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RESEARCH ARTICLE

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The effect of olive pomace biochar on some characteristics of Vertisols

Remzi İlay[1] | **Seda Özer Bodur**[2] | **S. Tuğçe Eren**[1] | **Yasemin Kavdır**[1] | **Hüseyin Ekinci**[1]

[1]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Çanakkale Onsekiz Mart University, Çanakkale, Türkiye

[2]Niigata Graduate School of Science and Technology, Niigata University, Niigata, Japan

Correspondence
Remzi İlay, Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Çanakkale Onsekiz Mart University, 17020 Çanakkale, Türkiye.
Email: rilay@comu.edu.tr

Abstract

The aim of this study was to investigate the effect of olive pomace biochar (OB) application on the mechanical, physical and chemical properties of Vertisols. For this study, soil samples classified as Vertisol in Çanakkale, where internal drainage and surface ponding are major problems, were used. The OB was produced at 450°C and then mixed with 0% (control), 3%, 6% and 9% of the soil by weight. Various soil parameters, including the Atterberg limits (liquid limit [LL], plastic limit [PL], plasticity index [PI], shrinkage limit [SL]), saturated hydraulic conductivity (K_{sat}), field capacity (FC), total carbon (TC) and total nitrogen (TN), were determined. The values of all the soil parameters increased, except for the PI. Moreover, the K_{sat} value increased by 127% and 136% with 6% and 9% OB application, respectively, compared to that of the control. Additionally, the FC, TN and TC levels in the soils increased in response to biochar application. In conclusion, OB application has a positive effect on the specific properties of Vertisol and can improve its physical properties.

KEYWORDS

Atterberg limits, biochar, carbon, hydraulic conductivity, olive pomace, Vertisol

Résumé

Le but de cette étude était d'étudier l'effet de l'application du biochar du Marc d'olive (OB) sur les propriétés mécaniques, physiques et chimiques des Vertisols. Pour cette étude, on a utilisé des échantillons de sol classés comme des vertisols dans le site de Canakkale, où le drainage interne et les bassins de surface sont des problèmes majeurs. L'OB a été produit à 450 °C, puis mélangé à 0% (témoin), 3%, 6% et 9% du sol en poids. Divers paramètres du sol, y compris les limites d'Atterberg ((limite de liquide (LL), limite de plastique (PL), indice de plasticité (PI), limite de retrait (SL)), conductivité hydraulique saturée (K_{sat}), capacité de champ (FC), carbone total (TC) et azote total (TN), ont été déterminés. Les valeurs de tous les paramètres du sol ont augmenté, sauf pour le PI. En outre, la

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valeur K_{sat} a augmenté de 127% et 136% avec 6% et 9% d'application OB, respectivement, par rapport à celle de la réglementation. De plus, les concentrations de FC, de TN et de TC dans les sols ont augmenté en réponse à l'application de biochar. En conclusion, l'application OB exerce un effet positif sur les propriétés spécifiques du Vertisol et peut améliorer ses propriétés physiques.

MOTS CLÉS
biochar, vertisol, marc d'olives, limites d'atterberg, carbone, conductivité hydraulique

1 | INTRODUCTION

Vertisols are soils characterized by a high proportion of 2:1-layer-type smectite-group clay (fine clayey), which deeply cracks during specific times of the year and typically exhibits a very high bulk density. The moisture regimes and consequently soil colours show significant variations. Soil temperature regimes range from mesic to isohyperthermic but generally tend to be thermic or warm (Soil Survey Staff, 1999). According to the Food and Agriculture Organization of the United Nations (FAO, 2001), Vertisols cover 335 million ha worldwide, with approximately 45% of this area reported as suitable for cultivation (Figure 1; FAO & IIASA, 2023). Vertisols contain 30% or more clay, have deep wide cracks when dry and have either gilgai microrelief, intersecting slickensides or wedge-shaped structural aggregates tilted at an angle from the horizon (SSSA,1997). It was added as an order in the US system of soil taxonomy and as a Reference Soil Group (RSG) in the World Reference Base for Soil Resources (WRB), and its environment has been described as ‘depressions and level to undulating areas, mainly in tropical, semi-arid to (sub)humid and Mediterranean climates with an alternation of distinct wet and dry seasons’ (Driessen & Dudal, 1991).

They are usually formed on limestone, basalt and parent materials that are rich in calcium (Ca) and magnesium (Mg). Crumbs from the surface flow into soil cracks and mix with the subsoil. When it rains, the water entering through the cracks causes the 2:1-type clays in the subsoil to swell and the cracks to close. In this process, the increased soil volume is pushed horizontally and upwards. The subsoil masses slide over each other due to pressure, forming smooth sliding surfaces

