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Comparative Influence of Biochar and Zeolite on Soil Hydrological Indices and Growth Characteristics of Corn (*Zea mays* L.)

Mohammad Ghorbani [1,*], Elnaz Amirahmadi [1], Petr Konvalina [1], Jan Moudrý [1], Jan Bárta [2], Marek Kopecký [1], Răzvan Ionuț Teodorescu [3] and Roxana Dana Bucur [4]

[1] Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia, Branišovská 1645/31A, 370 05 České Budějovice, Czech Republic
[2] Department of Plant Production, Faculty of Agriculture and Technology, University of South Bohemia in České Budějovice, Na Sádkách 1780, 370 05 České Budějovice, Czech Republic
[3] Environment and Land Reclamation Department, Faculty of Land Reclamation and Environmental Engineering, University of Agronomic Sciences and Veterinary Medicine of Bucharest, Mărăşti Blvd., No. 59, Sector 1, 011464 Bucharest, Romania
[4] Department of Fundamental Sciences in Animal Husbandry, Faculty of Food and Animal Sciences, Iasi University of Life Sciences, 8 Mihail Sadoveanu Alley, 700490 Iasi, Romania
* Correspondence: ghorbm00@fzt.jcu.cz

Abstract: Biochar and zeolite, due to their porous structure, are supposed to be appropriate soil amendments especially in agricultural areas with a lack of water or unsuitable soils with coarse texture. Two soil additions that are intended to assist an increase soil water content (AWC) are biochar and zeolite. With this aim, the effects of biochar and zeolite at two levels of 5 and 10 t ha^{-1} (known as B5, B10, Z5, and Z10) on soil hydrological properties and consequently corn growth were investigated in this study. The results showed that the application of B5 and B10 significantly improved AWC by 76% and 48% due to increasing soil micro- and meso-pores. The application of Z5 and Z10, associated with an increase of macro-pores in soil, enhanced saturated hydraulic conductivity (Ks) up to 174% and 303% and caused losses. The highest specific surface area and mean weight diameter in soil obtained from B10 had an increase of 171% and 197% over the control. Biochar treatments considerably affected plant growth features and shoot nutrient content, whilst zeolite treatments had an impact that is much less apparent than that of biochar. Observations indicate that biochar greatly boosted nutrient availability and water retention in the soil by raising the share of micro- and mezzo-pores, respectively, and as a result, has benefited plant growth. Increasing the level of biochar application from 5 to 10% would have more positive effects on the water available in the soil and on plant root systems. In contrast, the high rate of application of zeolite particles due to coarseness and adding Na^+ ions to the soil caused the dispersion of soil particles, the destruction of soil structure, increasing Ks and water loss and consequently a reduction in plant growth.

Keywords: water availability; field capacity; soil structure; porosity; soil amendment

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1. Introduction

The soil's structure, which is its most important factor, is primarily responsible for the soil's ability to provide moisture, nutrients, aeration, a habitat for microorganisms, and a suitable environment for the growth of plant roots [1–5]. Porosity, bulk density, pore size distribution, hydraulic conductivity, and ultimately the amount of water accessible for plant roots are all dramatically altered by changes in soil structure, which is defined as a change in the arrangement of organic and inorganic particles [6,7]. However, extreme hydrological events including prolonged droughts, extraordinarily high precipitation, and frequent wet–dry cycles have risen due to global climate change [8]. As a result, there may be more uncertainty over global agricultural production. Increasing the soil's ability to retain water can boost the resilience of agroecosystems and the water-dependent soil microbial ecosystems [9]. Today, it is advised to apply amendments to alter the soil structure in order to address the numerous issues related to water resources in agriculture and boost the productivity of low water soils [10–12]. Due to their porous nature, zeolite and biochar are two examples of amendment materials that appear to have the capacity to alter soil moisture conditions [13–16].

Zeolites are classified as crystalline aluminosilicates and play a significant role in soil amendments by enhancing soil aeration, nutrient availability, and plant production [17]. Along with the more than 60 known naturally occurring zeolites, the International Zeolite Association has certified more than 230 distinct zeolites and zeotype frameworks [18]. Zeolites are a common substance that can be used as a low-cost modification to reduce heavy metal toxicity [19,20]. Clinoptilolite is one of the most significant natural zeolites and is also extremely common [21]. Zeolites have an open three-dimensional structure that allows them to store water and improve nutrient availability for plants [22,23]. Additionally, zeolites have a high cation exchange capacity (CEC) [13,24]. Due to its high ion-exchange capacity and porous structure, natural zeolite is suggested for removing or stabilizing heavy metals from soil that has been anthropogenically contaminated with Cd, Zn, Pb, and Ni [25]. Due to its porous nature, zeolite has been shown in several studies to have good impacts on minimizing nitrate leaching and promoting crop development [26,27]. According to reports, the use of zeolite can increase the nutrients and water availability for plant roots due to its contribution to soil aggregation and boosting soil CEC [28,29].

