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Short-Term Effects of Olive Mill Wastewater Land Spreading on Soil Physical and Hydraulic Properties

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Abstract In this study, we investigated the effect of olive mill wastewater on selected soil physical and hydraulic properties. Olive mill wastewater was added to each column every week at different loading rates (0, 50, 100, and 200 m^3 ha^{-1}). Physicochemical and hydraulic properties were determined for surface (0–8 cm) and subsurface layers (8–16 and 16–24 cm). The highest loading rate (200 m^3 ha^{-1}) showed an increase in aggregate stability from 18% (control) to 31 and to 38%, penetration resistance from 1.8 kg cm^{-2} (control) to 3.5 and to 4.5 kg cm^{-2}, hydraulic conductivity from 43 cm day^{-1} (control) to 15.3 and 3.3 cm day^{-1}, and water repellency from < 5 s (control) to 120 and 261 s in the first and second months for the surface layer, respectively. The opposite was observed for the infiltration rate, where it decreased from 39.01 mm h^{-1} (control) to 1.26 and 0.42 mm h^{-1} for the first and second months, respectively. This study showed that application of olive mill wastewater deteriorated the physical and hydraulic properties of soil proportional to loading rates and more specifically at the surface layer.

Keywords Olive mill wastewater · Aggregate stability · Hydraulic conductivity · Water repellency · Infiltration rate

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1 Introduction

Olive oil production represents a significant sector in the economy of the Mediterranean countries, which is regularly increasing. Within a short period of time after harvest (November to January), this sector produces two by-products, namely, solid residues (pomace) and a significant amount of olive mill wastewater (OMW) (Mekki et al. 2013; Sahraoui et al. 2015; Steinmetz et al. 2015). The estimated volume of wastewater generated from the Mediterranean olive oil–producing countries is about 30 million m^3 $year^{-1}$ (Ouzounidou and Asfi 2012). OMW contains a high level of organic matter (OM), microbial inhibitory compounds, and toxic phenolic compounds which are considered, in disposal areas, potential pollutants to surface water and groundwater. Because of the high levels of polyphenol concentrations (0.5 to 25 g L^{-1}) and other toxic organic load (Rusan et al. 2015, 2016), olive oil–producing countries are facing environmental problems because of the lack of practical or reasonable solutions to the disposal of olive mill wastewater (OMW) (Mohawesh et al. 2014). Therefore, the improper disposal of OMW imposes serious problems for the environment and public health (Azam et al. 2002).

OMW is characterized by dark color, high levels of total phenols (TP), high chemical oxygen demand (COD), high biological oxygen demand (BOD), low pH, high electrical conductivity (EC), and the presence of phytotoxic and antimicrobial compounds (Mekki et al. 2006, 2007; Rusan et al. 2015, 2016). Because of the high organic load of OMW consisting of largely simple phenolic compounds, it is not allowed to be directly discharged into domestic wastewater treatment plants (Sayadi et al. 2000; Zenjari and Nejmeddine 2001). On the other hand, OMW treatment is considered expensive and technically difficult due to its biological and chemical characteristics. One of the common methods of OMW disposal is storing in evaporation ponds. However, most of these ponds are permeable which will negatively affect the surrounding soil and water resources. Among other solutions proposed for OMW disposal in the Mediterranean region is direct spreading on agricultural lands. It is widely accepted in most of these countries according to certain regulations adopted by these countries (Ayoub et al. 2014). The controlled land application is commonly permitted and considered a practical option for rural OMW management in olive oil–producing countries (Saadi et al. 2013; Steinmetz et al. 2015). Despite such controlled land spreading of untreated OMW, researchers have reported potential phytotoxic effects on certain crops and under certain conditions (Hanifi and El-Hadrami 2008; Piotrowska et al. 2011; Rusan et al. 2015; Saadi et al. 2013). Moreover, it can adversely affect soil properties (Kapellakis et al. 2015; Mekki et al. 2013; Rusan et al. 2016).

Abichou et al. (2009) studied the spraying OMW at rates of 50, 100, and 200 m^3 ha^{-1} for 10 years on poor sandy soil. They showed that aggregates larger than 2 mm significantly increased to 34% for the 200 m^3 ha^{-1} compared with other treatments which lead to an increase in aggregate stability and consequently improvement in the soil structure. Similarly, Levy et al. (2017) also reported an increase in the aggregate stability of an OMW-amended clay soil as well as sandy loam soil. The effect of OMW application has shown contrasted results due to the differences in soil texture and the period of application. Application of OMW increased soil aggregate stability especially in the short-term of application (Barbera et al. 2013; Kavdir and Killi 2008). Moreover, Mahmoud et al. (2012) investigated the effect of irrigated OMW for 5 and 15 years at different doses. The results showed that regular application of OMW increased soil aggregate stability compared with the control. However, aggregate stability may be degraded after repeated spreading of OMW for a long term as soil calcium is replaced by potassium, sodium, and magnesium from OMW (Mekki et al. 2006). Therefore, repeated application of OMW on clay soils is not recommended to avoid the soil disaggregation. Mahmoud et al. (2010) studied OMW application for 5 and 15 years; they showed a decrease in infiltration rate compared with the control after 5 years. However, the infiltration rate increased after 15 years of application which was attributed to the crack formation after clay dispersion. Contradictory results were reported on the effect of OMW application on saturated hydraulic conductivity. Steinmetz et al. (2015) reported no significant effect on saturated hydraulic conductivity while Mahmoud et al. (2010) reported a reduction in saturated hydraulic conductivity after a different time of OMW application. Contrarily, Abu-Zreig and Al-Widyan (2002) reported an increase in saturated hydraulic conductivity after OMW application. OMW is characterized by the high content of oil and grease, and their regular application has been shown to increase soil hydrophobicity (Mahmoud et al. 2010; Tarchitzky et al. 2007; Steinmetz et al. 2015).

The increased amount of OMW production in olive-producing countries which have low fertility soil in addition to the water scarcity issues has led to that most of the works that have been done were to assess the impact of the direct application of OMW on soil fertility (Chaari et al. 2014; Mekki et al. 2009; Mohawesh et al. 2014), and on chemical properties and plant performance (Bene et al. 2013; Piotrowska et al. 2006; Sahraoui et al. 2015). However, very few studies, up to our knowledge, investigated the impact of the direct application of OMW on the physical and hydraulic properties of the soil. Therefore, the objective of this study was to evaluate the potential use of OMW in irrigation and to determine its effect on soil physical and hydraulic properties.

2 Materials and Methods

2.1 Soil Sampling

The soil used in this study was collected from 0- to 20-cm depths of a silty loam soil located south-east of Jordan University of Science and Technology, Jordan (32° 26′50.3″ N 35 ° 58′ 41.1″ E). The soil sample was brought to the lab, air-dried, and gently crushed to pass through a 2-mm sieve. The soil contains on average 80 g kg^{-1} clay, 500 g kg^{-1} silt, and 420 g kg^{-1} sand. The soil has an electrical conductivity (EC) of 3.24 dS m^{-1} and pH of 7.93.

2.2 Olive Mill Wastewater Sampling

Olive mill wastewater (OMW) was collected during harvest season (November 2015) from a three-phase centrifugal extraction olive mill located in Irbid city, north of Jordan (Hatem olive mill). OMW was left to settle for at least 1 week as a pre-treatment stage. After settling, the supernatant was stored in a plastic container for further analysis and treatment. The main characteristics of the OMW are presented in Table 1.

2.3 Column Setup and Experimental Procedure

Polyvinyl chloride (PVC) columns (19-cm internal diameter and 30-cm length) were used in this experiment. A crushed stone layer was soaked with 1 M HCl to remove calcium deposits and then washed with running tap water until the effluent was clear, rinsed with distilled water, and placed in the bottom as a drainage layer (40 mm). A filter paper was then placed on top of the drainage layer to prevent mixing with the soil, after which the air-dried soil sample (9.0 kg) was packed in each column to reach 24.5 cm in height (Gharaibeh et al. 2011).

The columns were divided into two groups, with 12 each. The first group was subjected during the first month to four wetting and drying cycles. Every week, OMW was added at different loading rates (0, 50, 100, and 200 $m^3\ ha^{-1}$) for each column in three replicates. The OMW-added quantities corresponded to 140 mL, 280 mL, and 560 mL OMWs $column^{-1}$, respectively, for the loading rates mentioned above. The second group was continued to be irrigated weekly for another month (eight wetting and drying cycles were performed in total).

In each cycle, soil columns were allowed to air dry at room temperature (22 °C) before the next OMW application. At the end of the fourth and eighth wetting and drying cycles, soil columns were taken out, divided into three depths (0–8, 8–16, 16–24 cm), to perform the physical and hydraulic analysis.

2.4 Aggregate Stability

Aggregate stability (AS) of soil samples was determined using the wet sieving method of Kemper and Rosenau (1986). This test measures the resistance of aggregates against the destructive force of flowing water. A few grams of air-dried soil was weighed and transferred to a 4-cm-diameter sieve with a 250-μm mesh size. Then, the soil aggregates were slowly saturated by capillary rise from a wet paper towel placed underneath the mesh, in order to minimize slaking. After that, the sieves were submerged in labeled cans filled with water and shaken using a wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) at a regular up-and-down motion for 3 min. The mass of soil collected in the cans below the sieves (M_1) was then determined after evaporating the supernatant water in the oven. The aggregates remaining were subjected to a second round of wet sieving using another set of labeled cans filled with dispersing solution (2 g L^{-1} sodium hexametaphosphate). The mass of soil collected in the second set of cans (M_2) was determined by evaporating the supernatant solution in the oven. Then, the percentage of the water stable aggregates was calculated as

$$\mathrm{AS\%} = \frac{M_2 - M_\mathrm{d}}{M_1 + M_2 - M_\mathrm{d}} \times 100$$

where M_d is the mass of dispersing agent used in the second round of sieving.

2.5 Penetration Resistance

Soil penetration resistance was measured at each depth of each treatment using a pocket soil penetrometer (Humboldt Mfg. Co., USA). The stainless steel piston tip with diameter of 6.4 mm was pressed into the soil

Table 1 Physicochemical properties of treated and untreated olive mill wastewater (OMW)

pH	EC[a]	TSS[b]	TP[c]	Na	K	P	Ca	Mg	COD[d]
–	dS m^{-1}	mg L^{-1}							g L^{-1}
4.22	7.87	1277	1813	68.9	1668	230	317	201	26.55

[a] Electrical conductivity

[b] Total suspended solids

[c] Total polyphenols

[d] Chemical oxygen demand

until the tip penetrated 6.4 mm into the soil (to the engraved line) according to the manufacturer's manual. Readings were taken from the scale indicator.

2.6 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (HCsat) was determined using the constant head method with a UMS KSAT Benchtop Saturated Hydraulic Conductivity Instrument (UMS Inc., Munich, Germany). HCsat was determined per the manufacturer's recommendation as

$$HC_{sat} = \frac{A_{burette}}{A_{sample}} \times b \times L$$

where $A_{burette}$ is the cross-sectional area of the water column, A_{sample} is the cross-sectional area of the sample, L is the length of the sample, and b is an exponent determined via curve-fitting between the measured pressure head (h, starting at some initial pressure head h_0) and time

$$h(t) = h_0 \times e^{-bt}$$

A stainless steel core was inserted in the soil column, and then it was saturated with deionized water by the capillary to prevent trapping the air within the sample. After that, the sample was transferred into the KSAT device, which was equipped with a pressure sensor that monitors the water drawdown in a burette as water passes vertically through the soil column. The KSAT was determined through the manufacturer's software (KSAT; Version 1.4.2) utilizing a constant head methodology.

2.7 Infiltration Rate

Infiltration rate measurements were determined using a mini disk infiltrometer (MDI) (Decagon Devices, Inc., Pullman, WA, USA) filled with deionized water. At time 0, the mini disk infiltrometer was lowered until it touched the soil surface and a full contact was achieved. Once the MDI was mounted above the soil surface, water passes into the soil. The suction of MDI was controlled by the suction control tube at the top of the MDI, and 5 cm was used as the optimal suction setting (Decagon 2014). The volume of infiltrating water was recorded manually every 30 min until steady-state conditions were reached. Each treatment was replicated three times.

Steady infiltration was determined from measured cumulative infiltration over time using the method proposed by Zhang (1997). Cumulative infiltration and time can be fitted with the function

$$I = At + S\sqrt{t}$$

where I is the cumulative infiltration, t is the cumulative time, and A and S are parameters. A is the slope of the curve of the cumulative infiltration versus the square root of time, and S is the soil sorptivity.

2.8 Water Repellency

Soil water repellency was assessed using a water drop penetration time (WDPT) test following Woudt (1959). Briefly, a droplet of distilled water was placed on the soil surface of each depth and the time required to complete penetration of each droplet was recorded, and the class of hydrophobicity was determined using the Dekker and Jungerius (1990) classification.

2.9 Statistical Analysis

All measurements in this study were conducted on three replicate samples. All reported data points denote the means of the replicates, and error bars are represented by standard error. Data analysis was conducted using the statistical analysis software program R. Significant differences among means were analyzed by Tukey's HSD (honestly significant difference) test at probability level $\alpha < 0.05$, and the different letters within the same layer depth mean significant difference recorded at $P < 0.05$ within different treatments for both months of OMW application.

3 Results and Discussion

3.1 Aggregate Stability

The effect of OMW application on soil aggregate stability at different depths is presented in Fig. 1. Values of reported AS are average of three replicates, and the error bars indicate the standard error. The depicted results showed that after the first (Fig. 1a) and second months (Fig. 1b) of OMW applications, the soil aggregate stability generally increased with increasing OMW loading rate compared with the control. However, this increase

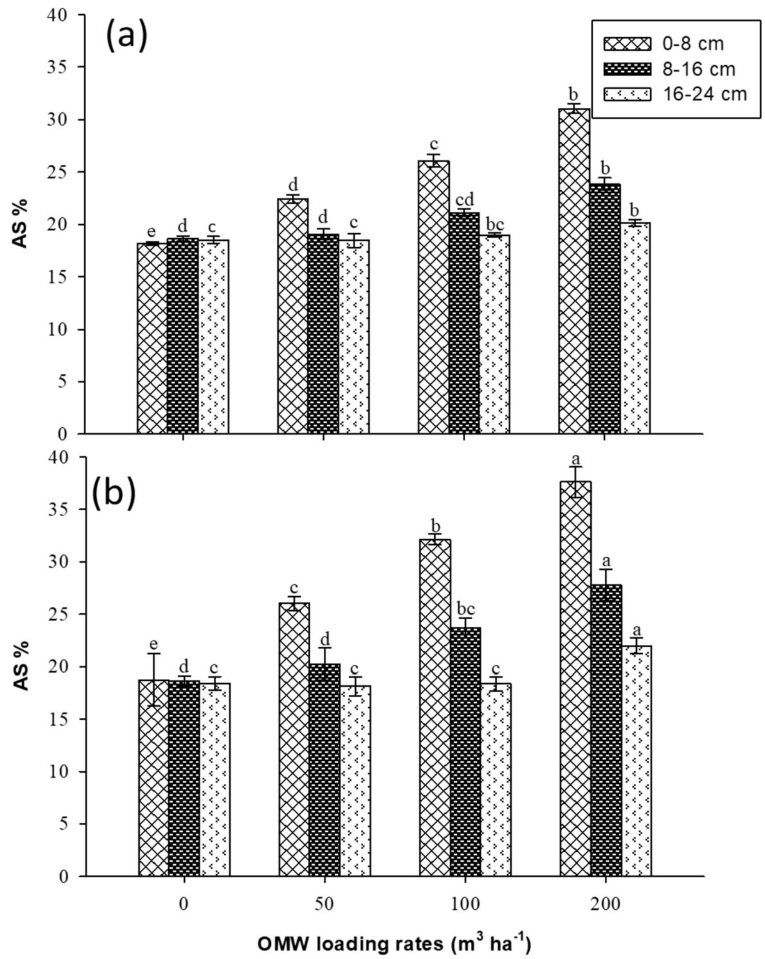


Fig. 1 The effects of different OMW loading rates on soil aggregate stability after the first (**a**) and second (**b**) months of OMW application

was more pronounced in the top layer (0–8 cm) compared with the deeper layers (8–16 and 16–24 cm) in both months. As the OMW loading rate increased, the AS became more pronounced with depth especially in the second month. AS increased after the second month more than the first month in all of the loading rates at surface depth. The maximum value of 38% at the loading rate of 200 m^3 ha^{-1} at depth of 0–8 cm was observed after the second month and 31% after the first month at the same loading rate compared with 18% for the control treatment. At 100 m^3 ha^{-1} treatment, AS reached 26% and 32% after the first and second months, respectively, at the surface layer (0–8 cm). The 50 m^3 ha^{-1} treatment produced significant differences only at the surface layer (0–8 cm) after the first and second months of OMW application. However, at the lower layers (8–16 and 16–24 cm), treatments had no effect compared with the control treatment. These results can be explained by the amount of organic matter added to each treatment, where higher rates allowed more OMW to move down to the lower layers and consequently more organic matter.

Similarly, Mahmoud et al. (2012) reported that the regular application of OMW for 5 and 15 years increased the AS compared with the control, and attributed this increase to the significant increase in the OM content in the OMW-treated soil. Moreover, Abichou et al. (2009) reported similar results where they showed that the spreading of OMW on sandy loam soil at the rate of < 200 m^3 ha^{-1} increased soil aggregates as a result of increased OM in OMW. Also, Levy et al. (2017) showed a significant increase in AS for both clay and sandy-loam soils after OMW application compared with the control.

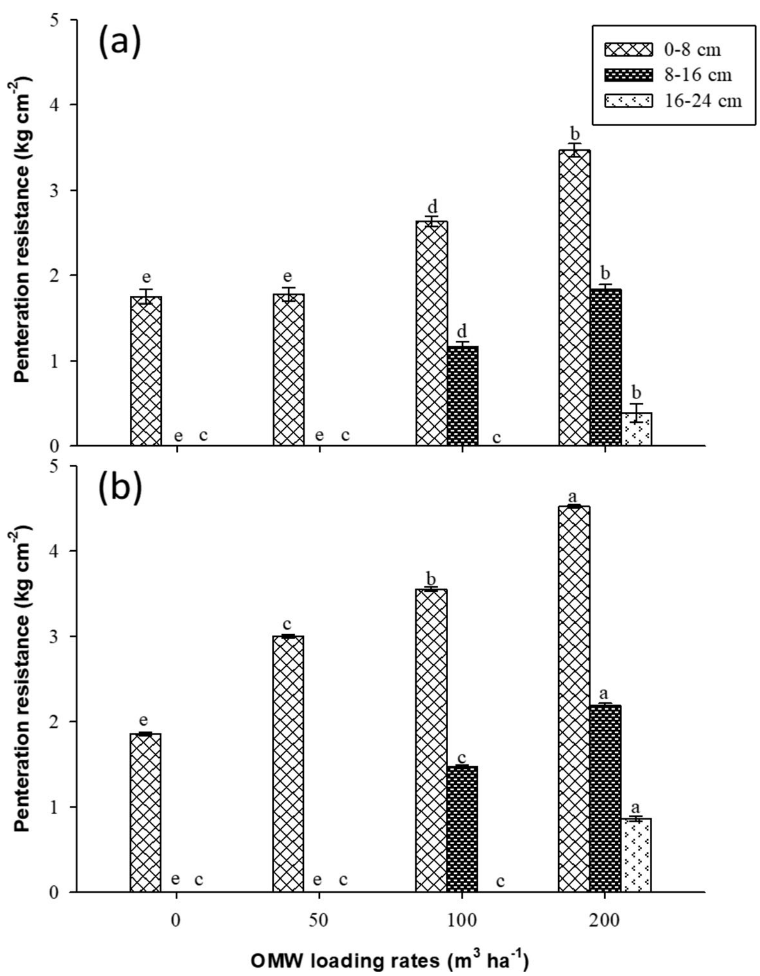
The increase in OM levels in soil resulted in an increase in the cementation of the soil aggregate which plays an important role in bonding smaller aggregates and soil particles together (Albalasmeh and Ghezzehei 2014; Tisdall and Oades 1982). Moreover, OM increases aggregate slaking resistance and swilling of clay by binding the mineral particles and increasing their cohesion (Chenu et al. 2000).

3.2 Penetration Resistance

The effect of OMW application on soil penetration resistance at different depths at four different loading rates of OMW is shown in Fig. 2. The depicted results showed that soil penetration resistance increased after OMW application. Specifically, this increase was more pronounced in the top layer (0–8 cm) compared with the lower layers (8–16 and 16–24 cm) in both months. Interestingly, as the OMW loading rate increased, soil penetration resistance was more pronounced with depth especially in the second month.