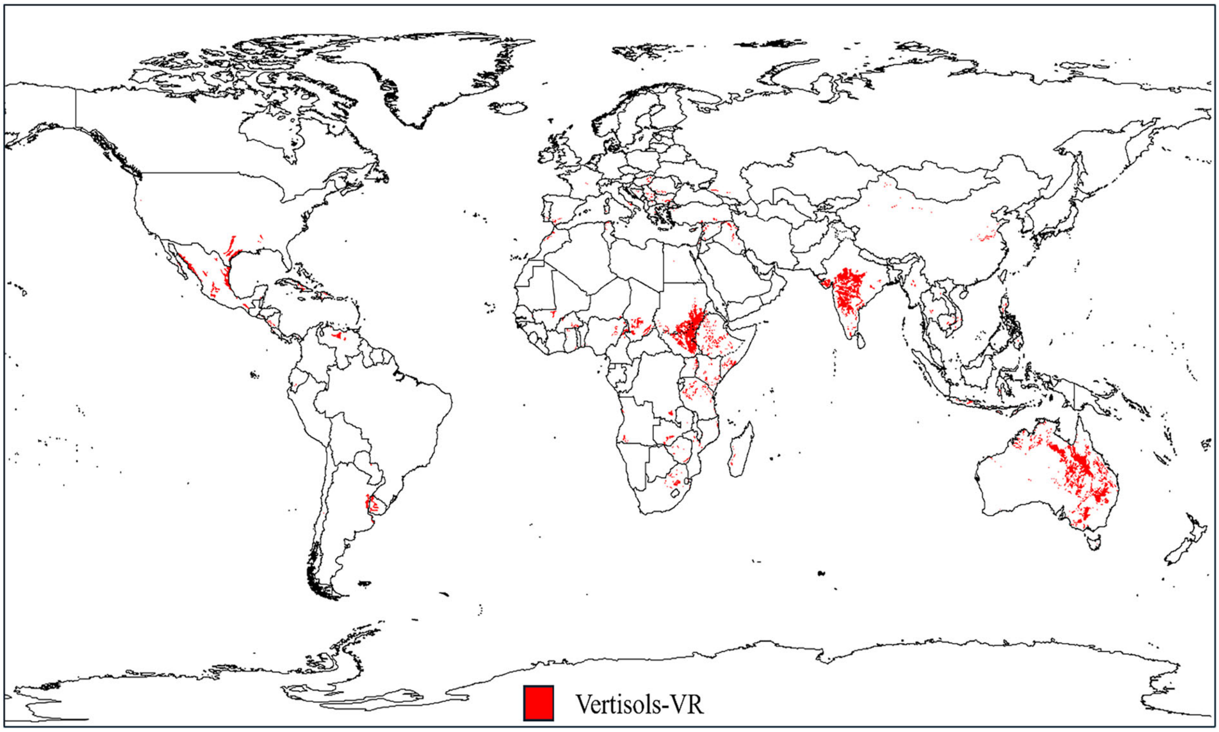

FIGURE 1 Distribution of Vertisols worldwide. *Source:* FAO & IIASA (2023).

(slickensides) (Weil & Brady, 2017). The slickensides, in turn, intercept percolating water and focus flow to the microbasins, where salts, gypsum and carbonates accumulate (Buol et al.,1997). Dry Vertisols (cracked) with surface mulch have a high initial infiltration rate. The surface soil is thoroughly wetted, the soil swells, the cracks close and further infiltration is almost nil. The very process of swelling/shrinking implies a discontinuous and non-permanent pore system. In general, Vertisols have a high cation exchange capacity (CEC), a high base saturation percentage and pH values between 6.0 and 8.0. Vertisols are highly productive soils whose problems are eliminated by reclamation and mechanical treatment (Driessen & Dudal, 1991).

In heavy- or very heavy-textured Vertisols, wide cracks are formed during dry periods due to the shrinkage characteristics of the clay type. In addition, water ponding often occurs on soil surfaces during rainy periods, reflecting their high swelling capacity. As a result, Vertisol soils have relatively low hydraulic conductivities. Dry Vertisols exhibit a hard consistency, whereas wet Vertisols are highly plastic and sticky, posing a challenge to various agricultural activities, from seed germination to tillage. Although Vertisols have favourable chemical fertility, their physical soil characteristics present challenges, particularly in terms of water management. (FAO, 2001). The distinctive characteristics of Vertisols limit the effective management and planning of agricultural and other engineering activities and require improvement.

Traditionally recognized options for improving Vertisols include the application of barnyard manure, waste sludge, compost, urban waste and crop residues (Bravo-Garza et al., 2009; Malkawi et al., 1999; Pillai & McGarry, 1999). Additionally, studies have explored the effects of biochar on the mechanical properties of clay soils (Cuilan et al., 2018; Lu et al., 2014; Zong et al., 2014). Lu et al. (2014) reported that the tensile strength and the coefficient of linear extensibility (COLE) values of soil decreased with rice husk biochar application, Cuilan et al. (2018) reported that soil shrinkage decreased with corn straw and peanut shell biochar application, and Zong et al. (2014) reported that the plastic limit (PL) and liquid limit (LL) increased with woodchips biochar applications. Omondi et al. (2016) investigated the effects of various biochar types on soil properties, including dry bulk density, water content, saturated hydraulic conductivity (K_{sat}) and aggregate stability. According to their study, the average dry bulk density of biochar-amended soil decreased by 8%, while the porosity increased by 8%. They also reported that biochar application increased aggregate stability by 8%, available water holding capacity by 15% and K_{sat} by 25%. Guharay et al. (2019) reported that biochar produced from *Prosopis juliflora* at 500°C and applied at levels of 5% and 10% reduces the free-swelling index and plasticity index (PI) in clay soils, indicating its potential as a stabilizing material for Vertisols.

The LL, PL and shrinkage limit (SL), which indicate the varying consistency of soil based on its moisture content, are collectively referred to as Atterberg limits. These limits are crucial for evaluating the long-term impact of land use and tillage on the mechanical and rheological properties of soil (Terzaghi et al., 1988). Atterberg limits are influenced by various dynamic factors, including the quantity and type of clay minerals, pH, temperature, CEC and the type and quantity of cations in solution (Polidori, 2007). Determining these limits is essential for planning both structures (buildings, roads, etc.) and agricultural activities.

