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Long-term impact of irrigation with olive mill wastewater on aggregate properties in the top soil

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ABSTRACT

Olive mill wastewater (OMW) is the main waste product generated by the olive oil extraction process. The uncontrolled disposal of OMW is becoming a serious environmental problem. The objective of this study was to investigate the long-term effects of OMW irrigation on soil aggregate stability, on solute diffusion into aggregates and on aggregate structure formation. The soil aggregates were sampled from three sites: non-irrigated with OMW (T0) and regularly irrigated with untreated OMW for 5 (T5) and 15 (T15) years. The results showed that the regular application of OMW for 5 and 15 years increased the soil aggregate stability, as a result of a rising organic matter content of OMW sites. OMW application furthermore reduced the effective diffusion coefficient into aggregates, because the organic matter of OMW forms a coating on the aggregates and blocks the pore mouths. OMW is characterized by its adhesive behaviour that affects the aggregation and structure of the topsoil by binding micro-aggregates together to form macro-aggregates and larger pore spaces between micro-aggregates. Consequently, the use of OMW for irrigation over long time periods alters the surface layer of the soil and makes it fragmented, which may increase the risk for preferential solute transport.

1. Introduction

Olive (*Olea europaea*) oil is a typical and valuable agro-industrial product in Syria, which is ranked fifth in the world in production of olive oil. The average production of olive fruits and olive oil reaches 880 and 175 thousand tons, respectively (Al-Ashkar, 2007). There are 920 olive mills which are scattered all over the country, and the number is expected to rise in the future due to the rapid increase of olive production (UN, 2009). The main waste generated by the olive oil extraction process is olive mill wastewater (OMW). The total wastewater from Syria's olive oil production amounts to 900,000 m^3 per year during the olive mill season from early October to late December (Directorate of Olive Bureau, Ministry of Agriculture and Agrarian Reform, Arab Republic of Syria, personal communication). In the olive growing countries of the Mediterranean, more than 30 million m^3 OMW are produced per year (D'Annibale et al., 2004).

The OMW characteristics depend on the olive variety and ripeness, climate and soil conditions and the oil extraction method. Olive oil production involves one of the following extraction processes: (i) press olive oil extraction, (ii) three-phase centrifugal olive oil extraction and (iii) two-phase centrifugal olive oil extraction. The volume of OMW produced in traditional presses and in three-phase extraction systems amounts to about 600 and 1000 l per ton of processed olives, respectively, while it is much lower in the two-phase process (Azbar et al., 2004). In general, OMW has an extremely high biological and chemical oxygen demand, a high organic matter content (polysaccharides, sugars, polyalcohols, proteins organic acids and oil), and contains large amounts of suspended solids and mineral elements (Niaounakis and Halvadakis, 2004). Moreover, OMW contains high concentrations of phenolic compounds that are phytotoxic and difficult to biodegrade (Nikolopoulou and Kalogerakis, 2007). Mekki et al. (2007) detected phenolic compounds at a depth of 1.2 m four months after the last application of OMW, and a moderate phytotoxic residual phenolic fraction was extracted from the topsoil layer one year after OMW application. OMW has been shown to inhibit the arbuscular mycorrhizal fungal root colonization, which reduces the nutrient uptake of the olive trees (Mechria et al., 2011).

The need for disposal of OMW on the one hand, and water scarcity and low soil fertility in olive producing countries on the other hand, has brought about that large amounts of OMW are used for irrigation and fertility purposes in Syria and other Mediterranean countries. The law No. 190/T issued in 2007 by the Ministry of Agriculture in Syria allows the spreading of up to 50 $m^3\ ha^{-1}$ OMW from traditional presses and up to 80 $m^3\ ha^{-1}$ OMW from modern centrifugal mills; the very same application rates are also permitted, e.g., in Italy (Giuffrida, 2010). OMW application, however, has been found to significantly affect the

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soil's biological (Saadi et al., 2007; Mechri et al., 2008), chemical (Jarboui et al., 2008; López-Piñeiro et al., 2008; Kavvadias et al., 2010) and physical properties. The long-term application of untreated OMW decreases the saturated hydraulic conductivity, and increases the soil's disposition to water repellency (Mahmoud et al., 2010). The enhanced organic matter content of OMW furthermore increases sorption and degradation processes, and OMW application may therefore retard the mobility of pesticides (Cox et al., 1997).

