Asian Journal of Advances in Research

Volume 8, Issue 1, Page 1-15, 2025; Article no.AJOAIR.4493

The Impact of Biochar and Olive Mill Wastewater Amendments on Soil Physical and Hydrodynamic Characteristics and Soybean Productivity in the Syrian Coast

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.56557/ajoair/2025/v8i1500

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.mbimph.com/review-history/4493

Original Research Article

Received: 03/11/2024
Accepted: 06/01/2025
Published: 09/01/2025

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Cite as: *Dayoub, Evan Bassam, Jihad Ibrahim, Samar Hasan, and Ola Kajo. 2025. "The Impact of Biochar and Olive Mill Wastewater Amendments on Soil Physical and Hydrodynamic Characteristics and Soybean Productivity in the Syrian Coast". Asian Journal of Advances in Research 8 (1):1-15. https://doi.org/10.56557/ajoair/2025/v8i1500.*

ABSTRACT

One of the most critical problems facing countries in the Mediterranean basin and posing restrictions on agricultural production is poor soil quality caused by low organic matter content (OM). Biochar, a carbon-enriched material obtained by pyrolysis of agricultural wastes proved to be efficient in soil improvement. On the other hand, olive mill wastewater (OMWW) is a byproduct of olive oil production. The combined use of these materials will reduce environmental damage paving the way to sustainable agriculture and may also offer a practical solution for enhancing soil physical properties. This research aimed to evaluate the effect of biochar and OMWW on the physical and hydrodynamic characteristics of a loam soil in the syrian coast. A field experiment was carried out using four rates of biochar (0, 1, 3, and 6 t ha^{-1}) and three levels of OMWW (0, 50, and 100 m^3 ha^{-1}). Results showed that with increasing the levels of biochar and OMWW the soil bulk density (BD) and pores containing unavailable water <0.2 µm (PUW) decreased reachig the highest significant reduction at the biochar dose of 6 t ha^{-1} and OMWW level of 100 m^3 ha^{-1} in comparison to the control. On the other hand, the combined supply of 100 m^3 ha^{-1} OMWW and 6 t ha^{-1} of biochar led hydrodynamic constants (a and b) to increase indicating enhanced water absorption capacity for plants. Moreover, the soil total porosity (TP) increased significantly by (10.5%v), pores containing plant available water (0.2-10 µm) (PAW) (4.2%v) and macropores (soil air capacity) >10 µm (9.2%v) after adding 100 m^3 ha^{-1} of OMWW and soil biochar addition at 6 t ha^{-1}, also soybean productivity rose by (%222.187).

Keywords: Biochar; olive mill wastewater; bulk density; plant available water; hydrodynamic constants.

1. INTRODUCTION

Spain, Italy, and Syria are among the top olives' producers (Mohawesh et al. 2019, Khdair & Abu-Rumman 2020). The environmental consequences of olive oil production are significant in all Mediterranean olive oil-producing nations (Khdair & Abu-Rumman 2020). One of the most important wastes in olive oil production is olive mill wastewater (OMWW) since the volume of olive pressing water in the Mediterranean region is estimated at more than 30 million cubic meters, including around one million cubic meters from Syria (Beccari et al. 2001). Soils in the Mediterranean area have a low organic matter content (OM), which reduces fertility and productivity (Brunetti et al. 2007). To improve soil fertility in this area, regulated ground application of OMWW is a familiar technique that has been confirmed and licensed (Saadi et al. 2013, Collivignarelli et al., 2019, Mohawesh, et al., 2020). The high content of organic carbon and humic compounds and the abundance of macronutrients in OMWW make this material an excellent soil conditioner with high fertilization capacity (Mechri et al. 2011, Buono et al., 2011, Aranda et al., 2016, Vella et al., 2016). Another important benefit of OMWW is improving soil physical characteristics such as structure, total porosity (TP), bulk density (BD), and saturated hydraulic conductivity (Belaqziz et al., 2008, Kavvadias et al., 2015). Some studies also reported an increase in water holding capacity (Mekki et al., 2006, Mohawesh et al., 2014). Similarly, OMWW improved soil chemical properties such as macronutrients and OM contents (Ayoub et al., 2014).

Among organic materials used to improve soil properties, biochar has attracted more attention in the last decade because it represents a unique material with high porosity and stable carbon due to its production under anaerobic conditions and high temperatures (pyrolysis) (Brynda et al., 2020). Biochar can be produced from a variety of biomass sources including straw waste, wood residues, animal manure, and other waste products (He et al., 2017). The type of feedstock, pyrolysis temperature, pyrolysis time, and design of the pyrolysis device all affect the physicochemical properties of the resulting biochar (Mimmo et al., 2014). Biochar provides an alternative soil management option as it improves soil structure (Jien et al., 2013), aggregate stability, and TP (Liang et al., 2006, Kimetu, & Lehmann 2010). It also reduces the BD of soil (Abrishamkesh et al., 2016, Chen et al., 2018). It increases the PAW in different types of soil (Kameyama et al., 2016, Ma et al., 2016, Pudasaini et al., 2016, Shenghai, et al., 2019, Wang et al., 2019). Moreover, it is also more stable than any other soil additive, increasing the availability of elements beyond the effect of fertilizers (Lehmann 2009, Guo et al., 2020). Furthermore, after applying biochar, the researchers observed an increase in water retention capacity (Glab et al., 2018, Villagra-Mendoza & Horn 2018). The ground inputs of biochar and OMWW, cause improvements in soil physical and chemical properties, for example (TP, PAW, water retention capacity, aggregate stability) and (macronutrient and OM contents), which promote crop growth and productivity (Premalatha et al. 2023).

