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Effect of Compost Addition on Porosity and Hydraulic Properties of Different Textured Soils

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Abstract − This research aimed to investigate the temporal variations in soils of three distinct textures that were amended with composts derived from olive pomace (OPC) and vineyard pruning waste (VPC). The compost was prepared in reactors with automatic temperature and aeration control. This research encompasses three distinct soil textures, five varying compost applications, and ten separate sampling intervals following the compost application and replicated four times. After 210 days of incubation, 6% VPC application increased the field capacity value by 27.7% compared to the control, especially in sandy loam soil. At the same treatment and time, total porosity increased by 14.29% in clay soil. The highest increase in hydraulic conductivity was observed in clay and loam soil with 6% VPC and in sandy loam soil with 6% OPC. Compost applications increased field capacity the most in sandy loam soil. The impact of compost on field capacity and porosity of soils varied according to soil texture, compost material, application amount, and time elapsed after compost application. The high BJH surface area of clay soil decreased from 15.830 m^2/g to 12.977 m^2/g with the addition of OPC.

Keywords − *Vineyard pruning waste, olive pomace, compost, hydraulic conductivity, soil physics*

1. Introduction

Soil is a critical component in maintaining terrestrial ecosystems by providing essential ecosystem services such as maintaining nutrient cycling for all living organisms' lives, filtering and transforming substances, and providing the physical environment to support plant growth. Soil quality can be classified into three primary categories: physical, chemical, and biological [1]. The physical characteristics of soil play a crucial role in ensuring agricultural land's sustainability and environmental quality protection [2]. Soil physics is primarily concerned with the interactions between soil and water. Consequently, the physical, chemical, and biological processes within the soil are influenced by the quantity and composition of water present [3]. The water-holding capacity of soils is also related to the soil's total porosity and specific surface area and soil texture directly affecting the water-holding capacity. Sandy soils have less total pore volume than clay soils and low water-holding capacities [4]. Pore size distribution is an essential physical property of soil that provides the ability of soil to store water and air [5]. Soil porosity and pore size distribution affect water retention, gases, and root growth [6].

The gradual reduction of organic matter in the soil, attributable to intensive agricultural practices, results in the deterioration of soil structure and contributes to soil degradation. Therefore, enhancing and stabilizing the amount of soil organic matter [7-8]. Concerns about global warming resulting from the increase in atmospheric

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carbon dioxide (CO_2) and methane (CH_4) emissions in recent years have led to increased research on the carbon stock potential of soils. Incorporating organic materials, such as compost, into soil decomposes a portion of the organic carbon, subsequently releasing CO_2, while the rest remains in the soil [9]. Therefore, it has been stated [10] that when an organic carbon source is added to the soil, it should be considered for its positive effects on the soil while simultaneously causing an increase in CO_2 concentration in the atmosphere. Small soil pores retain water strongly, while large pores drain easily. Applying compost can modify soil's hydrological characteristics by altering its texture, thereby increasing the size and quantity of soil pores. [5]. Many studies [11-13] have reported that soil organic carbon enhances hydraulic conductivity by stabilizing soil aggregates [14] and increasing porosity. The influence of organic materials on soils with varying textures may differ significantly. It has been reported in many studies [15-17] that the beneficial effects of compost addition are significant, especially in sand and clay soils. It can improve plant water and nutrient availability in sandy soils with low water holding capacity [18] and improve aeration and structural stability in clay soils with low aeration [19]. Given the diverse microbial properties inherent in different organic materials, their impacts on soil characteristics can vary considerably [20]. Among composts with other properties, the ones with higher carbon content may have a greater effect on soil organic matter content [21]. This study aimed to assess the impact of various compost types, specifically olive pomace (OPC) and vineyard pruning waste (VPC), on the physical properties and hydrological characteristics of soils with three distinct textures: clay (C), loam (L), and sandy loam (SL). To achieve this objective, a 210-day soil incubation experiment was conducted. Temporal variations in total porosity (TP) and field capacity (FC) within the soil-compost mixtures were monitored through sampling at ten different intervals. Following a 210-day incubation period, measurements of saturated hydraulic conductivity (K_{sat}) and Brunauer-Emmett-Teller (BET) results were obtained for soils characterized by three different textures.