Soil penetration resistance increased after the second month (Fig. 2b) more than the first month (Fig. 2a) at all depths under all loading rates. It reached a value of 3.5 and 4.5 kg cm^{-2} after the first and second months, respectively, at the rate of 200 m^3 ha^{-1} for the surface layer (0–8 cm) compared with 1.8 kg cm^{-2} for the control at the same depth. In a similar trend for the 100 m^3 ha^{-1} treatment, the PR increased significantly compared with the control for both months. However, the difference in PR was significant only after the second month of OMW application only for the 50 m^3 ha^{-1} treatment compared with the control. Furthermore,

Fig. 2 The effects of different OMW loading rates on soil penetration resistance after the first (**a**) and second (**b**) months of OMW application



comparing the 50 m^3 ha^{-1} treatment after the first and second months of OMW application revealed that there was no resistance for the penetrometer penetration at the deeper layers (8–16 and 16–24 cm) similar to the control.

Our results are matching the concept of soil penetration resistance (PR) where it is a commonly used soil mechanical property to determine soil strength which leads to increased soil compaction and bulk density. The results of soil penetration resistance at different depths as well as loading rates (Fig. 2) are in agreement with the results of the aggregate stability (Fig. 1), and this can be explained by the amount of the OMW added to each treatment, which will affect the amount of OMW reaching a deeper depth.

Urena et al. (2013) showed that application of OMW increased soil bulk density and hence soil compaction and penetration resistance. Similarly, Attom et al. (2016) reported an increase in the maximum dry unit weight for soils after using treated wastewater which resulted in an increase in soil compaction and therefore increases the soil resistance to penetration. Also, Azouzi et al. (2015) and Abedi-Koupai (2006) reported an increase in the bulk density and reduction in the porosity and therefore increase in the soil penetration resistance for different soil types. Moreover, bulk density always increases with depth. They explained their results by the amount of the total suspended solids that exist in the treated wastewater used in their experiment.

3.3 Saturated Hydraulic Conductivity

Figure 3 shows the effect of OMW application on saturated hydraulic conductivity (HCsat) at different depths at four

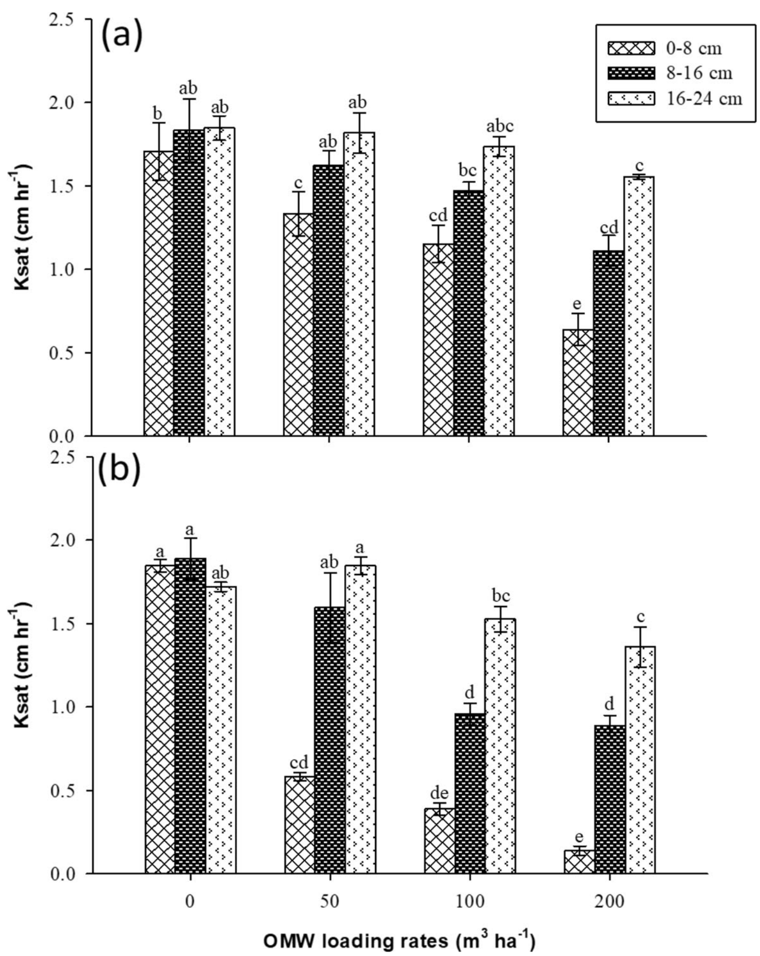


Fig. 3 The effects of different OMW loading rates on soil saturated hydraulic conductivity (KSAT) after the first (**a**) and second (**b**) months of OMW application

different loading rates of OMW. The depicted results showed that after the first (Fig. 3a) and second (Fig. 3b) months of OMW application, HCsat generally decreased at all depths with increasing loading rates compared with the control. Moreover, this decrease was more pronounced in the top layer (0–8 cm) compared with the lower layers (8–16 and 16–24 cm) in both months.

A sharper decrease in HCsat could be observed after the second month of OMW application compared with that after the first month at all OMW loading rates as well as depths. The maximum reduction in HCsat could be observed in the surface layer (0–8 cm) at an OMW loading rate of 200 m^3 ha^{-1}. It decreased from 1.85 cm h^{-1} for the control to 0.64 and 0.14 cm h^{-1} after the first and second months of OMW application, respectively. The statistical analysis showed that all treatments are significantly different compared with the control for the surface layer (0–8 cm). However, it did not significantly differ in the lower layers (8–16 and 16–24 cm) at both months of OMW application.

The decrease in saturated hydraulic conductivity is most likely the result of a reduction in soil drainable porosity, which can be seen from the increase in soil resistance to penetration (Fig. 2) and consequently bulk density. This reduction can be explained by the high amount of organic matter and suspended materials in the applied OMW that could have partially blocked soil pores (Gharaibeh et al. 2007; Mahmoud et al. 2010). Moreover, the high content of oil and grease in the OMW could slow water movement within the soil significantly (Travis et al. 2008).

Our results are in agreement with the results reported by Mahmoud et al. (2010) who reported a significant decrease in saturated hydraulic conductivity by approx. 18% after a long term of OMW applications at all depths. Moreover, Gharaibeh et al. (2007) reported that irrigation using treated wastewater for long periods reduced soil hydraulic conductivity as compared with the control. Contrary to our results, Steinmetz et al. (2015) and Levy et al. (2017) reported that no significant effect on the soil hydraulic conductivity was observed while Abu-Zreig and Al-Widyan (2002) reported a slight increase in hydraulic conductivity after 3 months of Olive mill solid waste application.

3.4 Infiltration Rate

The effect of OMW application at different loading rates on soil infiltration rate at different depths after the first and second months of application is depicted in Figs. 4 and 5, respectively. Both Figs. 4 and 5 show that OMW application decreased the infiltration rate in all soil depths under all OMW application rates. Also, it was more pronounced after the second month of application. Generally, the decrease in the infiltration rate was higher with increasing loading rates. The lowest value of infiltration rate after the first month (1.26 mm h^{-1}) was observed at 200 m^3 ha^{-1} at the 0–8-cm depth (Fig. 4) whereas it reached 0.42 mm h^{-1} (Fig. 5) under same conditions compared with the control (39.01 mm h^{-1}).