The LL and PL of the soil generally depend on the clay content, clay type and soil organic matter content (De Jong et al., 1990). Odell et al. (1960) reported significant correlations between the LL, PL and PI and the percentage of soil organic carbon, clay and montmorillonite in clay. In addition, Blanco-Canqui et al. (2006) reported that changes in the amount of total organic carbon can affect physical properties defining the boundaries of soil consistency, such as the LL, PL and PI.

Soil tillage should be performed when the moisture content is close to or below the PL value to avoid degrading soil structural properties. The PL value indicates that the soil moisture level is at the upper limit in terms of suitability for tillage (Larney et al., 1988). Soils with a high clay content may have a significant shrinkage–swelling potential, leading to soil cracking. While cracking may facilitate rapid water infiltration and groundwater rise in clay soils, it may also diminish soil fertility by causing loss of water and nutrients from the root zone (Zong et al., 2016). Ganesan et al. (2020) reported that the LL and PL values increased with the addition of 5% and 10% by weight of biochar produced at temperatures of 350°C and 550°C to the soil. This increase may be due to the large internal pore volume of biochar and its ability to retain more water. In the same study, the PI increased as the biochar dose and pyrolysis temperature increased. Ajayi et al. (2016) reported that biochar application decreased the K_{sat} value of fine sandy soils while increasing the K_{sat} value of sandy loam silt (Calcic Gleysol) soils. Similarly, in some studies conducted in clay-rich soils, the K_{sat} value increased with the addition of biochar to the soil (Asai et al., 2009; Barnes et al., 2014; Chaganti & Crohn, 2015; Lim et al., 2016).

Many studies on biochar emphasize that factors such as the type of feedstock, production technique, particle size of biochar, application dose and carbon content of biochar may affect soil properties (Blanco-Canqui, 2017;

İlay, 2020, 2022, 2024; İlay et al., 2020; Kavdır et al., 2023). Atterberg limits vary depending on the amount of soil organic carbon. Kumar et al. (2019) investigated the effects of various types of biochar at the 5% and 10% levels on the Atterberg limits of loamy soil. The results showed that the application of sawdust, water hyacinth, peanut shell and poultry waste biochars increased the LL values by 15%–52%, 14%–37%, 30%–38% and 26%–34%, respectively, for the 5% and 10% application rates. The PL increased with the application of sawdust biochar by 2% and 26%, water hyacinth biochar by 11% and 66% and peanut shell biochar by 12% and 18% for the 5% and 10% application rates, respectively. Furthermore, the 5% application of poultry waste biochar decreased the PL value by 4%, while the PL value increased by 13% with the 10% application dose.

Zong et al. (2014) conducted a study using various types of biochar and found that the application of woodchips biochar increased the soil PL value compared to that of the control. The greatest increase (25%) was observed with a 4% woodchips biochar application, while a decrease between 2% and 11% was reported with the application of wheat straw biochar. Compared with those in the control treatment, the LL in the treatment group treated with 6% wheat straw biochar increased by 0.7%, while the LL in the treatment groups treated with other biochar types and levels decreased (Zong et al., 2014).

Dindaroğlu et al. (2014) reported that the LL of clay soils increased by 4%, 10% and 1% after pomace, leonardite and gyttja application, respectively, compared to that of the control. Similarly, an increase in LL was detected as a result of the application of hazelnut husk compost to sandy loam- and clay loam-textured soils (İslam, 2016).

Gülser and Candemir (2004) found a positive relationship between the addition of organic wastes to soils and LL values. Yakupoğlu and Özdemir (2006) investigated the effect of organic waste addition on the physical properties of eroded soils and reported that the LL increased as a result of organic waste application. Gui et al. (2021) reported that an increase in the organic matter content of the soil caused an increase in the LL values of clay soils.

The aim of this study was to investigate the effects of the application of olive pomace biochar (OB) to Vertisol at different doses on Atterberg limits and some soil properties.

2 | MATERIALS AND METHODS

The Vertisol soil samples used in this study were collected from the Umurbey Plain of Çanakkale Province, Türkiye, at a depth of 30–60 cm using a shovel (Figure 2). The air-dried soil samples were sieved through a 2-mm sieve and then stored in closed containers. Olive pomace was dried in an oven at 60°C for 3 days prior to biochar production. From each dry pomace sample, 100 g was taken and placed in a ceramic crucible with an aluminium foil lid. The OB was pyrolyzed under limited oxygen conditions at 450°C for 15 min and then cooled to room temperature. Soil texture was determined using the hydrometer method as described by Bouyoucos (1951). The electrical conductivity (EC) and pH were measured using an EC-pH meter after the air-dried soil samples were sieved through a 2-mm sieve and mixed with distilled water at a ratio of 1:2.5 (w/w) (US Salinity Laboratory Staff, 1954). The soil moisture content was determined by measuring the weight loss after drying in an oven at 105°C until a constant weight was reached. The total carbon (TC) and total nitrogen (TN) content of the soil, biochar and mixtures were analysed using a LECO TruSpec CN analyser (Kirsten, 1983).