2. Materials and Methods

2.1. Properties of Compost

Olive pomace and vineyard composts were produced at ÇOMU-TETAM. The olive pomace (OP) was obtained from an olive oil factory, while the vineyard pruning waste (VP) was collected from a local orchard in Çanakkale. The compost used in the research was produced in specially constructed stainless steel compost reactors, each with a capacity of 100 liters. To monitor the compost temperature hourly, three K-type thermocouples were strategically positioned at each reactor's bottom, center, and top. Aeration fans were employed to facilitate proper aeration within the reactors. The fans are activated if the compost temperature is higher than the set temperature (above 60 °C). The temperature and aeration parameters of the composting processes were carefully controlled, and data was systematically recorded utilizing a programmable logic controller. The water content of compost was assessed three times per week by subjecting a compost sample to drying in an oven at 70 °C for 48 hours.

The moisture levels of the compost were regulated to remain within the range of 45-60% through the addition of water. The ratios of compost feedstock mixtures were established through calculations to guarantee that the resultant compost would achieve the desired carbon-to-nitrogen (C:N) ratio. The olive pomace compost comprised an equal proportion of pomace and farmyard manure (FM). In contrast, the VPC was formulated with 20% FM and 80% VPW. The pH and EC values of OPC and VPC were 6.82 and 4.81 mS/cm and 8.04 and 5.95 mS/cm, respectively. The total phenolic content of OPC and VPC were 3.09 and 1.99 mg GAE /g. The C:N values of OPC and VPC were 11.7 and 20.7, and the CEC values were 51.7 and 35.1 cmol/kg, respectively [22].

2.2. Soil Properties

Soil with clay texture was taken from 40°15'04.2 "N, 26°34'52.3" E in Çanakkale and classified in the Chromic Haploxererts sub-group of the Vertisol order according to Soil Taxonomy. The soil with a sandy loam texture was obtained from Çanakkale (40°15'58.8 "N, 26°35'40.2" E), and it was included in the Entisol order Xerofluvents large group [23]. The soil with loam texture was sampled from the Lapseki, Çanakkale (40°18'51.8 "N, 26°38'36.4" E). According to soil taxonomy, it was included in the Haploxerolls large group of the Mollisol order [24].

2.3. Incubation Study

After air-drying, the soil was sieved through a 6 mm sieve and used in the incubation study. Some physical and chemical analyses of the soils were performed after sieving the soil through a 2 mm sieve, and the results are presented in Table 1. The prepared compost [22] was dried in an oven at 65 °C, then ground and sieved through a 2 mm sieve. For the incubation study, plastic rectangular storage containers with a capacity of two liters were utilized. To maintain aerobic conditions, ventilation holes were drilled near the top of the containers. A mixture of 3% and 6% VPC and OPC was prepared separately for soils of all three textures. The control treatment consisted of soils without compost. The experiment was conducted using a randomized design that included five distinct treatments, three varying textures, four replications, and ten incubation periods. The treatments comprised a control group at 0%, 3%, and 6% of olive pomace and vineyard pruning waste composts. According to our previous studies, a positive effect of 2% OPC treatment on selected soil properties was observed, and it was concluded that OPC treatment above 6% was not economical [25,26]. The study utilized 600 samples subjected to controlled atmospheric conditions at a temperature of 26 ± 2 °C during the incubation period. To ensure appropriate moisture levels, the containers were periodically weighed, and water was added as needed to maintain a moisture level of 60% of field capacity. Soil analyses were performed at 15-day intervals during the initial phase of the experiment, and then soil analyses were carried out every 30 days for the following 210-day period.

Table 1. Some physical and chemical properties of soils [22]

Texture	Clay (%)	Silt (%)	Sand (%)	Field Capacity(%)	$CaCO_3$ (%)	pH	EC (µS/cm)	TC (%)	CEC (cmol/kg)
Clay	46.92	34.22	18.86	35.13	11.72	8.33	391	3.32	37.64
Loam	23.65	44.86	31.49	33.87	13.09	8.31	365	2.81	34.40
Sandy loam	12.22	22.62	65.16	27.02	1.58	8.07	147	0.86	21.16

FC; Field Capacity, TC; Total Carbon, OM; Organic Matter, TN; Total Nitrogen. CEC; Cation Exchange Capacity