A similar trend occurred for the subsurface layers where the reduction in infiltration rate was less with depth at the same OMW application rate for both months. Applying 200 m^3 ha^{-1} of OMW decreased the infiltration rate to 2.52 and 27.69 mm h^{-1} after the second month of OMW application at the depth of 8–16 and 16–24 cm, respectively (Table 2). This decrease in infiltration rate could be attributed to the effect of suspended solids in the OMW that clogged the pores and reduced water infiltration (Cox et al. 1996; Mahmoud et al. 2010). Moreover, OMW contains oil and grease that would cause the soil to be hydrophobic, which will eventually reduce the infiltration rate (Abu-Zreig and Al-Widyan 2002).

Similar to our conclusion, Rusan and Malkawi (2016) investigated the effect of dilution of OMW on infiltration rate. They showed that during the first 5 min, the lowest infiltration rate was observed with the highest concentration (undiluted) followed by 75% OMW application compared with other treatments. Moreover, Mahmoud et al. (2010) reported a decrease in soil infiltration rate after 5 years of OMW application due to the surface sealing because of the suspended solids. Also, Tamimi (2016) and Zenjari and Nejmeddine (2001) in other studies reported a decrease in soil infiltration rate after OMW application.

3.5 Water Repellency

The effect of OMW application on soil water repellency at different depths under four different loading rates of OMW is depicted in Fig. 6. Water drop penetration time (WDPT) is a commonly accepted technique to measure the degree of soil water repellency (Mahmoud et al. 2010; Tarchitzky et al. 2007). The depicted results show that after the first (Fig. 6a) and second (Fig. 6b) months of OMW application, WDPT and hence the hydrophobicity generally increased with increased OMW rates. The differences

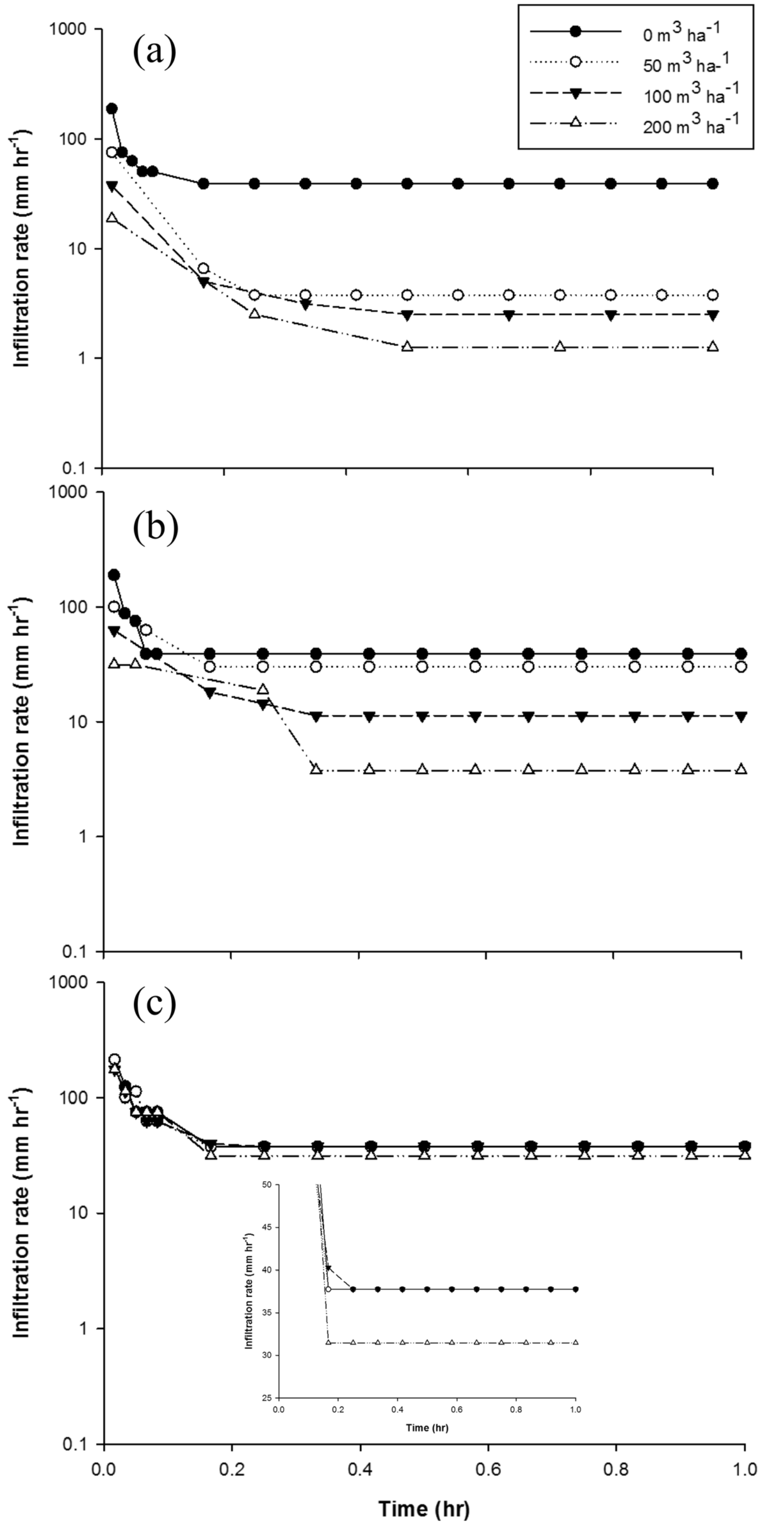


Fig. 4 Effects of different OMW loading rates on infiltration rate at depths of 0–8 cm (**a**), 8–16 cm (**b**), and 16–24 cm (**c**) after the first month of OMW application

between treatments were significant ($P < 0.05$) for the top soil (0–8 cm) for both months after OMW application. Generally, WDPT increased after the second month more than the first month at all loading rates and depths. The top

