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Effect of olive mill wastewater land-spreading on soil properties, olive tree performance and oil quality

Salam Ayoub[a,*], Khalid Al-Absi[b], Saleh Al-Shdiefat[a], Doaa Al-Majali[a], Danial Hijazean[b]

[a] Olive Research Department, National Center for Agricultural Research and Extension, P.O. Box 639, Baqa 19381, Jordan
[b] Department of Plant Production, Faculty of Agriculture, Mutah University, P.O. Box 7, 61710, Jordan

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ABSTRACT

The application of fresh olive mill wastewater (OMW) to the soil surface of an olive (*Olea europaea*, L.) orchard was studied for three consecutive years (2011, 2012 and 2013). The experiment was conducted at a private olive orchard located in Raba area at Al-Karak governorate. Olive mill wastewater was applied to olive orchard with 15-year-old trees (cv. Nabali Muhassan) in winter at five application rates: control (no application of OMW), 5 L m^{-2} one dose, 10 L m^{-2} one dose, 20 L m^{-2} one dose and 20 L m^{-2} at four equal doses at monthly intervals. The effect on soil properties, plant performance, fruit set, yield, oil content and oil quality was studied. Results of the study indicated that, there was no negative effect of OMW application on soil properties. The concentrations of K, organic matter, phenolic compounds and total microbial count were significantly higher in OMW-treated soil as compared to the control soil. Olive mill wastewater applied at 10 L m^{-2} and 20 L m^{-2} gave significant increase in shoot growth, photosynthesis, fruit set and fruit yield. No negative effects were observed for OMW application on oil quality parameters throughout the experimental period. Results of this study indicated that the annual application of OMW at 10 L m^{-2} is recommended to improve soil fertility and plant performance.

1. Introduction

Olive is the main agricultural crop in Jordan. Increasing demand for olive oil motivated a fast increase in the planted area of about 5% annually over the last 15 years. Approximately 130,000 ha of olives are grown in Jordan. There are approximately 130 olive mills in Jordan serving olive plantation and generating around 200,000 m^3 of OMW annually (Ministry of Agriculture, 2012).

The reuse of treated wastewater in agriculture is considered as an alternative source of irrigation water and expected to increase significantly in countries, which suffer from shortage in fresh water resources. Many types of effluents suitable for reuse are produced in large quantities. Olive mill wastewater (Ben Rouina et al., 2006), municipal (Shdiefat et al., 2009) and textile and steel reclaimed effluents (Bhati and Singh, 2003; Al-Absi et al., 2009) have been evaluated for use in agriculture and crop production. The olive oil extraction industry is an important activity in Mediterranean countries, producing a large amount of olive mill waste during oil extraction. Olive mill wastewater (OMW) is the liquid by-product obtained from olive oil processing either by pressure or centrifugation systems. The most common extraction process yields three phases of products: an oily phase, a solid residue and an aqueous phase. The latter, when combined with the washing water process forms OMW. The average volume of OMW discharged, depends on the extraction type, from 0.5 to 1.5 m^3 ton^{-1} of processed olives (Monteoliva-Sanchez et al., 1996). The overall annual production of OMW in the Mediterranean region is estimated to be over 30 million m^3 (Cabrera et al., 1996; Ballesteros et al., 2001) creating a significant problem concerning their proper disposal.

Olive mill wastewater generated by the three-phase process has extremely high biological (BOD) and chemical (COD) oxygen demand (as high as 100,000 and 220,000 mg L^{-1}, respectively), high concentrations of fats, oils and greases (FOGs), and several to 10 g of total polyphenols per liter (Azbar et al., 2004). The presence of phenols as well as short- and long-chain fatty acids is believed to contribute to the phytotoxic (e.g. Cassa et al., 2003) and antimicrobial (Isidori et al., 2005) nature of these wastes. These characteristics of OMW prevent their direct discharge into municipal sewage systems. In addition to the high organic load and toxicity, a major constraint to OMW treatment is the fact that it is being produced only during a relatively short harvest period (mostly mid-October to mid-January). Presently, most of the OMW in Jordan are without adequate treatment, thus threatening the quality of the valuable and scarce water resources.

* Corresponding author. Tel.: +962 777492541; fax: +962 64726099.
E-mail addresses: sayoub@ncare.gov.jo, salamayoub@hotmail.com (S. Ayoub).