The effect of biochar on the consistency of clay soils was assessed by evaluating the Atterberg limits. Soils sieved through a 2-mm sieve and biochar sieved through a 0.25-mm sieve were mixed at weight ratios of 0%, 3%, 6% and 9% and placed into 750-mL plastic containers. Containers were arranged according to a randomized block design with three replications, and then soil analyses were conducted 20 days later under laboratory conditions.

The LL, PL and SL values of the mixtures were determined according to the American Society for Testing and Materials (ASTM) D4318 procedure (ASTM, 1995). The difference between LL and PL was calculated as the PI.

K_{sat} values were calculated from saturated soils under a constant water load after measuring the flow of water over time (Klute & Dirksen, 1986). To determine field capacity (FC), the moisture content that the soil samples could hold under $-1/3$ atm pressure was calculated using a ceramic pressure plate. The CEC of the soil was determined using the sodium acetate extraction method (US Salinity Laboratory Staff,1954).

The porosity was calculated by dividing the water volume by the total soil volume after the soil core was completely saturated and all the pores were filled with water. The dry bulk density (db) of the soil was determined using the method specified by Blake and Hartge (1986).

The pH and EC of the biochar were determined using a digital pH and EC meter in a mixture prepared with a 1:10 ratio of biochar to distilled water (Lee et al., 2013.). The data within the scope of the study were statistically analysed using the SPSS 26.0 package program, one-way analysis of variance and Duncan multiple comparison tests ($p \leq 0.05$).

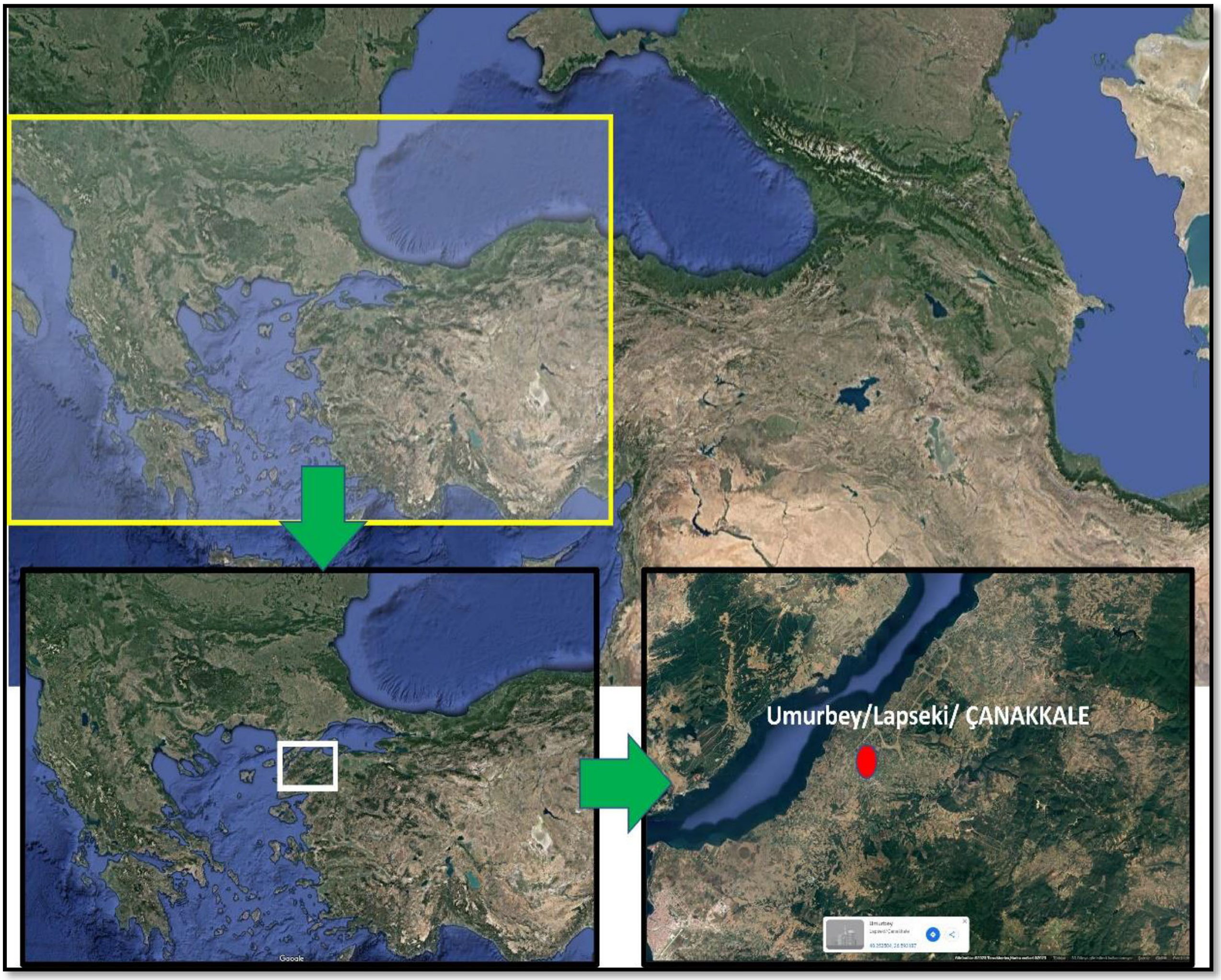

FIGURE 2 Location of Vertisol soil sample used in the experiment. *Source:* Google Earth (2023).