The land application of olive oil solid waste has been shown to improve the soil aggregate stability (Kavdır and Killi, 2008), because it increases the organic matter content and soil fertility (Yaakoubi et al., 2010). Aggregate stability is important in evaluating erosion resistance, soil permeability, steady state infiltration rate, and seedling emergence and in predicting the capacity of soils to sustain long-term crop production (Letey, 1985). However, the effect of liquid OMW application on aggregate stability has not been investigated so far.

OMW organic matter and contained residues of oil and grease form a coating on soil aggregates and pore walls (Bisdom et al., 1993), which may reduce anion diffusion into soil aggregates. Köhne et al. (2002) found that films or skins on the surface of aggregates decrease the diffusive mass transfer of anions between interaggregate regions and the soil matrix. The rate of diffusion furthermore decreases with decreased porosity (Hanson and Nex, 1953). Thus, it is expected that the OMW will affect the rate of diffusion into soil aggregates, since the long-term application of OMW decreases the soil drainable porosity ($\Phi < 30$ μm; Mahmoud et al., 2010), and changes the pore size distribution by a decrease of macropores and an increase of micropores (Cox et al., 1997).

The objective of this study was to investigate the long-term impact of OMW application on soil aggregate stability, on morphological features of aggregates, and on anion diffusion.

2. Materials and methods

2.1. Experimental sites and sampling of soil aggregates

All field sites are located in Saida village, south-western Syria (32°64′N, 36°18′E), at an altitude of 435 m a.s.l. The sites have a Mediterranean climate with an average annual precipitation of 200 mm and an average temperature of 35 °C in summer and 12 °C in winter. In January 2009, soil aggregates were sampled at three experimental field sites: non-irrigated with OMW (T0) and regularly irrigated with untreated OMW for 5 (T5) and 15 (T15) years. The fields were 350 m × 70 m (T0, T15) and 250 m × 70 m (T5) in size. Samples of soil aggregates were taken at 0–5 cm depth, they were randomly collected within each field. The olive orchards at all selected sites were irrigated by drop irrigation during the growth period. During the time period of olive mill operation from early October to late December, however, the experimental plots T5 and T15 were irrigated by furrow irrigation with untreated OMW. The volume of OMW varied from year to year depending on the amount of olive oil production per year. The amount of OMW applied on experimental field sites T5 and T15 was not quantified.

The field sites T5 and T15 were plowed once in early spring and twice in early summer and one to three times in late summer and autumn. The frequency of plowing depended on the amount and number of OMW applications and on weed density. The site T0 was plowed once in early summer and two times in late summer and autumn.

2.2. Soil and OMW characteristics

The soil at the three sites has been classified as a Cambisol according to FAO classification (2006). Soil texture is silt loam, and soil color is 7.5 YR 4/3 in all investigated profiles (down to 90 cm depth). The soils are poor in organic matter. The typical clay mineral is Montmorillonite, and the soils develop deep shrinkage cracks upon desiccation.

Table 1
Selected physicochemical properties of the olive mill wastewater.

Parameter	Value
pH	5.07
Dry matter ($g\,l^{-1}$)	33.25
Total organic carbon ($g\,l^{-1}$)	30.57
Mineral matter ($g\,l^{-1}$)	2.69
Soluble Cl^- ($mg\,l^{-1}$)	763.8
Soluble Na^+ ($mg\,l^{-1}$)	128.8
Soluble K^+ ($mg\,l^{-1}$)	1050.9
Soluble Ca^{2+} ($mg\,l^{-1}$)	137.5
Soluble Mg^{2+} ($mg\,l^{-1}$)	168.3

The main physicochemical characteristics of the OMW are given in Table 1. Additional details of soil and OMW properties are reported in Mahmoud et al. (2010).

2.3. Laboratory measurements

Total carbon and nitrogen contents were determined with the Elementar Vario EL analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) according to DIN ISO 10 694 (1996) and DIN ISO 13 878 (1998), respectively, while carbonate content was determined separately with the Scheibler equipment according to DIN ISO 10 693 (1995; measurement of the volume of degassing CO_2 after addition of hydrochloric acid). