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Potential nutritional value of olive-mill wastewater applied to irrigated olive (*Olea europaea* L.) orchard in a semi-arid environment over 5 years

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A B S T R A C T

Controlled spreading of olive mill wastewater (OMW) on cultivated soils is a low-cost disposal method of an otherwise problematic pollutant, with potential recycling of plant nutrients. The nutritional value of successive OMW applications was examined in an intensive olive orchard grown on sandy loam soil in a semi-arid region. Application at 50–150 $m^3\,ha^{-1}\,y^{-1}$ for 5 years had no negative effects on tree vegetative growth, fruit yield or oil quality. OMW application did not increase N content in the soil or plants; yet, it caused a consistent increase in soil P and K contents and significantly affected diagnostic leaf P and K concentrations. It also led to a significant increase in exchangeable potassium percentage (EPP) already from the first application, and soluble K migration to deep soil layers after 3 years of successive applications. Soil tillage after OMW application did not affect N, P or K dynamics in the soil or uptake of these nutrients by plants. Controlled application of OMW to intensive olive orchards can be a significant source of K and P and thus save on fertilizers without negatively affecting tree performance.

1. Introduction

Olive oil extraction systems generate large amounts of olive mill wastewater (OMW) in a relatively short time during the olive harvest season. Roig et al. (2006) estimated a volume of 1–1.6 m^3 of OMW per ton of processed olives in the three-phase extraction systems and 0.2 m^3 of OMW in the two-phase systems. The physicochemical properties of OMW depend on the characteristics of the processed olives and on the system used for olive oil extraction and its local operation conditions (Aviani et al., 2012). Improper treatment and/or uncontrolled disposal of OMW might cause severe environmental problems (Peikert et al., 2014). Typically, OMW is characterized by high organic load (up to 100,000 and 220,000 $mg\,L^{-1}$ biochemical oxygen demand [BOD] and chemical oxygen demand [COD], respectively), high salinity (5–12 $dS\,m^{-1}$), oil residues (1–23 $g\,L^{-1}$) (Azbar et al., 2004; Roig et al., 2006), and a highly phytotoxic nature (Aviani et al., 2009, 2012). Together with the fact that large OMW volumes are produced in a short period during the year, OMW discharge into domestic wastewater treatment plants is prohibited, as it may result in their collapse. Over the last decade, much work has been devoted to the search for efficient treatment processes with the aim of reducing organic load and overall toxicity, as well as to exploiting potentially valuable substances (Arvanitoyannis et al., 2007; Komilis et al., 2005; Roig et al., 2006). To date, the economic feasibility of various proposed methods is questionable as they seem to be barely supported by olive growers or olive mill owners. As a result, the most common solution for the disposal of OMW is still spreading it on the soil surface. In most olive oil-producing countries, there are regulations regarding the permissible annual amount of OMW application per unit area. Many researchers (Buchmann et al., 2015; Piotrowska et al., 2006; Rinaldi et al., 2003; Saadi et al., 2007; Sierra et al., 2007) have found that under conditions of controlled spreading in the range of several tens of cubic meters per hectare and even as high as 400 $m^3\,ha^{-1}$; (Chartzoulakis et al., 2010), most of the toxic effects of OMW are short term and virtually disappear after a period of weeks to months. Mekki et al. (2006) and Saadi et al. (2007) reported complete recovery from phytotoxicity symptoms in soil 3 months after OMW application at 72 $m^3\,ha^{-1}$. On the other hand, OMW contains large amounts of organic matter, and potentially

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Table 1
Chemical properties of the olive mill wastewater (OMW) used in each year of the experiment, average values (Avg.) and standard deviations (SD). Empty cells are missing data.

Property	Units	Halutza 2012 1 st appl.	Rahat 2013 2nd appl.	Rahat 2014 3rd appl.	Rahat 2015 4th appl.	Rahat 2016 5th appl.	Avg.	SD
pH		4.8	4.2	4.2	4.3	4.6	4.42	0.27
EC	dS m^{-1}	12.1	11.2	13.3	13.3	10.7	12.1	1.2
Cl	mg L^{-1}	1125	1100	841	902	774	948	157
Na	mg L^{-1}	437	506	218	198	78.2	287.5	178
Ca	mg L^{-1}	116	94	192	664	400	293	240
Mg	mg L^{-1}	186	146	186	195.6	122.7	167.3	31.3
N-NO_3	mg L^{-1}	14.7	22.0	7.9	11.8	9.7	13.2	5.52
N-NH_4	mg L^{-1}	21		34	56	46.0	39.3	15.2
total N	mg L^{-1}	1160	700	483	1454	1720	1103	513
soluble P	mg L^{-1}	181	148	300	242	242.0	222.5	59.2
total P	mg L^{-1}	283	201	323	368	283.0	291.6	61.6
K	mg L^{-1}	5122	4966	4570	6843	5040	5308	884
Fe	mg L^{-1}	1.1	30.2	50.5	26	31.2	27.8	17.7
Zn	mg L^{-1}	2.5	20.6	3.4	3.6	2.3	6.5	7.9
Mn	mg L^{-1}	4	1.2	2	2.3	2.5	2.4	1.0
Cu	mg L^{-1}	0.12		< 0.25	1.16		0.6	0.7
SAR	$(meq\ L^{-1})^{0.5}$	5.85	7.65	2.71	1.73	0.90	3.80	2.90
TS	g L^{-1}	101	67	54	78		75.1	20.1
Total COD	mg L^{-1}	126758	113471	85811	134540	118246	115765	18588
Sol. COD	mg L^{-1}	83126		74,646		45159	67644	19929
BOD total	mg L^{-1}	32250	27500	49880	42500	27000	35826	10026
BOD sol.	mg L^{-1}	28500				15000	21750	9546
Oils @ Grease	mg L^{-1}	13598	5008	12270	12107	17900	12177	4642