3 | RESULTS AND DISCUSSION

In this study, the effects of the addition of OB to Vertisol at 3%, 6% and 9% w/w on the changes in the mechanical, physical and chemical properties of the soil were investigated. Figure 3 presents a visual representation of the study, while Table 1 details some properties of the soil and OB. In general, the OB treatments had statistically significant effects on the PL, PI, K_{sat}, TN, TC and FC of Vertisol ($p \leq 0.05$).

3.1 | Effects of biochar application on soil Atterberg limits

The average LL of the soil sample used in the experiment was 56%, while the PL was 27%, resulting in a PI of 29%. According to the Unified Soil Classification System (USCS), the soil was classified as high-plasticity clay.

The effect of biochar applied at various doses on the LL values of Vertisol is illustrated in Figure 4a. Even though the difference was not statistically significant ($p \geq 0.05$), the highest average LL value was determined with a 3% OB application. Biochar application increased the LL values of the soils compared to those of the control. Kumar et al. (2019) and Zong et al. (2014) also reported that different biochar applications increased the LL of loam and clay soils. The LL value of soils is affected by the surface charge density, mineralogical composition and organic matter content of soil particles (Head, 1984; Munsuz, 1985).

The effect of different doses of OB on the PL of Vertisol is shown in Figure 4b. The PL values increased with increasing biochar dose, and the PL values were 9%, 9% and 10% greater in the 3%, 6% and 9% OB treatment groups, respectively, than in the control group, and the difference was statistically significant ($p \leq 0.05$). These results also agreed with findings reported by Dindaroğlu

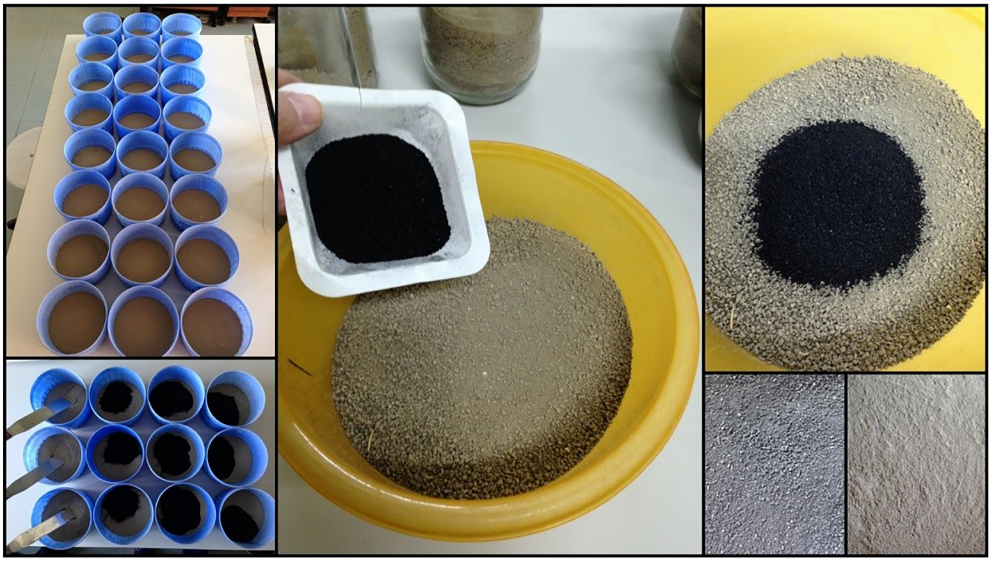

FIGURE 3 Experimental setup.

TABLE 1 Some physical and chemical properties of soil and biochar used in the study.

Some properties of Vertisol	
pH	8.23
EC (μS cm^{-1})	471
Sand (%)	21.89
Silt (%)	35.49
Clay (%)	42.62
Texture class	Clay
FC (%)	27.2
K_{sat} (cm day^{-1})	3.54
Total C (%)	2.95
Total N (%)	0.14
Porosity (%)	57
db (g cm^{-3})	1.14
CEC (cmol kg^{-1})	25.19
Organic C (%)	0.26
Some properties of olive pomace biochar	
pH	9.75
EC (μS cm^{-1})	1,507
Total C (%)	59.34
Total N (%)	1.36
C/N	43.63

Abbreviations: CEC, cation exchange capacity; db, dry bulk density; EC, electrical conductivity; FC, field capacity; K_{sat}, saturated hydraulic conductivity.

et al. (2014). They reported that the application of 6% olive pomace increased the clay soil PL by approximately 8%; in this study, this increase was found as 9% for 6% OB application. The PL values increased in the clay soil compared to those in the control, with the highest PL value (24%) was obtained with the 6% leonardite application, followed by the gyttja (23%) and olive pomace (22%) applications (Dindaroğlu et al, 2014), and these findings agree with the current study, where the highest PL was 29%. Similarly, applying rice husk biochar to Vertisol (Lu et al., 2014) and Acrisol (Arthur et al., 2019) soil increased the PL and LL. Smith et al. (1985) also reported significant positive relationships between the LL, PL and organic matter content. Canbolat and Öztaş (1997) determined significant positive correlations between the LL and PL values of soil samples and the clay content, organic matter quantity, lime content and CEC. Bhushan and Sharma (2002) reported that adding organic matter to soil increases the PL. Ganesan et al. (2020) observed a notable increase in the LL and PL values of biochar produced at two different temperatures (350°C and 550°C) when added to soil. These authors suggested that this increase may be attributed to the greater number of intraporous voids in the biochar.

