil fertility in organic farming systems. *Soil Use Management 18*: 239-247. https://doi.org/10.1111/j.1475-2743.2002.tb00265.x

Williams O S, Kostas E T, Durán-Jiménez G, Shepherd B J, Meredith W, Stevens L A & Lye G J (2020). Microwave pyrolysis of olive pomace for bio-oil and bio-char production. *Chemical Engineering Journal 387*: 123404. https://doi.org/10.1016/j.cej.2019.123404

Xu G, Wei L L, Sun J N, Shao H B & Chang S X (2013). What is more important for enhancing nutrient bioavailability with biochar application into a sandy soil: Direct or indirect mechanism?, *Ecological Engineering, 52*: 119–24. https://doi.org/10.1016/j.ecoleng.2012.12.091

Yılmaz H, Ozyakar H D & Dağ M M (2024). Exploratory factor analysis of manure utilization for sustainable dairy farming: Evidence from crop-dairy farming systems in Turkey, Waste Management Bulletin 1: 164-171. https://doi.org/10.1016/j.wmb.2023.10.010

Copyright © 2025 The Author(s). This is an open-access article published by Faculty of Agriculture, Ankara University under the terms of the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium or format, provided the original work is properly cited.