2.4. Methods for Analyzing Soil and Compost

Soil and compost pH and electrical conductivity (EC) values were assessed by preparing solutions with ratios of 1:2.5 for soil:water and 1:10 for compost:water. [27]. Total C and N content of materials were determined by dry digestion method using LECO Truspec 2000 C.N elemental analyzer [28], and cation exchange capacity (CEC) was measured by sodium acetate method [29]. The phenol content was quantified using the colorimetric method based on the Folin Ciacalteu [30]. The ammonium and nitrate content of the compost was determined by the Kjeldahl method using 2M KCl [31]. Soil texture was assessed using the standard hydrometer method outlined by Gee and Bauder [32], and CaCO3 content was determined using the Scheibler method [33]. Field capacity and total porosity were determined by saturating a certain volume of soil and determining on a weight basis [34]. After the undisturbed soil samples were saturated with 0.1 M calcium chloride ($CaCl_2$) solution, the hydraulic conductivity (K_{sat}) value was determined in accordance with Darcy's law [35] by measuring the amount of water passing through the soil column at specified times under constant water load. BET analyses of three different textured soils and control soils mixed with the highest dose of 6% OPC and 6% VPC compost and incubated for 210 days were carried out at ÇOMÜ-ÇOBİLTUM using the Brunauer, Emmet and Teller (BET) methodology [36] with BET surface area measuring device (Quantachrome Quadrasorb SI) in liquid nitrogen environment at 77K based on nitrogen (N_2) gas adsorption technique.

2.5. Method of Statistical Analysis

In order to examine the effect of texture, treatment, and time (X, Y, Z, ...) on the traits, the analysis of variance technique was used in a factorial arrangement of randomized plots experimental design. Tukey's multiple comparison test was subsequently applied to identify the specific groups or subgroups responsible for observed differences. The data collected during the study were analyzed using STATISTICA 12 software (StatSoft Inc.).

3. Results and Discussion

3.1. Changes in Soil Field Capacity Value After Incubation

The results of field capacity (FC) analysis of different doses of OPC and VPC applied to soils of three different textures at various times are presented in Figure 1. The difference between compost treatments on clay, loam, and sandy loam soil was statistically significant at all sampling times. In C, L, and SL soils, the highest value was found in 6% VPC application, whereas the control soil consistently exhibited the lowest values across all measurement intervals. In clay soil, the application of 6% VPC had a statistically significant effect on FC up to the 45th day after application, compared to other treatments. In loam soil, the FC began to increase from the 45th day onward, while in sandy loam soil, the FC value increased significantly until 90 days after application. It was [37] reported that although soil texture is the primary factor influencing water-holding capacity, an increase in organic carbon content also plays a crucial role in enhancing water-holding capacity. Furthermore, compost had a more pronounced effect on water-holding capacity in coarse-textured soils.