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Several chemical, physical and thermal methods have been developed for OMW purification. The viability of these technologies is questionable as they are fairly expensive and/or do not produce high-quality effluents. Contrary to the classical "wastewater treatment" approach, multiple studies advised the controlled spreading of OMW on cultivated soil as a viable recycling approach and suggested that OMW could be considered as a useful, low-cost soil amendment and fertilizer (Tomati and Galli, 1992; Saadi et al., 2007). The Italian law, for example, already permits annual spreading of up to 80 m^3 ha^{-1} (Rinaldi et al., 2003). In this respect, OMW is considered as a natural fertilizer at which, proper application rate, is not harmful to crops and can be disposed of without causing environmental damage.

The olive mill wastewater application significantly increased yield, grain yield, N, P, and K uptake by the wheat in the Cutanic Luvisol. Furthermore, significant increases in organic carbon, aggregate stability, total N, available K, cation-exchange capacity, oxygenation and hydraulic retention were observed in Mediterranean agricultural soils (Colucci et al., 2002; Lopez-Pineiro et al., 2006).

In 5 years study of olive tree cultivation Marsilio et al. (2006) reported that the spreading of 100 and 300 m^3 ha^{-1} reduced or eliminated, respectively, the need of using chemical fertilizers. The olive fruits production was equal or higher than that obtained in control plots while the quality of the olive oil was the same. The chemical and microbiological properties of the soil were not negatively affected by the different treatments with OMW. Ben Rouina et al. (2006) found that annual application of untreated OMW in an olive orchard located on a sandy soil, at a rate of 100 m^3 ha^{-1} for 10 years, markedly improved soil fertility. They showed increased content of organic matter, nitrogen and potassium, while phosphate and pH remained stable. Organic matter content increased from 0.3% to 1.3% and caused an improvement of soil's water retention capacity and water permeability. According to Chartzoulakis et al. (2006), the application of raw OMW during winter for 3 years, in doses up to 416 m^3 ha^{-1} did not have any negative effects on the nutritional soil status, neither on the yield nor on the physiology of olive trees. The increased levels of soil K can be considered as a positive effect on soil fertility, while phenols were decomposed rapidly in the soil and no toxicity symptoms were observed in olive trees during the experiments.

However, some studies also cautioned against potential phytotoxicity and decline in soil microbial activity under high-dose applications (Piotrowska et al., 2006). Other studies pointed out to the potential pollution that can result from excessive OMW application (S'Habou et al., 2005). It is clear that wise application of OMW should take into account soil type, climate, crops and other geographical and environmental conditions (Zenjari and Nejmeddine, 2001). Such a holistic approach has never taken in Jordan and only partly considered in other Mediterranean countries. Conducting this research under semi-arid conditions as the case in Jordan will greatly increase the scope of its applicability.

Most soils in Jordan are very poor in organic matter which negatively affects their fertility. Adding OMW-organic matter and nutrients in a controlled manner is expected to positively affect soil fertility. Therefore, this research aims to optimize OMW application in olive orchards and to study the effect of its application on soil properties, plant nutrition and yield.

2. Materials and methods

2.1. Experimental site and olive mill wastewater source

The experiment was conducted for three consecutive years (2011, 2012 and 2013) at a rain-fed olive orchard located in Raba area at Al-Karak governorate in Jordan (31°14′9″ N, 35°44′15″ E, elevation 996 m above sea level). The climate in this part of the country is Mediterranean. The annual rainfall during the study years 2011, 2012 and 2013 was 288.2 mm, 303.5 mm and 326.0 mm, respectively. The soil of the experimental field was vertisols, silty clay texture, pH 7.9 and EC 0.35 dS m^{-1}.Olive mill wastewater was obtained from an olive mill operated by centrifugation system and located close to the experiment orchard. This long-term experiment was essential to ascertain that no accumulation of pollutants or any gradual detrimental processes occur.

2.2. Plant material

Uniform, 15-year-old 'Nabali Muhassan' olive trees, grown on their own roots, were used in the experiment. All trees were managed following the common agronomical practices used for olive orchards. Nabali Muhassan cultivar was selected for its widespread cultivation in Jordan.

The following treatments were applied throughout the three consecutive seasons:

1. No application of OMW (control).
2. Annual application of OMW at 50 m^3 ha^{-1} (5 L m^{-2}) as one dose in December.
3. Annual application of OMW at 100 m^3 ha^{-1} (10 L m^{-2}) as one dose in December.
4. Annual application of OMW at 200 m^3 ha^{-1} (20 L m^{-2}) as one dose in December.
5. Annual application of OMW at 200 m^3 ha^{-1} (20 L m^{-2}) at four equal doses at monthly intervals between November and February.