Due to the difficulty of providing OM in sufficient quantities and its low content in the soil, it was necessary to consider using biochar with OMWW from local presses with an acidic effect and studying its effect on the physical and hydrodynamic properties of the soil and on soybean productivity.

2. MATERIALS AND METHODS

2.1 Study Area and Experimental Design

The field experiment was carried out at Fideo livestock farm, Latakia, Syria (35˚29'30"N 35˚52'08" E) (Fig. 1) in 2022. The altitude is 31 m, the mean annual temperature is 21 ˚C, and the mean annual precipitation is 645 mm. Four rates of biochar (0, 1, 3, and 6 t ha^{-1}) and three levels of OMWW (0, 50, and 100 m^3 ha^{-1}) were arranged in a complete randomized block design in triplicate (Fig. 2).

2.2 Soil, Biochar, and OMWW Properties

Disturbed soil samples were collected from the topsoil (0–20 cm) to determine soil texture using pipette method (Bernharat 1967), according to (TGL), OM % was determined by oxidization with $K_2Cr_2O_7$ and calibration with $FeSO_4$ (0.25 mol dm^{-3}) (Ryan et al., 2001). Total $CaCO_3$ % was determined using HCl as medium and calibration with NaOH (0.5 mol dm^{-3}), and effective $CaCO_3$ % using $C_2O_4(NH_4)_2$ as medium and calibration with $KMnO_4$ (0.2 mol dm^{-3}) (Ryan et al., 2001). Cation exchange capacity (CEC) meq $100g^{-1}$ using $NaCH_3COO$ (1 mol dm^{-3}) (Ryan et al., 2001), and particle density (PD) g cm^{-3} using pycnometer (Blake & Hartge 1986). Undisturbed soil samples (0–20 cm) used to calculate field capacity $pF_{2.5}$ (FC), and wilting point $pF_{4.2}$ (WP) (pressure plate) (Table 1.).

Biochar. Olive tree (Alkelkali variety) wood resulting from regenerative pruning of a planted orchard in Upper Kefarieh village (Latakia governate) pyrolyzed at 500 ˚C using an electric furnace in the Tishreen University nursery. The pyrolysis residence time was 1 hour, and the olive wood yield of biochar was 33.41%. The measured physical characteristics of biochar were as follows: particle density (PD) g cm^{-3} using pycnometer (Blake & Hartge 1986),