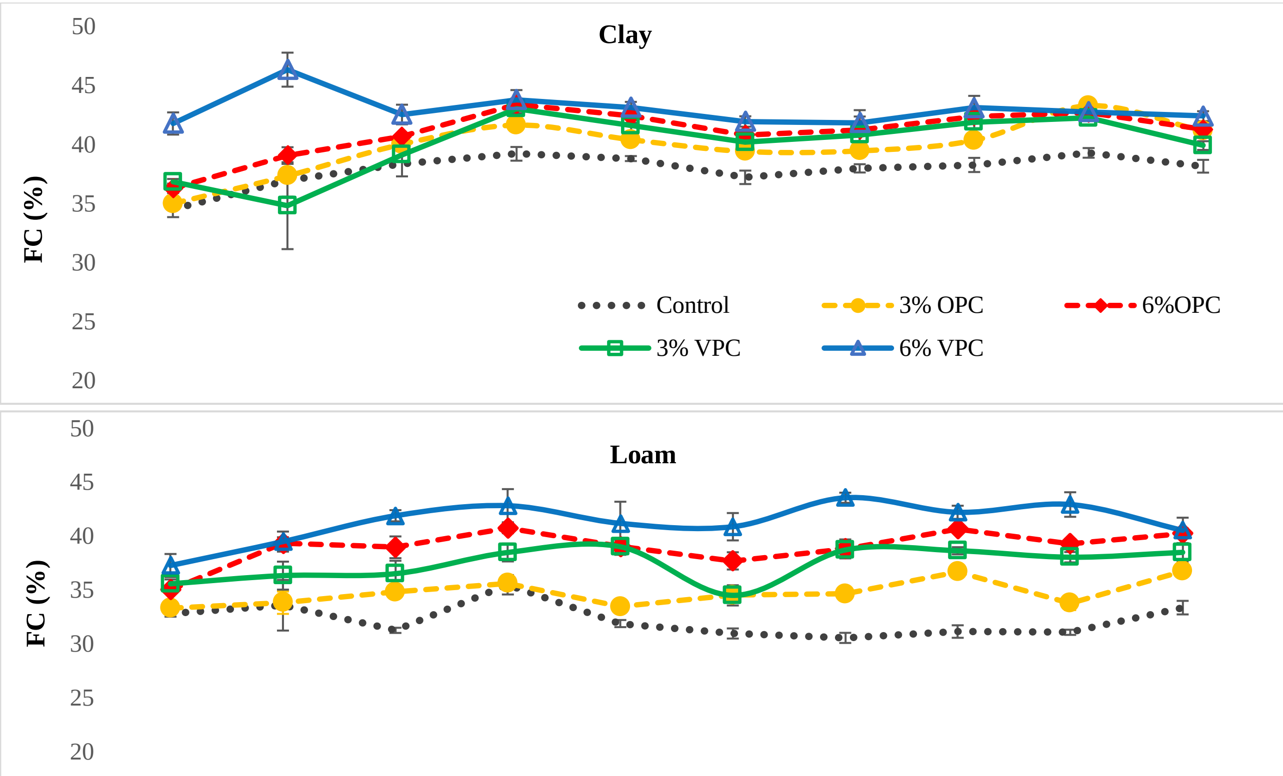

Figure 1. The impact of varying VPC and OPC application rates on field capacity over a 210-day incubation period. Error bars represent the standard errors of the means ($n = 4$)

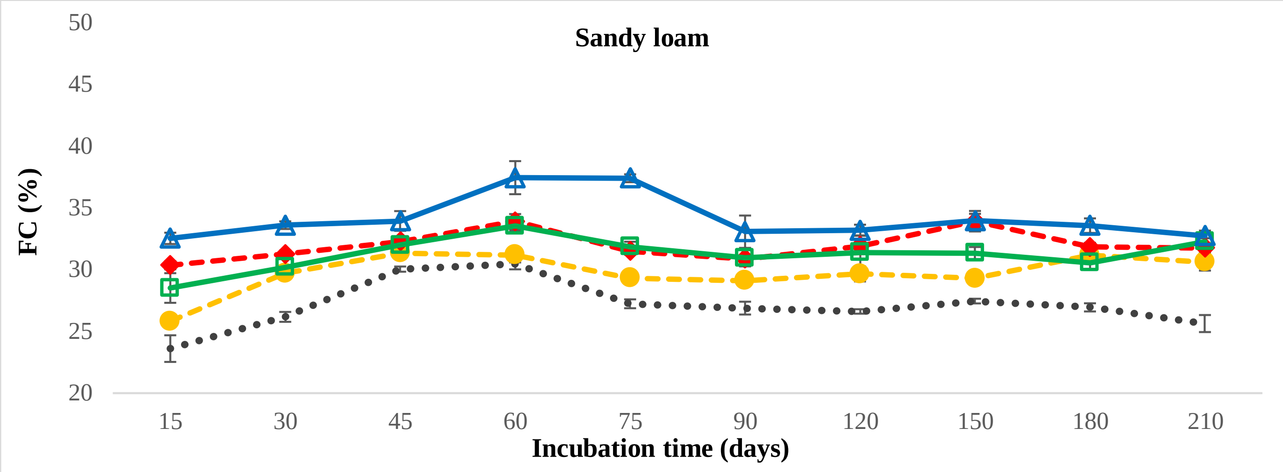

Figure 1. (Continued) The impact of varying VPC and OPC application rates on field capacity over a 210-day incubation period. Error bars represent the standard errors of the means ($n = 4$)

When analyzing the variation between sampling times for the same soil texture and treatment, the difference in sampling times following 3% OPC application was statistically significant ($p \leq 0.05$) in clay and sandy loam soils. However, this significance is not observed in loam soil.