In all cases, fresh OMW (after 24 h sedimentation at the olive mill) was used. Olive mill wastewater was applied between the rows of olive trees at a distance of 70 cm from the trunk using a tractor with tank trailer (spreading machine). Tree spacing-density was 6 m × 6 m. The setup of the experiment provides two "inner" trees in each block that are completely influenced by the given treatment to be used for monitoring and data collection.

2.3. OMW analysis

Samples of the OMW were taken at the date of application after 24 h from production to allow sedimentation of solid materials and to reduce clogging of the spreading tank nozzles. Samples of OMW were sent to the laboratory for analysis of pH, electrical conductivity (EC), total solids (TS), total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), dry matter (%), oil and fat content (%), total phenols, total nitrogen, NO_3, P, K, Ca, Mg, Na, Cl, SO_4, Fe, Zn, Cd and Pb. Analysis was carried out according to standard methods for water and wastewater analysis (Anonymous, 1998).

2.4. Soil and leaf analysis

Soil samples were taken after 1 month from the application of the treatments at two depths (0–30 cm and 30–60 cm). Soil samples were air-dried at room temperature and ground to pass a 2-mm sieve. Soil samples were analyzed for pH, EC, Na, Cl, Ca, Mg, N, P, K, Fe, Cu, organic matter (%), moisture content (%), total phenols, total microbial count and soil texture. Analysis was carried out according to methods of soil analysis (Anonymous, 1994).

Olive leaves from the middle of new shoots (full matured) were collected each year in July and analyzed for the nutrients: N, P, K,

Table 1
Properties of olive mill wastewater (OMW) used in the experiment.

Parameter	Average value[a]
pH	4.91 ± 0.46
EC (dS m^{-1})	7.64 ± 0.45
Total solids (mg L^{-1})	69,835 ± 4107.48
TDS (mg L^{-1})	26,345 ± 1260.26
COD (mg L^{-1})	58,614 ± 3040.51
BOD_5 (mg L^{-1})	36,329 ± 6070.92
Dry matter (%)	7.05 ± 0.50
Oil and fat content (%)	1.14 ± 0.18
Phenols (mg L^{-1})	2269 ± 435.56
Total nitrogen (mg L^{-1})	544 ± 322.65
Nitrate (mg L^{-1})	33.2 ± 30.26
Total phosphorus (mg L^{-1})	245 ± 56.93
Potassium (mg L^{-1})	2783 ± 172.43
Calcium (mg L^{-1})	294 ± 125.37
Magnesium (mg L^{-1})	227 ± 83.86
Sodium (mg L^{-1})	59.7 ± 5.05
Chloride (mg L^{-1})	504 ± 204.70
Sulfate (mg L^{-1})	99.7 ± 39.52
Iron (mg L^{-1})	38.23 ± 11.01
Zinc (mg L^{-1})	5.8 ± 5.01
Cadmium (mg L^{-1})	<0.005
Lead (mg L^{-1})	<0.09

[a] The average values are the mean of three samples ± standard deviation.

Ca, Mg, Na, Cl, Fe, Cu, Mn and Zn according to Official Methods of Analysis of AOAC (Horwitz, 2000).

2.5. Plant measurements

Seasonal increase in shoot growth was recorded by measuring labeled shoots (four shoots per each tested tree) at the beginning of the season and at the end of the season. Fruit set (%) was recorded for each tree. Olive tree gas exchange (net photosynthesis rate, transpiration rate and stomatal conductance) were measured using a portable photosynthesis-measuring device (CI-340, CID Bio-Science, Inc., USA).

Olive trees were harvested and the yield was recorded for each tree. Each olive tree was harvested according to its appropriate ripening stage. Ripening level was determined in accordance to fruit skin color (50% black). Each examined tree was harvest separately. Fruit samples were taken from each tree and average fruit weight and oil content were measured. Fruit oil content (%) was determined using Soxhlet extraction method. Oil extraction was performed using small scale olive mill (two phase centrifugal system, Model BuonOlio Campagnola, Italy).

Olive oil samples were taken and analyzed for acidity, peroxide value and UV absorbance (K_{270}, K_{232}, ΔK) (IOOC, 2008).

2.6. Statistical analysis

The experimental design was a randomized complete block (RCBD) with four replicates. Each replicate plot includes 3 rows × 4 trees per row. Data were analyzed using two-way analysis of variance (ANOVA) through the MSTAT-C software Version 2.1 (Freed, 1993). Mean separation was performed using Duncan's multiple-range test. The significance level of $P \leq 0.05$ was used for mean separation.