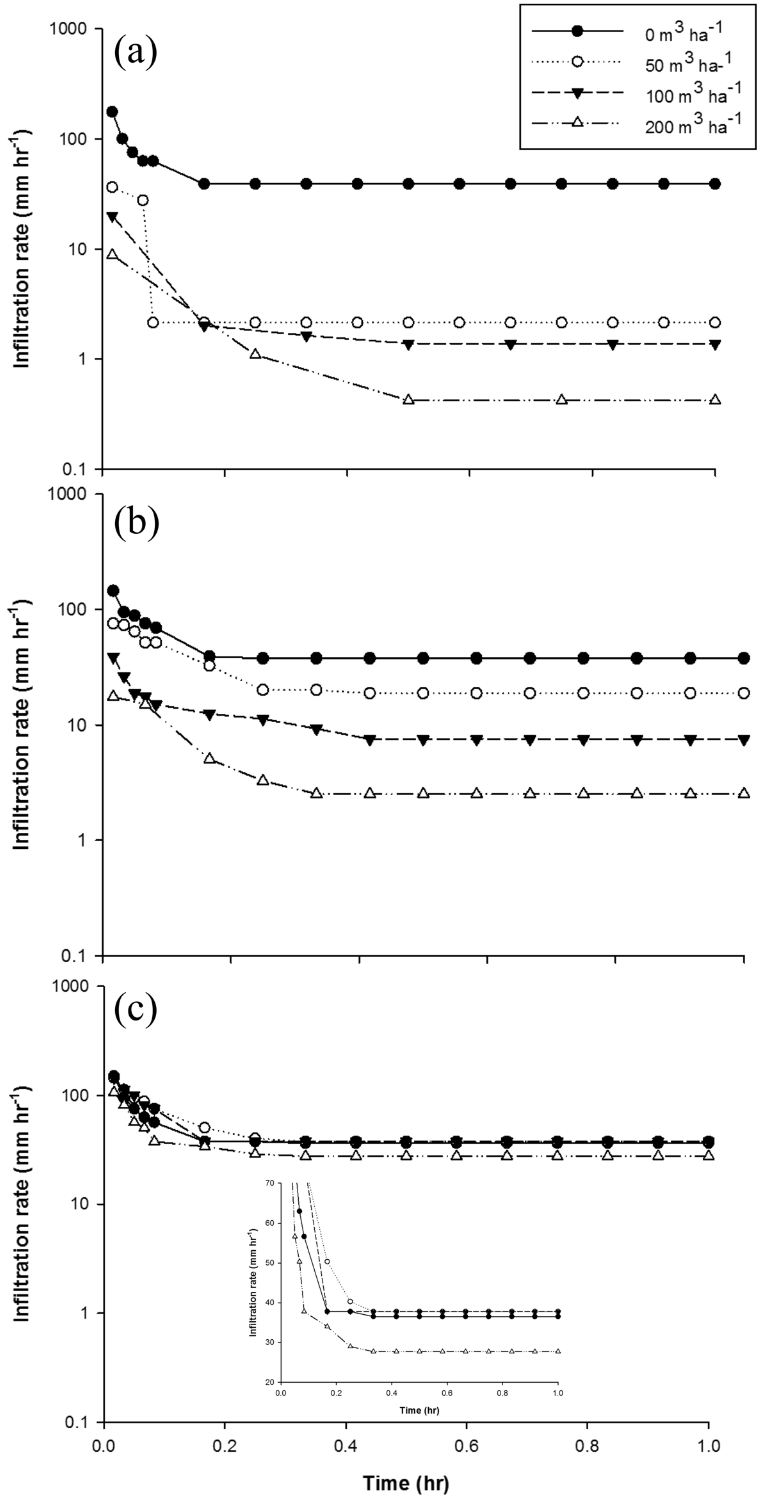


Fig. 5 Effects of different OMW loading rates on infiltration rate at depths of 0–8 cm (**a**), 8–16 cm (**b**), and 16–24 cm (**c**) after the second month of OMW application

soil's penetration time increased from < 1 s in the control (0 m^3 ha^{-1}) to 34 s (50 m^3 ha^{-1}), 74.2 s (100 m^3 ha^{-1}), and 120 s (200 m^3 ha^{-1}) after the first month of OMW application (Fig. 6a). More application of OMW significantly affected WDPT where the penetration time increased from < 1 in the control (0 m^3 ha^{-1}) to 72.1 s

Table 2 Effects of different OMW loading rates on infiltration rate at different depths after the first and second months of OMW application

Final infiltration rate (mm h^{-1})

Depth (cm)	Loading rate after the first month (m^3 ha^{-1})				Loading rate after the second month (m^3 ha^{-1})			
	0	50	100	200	0	50	100	200
0–8	39.01	3.77	2.52	1.26	39.01	2.12	1.38	0.42
8–16	39.01	39.20	11.32	3.78	39.01	18.88	7.55	2.52
16–24	39.01	39.01	39.01	31.50	39.01	39.01	39.01	27.69

(50 m^3 ha^{-1}), 162.8 s (100 m^3 ha^{-1}), and 261.7 s (200 m^3 ha^{-1}) after the second month of OMW application (Fig. 6b).

Based on the results from Fig. 6 and Table 3, the top soil (0–8 cm) generally exhibited a strongly water repellent, while the middle layer (8–16 cm) generally exhibited a slightly water repellent. However, the lower layer (16–24 cm) generally exhibited a wettable condition for all treatments. This increase in water penetration time and hence hydrophobicity could be attributed to the high content of organic matter in the OMW as well as the oil and grease in it that may coat the soil particle and prevent water penetration (Bisdom et al. 1993; Gonza´lez-Vila et al. 1995). A study by Kurtz et al. (2015) confirmed that the increase in the WDPT could be explained by the high level of organic matter in

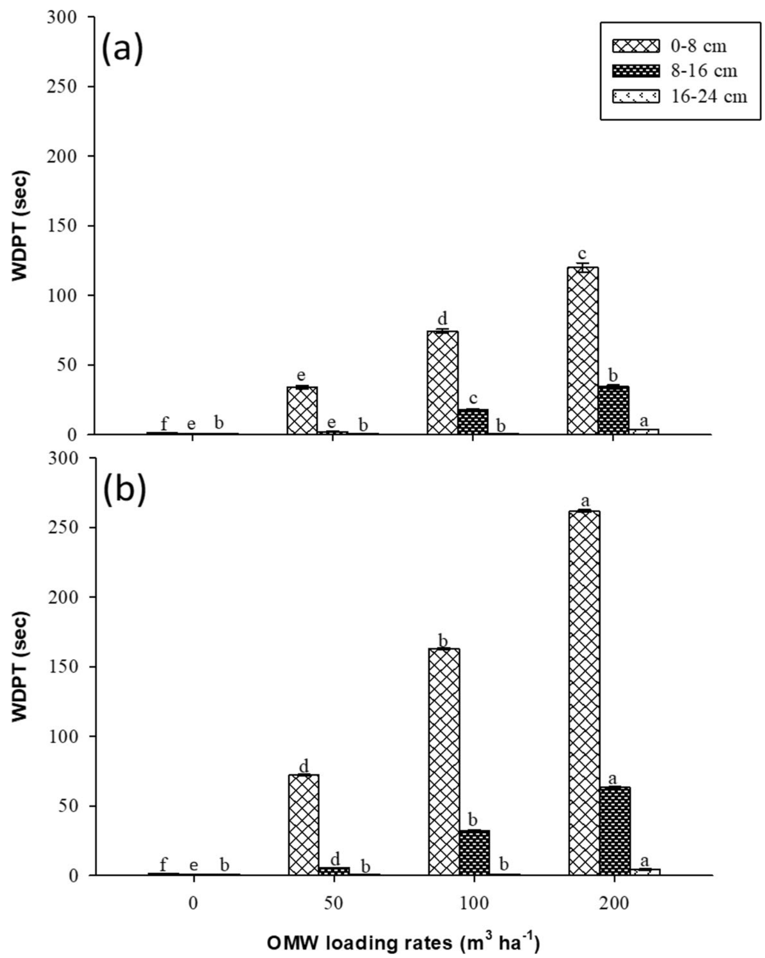


Fig. 6 Effects of different OMW loading rates on water drop penetration time (WDPT) after the first (**a**) and second (**b**) months of OMW application

Table 3 Effects of different OMW loading rates on soil hydrophobicity at different depths after first and second month of OMW application

Time of application	Loading rate (m^3 ha^{-1})	Soil depth (cm)		
		0–8	8–16	16–24
First month	0	Wettable	Wettable	Wettable
	50	Slightly water repellent	Wettable	Wettable
	100	Strongly water repellent	Slightly water repellent	Wettable
	200	Strongly water repellent	Strongly water repellent	Wettable
Second month	0	Wettable	Wettable	Wettable
	50	Strongly water repellent	Strongly water repellent	Wettable
	100	Strongly water repellent	Strongly water repellent	Wettable
	200	Strongly water repellent	Strongly water repellent	Wettable

OMW, consisting largely of fatty acids and other amphiphilic molecules.