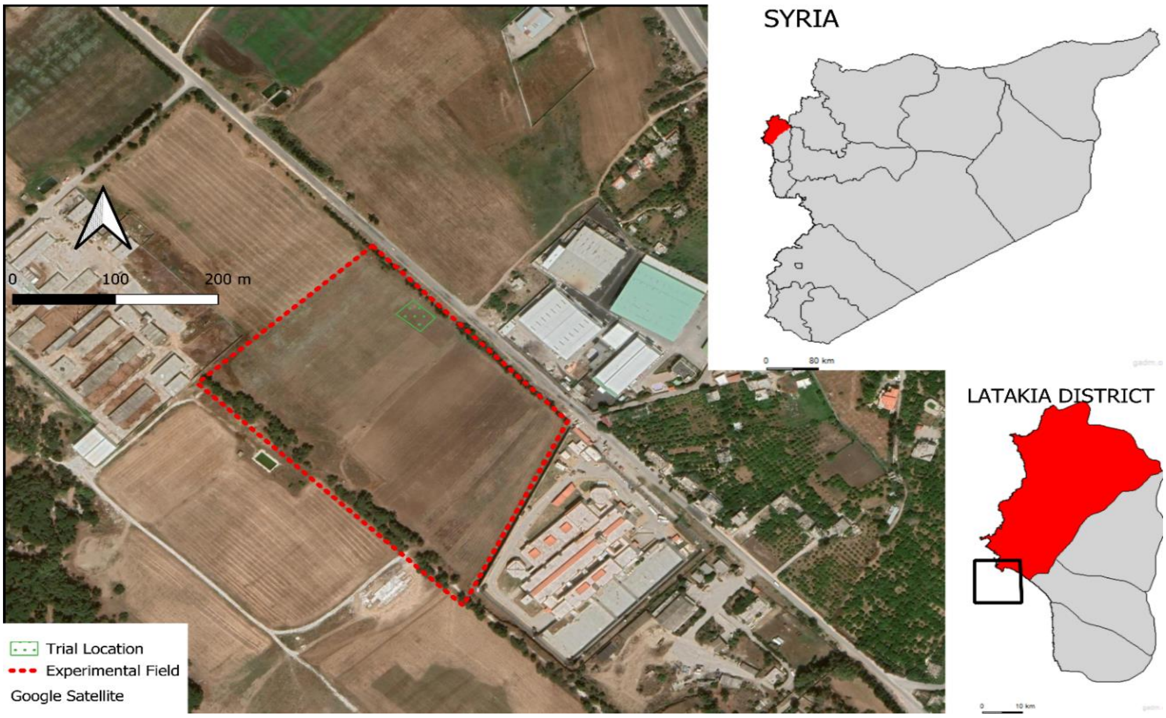

Fig. 1. Location of the experiment

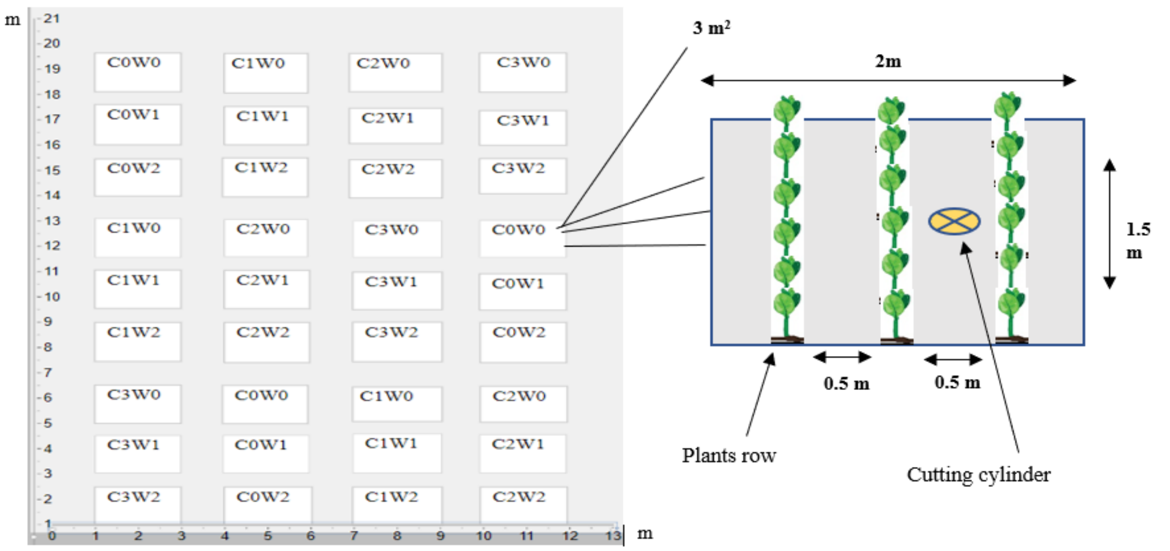

Fig. 2. Field experiment layout where: C0 - without biochar, C1 - 1 t ha^{-1}, C2 - 3 t ha^{-1}, C3 - 6 t ha^{-1}, W0 -no OMWW, W1 - 50 m^3 ha^{-1}, W2 - 100 m^3 ha^{-1}.

Table 1. Physical and chemical characteristics of the soil

Parameter	Soil
CL (%)	21.91
SI (%)	22.25
SA (%)	55.84
Texture	Loam (TGL)
OM (%)	2.2
Total $CaCO_3$ (%)	16.25
Effective $CaCO_3$ (%)	5.5
CEC (meq 100g^{-1})	23.88
FC (%v)	31.7
WP(%)	13
PD(g cm^{-3})	2.62

Explanation: CL - clay, SI- silt, SA- sand, OM- organic matter content, Total $CaCO_3$- total lime, Effective $CaCO_3$- effective lime, CEC- cation exchange capacity, FC- field capacity, WP- wilting point, PD- particle density, N tot- total nitrogen, P tot- total phosphorous, K tot- total potassium, pH- reaction degree, EC-electrical conductivity.

and bulk density BD (g cm^{-3}) using metal cylinders. The measured chemical characteristics of biochar were as follows: Total nitrogen (N_{tot}) % was determined by Kjeldahl. Total phosphorous (P_{tot}) %, and total potassium (K_{tot}) % were determined by (digestion with sulfur and salicylic acids in the presence of selenium (Tendon 2005) pH, and EC (electrical conductivity) mmhos cm^{-1} were determined in a soil/water suspension in the ratio of (1:5) (v/v), TC% according to Ryan et al., (2001). (Table 2).

OMWW was taken from a three-phase centrifuge extraction system of an olive press near Latakia city (4 km), stored in 50 liter plastic containers, and stirred homogeneously before addition to the soil. The measured chemical characteristics of OMWW were as follows: Total nitrogen (N_{tot}) % was determined by Kjeldahl. Total phosphorous (P_{tot}) %, and total potassium (K_{tot}) % were determined by (digestion with sulfur and salicylic acids in the presence of selenium (Tendon 2005), pH, and EC (electrical conductivity) mmhos cm^{-1} were determined in a soil/water suspension in the ratio of (1:5) (v/v), OM % using (incineration at 550 ˚C) (Table 3.).

2.3 Experimental Field

After deep plowing (30 cm), the soil surface was smoothed using a rotary cultivator to create plots (experimental units). Each plot has three rows,

Table 2. Physical and chemical characteristics of the biochar

Parameter		Biochar
Particles Size Distribution (%)	>63 µm	2.16
	125-63 µm	7.57
	500-125 µm	56
	1000- µm500	22.16
	<1000<2000 µm	12.1
TP (%v)		50.74
PD (g cm^{-3})		1.34
BD (g cm^{-3})		0.66
Air dry moisture (%)		4.95
N_{tot} (%)		0.36
K_{tot} (%)		0.2
P_{tot} (%)		0.04
pH_{H2O}		8
EC (mmhos cm^{-1})		0.36
TC (%)		89.5

Explanation: TP -total porosity, PD- particle density, BD- bulk density, N tot- total nitrogen, P tot- total phosphorous, K tot- total potassium, pH- reaction degree, EC-electrical conductivity, TC- total carbon.