The impact of OB application on the SL of Vertisol is presented in Figure 4c. Compared to control treatment, the SL in the OB treatments increased ($p \geq 0.05$). The maximum SL value was found in the soil treated with 6% OB, and this value was 5% greater than that of the control. Factors such as soil texture, biochar feedstock, pyrolysis temperature and application dose affect the physical properties of the soil in various ways (İlay, 2020, 2022, 2024; İlay et al.,2020; Kavdır et al., 2023). Kumar et al. (2019) investigated the effects of various biochars at doses of 5% and 10% on the SL of loamy soil. The researchers found that adding sawdust biochar increased the soil's SL value by 9% and 12% compared to that of the control. In contrast, biochars derived from water hyacinth, peanut

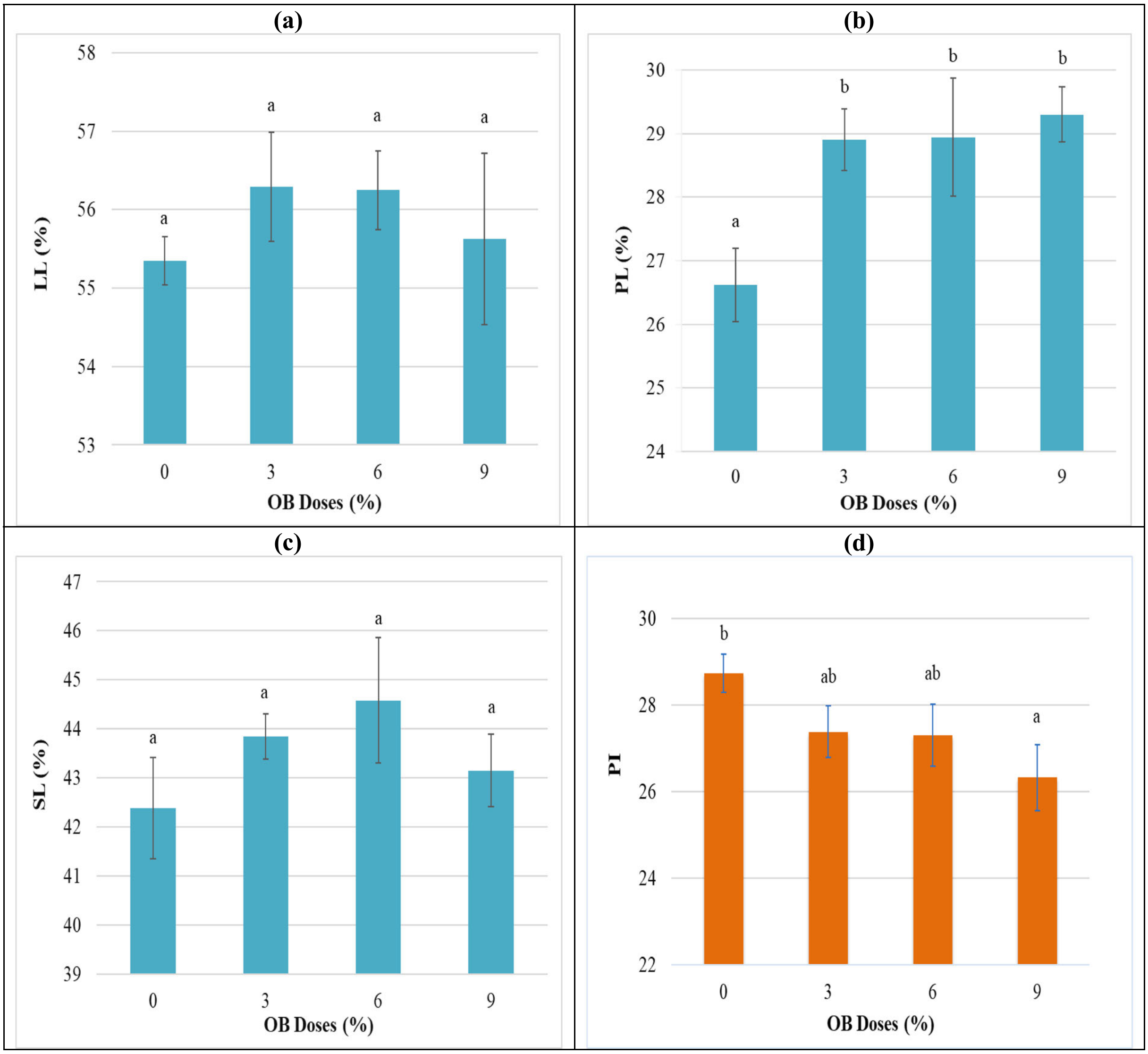

FIGURE 4 Effect of different doses of OB on Atterberg limits. Bars represent standard error of mean ($n = 8$). Means followed by a different letter indicate significant differences at $p \leq 0.05$ according to Duncan's multiple range test. LL, liquid limit; PL, plastic limit; PI, plasticity index; SL, shrinkage limit; OB, olive pomace biochar.

shells and poultry waste decreased the SL between 1.4% and 34%. However, it was determined that applying corn straw and peanut shell biochar to Vertisols reduced the SL by approximately 45% (Cuilan et al., 2018). In another study using compost made from garbage, tobacco processing waste and rice husk, the SL values increased significantly (Özdemir et al., 2016). Zong et al. (2014) explained that the effect of biochar obtained from different materials on soil consistency limits was different; sometimes these values increased and sometimes decreased as the dose increased, which was explained by the interaction of organic carbon with soil minerals, which changed the bond strength and surface tension properties of the soil.