3. Results

3.1. Analysis of olive mill wastewater

Results of OMW analysis are shown in Table 1. Results of OMW analysis showed normal properties of OMW used in Jordan. It is characterized by acidic pH, high EC, very high concentrations of total solids, TDS, COD and BOD_5, and high phenol and potassium content.

3.2. Soil analysis

Results of soil analysis after 3 years of OMW application are shown in Table 2. At soil depth 0–30 cm, results showed no significant effect of OMW treatments on soil pH, however, the effect was significant on soil EC and all other measured parameters as compared to the control. Application of OMW at 20 L m^{-2} (T4) results in the highest soil EC, Na, P, K, organic matter and total phenols as compared to other treatments. No significant differences were observed between T3, T4 and T5 treatments regarding organic matter content and total microbial counts at 0–30 cm soil depth. However no significant differences were observed between the treatments and the control regarding pH, Na, Ca, N, K, and Cu at 30–60 cm soil depth. While the T4 treatment gave significantly the highest soil P content as compared to the other treatments and the control (Table 2).

3.3. Olive leaf nutrient analysis

Olive leaf nutrient content showed no significant differences between all treatments except for Fe and Cu leaf content. Application of OMW at 10 L m^{-2} (T3) and 20 L m^{-2} (T4) gave the highest Fe leaf content compared to the other treatments and the control. However, Cu leaf content was significantly the highest for treatments T3, T4 and T5 as compared to the control (Table 3).

3.4. Seasonal shoot growth, photosynthesis rate, transpiration rate and stomatal conductance

Results of the effect of OMW soil spreading on olive tree shoot growth, photosynthesis rate, transpiration and stomatal conductance are shown in Fig. 1. Application of OMW at 20 L m^{-2} for 2011 season gave significantly the highest increase in shoot length compared to the other treatments and the control, but it was not significantly different from the application of OMW at 10 L m^{-2}. As for 2012 season, application of OMW at 20 L m^{-2} gave significantly the highest increase in shoot length compared to T1, T2 and T5 treatments but not from T3 treatment. Regarding 2013 season, application of OMW at 20 L m^{-2} gave significantly the highest increase in shoot length compared to the control (T1), T2 and T5 treatments but without being significantly different from T3 treatment (Fig. 1A).

Application of OMW at 20 L m^{-2} (T4) gave significantly the highest photosynthesis rate for 2011 season compared to the control and T2 treatment, but it was not significantly different from T3 and T5 treatments. Application of OMW at 20 L m^{-2} at four equal dozes (T5) for the second season gave the highest photosynthesis rate, which was significantly different from the control treatment but not from the other treatments. While application of OMW at 10 L m^{-2} (T3) for 2013 season gave the highest photosynthesis rate, which was significantly different from the control treatment but not from the other treatments (Fig. 1B).

No significant differences were observed between all treatments regarding transpiration rate for the three seasons (Fig. 1C). However, significant differences in stomatal conductance between treatments were observed in the first season, while the differences were not significant in the second and the third seasons (Fig. 1D).

3.5. Yield, fruit measurements and oil quality analysis

Results for 2011 season, showed low values for fruit set (%) and yield during this season. Fruit set range was from 1% to 3.2% and the range of the tree yield was from 2 to 16.2 kg. Application of

Table 2
Effect of OMW application on soil chemical and physical properties.