Table 3. Chemical characteristics of OMWW characteristics

Parameter	OMWW
N_{tot} (%)	28.5
P_{tot} (%)	20.5
K_{tot} (%)	38.44
pH (v/v)	5.81
EC (mmhos cm^{-1}) (v/v)	4.12
OM (%)	4

with 50 cm between lines and 20 cm between plants in each row. Biochar, OMWW, and basic fertilization as recommended kg per 1 hectare: (P_2O_5)70–(K_2O) 60 (Rokaia 1997) were added before cultivation and after plowing. Biochar, OMWW, and basic fertilization were mixed homogenously into the top soil (0–20 cm). Three seeds of Soybean sb44 (brought from the General Authority for Agricultural Research (Damascus) were planted in holes (2–2.5 cm depth) on the 7th of June 2022.

Plants were irrigated weekly via rows of 1.5 m in length using surface irrigation, where the water coefficient was calculated (the amount of water required to be distributed homogenously on the area at a specific time), reaching 80% of field capacity from a water source higher than the field. The first dose of nitrogen fertilizer (N), 230 kg per ha (Rokaia 1997), was added as urea (46%) at planting. Five days later, germination started until completion in 10 days, when the plants were thinned to one plant in each hole and a second nitrogen dose was added. The third dose was added at the beginning of the flowering period. Plants were harvested after 4 months and 20 days (seed moisture of 20%) and left to dry (seed moisture of 13%).

2.4 Soil Sampling and Sample Analysis

After harvest, undisturbed soil (0–20 cm) sampling was done in between rows using metal cylinders with a volume of 100 cm^3. Three replicates were taken from each treatment (one from each replicate) to calculate:

- Bulk density (BD):

$$BD\ g\ cm^{-3} = M_s\ V_t^{-1} \qquad \text{Equation 1}$$

Where: M_s - oven dry weight of the sample (105 ˚C);

V_t cm^3- total volume of the cylinder (100 cm^3).

- -Soil water retention curves (WRCs) and Hydrodynamic constants. These samples were initially saturated with water before being balanced to acheive gradual soil water potential values for 48 hour. Hydrodynamic constants were determined via pressure plate apparatus (Eijkelkamp Agrisearch Equipment 6987 ZG Giesbeek,The Netherlands) by–applying increasing pressures starting with $pF_{1.8}$, pF_2, $pF_{2.5}$, pF_3, $pF_{3.5}$ and $pF_{4.2}$. The averages of moisture content were calculated at different moisture tension levels. Ψ is (moisture tension – cm column of water (h) and $pF=\log_{10}(h)$. Soil volumetric water content (Θ) was expressed as part of 1. Then log Ψ and log θ (a negative number) were calculated. The relationship between log Ψ and log θ was calculated via a first-degree relationship:

$$\log \Psi = a + b\log \theta \quad \text{Equation 2}$$

a= is a constant; *b* is the curve slope.

Then we convert the equation (2) to an exponential relationship to reach Gardner format:

$$\Psi = 10^{m}.\theta^{b} \quad \text{(Gardner et al., 1970)} \quad \text{Equation 3}$$

After that, equations and hydrodynamic constants (a and b) were determined as an average of three replicates.

- Soil pore size distribution (PSD) using pressure plate apparatus:

To calculate the required pressure, we entered the pore diameter in the following equation:

$$Pm = 4\sigma w/d \quad \text{(Ibrahim et al. 2021)} \quad \text{Equation 4}$$

Where: *Pm* - applied pressure pascal;

d - pore diameter m;

σw - surface tension of water - newton m^{-1} (0.073).

By the end of each pressure related to each pore size group, we will get the volumetric water content:

$$WvolpF_x = (\text{mm } pF_x - M_s/v_t) \quad \text{Equation 5}$$

$WvolpF_x$ - volumetric water content at specific pressure;

mm pFx- the weight of the cylinder (soil sample) at the end of specific pressure;

V_t - the volume of the cylinder;
M_s - the dry weight of the soil (105 C°).

The size of the pore groups is determined as follows:

$$PV\% > 50\ \mu m = TP - Wvol.\ pF_{1.8} \quad \text{Equation 6}$$

$$PV\% > 10\ \mu m = TP - Wvol.\ pF_{2.5} \quad \text{Equation 7}$$

$$PAW\%\ (0.2\text{-}10)\ \mu m = Wvol.\ pF_{2.5} - Wvol.pF_{4.2} \quad \text{Equation 8}$$

$$PV\% < 0.2\ \mu m = Wvol.\ pF_{4.2} \quad \text{Equation 9}$$

$$TP\% = (1 - BD/PD) \times 100 \quad \text{Equation 10}$$

Where: TP% - Total porosity;
BD - bulk density of the soil g cm^{-3};
PD - particle density of the soil g cm^{-3}.

2.5 Statical Analysis

The experimental procedures in this investigation involved processing all assessments in triplicate, and the resulting data were presented as the mean value. The statistical analysis was conducted using the Web Agri Stat Package (WASP). The study employed one-way variation analysis (ANOVA) to examine inter-group differences. The least significant difference (LSD) test was utilized with a significance level of 5% ($p < 0.05$) (Grech 2018).

3. RESULTS AND DISCUSSION

3.1 Bulk Density (BD)

The effect of biochar and OMWW on BD is shown in Table 4. BD experienced a downward trend while using biochar and OMWW separately and together. Biochar rates alone had a greater impact on BD reduction than OMWW. However, a biochar dose of 6 t ha^{-1} was characterized by the highest reduction in BD by 0.29 g cm^{-3}, when the soil was amended with OMWW at 100 m^3 ha^{-1} in comparison to the control.