The PI is defined as the difference between the LL and the PL. It may also be expressed as an indicator of the moisture content of soil that is prone to compaction (Zong et al., 2016). The PI values obtained within the scope of this study are presented in Figure 4d. The soil PI decreased with increasing OB amount. The highest PI value was found in the control treatment (28.7), while the lowest PI value (26.3) was detected in the 9% OB treatment group. Malkawi et al. (1999) reported similar findings for soil containing illite clay minerals. The PI of the soil is determined by the type of clay and its content, as well as the presence of organic material. In this study, it is thought that the clay content decreased proportionally with the addition of organic matter to the soil using biochar, resulting in a decrease in the PI value. Zong et al. (2014) determined that the PI increased with the application of wheat straw biochar produced at 500°C compared to that of the control. However, it decreased with the application of woodchips and wastewater sludge biochar. The greatest increase in PI compared with that of the control was observed at the 7% level with the application of 4% wheat straw biochar, while the greatest decrease was obtained with the application of 2% and 4% woodchips biochar (−53%). Similarly, the addition of rice husk biochar to clay decreased the PI (Lu et al., 2014).

3.2 | Influence of biochar on soil water characteristics

The impact of OB application on the FC of Vertisol is presented in Figure 5a. The soil FC increased as the amount of OB applied increased, and the highest FC value was reached with the 9% OB treatment, while the lowest FC value was found in the control treatment. The effect of OB application on the FC value was statistically significant ($p \leq 0.05$). Biochar, a porous material, can retain water within its pores and between particles due to its high specific surface area. Micropores, in particular, can retain water more effectively than macropores and mesopores because of capillary and adhesive forces. Therefore, adding biochar to the soil can alter the overall porosity, pore size distribution, water permeability and water retention properties. In another study, it was found that biochar produced at 700°C had approximately 100 times more surface area than biochar produced at 350°C (Kavdır et al., 2023). Applying biochar varieties with a high surface area to areas where plants will grow may contribute to reducing the frequency of irrigation, especially in regions with limited water resources or semi-arid regions. The positive effect of biochar on the soil's water-holding capacity may be more pronounced in sandy soils than in clay soils, as coarse-textured soils have lower microporosity and a smaller specific surface area than clay soils.

The K_{sat} describes the ease of water flow through saturated soil and can be directly measured through flow-through experiments or estimated using theoretical or experimental models (Mazaheri & Mahmoodabadi, 2012). Vertisols are typically known to have extremely low hydraulic conductivity values due to their high clay content. In this study, the soil had a K_{sat} value of 3.54 cm day^{-1} (Figure 5b). The K_{sat} value of the soil increased depending on the OB dose applied, and the effect of OB application on K_{sat} was statistically significant ($p \leq 0.05$). With OB added to the soil at 6% and 9%, the K_{sat} value increased by 127% and 136%, respectively, compared to that of the control. However, the difference between these two application doses was not found to be statistically significant ($p \geq 0.05$). The application of biochar to clay-rich soil is thought to reduce the clay content and increase soil porosity, depending on the type of biochar used, resulting in significantly increased K_{sat} values. Numerous studies (Barnes et al.,2014; Yazdanpanah

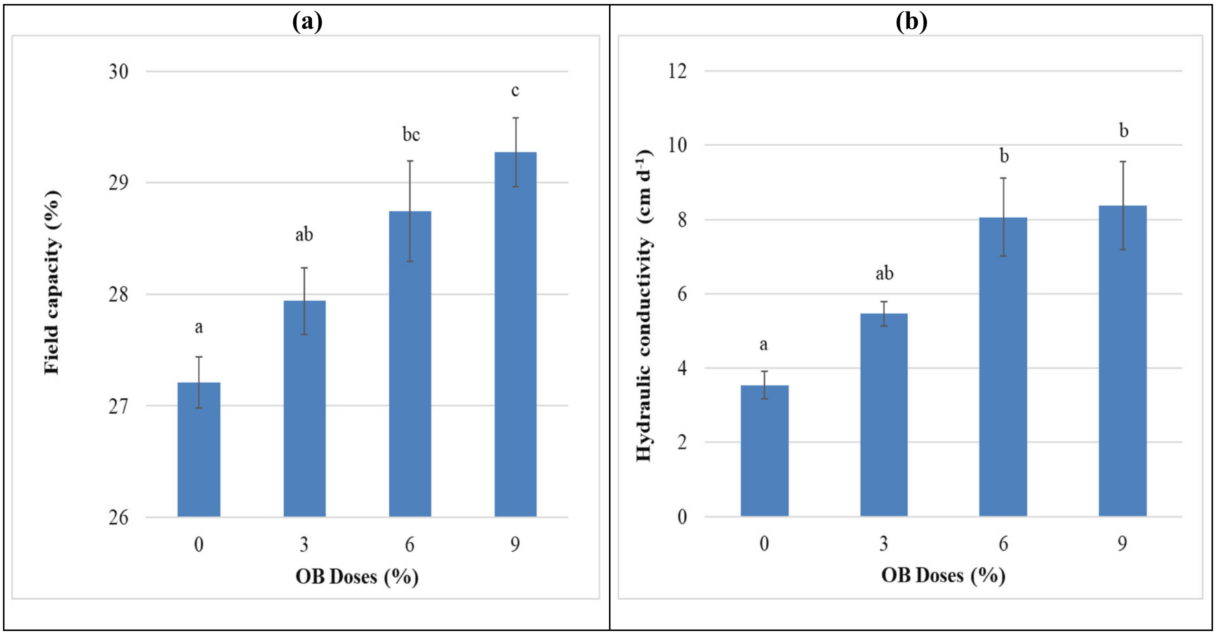

FIGURE 5 Effect of different doses of OB on Vertisol's field capacity (A) and K_{sat} (B) values. Bars represent standard error of mean ($n = 4$). Means followed by a different letter indicate significant differences at $p \leq 0.05$ according to Duncan's multiple range test. K_{sat}, saturated hydraulic conductivity; OB, olive pomace biochar.