Parameter	Unit	Soil depth/0–30 cm					Soil depth/30–60 cm				
		Control	5 L m^{-2}	10 L m^{-2}	20 L m^{-2}	20 L m^{-2} at four doses	Control	5 L m^{-2}	10 L m^{-2}	20 L m^{-2}	20 L m^{-2} at four doses
pH		7.72 a*	7.62 a	7.60 a	7.30 a	7.38 a	7.95 a	7.82 a*	7.85 a	7.72 a	7.80 a
EC	dS m^{-1}	0.79 b	1.20 a	1.38 a	1.51 a	1.32 a	0.38 b	0.86 a	0.52 ab	0.60 ab	0.56 ab
Na		1.49 b	3.28 a	3.79 a	4.52 a	3.72 a	1.13 a	1.72 a	1.35 a	1.61 a	1.25 a
CL	meq L^{-1}	2.38 b	3.95 ab	5.12 a	4.60 ab	2.98 ab	1.24 b	2.45 a	2.52 a	2.50 a	2.42 a
Ca		2.9 c	16.7 a	7.05 bc	17.88 a	14.28 ab	2.65 a	4.28 a	3.70 a	4.15 a	3.98 a
Mg		4.63 b	31.34 a	7.99 b	52.24 a	33.0 a	0.88 b	2.02 a	1.22 ab	1.32 ab	1.17 ab
N	%	0.06 b	0.07 ab	0.08 a	0.09 a	0.09 a	0.05 a	0.06 a	0.07 a	0.06 a	0.07 a
P		5.58 c	24.05 b	24.52 b	41.95 a	20.18 c	5.10 c	4.92 c	5.08 c	13.70 a	10.52 b
K	ppm	328.7 b	798.8 ab	703.6 ab	1200.4 a	779.2 ab	325.91 a	360.83 a	335.90 a	470.54 a	378.06 a
Fe		3.89 b	6.17 a	6.54 a	6.95 a	4.78 b	3.83 b	4.36 b	7.85 a	8.45 a	5.47 b
Cu		1.86 b	2.28 ab	2.44 ab	2.78 a	2.47 ab	1.64 a	1.80 a	1.83 a	1.84 a	1.87 a
Organic matter	%	0.76 c	1.40 b	1.89 ab	2.19 a	1.66 ab	0.24 b	0.54 a	0.64 a	0.75 a	0.28 b
Moisture content	%	9.62b	10.54b	14.23a	14.69 a	13.85a	11.50 a	11.87 a	12. 96 a	13.41a	12.27 a
Total phenols	ppm	1.86 c	9.65 b	16.08 b	25.52 a	14.32 b	1.11 c	1.26 c	2.50 ab	3.45 a	2.02 bc
Total microbial count	CFU g^{-1}	635 b	978 b	1884a	1942 a	1945 a	327 b	351 b	502a	548 a	392b
Soil texture		Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay

* Means within rows for each parameter having the same letters are not significantly different at 5% probability level according to Duncan's multiple-range test.

Table 3
Effect of OMW application on leaf nutrient content of 'Nabali Muhassan' olives.

Parameter	Unit	Treatments					Standard sufficient level of nutrients
		Control	5 L m^{-2}	10 L m^{-2}	20 L m^{-2}	20 L m^{-2} at four doses	
N		1.39 a*	1.67 a	1.66 a	1.79 a	1.52 a	1.5–2.0
P		0.11 a	0.09 a	0.10 a	0.11 a	0.12 a	0.1–0.3
K		0.51 a	0.56 a	0.52 a	0.57 a	0.60 a	>0.8
Ca	%	1.79 a	1.69 a	1.74 a	1.62 a	1.74 a	>1.0
Mg		0.26 a	0.26 a	0.26 a	0.28 a	0.26 a	>0.1
Na		0.01 a	0.02 a	0.02 a	0.03 a	0.02 a	Toxic > 0.2
Cl		0.10 a	0.11 a	0.11 a	0.13 a	0.10 a	Toxic > 0.5
Fe		144.75 b	152.27 b	196.42 a	205.26 a	158.10 b	100–400
Cu	ppm	5.82 b	6.18 b	6.68 a	6.98 a	6.81 a	>40
Mn		33.72 a	34.28 a	35.03 a	40.93 a	35.72 a	>20
Zn		16.52 a	17.41 a	18.13 a	18.64 a	17.56 a	–

* Means within rows for each parameter having the same letters are not significantly different at 5% probability level according to Duncan's multiple-range test.

OMW at 20 L m^{-2} gave significantly the highest fruit set (%) as compared to the other treatments except T5 treatment. While results for 2012 season showed higher fruit set and yield than 2011 season. Application of OMW at 20 L m^{-2} (T4) gave significantly the highest fruit set (%) as compared to the other treatments and the control (Fig. 2A). Tree yield was significantly the highest for T4 treatment as compared to the other treatments and the control, but not significantly different from T3 treatment (Fig. 2B). Concerning 2013 season, results showed that application of OMW at 10 L m^{-2} (T3) and 20 L m^{-2} (T4) gave significantly higher fruit set (%) and yield as compared to the other treatments and the control (Fig. 2A and B).

Results showed no significant differences between all treatments regarding fruit weight for the three seasons (Fig. 2C). Fruit oil content was the highest for T4 and T3 treatments as compared to T2 treatment and the control for all seasons (Fig. 2D).