available plant nutrients: nitrogen [N], phosphorus [P], potassium [K]. Therefore, controlled application of OMW to agricultural soils can result in an increase in soil organic matter (Barbera et al., 2013; Regni et al., 2017) and can contribute to soil nutritional status (Belaqziz et al., 2016; Chaari et al., 2014; Chartzoulakis et al., 2010; Sierra et al., 2007). Piotrowska et al. (2006) reported that soil P and K concentrations increased as a result of OMW application of 40 and 80 $m^3\ ha^{-1}$, whereas the toxic effects diminished after a relatively short time (42 days). Moreover, Magdich et al. (2012) reported an increase in fruit yield in rain-fed olives in Tunisia as a result of annual application of 100 $m^3\ ha^{-1}$ OMW over 6 successive years.

Undesired leaching of OMW components may be minimized by soil tillage after OMW application. Laor et al. (2011) observed for a clay soil greater leaching of dissolved organic carbon (DOC) and phenolic compounds after surface spreading of OMW, compared to surface spreading followed by tillage. Levy et al. (2017) who studied the experimental plots described in the present study, observed higher increase in OC content in the tilled plots and suggested that it might be caused by the better interactions between the added organic matter and soil particles upon tillage. Moreover, the observed effect of OMW spreading on soil hydrophobicity (water drop penetration time) in this experimental platform was not visible in tilled plots (Steinmetz et al., 2015).

Most of the studies reporting the effect of OMW application on soil and tree nutritional status have been carried out in rain-fed, non-intensive olive orchards. Under such conditions, total biomass production is quite limited and therefore, the demand for nutrients is lower than that in intensive orchards. Moreover, in non-intensive orchards, the available soil volume per tree is relatively high and tree nutrient demand can be satisfied even when soil nutrient concentrations are low. Thus, the objectives of the present study were to examine the impact of controlled OMW application to an intensive, irrigated olive orchard, with and without subsequent soil tillage on (i) tree performance, (ii) tree nutritional status, and (iii) soil nutritional potential, including the dynamics of OMW-borne P and K in the soil. These objectives were addressed over 5 years of successive OMW application at varying rates.

2. Materials and methods

The experimental field platform used in this study is located at the Gilat Research Center, in the northern Negev of southern Israel (31°20′N 34°40′E). The region is characterized by a semi-arid Mediterranean climate with a cool winter and a warm dry summer (average annual minimum of 14.2 °C and maximum 27.7 °C). The rainy season is between November and April and the average annual rainfall during the period of the experiment was 290 mm, with most of it, about 75% occurring prior to OMW application. The soil was classified as a sandy loam (Calcic Haploxeralf), composed of 50% sand, 35% silt and 15% clay with a pH of 8.2 and 11.5% calcium carbonate. Soil organic matter content was around 0.5%.

The experimental platform was managed for 5 years (2012–2016) in a 7-year-old olive orchard, where trees (cv. Leccino, mainly cultivated for olive oil production) were planted at 3.5 m × 7 m distance. The trees were drip irrigated with a single drip line per row, with 2 L h^{-1} drippers every 50 cm. Irrigation was generally performed from March to October with a Kc of 0.55 relative to Penman ET_0, which resulted in an annual amount of 650 mm. The orchard was fertilized commercially from 2004 to 2011 with 15, 8 and 30 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. No fertilizers were applied during the 5 years of the OMW application.

Every four trees formed a plot, with the two central ones being the measured trees and the other two - border trees. Each treatment had five replicates in a completely randomized block design (a total of 25 plots for the five treatments). To avoid underground migration of OMW between plots and to restrict the root zone to the targeted treatment, vertical 0.2-mm thick plastic partitions were buried along the rows, in the center between rows, at a depth of 1 m. This resulted in a plot size of 7 m wide by 14 m long. Five OMW treatments were studied: (i) no application of OMW (control), (ii–iv) annual application of OMW at rates of 50, 100 or 150 $m^3\ ha^{-1}$, respectively, and (v) annual application of 100 $m^3\ ha^{-1}$ followed by superficial soil tillage with a hand rototiller to a depth of 5 cm, 3 weeks after OMW application. In treatments (ii)–(v), the OMW was applied shortly after the end of the olive milling season (January–February). The OMW was taken from three-phase medium-size olive mills (Halutza mill in 2012 and Rahat mill in