Our results are in agreement with Steinmetz et al. (2015) and Tamimi (2016) who found that OMW application significantly increased WDPT in the treated soils compared with the control. Moreover, Kurtz et al. (2015) reported a significant increase in soil repellency due to the application of OMW in the upper layer because of the hydrophobic compounds like organic matter, oil, and grease that remained in the upper layer. Many other studies concluded the same results where applying OMW on the soil would increase soil water repellency (Diamantis et al. 2013; Gonza´lez-Vila et al. 1995; Mahmoud et al. 2010; Peikert et al. 2015; Travis et al. 2008) due to the increase in oil and grease content in OMW which in turn increased the contact angle between soil and solution (Abu-Zreig and Al-Widyan 2002).

4 Conclusion

This study investigated the effects of olive mill wastewater application on selected soil properties. Application of olive mill wastewater on soil for 1 and 2 months has been shown to have distinct effects on the soil physical and hydraulic properties. It results in an increase in aggregate stability, penetration resistance, and water repellency especially in the top soil (0–8 cm) due to the accumulation of organic matter and a decrease in hydraulic conductivity and infiltration rate. Moreover, the effect of olive mill wastewater was noticeable at 200 m^3 ha^{-1} loading rate at the top soil layer (0–8 cm) compared with the lower soil layers (8–16, 16–24 cm). The data suggest that olive mill wastewater remains in the upper layers of the soil whereas it moves more through the soil to greater depths depends on the application rate. These results could be attributed to the hydrophobic compounds and organic matter generally presented on olive mill wastewater which binds the soil particles.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Abedi-Koupai, J., Mostafazadeh-Fard, B., Afyuni, M., & Bagheri, M. (2006). Effect of treated wastewater on soil chemical and physical properties in an arid region. *Plant, Soil and Environment, 52*, 335–344.

Abichou, M., Labiadh, M., & Cornelis, W. (2009). The olive mills waste water (OMW) as an organic amendment for controlling wind erosion in southern Tunisia by improving the soil surface structure. *Journal of Arid Land Studies, 19-1*, 242–246.

Abu-Zreig, M., & Al-Widyan, M. (2002). Influence of olive mills solid waste on soil hydraulic properties. *Communications in Soil Science and Plant Analysis, 33*, 505–517.

Albalasmeh, A. A., & Ghezzehei, T. A. (2014). Interplay between soil drying and root exudation in rhizosheath development. *Plant and Soil, 374*, 739–751.

Attom, M., Abed, F., Elemam, M., Nazal, M., & ElMessalami, N. (2016). The effect of treated waste-water on compaction and compression of fine soil. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 10*, 1111–1115.

Ayoub, S., Al-Absi, K., Al-Shdiefat, S., Al-Majali, D., & Hijazean, D. (2014). Effect of olive mill wastewater land-spreading on soil properties, olive tree performance and oil quality. *Scientia Horticulturae, 175*, 160–166.

Azam, F., Mu¨ller, C., Weiske, A., Benckiser, G., & Ottow, J. (2002). Nitrification and denitrification as sources of atmospheric nitrous oxide – Role of oxidizable carbon and applied nitrogen. *Biology and Fertility of Soils, 35*(1), 54–61.

Azouzi, R., Charef, A., zaghdoudi, S., Khadhar, S., Shabou, N., Boughanmi, H., Hjiri, B., & Hajjaj, S. (2015). Effect of long-term irrigation with treated wastewater of three soil types on their bulk densities, chemical properties and pahs content in semi-arid climate. *Arabian Journal of Geosciences, 9*, 3.

Barbera, A. C., Maucieri, C., Cavallaro, V., Ioppolo, A., & Spagna, G. (2013). Effects of spreading olive mill wastewater on soil properties and crops, a review. *Agricultural Water Management, 119*, 43–53.

Bene, C. D., Pellegrino, E., Debolini, M., Silvestri, N., & Bonari, E. (2013). Short- and long- term effects of olive mill wastewater land spreading on soil chemical and biological properties. *Soil Biology and Biochemistry, 56*(0), 21–30.

Bisdom, E., Dekker, L. W., & Schoute, J. F. (1993). Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma, 56*(1), 105–118.

Chaari, L., Elloumi, N., Gargouri, K., Bourouina, B., Michichi, T., & Kallel, M. (2014). Evolution of several soil properties following amendment with olive mill wastewater. *Desalination and Water Treatment, 52*, 2180–2186.

Chenu, C., Le Bissonnais, Y., & Arrouays, D. (2000). Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal, 64*, 1479–1486.

Cox, L., Becker, A., Celis, R., López, R., Hermosin, M., & Cornejo, J. (1996). Movement of clopyralid in a soil amended with olive oil mill wastewater as related to soil porosity. *Fresenius Environmental Bulletin, 5*, 167–171.

Decagon. (2014). *Minidisk Infiltrometer User's Manual* (09th ed.). Pullman: Decagon Devices, Inc.

Dekker, L. W., & Jungerius, P. D. (1990). Water repellency in the dunes with special reference to the Netherlands. *Catena, 18*, 173–183.

Diamantis, V., Pagorogon, L., Gazani, E., Doerr, S. H., Pliakas, F., & Ritsema, C. J. (2013). Use of olive mill wastewater (OMW) to decrease hydrophobicity in sandy soil. *Ecological Engineering, 58*(0), 393–398.

Gharaibeh, M. A., Eltaif, N. I., & Al-Abdullah, B. (2007). Impact of field application of treated wastewater on hydraulic properties of vertisols. *Water, Air, and Soil Pollution, 184*, 347–353.

Gharaibeh, M. A., Eltaif, N. I., & Albalasmeh, A. A. (2011). Reclamation of highly calcareous saline sodic soil using Atriplex halimus and by-product gypsum. *International Journal of Phytoremediation, 13*(9), 873–883.

Gonza´lez-Vila, F., Verdejo, T., Rio, J. D., & Martin, F. (1995). Accumulation of hydrophobic compounds in the soil lipidic and humic fractions as result of a long term land treatment with olive oil mill effluents (alpechin). *Chemosphere, 31*, 3681–3686.

Hanifi, S., & El-Hadrami, I. (2008). Olive mill wastewaters fractioned soil-application for safe agronomic reuse in date palm (phoenix dactylifera l.) fertilization. *Journal of Agronomy, 7*, 63–69.