Oil quality analysis results in terms of acidity, peroxide value, UV absorbance at 232 nm, 270 nm and ΔK showed no significant differences between all treatments for the three seasons. All oil samples were within the limits of the olive oil standard and they were classified as extra virgin olive oil for the three seasons (Table 4).

4. Discussion

Characteristics of OMW used in this experiment were similar to OMW characteristics reported in several previous studies. Typical OMW composition by weight is 83–94% water, 4–16% organic compounds and 0.4–2.5% inorganic compounds (mineral salts) (Fountoulakis et al., 2002; Azbar et al., 2004; Davies et al., 2004; Sabbah et al., 2004).

After 3 years of raw OMW application soil analysis showed that there were no harmful effects on soil properties, despite the low pH and high EC values of OMW, indicating that the buffering capacity of the soil could counter balance these negative effects (Chartzoulakis et al., 2006).

The concentration of N in OMW-treated soils was higher than in the control soil at 0–30 cm soil depth. An increase in soil N after the application of raw OMW has been attributed to the increase of N-fixing micro flora as mentioned by Marsilio et al. (1990).

The concentration of K and phenolic compounds in the soil was significantly higher in OMW-treated soil as compared to the control and mainly in the upper soil layer (0–30 cm), indicating that despite the fact that OMW was applied during the raining season, both K and phenols did not move rapidly across the soil profile. These results are in agreement with previous studies conducted on spreading of OMW (Paredes et al., 1987; Levi-Minzi et al., 1992; Mechri et al., 2008). It was reported that the phenolic compounds concentration in the soil increased soon after OMW application; however, their concentration in the soil was rapidly reduced thereafter, reaching low levels at the end of the season. This could be due to their decomposition or incorporation into the humic fraction of the organic matter present in the soil (Chartzoulakis et al., 2006; Sierra et al., 2001; Saadi et al., 2007).

Result of total microbial counts indicated higher microbial activity in OMW-treated soil as compared to the control. This indicates that certain organic constituents in the fresh OMW serve as substrates for soil bacteria and fungi. El-Hassani et al. (2007) reported that the abundance of soil total microflora is enhanced after OMW application. Furthermore, Di Serio et al. (2008) reported