OMWW usage at 50 m^3 ha^{-1} with biochar gradual rates at 1, 3, and 6 t ha^{-1} together resulted in BD reductions of 0.12–0.15–0.2 g cm^{-3} as compared to the control (C0W0). In comparison to the control (C0W0), the combination of 100 m^3 ha^{-1} OMWW and biochar additions at 1, 3, and 6 t ha^{-1} produced significant decreases in BD (0.13–0.2–0.29 g cm^{-3}) for the examined soil.

The high reduction in BD after biochar amendment was confirmed by wahhab & Şeker (2021), who reported a significant decrease in soil BD after the highest biochar amendment of 4% to sandy loam soil. On the other hand, BD reductions after OMWW additions are in line with Khalil et al., (2024), who mentioned a decrease in the BD value of clay soil in all studied treatments (0, 5, 10, and 15 L m^{-2}) compared to the control treatment.

Table 4. Changes in BD (g cm^{-3}) under the effect of biochar and OMWW different rates

Treatment	BD(g cm^{-3})
C0W0	1.35 [a]
C0W1	1.31 [a]
C0W2	1.25 [b]
C1W0	1.31 [a]
C1W1	1.23 [bc]
C1W2	1.22 [bc]
C2W0	1.23 [bc]
C2W1	1.20 [cd]
C2W2	1.15 [e]
C3W0	1.17 [de]
C3W1	1.15 [e]
C3W2	1.06 [f]
Lsd $_{0,05}$	0.038

3.2 WRCs and Hydrodynamic Constants

After determining the water content for soil in the studied treatments at different levels of moisture retention (pF) the relathionship between θ and pF was determined in the form of : $\Psi = a\theta^b$ (Gardner et al., 1970). According to the following equations in Table 5.

From the equations in Table 5, we draw out WRCs to obtain Figures (3, 4, and 5). Figs. (3, 4, and 5) indicated that the moisture content of the soil decreases with increasing moisture retention and at pF=3 the path of the WRCs changes due to the change in the distribution of the PSD.

From the previous equations, the hydrodynamic constants (a and b) were found for the studied soil, as shown in Table 6.

Hydrodynamic constants (a and b) increase with increasing the addition rate of biochar and OMWW while using them seperately and together in comparison to the control. Biochar had a greater effect than OMWW in increasing a and b. The value of the constant a ranged between 0.157 in the control and 0.622 at the addition level of biochar 6 t ha^{-1} and OMWW 100 m^3 ha^{-1}, and the values of the constant b ranged between -6.679 in the control and -5.374 at the addition level of biochar 6 t ha^{-1} and OMWW 100 m^3 ha^{-1}. The amendment of OMWW at 50 m^3 ha^{-1} and biochar rates 1, 3, and 6 t ha^{-1} jointly caused constant a to increase, reaching 0.384 and b = -5.866 (Table 6).

3.3 Soil Pore Size Distribution (PSD)

Biochar and OMWW effects on PSD are shown in Table 7. While TP, PAW, and macropores >10 µm experienced an upward trend, PUW had the opposite. Biochar had a greater effect than OMWW in increasing the TP and PAW, while the combined usage of OMWW at 100 m^3 ha^{-1} and biochar at 6 t ha^{-1} was characterized by possessing the highest values of TP (58.9%v), PAW (18.4%v), and macropores >10 µm (25.9%v), and the lowest value of PUW (14.6%v).

The increase in OMWW and biochar doses alone and together boosted TP, especially the usage of OMWW at 100 m^3 ha^{-1} and biochar at 1, 3, and 6 t ha^{-1} jointly. OMWW addition alone affected PAW significantly only at 100 m^3 ha^{-1}, whilst biochar supply at 3 and 6 t ha^{-1} without OMWW achieved significant increments of 2.1–2.6%v, respectively over the control (C0W0).

Table 5. Equations and hydrodynamic constants for the relationship between pF and θ under the effect of biochar and OMWW different rates

Treatment	Equation	Determination coefficient (r^2)
C0W0	Ψ=0. 157 $\theta^{-6.679}$	0.99
C0W1	Ψ=0. 1288 $\theta^{-6.862}$	0.99
C0W2	Ψ=0. 295 $\theta^{-6.115}$	0.98
C1W0	Ψ=0. 216 $\theta^{-6.396}$	0.98
C1W1	Ψ=0. 199 $\theta^{-6.354}$	0.98
C1W2	Ψ=0. 246 $\theta^{-6.247}$	0.98
C2W0	Ψ=0. 388 $\theta^{-5.816}$	0.98
C2W1	Ψ=0. 334 $\theta^{-6.011}$	0.98
C2W2	Ψ=0. 279 $\theta^{-6.043}$	0.97
C3W0	Ψ=0. 496 $\theta^{-5.60}$	0.97
C3W1	Ψ=0. 389 $\theta^{-5.866}$	0.98
C3W2	Ψ=0. 622 $\theta^{-5.347}$	0.96

Table 6. Changes in hydrodynamic constants under the effect of biochar and OMWW different rates

Treatment	Hydrodynamic constants	
	a	b
C0W0	0. 157	-6.679
C0W1	0.129	-6.862
C0W2	0. 295	-6.115
C1W0	0. 216	-6.396
C1W1	0. 199	-6.354
C1W2	0. 246	-6.247
C2W0	0. 388	-5.816
C2W1	0. 334	-6.011
C2W2	0. 279	- 6.043
C3W0	0. 496	-5.60
C3W1	0. 384	-.5.866
C3W2	0. 622	- .5.347