Biochar, a stable carbon compound produced by the pyrolysis process, because of its potential as an agricultural soil stabilizer, has received particular attention in a number of studies on plant nutrition [30,31]. The inherent qualities of biochar, such as its high specific surface area, high porosity, and accessibility to nutrients, which make it a priceless and multifaceted soil modifier, enable the management of agricultural residues, the enhancement of the physicochemical characteristics of soil, the reduction of air, soil, and groundwater pollution, and the enhancement of plant growth [32]. The use of biochar can improve the arrangement of soil particles, as well as the physical and chemical properties of the soil, such as noticeably decreasing soil bulk density [33], increasing soil porosity to aid in plant growth and development [34], and encouraging crop nutrient uptake to boost crop yield [31]. It has been shown that biochar may greatly increase the water conductivity and field water retention capacity of farmed soils [35]. Additionally, biochar can raise soil pH, especially in acidic soils [36], as well as nutrient absorption and cation exchange capacity sorption characteristics [37]. Base cations found in biochar can form cationic bridges with clay and organic particles to combine them, improving the soil's structural conditions [38]. Numerous studies have also claimed that biochar produced through slow pyrolysis increases the amount of water that is readily available (AWC) in soils with both fine and course textures [39–42]. AWC is actually the most critical aspect in irrigation schemes; for instance, with a higher AWC, the amount of irrigation water used and the watering interval may be lowered. The moisture level of the soil was improved by the use of biochar [39,40].

Agroecosystems and water-dependent soil microbial communities may become more adaptable as a result of optimizing soil water content [43,44]. It is crucial to use practical and ecological methods to increase soil fertility. Despite several studies on the impact of zeolite and biochar on the physical and chemical characteristics of soil, there has not yet been a comparison of these two amendments. The most apparent similarity between these two amendments is that they both have porous structures. However, despite the significance of this issue in conserving soil moisture, a thorough examination of each one's impact on soil hydraulic indices has gone unreported. On the other hand, since plant growth has previously gone unnoticed, it is the simplest approach to assess each one's effectiveness. This study was carried out to compare the effects of zeolite and biochar on soil physical characteristics, particularly moisture content and corn plant development efficiency in response to soils treated with these amendments.

2. Materials and Methods

2.1. Experimental Procedure

The pot experiment was carried out in a greenhouse at the Faculty of Agriculture, University of Guilan in Rasht, Iran (37°11′59.3″ N 49°38′54.6″ E) from the beginning of June to the end of August 2020. Throughout the trial, the average day and nighttime temperatures were 23.6 °C and 15.7 °C, respectively. Relative humidity was 75% on average. The treatments were created in a completely randomized form with three duplicates. The *Zea mays* L. (corn) cultivar Single Cross 704 was the target plant for the analysis of changes in growth traits. Unbroken grains of the same size and color were cleaned in distilled water, sterilized for approximately 15 min in a solution of sodium hypochlorite at a 10% concentration, and then dried by air. After that, the grains were seeded in 6-kg plastic pots. The type of soil that was used was sandy loam. In each pot, 5 grains were sowed at a depth of 30 mm. N, P, and K were applied at levels of 480 kg N ha^{-1} (1.15 g N/pot, in the form of urea), 39.6 kg P ha^{-1} (0.126 g P/pot, in the form of calcium superphosphate), and 99.6 kg K ha^{-1} (0.313 g K/pot, in the form of potassium chloride), respectively, as base fertilizers. Zeolite and biochar were used as treatments, and they were applied at two different amounts of 5 and 10 t ha^{-1}, or 12.1 and 24.2 g/pot, respectively. The following treatments were used: Control (no zeolite or biochar), B5, B10, Z5, and Z10. The treatments and soils were uniformly combined three days prior to planting.

By pyrolyzing rice straw at 500 °C in a muffle furnace, biochar is created. Under the brand name Anzymite, zeolite was supplied by the Afrand Tosca Company. In Table 1, some characteristics of soil, biochar, and zeolite are listed.

Table 1. Chemical characteristics of soil and applied materials.

	pH	CEC (cmol$^{(+)}$ kg^{-1})	OC (%)	Ca^{2+} (cmol$^{(+)}$ kg^{-1})	Mg^{2+} (cmol$^{(+)}$ kg^{-1})	Na^{+} (cmol$^{(+)}$ kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	N_{tot} (%)	SSA (m^2 g^{-1})
Soil	6.61	25.6	0.51	4.61	6.12	3.26	2.87	2.51	0.88	118
Biochar	9.42	185.2	52.4	25.9	38.5	13.5	10.1	28.7	1.51	278
Zeolite	8.11	148.1	-	17.7	12.3	45.8	1.31	2.12	0.31	78.9

Note(s): CEC: cation exchange capacity; OC: organic carbon; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; Na^{+}: exchangeable sodium; P: phosphorus; K: potassium; N_{tot}: total nitrogen; SSA: specific surface area.