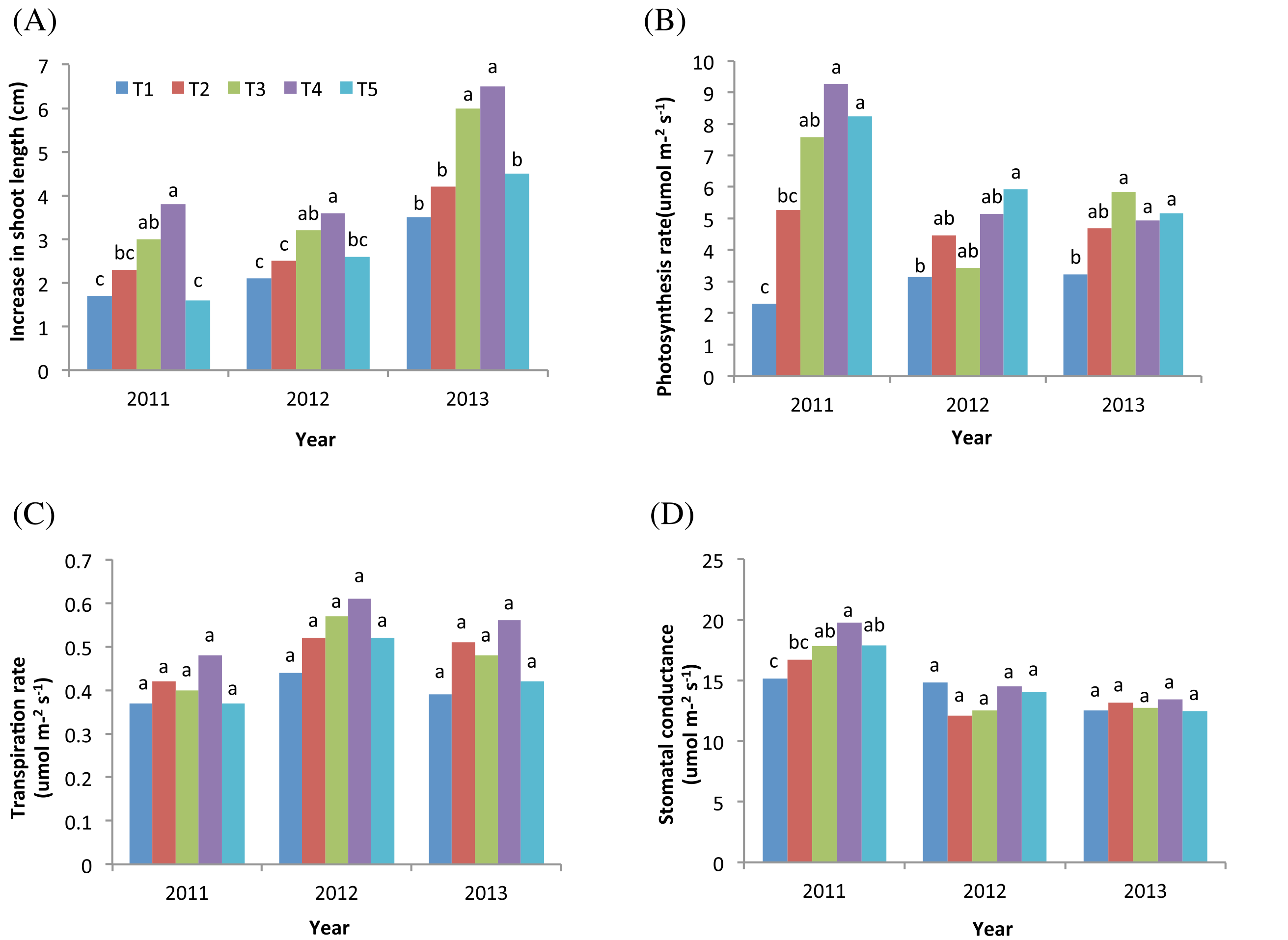

Fig. 1. Effect of OMW soil spreading on shoot length (A), photosynthesis rate (B), transpiration rate (C) and stomatal conductance (D) of 'Nabali Muhassan' olive trees. T1 = control, T2 = 5 L m^{-2}, T3 = 10 L m^{-2}, T4 = 20 L m^{-2}, T5 = 20 L m^{-2} at four doses. Means followed by the same letters for each year are not significantly different at 5% probability level.

Table 4
Olive oil quality analysis as affected by the treatments.

Treatment	Olive oil acidity (%)	Peroxide value (meq O_2 kg^{-1} oil)	Absorbance at 270 nm	Absorbance at 232 nm	ΔK	Olive oil category
Control	0.64 a*	8.8 a	0.11 a	1.64 a	0.002 a	Extra virgin
5 L m^{-2}	0.42 a	7.6 a	0.10 a	2.12 a	0.001 a	Extra virgin
10 L m^{-2}	0.52 a	8.2 a	0.12 a	1.60 a	0.001 a	Extra virgin
20 L m^{-2}	0.68 a	7.9 a	0.11 a	1.85 a	0.002 a	Extra virgin
20 L m^{-2} at four doses	0.65 a	9.4 a	0.10 a	2.26 a	0.001 a	Extra virgin
Limit value	Max 3.3	Max 20	Max 0.22	Max 2.5	Max 0.01	

* Means within columns for each parameter having the same letters are not significantly different at 5% probability level according to Duncan's multiple-range test.

that OMW application in the soil increased the respiration activity with respect to the untreated soil, which is highly correlated with the organic matter decomposition in the soil.

In general, from the aspects of soil microbial activity and the limited phytotoxicity, the results of this study supported a safe application of OMW at the tested doses.

In general, the application of OMW did not affect significantly the leaf N, P, K, Ca, Mg and Na concentrations throughout the experiment. During the 3 years of the experiment, there was no toxicity symptoms observed in olive trees. This result is in agreement with Chartzoulakis et al. (2006).

Application of OMW at the doses used in this experiment had positive effect on shoot growth and photosynthesis. Chartzoulakis et al. (2006) reported that OMW did not negatively affect any of the plant parameters measured. Photosynthesis tended to be lower in OMW-treated plants early in the growing season, but this effect was transient and OMW-treated plants had similar or even higher photosynthetic rates than control plants toward the end of the growing season. While Proietti et al. (1988) also found no differences in photosynthesis among OMW-treated and control olive trees. On the other hand, stomatal conductance was not affected by the application of raw OMW, giving similar values to control trees.

Fruit set (%) and yield were low during 2011 season compared to 2012, this could be explained by the alternate bearing habit (off-season) for the olive trees. Application of OMW at 10 L m^{-2} and 20 L m^{-2} improved fruit set, fruit yield and fruit oil content, but had no effect on fruit weight and oil quality parameters. These results are in agreement with the finding of Andrich et al. (1992) and Chartzoulakis et al. (2006).