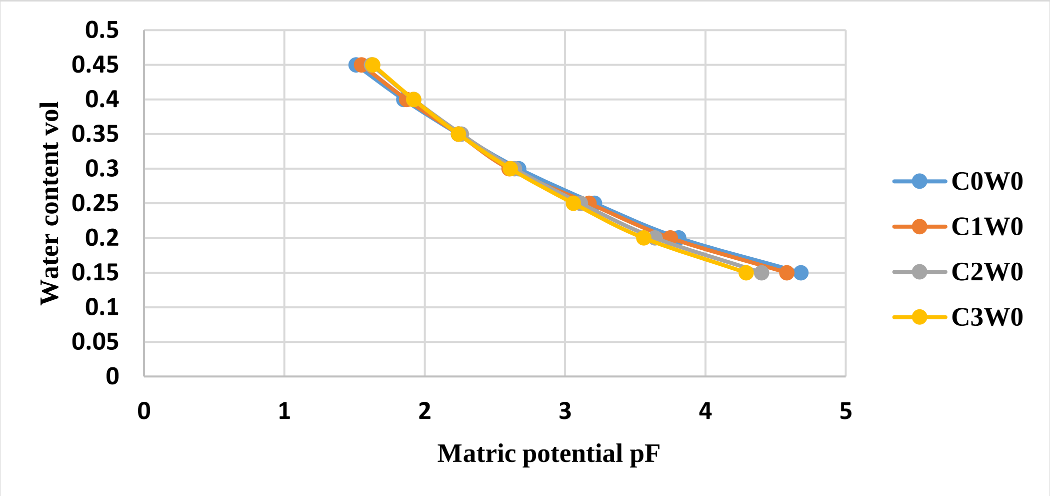

Fig. 3. WRCs under the influence of different rates of biochar 0-1-3-6 t ha^{-1}

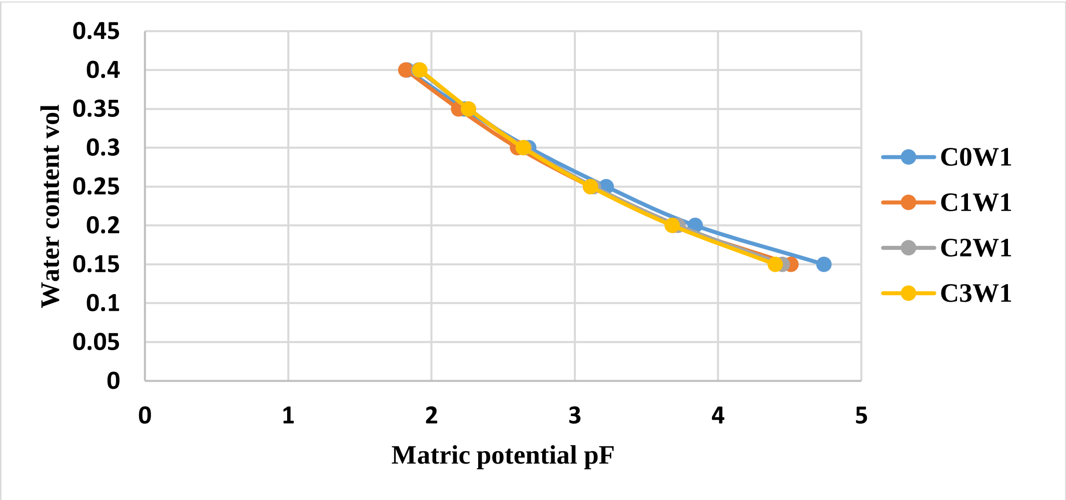

Fig. 4. WRCs under the influence of different rates of biochar 0-1-3-6 t ha^{-1} and OMWW at 50 m^3 ha^{-1}

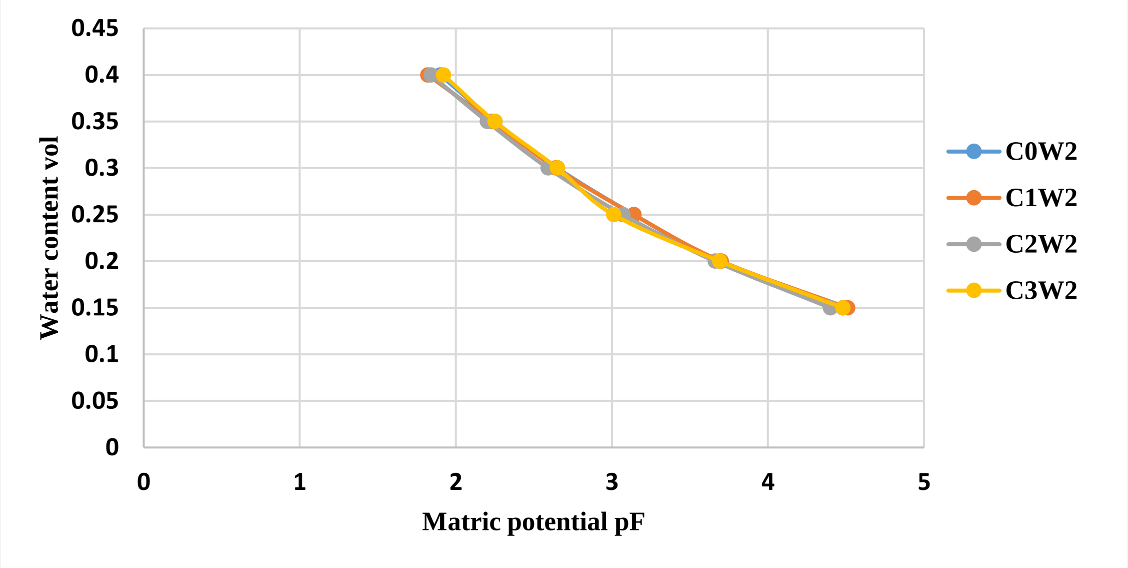

Fig. 5. WRCs under the influence of different rates of biochar 0-1-3-6 t ha^{-1} and OMWW at 100 m^3 ha^{-1}