2.2. Soil Measurements

At the end of the experiment, soil characteristics were evaluated using the following methods: pH and electrical conductivity (EC) by 1:1 (soil: water) solution, and soil organic matter (OM) was estimated by multiplying soil OC by 1.72 (Van Bemmelen factor) [45]. Cation exchange capacity (CEC) was measured by ammonium acetate extraction [31] and the soil's specific surface area (SSA) was calculated using the ethylene glycol monoethyl ether (EGME) adsorption method [46]. The soil total porosity (TP) was determined using the following equation after the soil bulk density (BD) was measured using the clod method [47]:

$$TP = 100 \times \left(1 - \frac{D_b}{D_p}\right),$$

where TP is the total porosity (%), D_b is the soil bulk density (g cm^{-3}); and D_p is the soil particle density (g cm^{-3}), which was assumed to be 2.65 g cm^{-3}.

The wet aggregate size distribution was evaluated using the wet-sieving technique. Following air drying, soils were given a 24-h tap water soak. The soil was placed on a set of sieves with sizes of 2, 1, 0.5, 0.25, and 0.053 mm, and the sieving process was carried out for 10 min at a rate of 35 vibrations per minute (along a 38.1 mm amplitude). After wet-shaking in each sieve, the residual material was carefully removed and dried at 105 °C. The weight ratio of aggregates from each filter to the total weight of aggregates was used to calculate the aggregate size distribution. Using the wet sieving data [48], the mean weight diameter (MWD) of the soil aggregates was calculated as follows:

$$MWD = \sum_{i=1}^{n} \overline{Xi}\, Wi,$$

where $\overline{Xi}$ is the average diameter of the aggregates remaining on each sieve, Wi is the weight ratio of aggregates per sieve to the total weight of the soil used, n is the number of sieves used.

Inductively coupled plasma optical emission spectrophotometry (PerkinElmer Optima 7300 V) was used to measure the quantity of soluble base cations (Ca^{2+} and Mg^{2+}), and a flame photometer was used to measure Na^+ (M410 Sherwood). The sodium absorption ratio (SAR) was then determined using the formula:

$$\text{SAR} = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \times 100.$$

Before removing the plant from the soil at the end of the experiment, intact soil cores (10 cm in diameter) were obtained to measure the saturated hydraulic conductivity (Ks) at 0–5 cm depth and the soil water retention curve. Pressure plate equipment and porous plate funnels were used to calculate the soil water retention curves [49]. The applied tensions were 0, −10, −33, −100, −300, −500, and −1500 kPa, respectively, which equates to 0, 2, 2.5, 3, 3.5, 3.7, and 4.2 pF (log matric potential). The field capacity (FC) and the permanent wilting point (PWP) were calculated to be −33 and −1500 kPa, respectively. There were three replications carried out. The difference between FC and PWP was used to compute the available water content (AWC). The soil water retention curve was used to determine the volume of macro-pores (>10 m), meso-pores (0.2–10 m), and micro-pores (<0.2 m), which correspond to <2.5 pF, 2.5–4.2 pF, and >4.2 pF [50]. The Ks was determined in a laboratory setting using the constant-head method at 0.1 kPa pressure by applying a steady hydraulic head to the top of water-saturated cores [51].

2.3. Plant Measurements

At the end of the growing season, the plants' height and growth were measured. After harvest, at the project's conclusion, the weight of the biomass was recorded (30 July 2020). After the project was completed, the plants were cleaned in distilled water, chopped into shoots and roots, and then placed at 70 °C until they reached a consistent weight. The root samples were first stained in methyl violet solution and then scanned by the Delta-T SCAN Image Analysis System to determine the root's length, surface area, and average diameter [52]. After the digestion and distillation processes, the total nitrogen (N) content of the shoot was determined using the titration technique with the Kjeldahl system. Flame photometry at an absorption wavelength of 766.5 nm was used to quantify potassium (K), and spectrophotometry was utilized to calculate the proportion of phosphorus (P) [53].

2.4. Data Analysis

A one-way analysis of variance (ANOVA) was carried out to determine the importance of variations in soil properties between various treatments. After the least significant difference (LSD) test at $p < 0.05$, lowercase letters in the figures denote statistically significant differences. All figures were created in Excel 2020 and all data were analyzed using SPSS 24.