The current investigation indicated that olive fruit production was equal or higher than that obtained in control plots while the quality of the olive oil was the same.

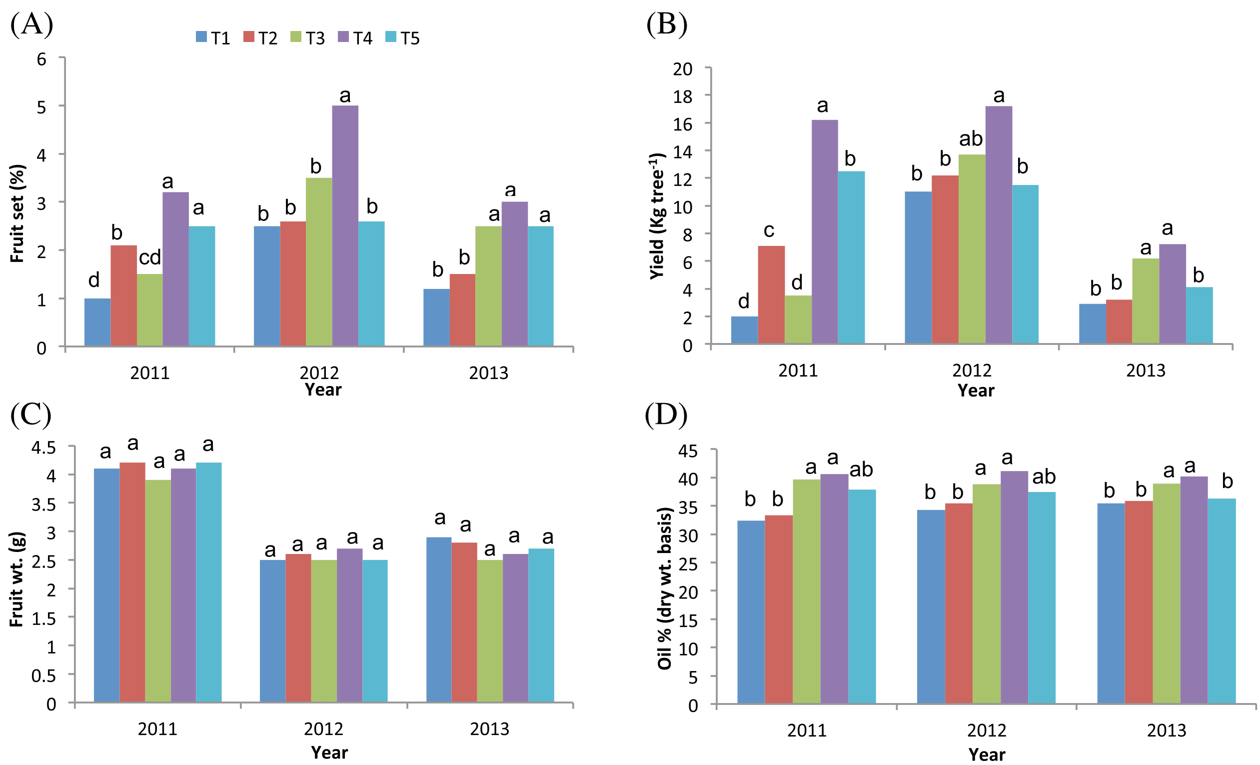

Fig. 2. Effect of OMW soil spreading on fruit set (A), yield (B), fruit weight, (C) and fruit oil content (D) of 'Nabali Muhassan' olive trees. T1 = control, T2 = 5 L m^{-2}, T3 = 10 L m^{-2}, T4 = 20 L m^{-2}, T5 = 20 L m^{-2} at four doses. Means followed by the same letters for each year are not significantly different at 5% probability level.

Our results are in general agreement with Marsilio et al. (2006) who reported that the spreading of 100 and 300 m^3 ha^{-1} reduced or eliminated, respectively, the need of using chemical fertilizers.

5. Conclusions

The present results show no negative effects of OMW application on soil and olive tree performance. Due to its high amounts of organic matter and macronutrients, OMW could be considered as a useful and low cost fertilizer. Controlled land spreading of olive mill wastewater is now adopted in several Mediterranean countries as a practical alternative for its disposal. In Jordan, the current experience is limited, and the present work indicates that the controlled application of OMW increased the fertility of the soil and improved plant performance.

The control and save application of OMW in Jordan, requires the adaptation of the local legislative status, similar to the one applied in other Mediterranean countries, before the method can be applied to commercial orchards.

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