In clay soil treated with pomace compost, the maximum value of FC was recorded on day 180 (43.30%), while the minimum value was observed on day 15 (35.02%). In sandy loam soil, the highest field capacity value was found on the 45th day (31,34%), and the lowest FC value was determined on the 15th day (25,83%). The difference between the 6% OPC application time averages was significant in all three textures. The 3% and 6% VPC applications were significant across all three textures. The highest FC value in C, L, and SL soils in 3% VPC treatment was 43.41%, 38.49%, and 33.55% on day 60, respectively. The highest FC value in clay, loam, and sandy loam textures in 6% VPC treatment was found on day 30 (46.36%), day 120 (43.57%), and day 60 (37.46%), respectively (Figure 1).

When the differences in soil texture averages were compared at the identical sampling times and treatments, each treatment showed statistically significant differences at each time point. The highest FC value of 6% VPC treatment was observed in loam soil on the 120th day and in clay soil at all other sampling times. The lowest FC value was found in sandy loam soil across all treatments and sampling times. The highest FC value for the control group and the treatments involving 3% and 6% OPC and 3% VPC was consistently recorded in clay soil across all measurement intervals. In contrast, the lowest value was recorded in sandy loam soil. Soil texture and organic matter content significantly affect soil water-holding capacity. Pore content distribution, pore size distribution, and surface area of soils are essential parameters that determine the soil's water-holding capacity [4]. Tension force in soil depends on pore diameter; therefore, water retention is stronger in small pores [38]. Furthermore, sandy soils have a reduced surface area and fewer micropores than clay soils, resulting in a lower capacity for water retention. It has been reported by many authors [39-43] that organic materials incorporation into the soil positively affects the water-holding capacity.

A positive correlation (r^2=0.79) between organic matter content and water-holding capacity in sandy soils was also reported by [40]. In this study, compost application increased the field capacity most in sandy loam soil. After 210 days of incubation, all treatments increased field capacity between 4.6% and 11.1% in clay soil, 10.1% and 21.5% in loam soil, and 19.4% and 27.7% in sandy loam soil.

3.2. Total Porosity Change After Incubation

According to the total porosity (TP) analysis of samples collected at various times from soils with different textures and varying doses of OPC and VPC, the differences between treatments in clay soil were statistically significant on days 15, 45, 60, 120, and 210 ($p \leq 0.05$). The maximum total porosity was observed in the 6%

VPC treatment on days 15, 45, and 120, the 3% VPC treatment on day 60, and the 3% OPC treatment on day 210 for clay soils.