The amendment of OMWW at 50 m^3 ha^{-1} in the presence of biochar at 1, 3, and 6 t ha^{-1} importantly increased PAW, but to a smaller degree compared to OMWW at 100 m^3 ha^{-1}. OMWW addition alone at 50 and 100 m^3 ha^{-1} was not able to cause any significant changes in macropores >10 µm, while biochar solely amendment started the significant response at 3 t ha^{-1}, continuing until 6 t ha^{-1}. Although OMWW at 50 m^3 ha^{-1} and biochar gradual rates (1, 3, and 6 t ha^{-1}) achieved significant rise in macropores >10 µm, doubling the OMWW rate to 100 m^3 ha^{-1} jointly with biochar at 1, 3, and 6 t ha^{-1} resulted in higher increments by 3.4–6.4–9.2%v, respectively, compared to the control (C0W0).

The amendment of OMWW alone at 50 m^3 ha^{-1} was not enough to bring an important reduction in PUW volume, but increasing the dose to 100 m^3 ha^{-1} led to a significant reduction. Yet, a duplicate dose of OMWW 100 m^3 ha^{-1} together with biochar at 1, 3, and 6 t ha^{-1} had the highest reductions in PUW by 1.2–1.9–2.9%v, respectively over the control (C0W0).

The decline in soil BD corresponds to the increase in soil TP after biochar and OMWW additions. TP positive response to both of the organic materials and their combination is confirmed by the upward trend of both types of pores: macropores >10 µm and PAW (Table 7). Higher TP values following biochar addition are closely related to higher soil macroporosity (Wang et al., 2023) lower soil BD (Toková et al., 2020), and biochar porosity (Sun & Lu 2014), as well as improving soil structure (Šimanský 2016). On the other hand, the increase in TP when using OMWW was referred to the combined effects of (suspended and soluble) OM, salts and enhancing the process of dissolution of soil's minerals carbonates in the presence of OMWW (Cox et al., 1997), and by increasing the number of extended conductive pores, the structure transitions from large, internally compact granular to smaller, more regular, semi-angular, polyhedral complexes separated by continuous, interconnected pores (Pagliai et al., 2001).

The positive relationship of biochar, OMWW, and the combination (biochar and OMWW) with PAW increments is linked to the reductions in PUW (Table 6). The favorable effect of biochar on PAW was in accordance with, Günal et al. (2018), who reported that the amendment of different types of biochar at gradual rates of 0.5, 1, 2, and 3% consistently increased PAW in both sandy and loamy soils. The increase in PAW is attributed to the pore size distribution of the biochar itself (Conte & Nestle 2015) and the reduction in PUW. The treatment (C3W2) recorded the best performance related to PAW, TP, and macropores >10 µm (18.4, 58.9, and 25.9%v) respectively. Similarly, it has the highest reductions regarding BD (1.06 g cm^{-3}) and PUW (14.6%v).

Table 7. Changes in pore size distribution under the effect of biochar and OMWW different rates

Treatment	TP (%v)	PV>50 µm (%v)	PV>10 µm (%v)	PAW (0.2 -10 µm) (%v)	PV<0.2 µm (%v)
C0W0	48.47 ^{g}	8.34 ^{i}	16.7 ^{e}	14.22 ^{e}	17.55 ^{a}
C0W1	50 ^{f}	10.7 ^{gh}	17.7 ^{de}	14.88 ^{de}	17.42 ^{a}
C0W2	52.10 ^{e}	11.97 ^{fgh}	18.89 ^{de}	16.46 ^{bc}	16.75 ^{b}
C1W0	50.38 ^{f}	10.08 ^{hi}	17.85 ^{de}	15.63 ^{cd}	16.9 ^{b}
C1W1	52.87 ^{de}	14.57 ^{de}	19.87 ^{cd}	16.52 ^{bc}	16.48 ^{bc}
C1W2	53.07 ^{de}	14.07 ^{e}	20.07 ^{cd}	16.66 ^{bc}	16.34 ^{bc}
C2W0	53.1 ^{d}	12.37 ^{efg}	20.8 ^{bc}	16.31 ^{bc}	15.99 ^{d}
C2W1	54 ^{cd}	13.5 ^{ef}	22 ^{b}	15.8 ^{cd}	16.2 ^{cd}
C2W2	55.59 ^{bc}	17.59 ^{c}	23.09 ^{b}	16.86 ^{bc}	15.64 ^{de}
C3W0	55.91 ^{bc}	17.4 ^{cd}	23.91 ^{b}	16.79 ^{bc}	15.21 ^{e}
C3W1	55.77 ^{b}	16.77 ^{b}	22.77 ^{b}	17.25 ^{b}	15.75 ^{de}
C3W2	58.91 ^{a}	21.61 ^{a}	25.91 ^{a}	18.37 ^{a}	14.63 ^{f}
Lsd $_{0,05}$	1.38	2.31	2.48	1.2	0.51

Explanation: TP – total porosity volume, PV>50 µm – volume of pores larger than 50 micrometre, PV>10 µm– volume of macropores larger than 10 micrometre, PAW (0.2 -10 µm) –volume of pores containing available water between 0.2 and 10 micrometre, PV<0.2 µm– volume of pores less than 0.2 micrometre.