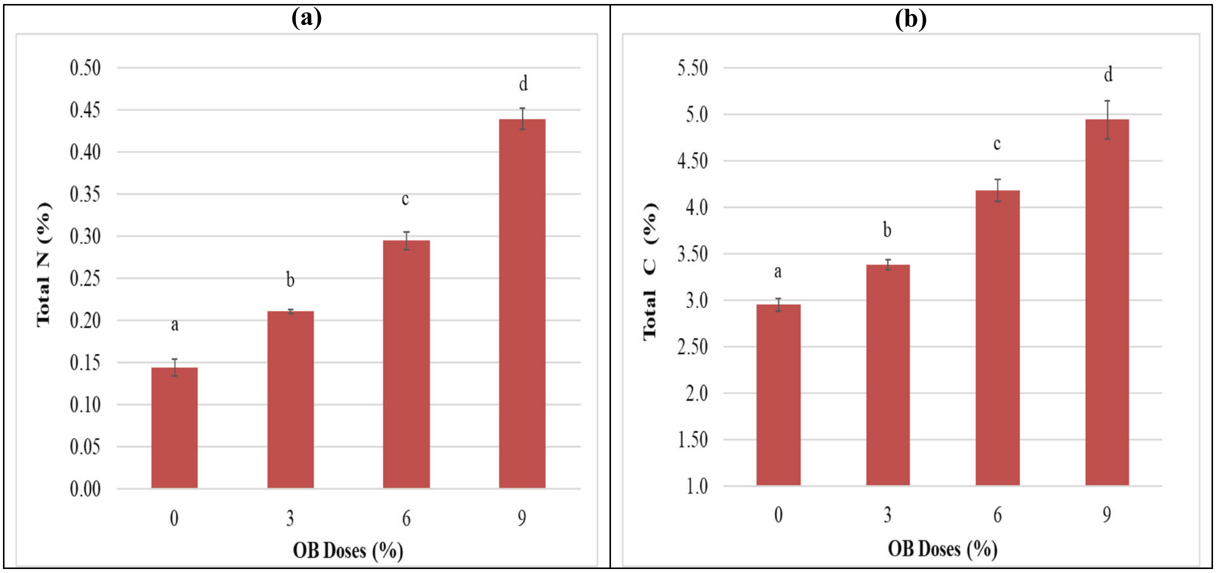

FIGURE 6 Effect of different doses of OB on total N (A) and total C (B) of Vertisol. Bars represent standard error of mean ($n = 4$). Means followed by a different letter indicate significant differences at $p \leq 0.05$ according to Duncan's multiple range test. OB, olive pomace biochar.

et al., 2016; Benjamin et al., 2008; Lado et al., 2004) have reported that soil organic carbon increases aggregate stability and porosity, leading to an increase in hydraulic conductivity. Omondi et al. (2016) reported that wood and manure biochars significantly increased the K_{sat} by 35.7% and by 6.6%, respectively. Similar studies involving biochar have consistently reported that its application increases hydraulic conductivity (Asai et al., 2009; Barnes et al., 2014; Chaganti & Crohn, 2015; Lim et al., 2016).

3.3 | Effects of biochar application on soil TN and TC

The effects of OB application on the TN and TC levels of the soils are illustrated in Figure 6a and b. The total N values of the soils ranged from 0.1% to 0.4%, while the TC values ranged from 2.9% to 4.9%. Both parameters increased in parallel with increasing OB dose, and the differences between the values were statistically significant ($p \leq 0.05$). These increases are attributed to the high C and N values of OB. Similar results were obtained in different studies with biochar (Jien & Wang, 2013; Kavdır et al., 2023).

4 | CONCLUSION

This study focused on investigating the effect of OB application on Vertisol characterized by high swelling and shrinkage and a 2:1 smectitic clay content. These physically problematic soils often pose a challenge for agricultural activities and require improvement of their limiting properties. In particular, this research investigated the effects of biochar derived from olive pomace, which is abundant in Mediterranean countries, on Atterberg limits and various soil properties. The results indicated that the application of OB increased the LL, PL, SL, FC, K_{sat}, TC and TN but decreased the PI. The findings suggest that the effects of OB application may vary across these parameters. Moreover, the 9% application rate in this study is quite high, and biochar (100–120 t ha^{-1}) may not be practical at the field scale for improving the physical and mechanical properties of Vertisols. Lower rates could be considered for field applications. The study concluded that applying OB to Vertisol had positive effects on the investigated soil properties, indicating the potential for soil reclamation. However, more precise assessments of the impact of biochar on soils with a high shrinkage–swelling potential are anticipated to require additional experimental field data.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions.

ETHICS STATEMENT

The authors also declare that the research involved no human participants or animals.

ORCID

Remzi İlay https://orcid.org/0000-0002-3558-3125

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