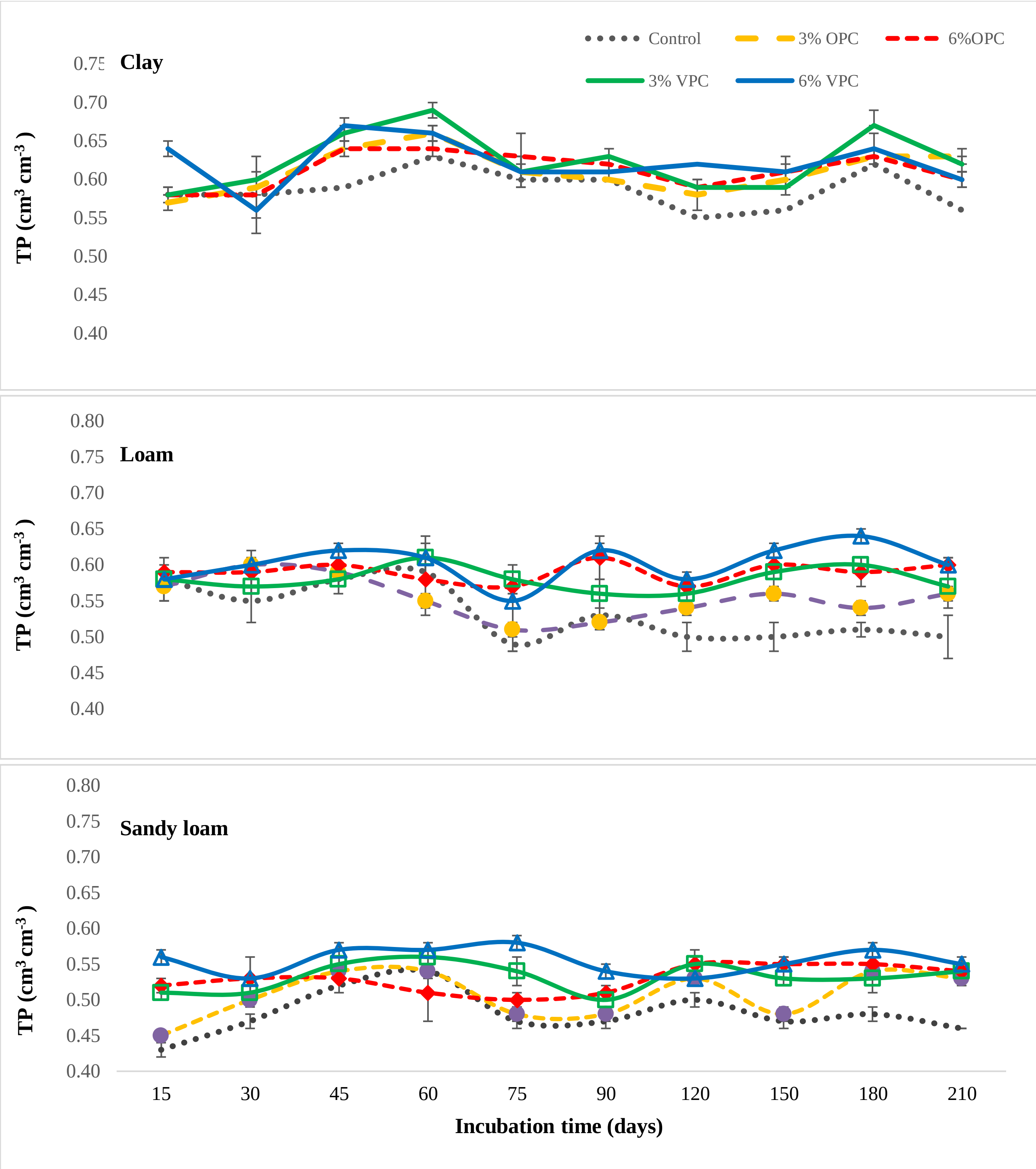

Figure 2. The impact of varying VPC and OPC application rates on soil total porosity over a 210-day incubation period. Error bars represent the standard errors of the means ($n = 4$)

In loam soil, the differences between the treatments were not statistically significant during the first four sampling periods; however, they became significant in the later periods. The highest total porosity (TP) value was obtained in the 6% VPC treatment between days 90 and 210.

There was no difference between the treatments on sandy loam soil on days 45, 60, and 120. The highest TP value was found in 6% of VPC applications on days 15, 30, 75, 90, 90, 150, 180, and 210 (Figure 2). Compost increases soil stability and, thus, macropores through various organisms [44]. [45] reported that the porosity of different composts varied between 60.7% and 72.4%.

According to the total porosity analysis results (Figure 2), the differences in incubation periods following the application of 3% OPC on C, L, and SL soils were found to be statistically significant ($p \leq 0.05$). The highest TP value was observed on day 60 in clay soil and on day 30 in loam soil treated with 3% OPC. Conversely, the lowest TP value was recorded on day 15 in sandy loam soil and on day 75 in loam soil. In contrast, the differences in the average TP values resulting from applying 6% OPC across all three soil textures were not statistically significant (Figure 2).

The difference in time averages for the 3% VPC application was significant in clay soil but not other soil textures. The highest TP value (0.69 cm^3/cm^3) was found on day 60, while the lowest TP value (0.58 cm^3/cm^3) was found on day 15 in clay soil. Additionally, the difference between the time averages of the 6% VPC application was significant in both C and L soils. In clay soil, the highest TP value (0.67 cm^3/cm^3) was found on day 45, and the lowest TP value (0.56 cm^3/cm^3) was found on day 30. The highest TP value was found in loam soil on day 180 and the lowest on day 75.