3. Results

3.1. Changes in Soil Characteristics

There was a significant difference between the biochar and zeolite treatments, and adding treatments considerably altered the physio-chemical features of the soil ($p < 0.05$) (Table 2). The highest pH was associated to B10 with 1.36 units more than the control (6.53). Applying zeolite had no significant influence on the pH of the soil. All biochar and zeolite treatments considerably raised soil CEC; however, B10 induced the maximum CEC with an amount of 139 cmolc kg^{-1}. B5-related CEC came in second place with a value of 115 cmolc kg^{-1}. With concentrations of 38 and 60 cmol kg^{-1}, Z5 and Z10 revealed CEC levels that were much lower than biochar treatments. Application of biochar resulted in a considerable increase in OM, with B5 and B10 seeing increases of 50% and 93% over controls, respectively. Zeolite use did not significantly alter the OM of the soil. In comparison to the control, the soil SAR in zeolite-treated soils increased by 65% and 143%, respectively, in Z5 and Z10. The addition of biochar had no significant impact on soil SAR. In contrast, zeolite-treated soils did not substantially differ from the control in terms of soil BD; adding biochar significantly reduced the quantity of BD. B10 and Z10 significantly increased soil porosity by 33% and 22% more than the control, respectively. Additionally, B5 and B10 use resulted in considerable changes to MWD, a measure of soil aggregation, with increases of 79% and 166% in comparison to the control. Z10 application resulted in a 48% reduction in soil MWD when compared to the control. Both biochar and zeolite treatments significantly increased soil surface area and the highest surface area was achieved from soil treated with B10, which had a surface area of 315 m^2 g^{-1}.

Table 2. Soil characteristics under biochar and zeolite treatments.

	pH	CEC (cmolc kg^{-1})	OM (%)	SAR (meq $l^{-1})^{0.5}$	BD (g cm^{-3})	TP (%)	MWD mm	SSA (m^2 g^{-1})
C	6.53^{c}	24.5^{e}	0.87^{c}	3.12^{c}	1.42^{a}	41.1^{c}	0.68^{c}	116^{d}
B5	7.35^{b}	115.1^{b}	1.31^{b}	3.39^{c}	1.33^{b}	49.3^{b}	1.22^{b}	251^{b}
B10	7.89^{a}	139.2^{a}	1.68^{a}	3.88^{c}	1.21^{b}	54.8^{a}	1.81^{a}	315^{a}
Z5	6.68^{c}	38.5^{d}	0.91^{c}	5.16^{b}	1.41^{a}	47.1^{b}	0.61^{c}	170^{c}
Z10	6.73^{c}	59.7^{c}	0.95^{c}	7.59^{a}	1.38^{a}	50.2^{ab}	0.35^{d}	281^{b}

Note(s): CEC: cation exchange capacity; OM: organic matter; SAR: sodium adsorption ratio; BD: bulk density; TP: total porosity; MWD: mean weight diameter; SSA: specific surface area. Different lowercase letters indicate significant differences between means ($p < 0.05$).

3.2. Changes in Soil Hydrologycal Indics

The pore size distribution of the soil significantly changed after the application of zeolite and biochar ($p < 0.05$) (Figure 1). The results revealed that applying biochar at a high rate (B10) increased the proportion of soil micro-pores by 33% compared to the control. Other treatments, however, failed to significantly alter the micro-pores. When it comes to meso-pores, applying biochar at both rates resulted in a 38% and 54% increase in the proportion of pores compared to the control. Zeolite soil treatment did not significantly alter the control in this region of pores. On the other hand, a considerable increase in the zeolite rate (Z10) led to a 61% rise in the proportion of macro-pores in comparison to the control. However, applying biochar had little impact on macro-pores.