Kapellakis, I., Tzanakakis, V., & Angelakis, A. (2015). Land application-based olive mill wastewater management. *Water, 7*, 362–376.

Kavdir, Y., & Killi, D. (2008). Influence of olive oil solid waste applications on soil pH, electrical conductivity, soil nitrogen transformations, carbon content and aggregate stability. *Bioresource Technology, 99*, 2326–2332.

Kemper, W., Rosenau, R., 1986. Aggregate stability and size distribution. In: Methods of soil analysis, part 1. Physical and mineralogical methods. Agronomy monograph. No. 9. Society of Agronomy/Soil Science Society of America, pp. 425–442.

Kurtz, M. P., Peikert, B., Bru¨hl, C., Dag, A., Zipori, I., Shoqeir, J. H., & Schaumann, G. E. (2015). Effects of olive mill wastewater on soil microarthropods and soil chemistry in two different cultivation scenarios in Israel and Palestinian territories. *Agriculture, 5*, 857–878.

Levy, G. J., Dag, A., Raviv, M., Zipori, I., Medina, S., Saadi, I., Krasnovski, A., Eizenberg, H., & Laor, Y. (2017). Annual spreading of olive mill wastewater over consecutive years: Effects on cultivated soils' physical properties. *Land Degradation & Development, 29*, 176–187.

Mahmoud, M., Janssen, M., Haboub, N., Nassour, A., & Lennartz, B. (2010). The impact of olive mill wastewater application on flow and transport properties in soils. *Soil and Tillage Research, 107*, 36–41.

Mahmoud, M., Janssen, M., Peth, S., Horn, R., & Lennartz, B. (2012). Long-term impact of irrigation with olive mill wastewater on aggregate properties in the top soil. *Soil and Tillage Research, 124*, 24–31.

Mekki, A., Dhouib, A., & Sayadi, S. (2006). Changes in microbial and soil properties following amendment with treated and untreated olive mill wastewater. *Microbiological Research, 161*(2), 93–101.

Mekki, A., Dhouib, A., & Sayadi, S. (2007). Polyphenols dynamics and phytotoxicity in a soil amended by olive mill wastewaters. *Journal of Environmental Management, 84*(2), 134–140.

Mekki, A., Dhouib, A., & Sayadi, S. (2009). Evolution of several soil properties following amendment with olive mill wastewater. *Progress in Natural Science, 19*, 1515–1521.

Mekki, A., Dhouib, A., & Sayadi, S. (2013). Effects of olive mill wastewater application on soil properties and plants growth. *International Journal of Recycling of Organic Waste in Agriculture, 2*, 1), 1–1), 7.

Mohawesh, O., Mahmoud, M., Janssen, M., & Lennartz, B. (2014). Effect of irrigation with olive mill wastewater on soil hydraulic and solute transport properties. *International journal of Environmental Science and Technology, 11*, 927–934.

Ouzounidou, G., & Asfi, M. (2012). Determination of olive mill wastewater toxic effects on three mint species grown in hydroponic culture. *Journal of Plant Nutrition, 35*(5), 726–738.

Peikert, B., Schaumann, G., Keren, Y., Bukhanovsky, N., Borisover, M., Garfha, M., Shoqeric, J., & Dag, A. (2015). Characterization of topsoils subjected to poorly controlled olive oil mill wastewater pollution in West Bank and Israel. *Agriculture, Ecosystems & Environment, 199*, 176–189.

Piotrowska, A., Iamarino, G., Rao, M. A., & Gianfreda, L. (2006). Short-term effects of olive mill waste water (OMW) on chemical and biochemical properties of a semiarid Mediterranean soil. *Soil Biology and Biochemistry, 38*(3), 600–610.

Piotrowska, A., Rao, M. A., Scotti, R., & Gianfreda, L. (2011). Changes in soil chemical and biochemical properties following amendment with crude and dephenolized olive mill waste water (OMW). *Geoderma, 161*(1–2), 8–17.

Rusan, M. J. M., & Malkawi, H. I. (2016). Dilution of olive mill wastewater (OMW) eliminates its phytotoxicity and enhances plant growth and soil fertility. *Desalination and Water Treatment, 7*, 1–9.

Rusan, M. J. M., Albalasmeh, A. A., Zuraiqi, S., & Bashabsheh, M. (2015). Evaluation of phytotoxicity effect of olive mill wastewater treated by different technologies on seed germination of barley (Hordeum vulgare L.). *Environmental Science and Pollution Research, 22*(12), 9127–9135.

Rusan, M., Albalasmeh, A. A., & Malkawi, H. I. (2016). Treated olive mill wastewater effects on soil properties and plant growth. *Water, Air, and Soil Pollution, 227*(5), 1–10.

Saadi, I., Raviv, M., Berkovich, S., Hanan, A., Aviani, I., & Laor, Y. (2013). Fate of soil-applied olive mill wastewater and potential phytotoxicity assessed by two bioassay methods. *Journal of Environmental Quality, 42*(6), 1791–1801.

Sahraoui, H., Kanzari, S., Hachicha, M., & Mellouli, H. J. (2015). Olive mill wastewater spreading effects on hydraulic soil properties. *The experiment, 30*(4), 2002–2011.

Sayadi, S., Allouche, N., Jaoua, M., & Aloui, F. (2000). Detrimental effects of high molecular- mass polyphenols on olive mill wastewater biotreatment. *Process Biochemistry, 35*(7), 725–735.

Steinmetz, Z., Kurtz, M. P., Dag, A., Zipori, I., & Schaumann, G. E. (2015). The seasonal influence of olive mill wastewater applications on an orchard soil under semi-arid conditions. *Journal of Plant Nutrition and Soil Science, 178*, 641–648.

Tamimi, N. (2016). *Effects of seasonal olive mill wastewater application on soil: Field experiment in Bait Reema village*. Palestine.

Tarchitzky, J., Lerner, O., Shani, U., Arye, G., Lowengart-Aycicegi, A., Brener, A., & Chen, Y. (2007). Water distribution pattern in treated wastewater irrigated soils: Hydrophobicity effect. *European Journal of Soil Science, 58*, 573–588.

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *European Journal of Soil Science, 33*, 141–163.

Travis, M. J., Weisbrod, N., & Gross, A. (2008). Accumulation of oil and grease in soils irrigated with greywater and their potential role in soil water repellency. *Science of the Total Environment, 394*, 68–74.

Urena, C., Azanon, J., Corpas, F., Nieto, F., Leon, C., & Perez, L. (2013). Magnesium hydroxide, seawater and olive mill wastewater to reduce swelling potential and plasticity of bentonite soil. *Construction and Building Materials, 45*, 289–297.

Woudt, B. D. v. (1959). Particle coatings affecting the wettability of soils. *Journal of Geo- physical Research, 64*, 263–267.

Zenjari, B., & Nejmeddine, A. (2001). Impact of spreading olive mill wastewater on soil characteristics: Laboratory experiments. *Agronomie, 21*(8), 749–755.

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal, 61*, 1024–1030.