When TP values of soils of different textures were compared at the same time and in the same application, 3% OPC application showed a difference according to texture at all times. The highest TP value was always found in C soil, and the lowest TP value was found in SL soil. In 6% VPC treatment, the difference was significant at all times except day 210. Loam soil had the highest TP value on days 15 and 30, while clay soil had the highest TP value at all other times. Sandy loam soil consistently had the lowest TP value. The difference was statistically significant throughout the 3% VPC treatment, except day 120. TP value was high in clay soil on days 15, 45, 60, 75, and 120 and loam soil on days 30, 90, 150, and 180. On day 75, loam soil had the lowest TP value; at other times, sandy loam soil had the lowest value (Figure 2). [46] reported that TP value varied between 0.59-0.64 cm^3/cm^3 in clay soil and 0.42-0.56 cm^3/cm^3 in loam soil after adding compost to the soil at different doses (0-75-150-300 m^3/ha). In this study, since the organic matter added to the soil increased with both compost treatments, it can be said that total porosity increased in all textures. The application that increased the most was 6% VPC. It was also reported by [47] that pruning waste compost increased soil porosity.

3.3. Saturated Hydraulic Conductivity Change After Incubation

The results of the K_{sat} analysis of soils after 210 days of incubation in which different doses of composts were applied to soils with different textures are presented in Table 2. According to the statistical analysis results, the effect of compost application on K_{sat} was found to be significant in C and L soil, while it was not statistically significant in L soil. In clay soil, the highest K_{sat} value (0.039 cm/s) was in 6% VPC application, and the lowest K_{sat} value (0.016 cm/s) was in control soil. In sandy loam soil, the highest K_{sat} value (0.033 cm/s) was in the 6% OPC treatment, and the lowest K_{sat} value (0.006 cm/s) was in the control soil.

Table 2. Impact of varying application rates of OPC and VPC on hydraulic conductivity (cm/s) of soils with different textures after 210 days of incubation

	Clay	Loam	Sandy loam
Control	0.006 ± 0.001 Cb	0.007 ± 0.001 Aab	0.016 ± 0.001 Ca
3% OPC	0.028 ± 0.004 Ba	0.013 ± 0.002 Ab	0.024 ± 0.003 ABa
6% OPC	0.029 ± 0.003 ABa	0.014 ± 0.001 Ab	0.033 ± 0.004 Aa
3% VPC	0.028 ± 0.001 ABa	0.015 ± 0.001 Ab	0.020 ± 0.005 Bab
6% VPC	0.039 ± 0.001 Aa	0.016 ± 0.001 Ab	0.022 ± 0.003 Bb

In the same column, the differences between the treatment mean shown with different capital letters are statistically significant ($p \leq 0.05$).
In the same row, the differences between the texture mean shown with different lower-case letters t are statistically significant ($p \leq 0.05$).

In the same compost application, the variations in the K_{sat} values of soils exhibiting varying textures were determined to be statistically significant ($p < 0.05$). In the control soil without compost application, the highest and lowest K_{sat} values were measured in sandy loam and clay-textured soil, respectively. In the applications involving 3% OPC, 3%, and 6% VPC, the maximum K_{sat} value was observed in clay, whereas the minimum

K_{sat} value was recorded in loam soil. In the 6% OPC application, the highest K_{sat} value was in sandy loam soil, and the lowest K_{sat} value was in loam soil (Table 2). Water infiltration rate in the soil is primarily influenced by various soil characteristics, including water content, soil texture, porosity, K_{sat}, swelling properties, and organic matter content [48,49]. In addition, properties such as aggregate size and distribution and the amount of carbon in the soil play an important role in controlling hydraulic conductivity [50]. Increasing organic carbon in the soil increases aggregate stability and porosity, thus increasing hydraulic conductivity [51,12]. This study obtained the highest Ksat values with 6% VPC application in clay soil and 6% OPC application in SL soil. Therefore, the hydraulic conductivity of clay soils increased in about 7 months after compost application.

3.4. Surface Area Results of Soils

According to the Barrett-Joyner-Halenda (BJH) method, the pore radius was 1.54 nm, 1.54 nm, and 2.18 nm for control, 6%OPC, and 6%VPC treatments in clay soil, respectively. In loam soil, it is 1.54, 1.55, and 1.72 nm; in sandy loam soil, it is 1.55 nm, 2.18 nm and 2.18 nm, respectively. The average pore radius of BJH of VPC was 2.47 nm, while that of OPC was 1.73 nm (Table 3). These results correlate with the results of the previous hydraulic conductivity analyses. The average pore radius increased in both compost treatments, and the hydraulic conductivity values (Table 2) also increased.