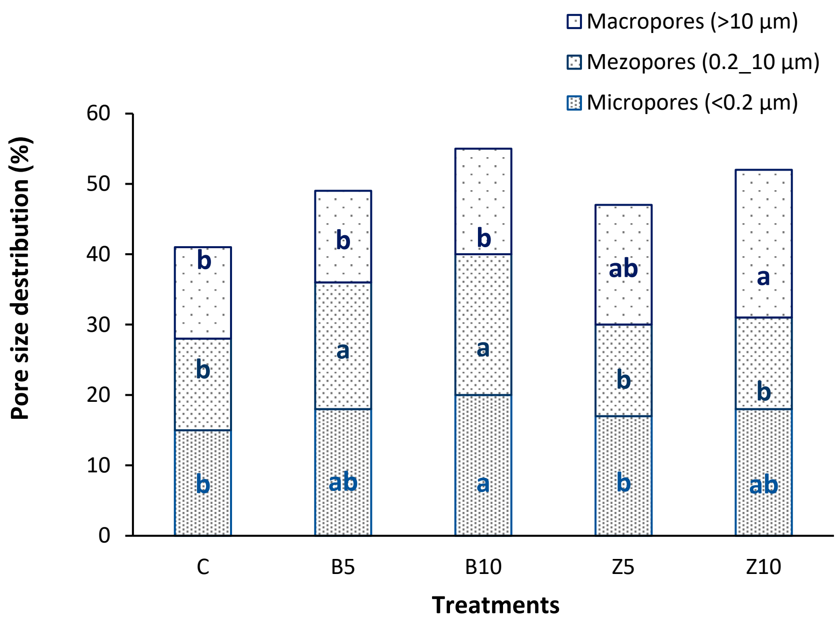

Figure 1. Effect of treatments on soil pure size distribution. Different lowercase letters with the same color indicate significant differences between means ($p < 0.05$).

Treatments and rates substantially altered the soil water retention curve ($p < 0.05$) (Figure 2). Results revealed that applying treatments had no significant impact on soil PWP; however, adding B10 caused a 47% rise in the FC point above that of the control, which was considerably significant. Furthermore, B5 significantly enhanced soil FC by 29% above the control. Although zeolite treatments increased soil FC, the effect was not significant.

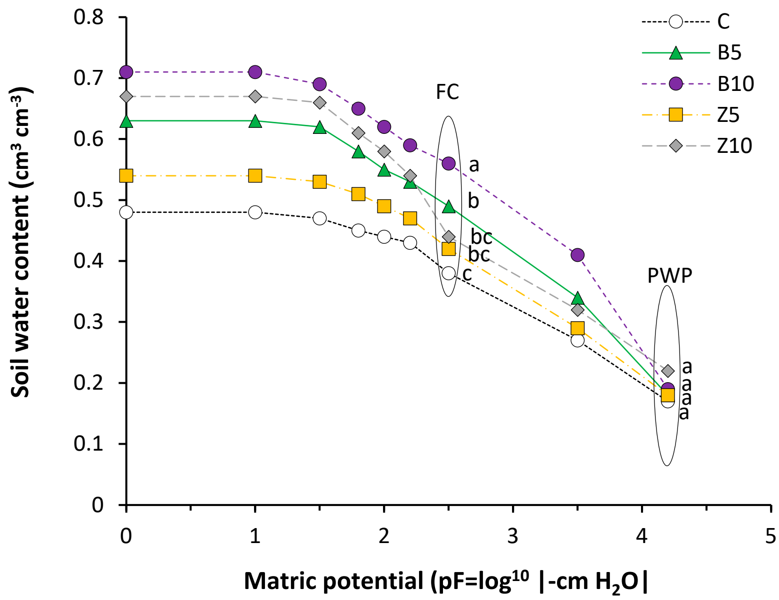

Figure 2. Effect of treatments on soil water retention curve. Different lowercase letters indicate significant differences between means ($p < 0.05$).

Treatments had a substantial impact on the soil's available water content (AWC; $p < 0.05$) (Figure 3). The B10 treatment showed the highest AWC, with a 76% increase over the control. Additionally, B5 was associated with the second-highest AWC, with a 48% increase above that of the control. There was no noticeable difference between the added zeolite at both doses and the control.

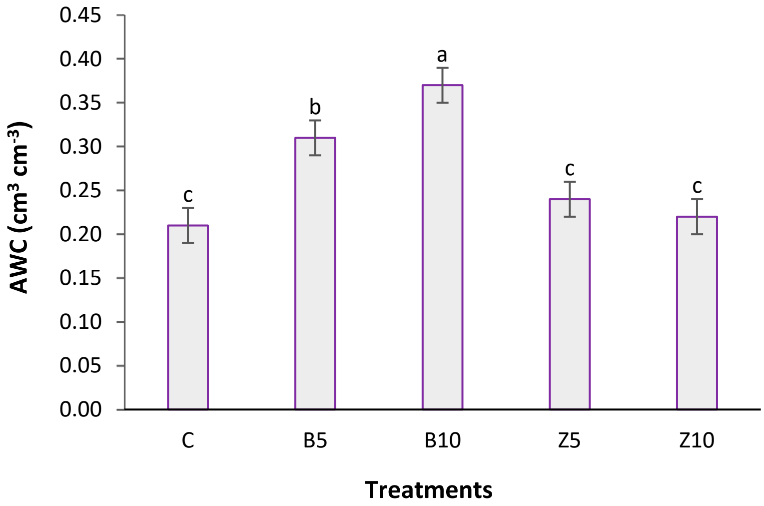

Figure 3. Effect of treatments on soil available water content (AWC). Different lowercase letters indicate significant differences between means ($p < 0.05$).