3.4 Soybean Sb44 Yield Components

3.4.1 Productivity

The results of OMWW and biochar effects on soybean productivity are shown in Table 8. Soybean productivity responded significantly after OMWW amendment at 50 and 100 m^3 ha^{-1} by (138.17 and 163.24%) higher than applying biochar rates (1, 3, 6 t ha^{-1}) alone which caused (108.207-125.29-133.863%) increments respectively compared to the control.

The amendment with OMWW 50 m^3 ha^{-1} at different doses of biochar (1, 3, 6 t ha^{-1}) rose the productivity substantially more than half while using 100 m^3 ha^{-1} and biochar together started with almost a third increment at 1 t ha^{-1} and continued to double the productivity (3-6 t ha^{-1}). The highest productivity values of soybeans were achieved at 100 m^3 ha^{-1} and biochar rate 6 t ha^{-1} jointly increased productivity by more than two times (%222.187). These results matched Zhu et al. (2019), who mentioned that the grain yield of soybean cultivar L13 increased significantly by 31.0 and 51.0%, when rice husk biochar was added at 5 and 10% doses, respectively, while for T3 cultivar it increased by 40.4 when 10% biochar was applied, compared with the control. On the other hand, Mohawesh et al. (2019) mentioned that wheat grain yeild increased significantly by 56.17% and 45.06% after adding OMWW to a clay loam soil at 60 and 80 m^3 ha^{-1} rates, while the combined usage of OMWW at 20% of 125 L ha^{-1} and biochar application at 10 t ha^{-1} to sandy soil significantly increased seed yield of peanut by 75 kg ha^{-1} in comparison to the control (Khalifa & Elareny 2020).

3.4.2 100 seeds weight (g)

Table 8. gives a breakdown of 100 seed weight (g) affected by OMWW and biochar rates. The amendment of each (OMWW and biochar) alone caused significant changes but stands at less than 13% in 100 seeds weight (g). The uppermost 100 seeds weight (g) was reached at 100 m^3 ha^{-1} of OMWW and biochar rates (3-6 t ha^{-1}) which increased substantially by~ fifth and a quarter respectively. No significant changes were seen between 50 m^3 ha^{-1} and 6 t ha^{-1} biochar and 100 m^3 ha^{-1} 3 t ha^{-1} which means any one of them is enough to increase 100 seeds weight (g) significantly. Liu et al. (2020), reported significant increments after straw corn biochar usage at 2.5 and 5% rates by 1.71 and 4.49%. The usage of OMWW at 20% of 125 L ha^{-1} and biochar together at 10 t ha^{-1} to sandy soil significantly rose the number of pods per peaut plant by 2.88 pods per plant in comparison to the control (Khalifa & Elareny 2020).

The improvement in hydrodynamic constants (a and b) after OMWW and/or biochar amendment led to easy water movement through soil, and the decrease in PUW towards PAW between pF (2.5 and 4.2) allowed additional amounts to be retained in the root zone. This facilitates longer durations between irrigations (Yin et al., 2012, Liu et al., 2017b). Ultimately, plant growth and productivity will positively affected by the improvement in hydrodynamic constants and PAW (Mengel & Kirkby 2004).

Table 8. Soybean productivity components changes under the effect of biochar and OMWW different rates

Treatment	Productivity kg dunum^{-1}	Productivity as percentage	100 seeds weight (g)
C0W0	200.5^{k}	100^{j}	15.46 ^{f}
C0W1	277.2^{g}	138.170^{g}	16.92 ^{de}
C0W2	327.26^{d}	163.240^{d}	17.15 ^{e}
C1W0	216.9^{j}	108.207^{i}	16.16 ^{e}
C1W1	304.9^{f}	152.060^{f}	17.02 ^{cde}
C1W2	366^{c}	182.750^{c}	17.85 ^{bcd}
C2W0	251.2^{i}	125.290^{h}	16.84 ^{de}
C2W1	313.83^{e}	156.527^{ef}	17.54 ^{cde}
C2W2	422^{b}	210.673^{b}	18.85 ^{ab}
C3W0	268.37^{h}	133.863^{g}	17.42 ^{cde}
C3W1	320.4^{de}	159.80^{d}	18.33 ^{abc}
C3W2	445.4^{a}	222.187^{a}	19.43 ^{a}
Lsd 0,05	13.9	4.677	1.179

4. CONCLUSION

The results in this research showed:

1. Generally, the higher the rate of the combination, the greater the improvement in soil physical and hydrodynamic properties.
2. Integrative usage of biochar at 6 t ha^{-1} and OMWW at 100 m^{3} ha^{-1} is a potential tactic to boost soil physical properties (BD, TP, PAW, macropores >10 µm, reduction in PUW) as well as hydrodynamic constants (a, b) and soybean productivity kg dunum^{-1}.
3. Using biochar alone had a stronger effect than OMWW on boosting TP, PAW, and hydrodynamic constants (a, b); nevertheless, biochar rates alone had reduced BD more strongly in comparison to OMWW.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ACKNOWLEDGEMENTS

We would like to express special thanks to Tishreen University administrative staff, Mr. Mostafa Alfawal, Dr. Ibrahim Hamdan Saker, Mr. Aqiil Dayoub, and Eng. Mounzer Deeb, for providing the facilities to the research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://prh.mbimph.com/review-history/4493