Specific surface area is an essential property in evaluating the physical interaction of soils with chemical stabilizers. The BJH surface area of clay soil was found to be 15.830 m^2/g. The high BJH surface area of the clay soil decreased significantly from 15.830 m^2/g to 12.977 m^2/g due to the addition of OPC (0.449 m^2/g) (Table 3). A similar result was observed for the BET surface area. Clay soil (62.470 m^2/g) had a much higher BET surface area than sandy loam soil (11.868 m^2/g) (Table 3). The BET surface area values of the different soil textures were found to be in the following order: clay > loam > sandy loam. According to the International Union of Fundamental and Applied Chemistry (IUPAC), solids with an average pore diameter <2 nm are called microporous, and those with 2-50 nm belong to mesoporous solids. Therefore, OPC and soils other than VPC can be classified as microporous. Microporous materials usually have a larger specific surface area than mesoporous materials, which may contribute to a higher biosorption capacity. The BET-specific surface area of OPC and VPC are 0.518 m^2/g and 0.555 m^2/g, respectively. These values are smaller than those of composted cow manure (2.085 m^2/g) and composted mushroom residues (1.16 m^2/g). The average pore radius increased with the application of VPC in all three soil textures. It is thought that the organic materials released by the decomposition of the compost during the incubation period clogged the surface pores of the clay and, therefore, blocked the nitrogen gas entry during BET surface area measurement, leading to a lower surface area value. The surface area results determined by [52] with the same method in clay soils with different properties are similar.

Table 3. BJH and BET values after 210 days of incubation in soils treated with 6% compost

		OPC	VPC	Clay			Loam			Sandy Loam		
				Control	OPC	VPC	Control	OPC	VPC	Control	OPC	VPC
BJH adsorption	Surface area (m^2/g)	0.449	2.815	15.830	12.977	14.526	10.540	14.249	16.331	5.530	3.952	4.228
	Pore volume (cm^3/g)	0.001	0.007	0.029	0.025	0.028	0.020	0.027	0.030	0.016	0.013	0.013
	Pore radius (nm)	1.73	2.47	1.54	1.54	2.18	1.54	1.55	1.72	1.55	2.18	2.18
Multi-Point BET	Surface area (m^2/g)	0.518	0.555	62.470	51.674	55.722	48.031	61.185	52.107	11.868	8.269	9.393
Total pore volume	Total pore volume smaller than the radius of interest (cm^3/g)	$6,87.10^{-2}$	$6,87.10^{-2}$	$5,28.10^{-2}$	$4,43.10^{-2}$	$4,89.10^{-2}$	$3,90.10^{-2}$	$5,04.10^{-2}$	$4,79.10^{-2}$	$1,95.10^{-2}$	$1,48.10^{-2}$	$1,56.10^{-2}$
	Pores smaller than <Å (Radius)	196.0	210.2	199.1	207.6	213.0	209.3	218.7	232.6	217.3	209.6	221.5

4. Conclusion

Incorporating compost into the soils enhanced their total porosity (TP) and field capacity (FC) across C, L, and SL soils. The compost application improved field capacity compared to the control group, with increases observed in clay soil from 4% to 11%, loam soil from 10% to 21%, and sandy loam soil from 19% to 27%. After 210 days of incubation, applying 6% VPC and 6% OPC increased overall porosity by 7.1% and 20.0%, respectively, with notable effects observed in clay and loam soils. In all three textures, the pore radius increased with 6% OPC and 6% VPC treatments. As a result of 6% OPC and VPC application, the hydraulic conductivity value of clay soil increased by 4.8 and 6.5 times, respectively, while it increased by 2.0 and 2.3 times in loam soil and 2.1 and 1.4 times in sandy loam soil, respectively, compared to the control.

Compost application increased the hydraulic conductivity value of clay textured soils and the field capacity value of sandy loam soils. Therefore, some negative physical properties of the soil due to its texture can be improved by compost application. Adding composts with high organic carbon content to the soil increased soil stability concerning the increase in total carbon content [22]. Since the obstacles that cause clogging of soil pores are eliminated, it can facilitate water movement in the soil by increasing porosity and, therefore, hydraulic conductivity in heavy textured soils with high clay content. A new study in which applying VPC and OPC at a rate of 6% will also be tested on plants under field conditions will benefit the widespread use of compost.

Author Contributions

All the authors equally contributed to this work. This paper is derived from the first author's doctoral dissertation supervised by the second author. They all read and approved the final version of the paper.

Conflicts of Interest

All the authors declare no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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