Both types of treatments had a significant impact on the soil's saturated hydraulic conductivity (Ks) ($p < 0.05$) (Figure 4). With increases of 174% and 303% over the control, respectively, the Z5 and Z10 showed the highest Ks, and there was a significant difference between them. B5 and B10, which increased Ks by 104% and 145% respectively, produced a noticeable difference from the control. Additionally, there were no significant variations across the biochar treatments.

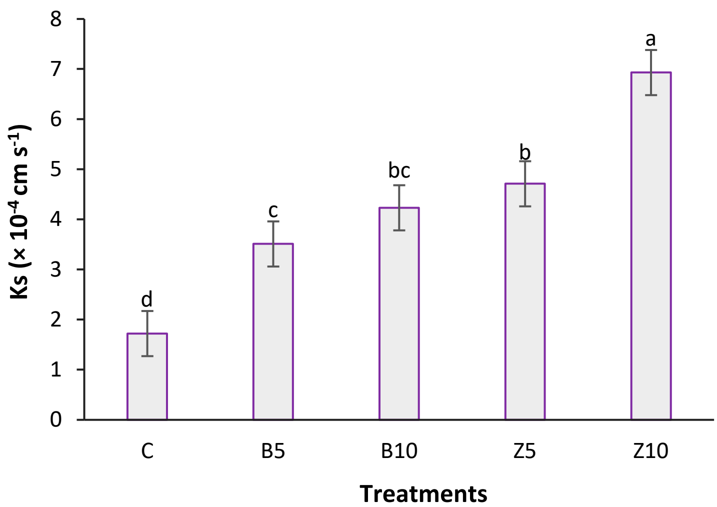

Figure 4. Effect of treatments on soil saturated hydraulic conductivity (Ks). Different lowercase letters indicate significant differences between means ($p < 0.05$).

3.3. Changes in Plant Growth

There was a substantial difference between the biochar and zeolite treatments, and adding treatments significantly altered the features of plant development ($p < 0.05$) (Table 3). Based on the findings of the root study, B10 significantly outperformed other treatments in terms of improving dry weight, total length, and root area. However, there was no discernible difference between Z5 and Z10; the application of biochar significantly increased root area and overall length. There was no discernible difference between treatments for root diameter. When biochar was added to a plant shoot analysis, the shoot dry weight rose considerably in B5 and B10, respectively, by 11% and 19% above the control. However, there was no significant variance between Z5 and Z10 and the control in terms of shoot dry weight. Similar to how zeolite treatments had little impact on shoot dry weight, they also had little impact on shoot length. On the other side, B5 and B10 significantly increased by 18% and 30% over the control, respectively. B5, B10, and Z5 significantly changed the nitrogen content of the shoots by increasing it by 113%, 179%, and 35%, respectively, in comparison to the control. Similar to nitrogen, the largest amount of shoot phosphorus was also obtained from B10 (220% more than the control). In the potassium case, B5 and B10 significantly increased the potassium levels in the shoot (55% and 90% more than the control), whereas zeolite treatments did not significantly vary from the control.

Table 3. Effect of biochar and zeolite treatments on plant growth characteristics.

	Root Analysis				Shoot Analysis				
	Root Dry Weight (g)	Root Total Length (cm)	Root Area (cm^2)	Root Diameter (mm)	Shoot Dry Weight (g)	Shoot Length (cm)	N ($mg\ g^{-1}$)	P ($mg\ g^{-1}$)	K ($mg\ g^{-1}$)
C	0.75 ^{c}	532 ^{d}	645 ^{c}	0.38 ^{a}	141 ^{c}	72 ^{c}	63.2 ^{d}	23.6 ^{d}	95.1 ^{c}
B5	0.88 ^{b}	664 ^{b}	689 ^{b}	0.39 ^{a}	156 ^{b}	85 ^{b}	134.4 ^{b}	61.8 ^{b}	147.5 ^{b}
B10	0.96 ^{a}	692 ^{a}	764 ^{a}	0.41 ^{a}	168 ^{a}	94 ^{a}	176.5 ^{a}	75.7 ^{a}	181.2 ^{a}
Z5	0.78 ^{c}	581 ^{c}	685 ^{b}	0.37 ^{a}	143 ^{c}	75 ^{bc}	85.2 ^{c}	39.2 ^{c}	101.5 ^{c}
Z10	0.85 ^{b}	605 ^{c}	694 ^{b}	0.38 ^{a}	144 ^{c}	77 ^{bc}	66.5 ^{d}	25.7 ^{d}	108 ^{c}

Note(s): N: nitrogen; P: phosphorus; K: potassium. Treatments with same letters in each column have not significant difference with each other ($p < 0.05$).

4. Discussion

Observations reveal that applying biochar as opposed to zeolite significantly changed the soil's structure, increasing the availability of nutrients, water retention, and ultimately plant growth. The improvement of soil aggregation in soils treated with biochar can be used to explain the initial cause of this modification. MWD is a crucial variable that is directly connected to the quality of the soil structure [41]. By enhancing plant rooting and ventilation, decreasing bulk density, expanding specific surface area, and increasing water availability, the MWD represents a high concentration of macroaggregates larger than 2 mm and the resistance of aggregates to degradation [14]. These factors contribute to a good soil structure for plant growth [54,55]. Additionally, the accumulation of soil organic matter is positively impacted by biochar, which can increase the quantity and availability of soil organic matter, consequently boosting the number of soil aggregates and thereafter MWD [56,57]. Soil aggregation improved as the rate of biochar increased [15]. However, the primary functional groups in biochar, including the hydroxyl, carboxyl, and benzene rings, give it a significant adsorption ability and a substantial ion exchange capacity [58]. When these unique light energy groups are combined with soil, they may absorb more organic matter from the soil solution and raise the amount of soil organic matter [59]. The biological activity in the application layer, the soil particle ratio, and the properties of soil water transport can all be improved by using some carbon-containing organic matter as a carbon source for microbial energy [60]. These are the primary causes of the boost in soil CEC and OM following the application of biochar [61]. However, the formation of bridges by cations between clay and OM particles lead to aggregation [62]. A detailed overview of the initial properties of biochar and zeolite (Table 1) reveals that the specific surface area and CEC of biochar are significantly higher than those of zeolite. These inherent qualities of biochar may emphasize the overall interaction between biochar particles and soil organic matter that led to aggregation. One of the causes of a rise in pH in soils treated with biochar may also be biochar's high CEC [63]. In fact, because there are more exchangeable sites and fewer possible acidic sites, the amount of exchangeable Al and soluble Fe in the biochar-treated soils tends to decrease [64]. In comparison to zeolite treatment, this demonstrated the ability of biochar as a soil amendment to rectify medium acidity. Numerous studies have shown that adding more biochar to the soil significantly enhances SSA [65]. This could happen as a result of the biochar's tiny pores. Fine pores in biochar with a size of 50 nm play a significant part in extending surface area [66]. This is mostly reliant on the temperature at which biochar was produced during pyrolysis. The results show that the ideal pyrolysis temperature for producing biochar with the greatest possible specific surface area is between 450 and 550 °C [58]. The temperature used in this investigation to create biochar was 500 °C. Additionally, increased sodium adsorption ratio (SAR) values in zeolite treatments indicate significant Na^+ addition to soil. It is evident from Table 1 that zeolite inherently contains far more Na^+ cation than biochar. Zeolite allows soil to provide Na^+ in exchangeable form, which then substitutes Ca^{2+} and Mg^{2+} adsorbed on the soil clays and ultimately leads to soil particle dispersion [67]. This dispersion leads to the breakdown of soil aggregation since the flocculation of clay particles is one of the fundamental prerequisites for the development of aggregates. This may possibly be the cause of the MWD decline with increasing zeolite treatment [68]. Another explanation is that when the amount of zeolite, which contains particles between 2.5 and 5 mm in size, rises, the smoothness and aggregation between the soil matrix particles declines and, as a result, the soil structure deteriorates [69]. The large amount of drainage water with rising zeolite levels during irrigation served as additional support for this hypothesis. As a result, more than 70% of the irrigation water discharged from the Z10-containing pots originated from their base. This is an obvious illustration of how the structure of the soil is destroyed when there is a high zeolite concentration.

Significant biochar addition led to the best improvement in soil overall porosity (Table 2). Additionally, certain differences emerged when the pore size distributions for zeolite and biochar were compared (Figure 1). A fundamental and important factor in soil aeration, root development, the transfer and storage of soil water and cations is pore size distribution [24]. However, zeolite enhanced the fraction of macro- and, somewhat, micro-pores; biochar treatment significantly raised the share of micro- and meso-pores. It is obvious that the smaller pores in soil structure are what keep water in the soil and prevent it from draining [70]. The presence of micro-pores helps light-textured soils hold onto water better. However, the water in the micro-pores may be kept there so firmly that it is challenging for the plants to access it. Meso-pores offer greater aeration and drainage, which makes it easier for plants to access water [71]. The application of biochar offers sufficient quantities of both types of pores to improve the soil's physical properties and boost the quantity of water that is accessible to plants [72]. The main cause of the observed increase in soil water availability (Figure 3), which is strongly affected by pore size distribution, and water content near field capacity (Figure 2), is this phenomenon [40]. On the other hand, the application of zeolite substantially enhanced the percentage of macro-pores. However, pores that do not develop capillary menisci and, as a result, do not hold water against gravity, are referred to as macro-pores [73]. Macro-pores can be found in fissures, fractures, rotted roots, earthworm channels, and interaggregate gaps [74]. In fact, a larger proportion of macro-pores in zeolite-treated soil increased hydraulic conductivity, which resulted in water loss and a reduction in the amount of water accessible to the root zone [75]. This is the primary cause of the rise in saturated hydraulic conductivity that occurred when zeolite application rates increased from Z5 to Z10 (Figure 4).

When compared to zeolite, biochar had a better effect on plant development (Table 3). This response was probably brought on by fundamental changes in soil structure, soil CEC, and nutrients contained on the biochar's surface [24]. Numerous studies have demonstrated that soil structure has an impact on plant establishment and the development of growth characteristics [76,77]. A crucial element in the stabilization of soil aggregates, the production of soil aggregates, and eventually the growth of plants, was enhanced soil structure, which also increased the OC (Table 2) [37]. In reaction to increased aggregates, plant roots can change their allocation mechanisms and they can develop in high MWD soil [78]. The key factor increasing plant root properties in biochar-treated soil is because of this. Additionally, the high surface area of biochar allows for high CEC and increases nutrient availability in soil [64]. Therefore, it is evident that plants have a greater chance of absorbing essential nutrients from biochar absorption sites in soil that has been treated with biochar. On the other hand, the amount of accessible water in the soil has a direct impact on the growth of plant weight and height [6,7]. The rate at which water percolates up larger pores increases, along with the loss of accessible water and nutrients for plant roots [9]. According to reports, adding 2 to 8 g of zeolite per kilogram of soil is enough to stop nutrient leaching in sandy loam soils caused by fast water flow [75]. As a result, Z5 has been more effective than Z10 at feeding the plant nutrients (Table 3). This is due to the water moving at the fastest rate near the center of big pores [79]. However, when positively charged surfaces are present, cation exclusion takes place [80]. Such surfaces eject cations, which then collect in the middle of pores. The average cation movement will be quicker than the average water movement because the highest water flow velocity occurs in the middle of pores [81]. While biochar treatments with micro- and meso-pores enhanced AWC and reduced the volume of irrigated water from draining, they also kept nutrients and cations close to the roots, which positively impacted plant development. Numerous studies have revealed that a greater Na^+ concentration in soils upsets the nutritional balance and interferes with the control of osmotic pressure in plant tissues [67]. Based on these findings, zeolite provided an extra Na^+ cation source to the soil–plant system in this study, increasing the Na^+/Ca^{2+} ratio [68]. The accumulation of Na^+ ions in plants would be boosted by a rise in the Na^+/Ca^{2+} ratio in the root environment, which would subsequently impact the Na+ concentration in the shoots as well as the Na^+/Ca^{2+} and Na^+/K^+ ratios of the roots and shoots [67]. The use of zeolite, however, has been shown to improve plant biomass by improving nutrient retention and preventing nutrient loss through leaching, according to certain studies [82,83]. According to earlier research, adding zeolite to heavy soils (clay loam and clay) with more tiny holes alters their size and form, improving soil structure and water transmission, which in turn promotes plant development [79]. This development will undoubtedly stop waterlogging in dense soil textures. On the other hand, adding zeolite at a high rate can significantly enhance hydraulic conductivity (Ks) in sandy loam (the type of soil utilized here) soil with bigger pores [75]. AlO_4 and SiO_4 tetrahedrals produce an open lattice structure with pores and channels as a result of the zeolite structure, which improves water mobility in the zeolite structure [83]. Therefore, by including zeolite in the soil, new water pathways may develop [80]. Thus, zeolite treatment increases hydraulic conductivity in sandy loam soils with a coarse texture [81]. Zeolite application at low rates would be acceptable in fine texture soils to reduce hydraulic conductivity and water transferability, which reduces deep percolation and soil water loss [79].

5. Conclusions

Utilizing the proper soil amendment ensures that the soil structure will improve and that the water content accessible to the plant will increase to its maximum. The findings show that, because of its unique structural characteristics, adding biochar to a sandy loam soil is obviously better than doing so with zeolite. High specific surface area, high exchange capacity, and a variety of functional groups on the surface of biochar contribute to the majority of this superiority, which in turn leads to the formation of micro and meso-pores in soil treated with biochar. Ideal circumstances for the formation and development of roots and plant growth are provided by the availability of a high percentage of water and nutrients in the fine soil pores, as well as by the enhancement of soil aggregation. The quality of soil structure, water retention, and plant development are all improved by using more biochar, although using more zeolite does have drawbacks. In fact, due to their coarseness, natural zeolite particles damage soil structure, disperse soil particles, increase water loss, and thus have a negative impact on plant development characteristics. Hence, in order to increase the effectiveness of irrigation water and agricultural fertilizers in soils with structural concerns and insufficient water supply, proper use of soil amendments at a precise application level is crucial.

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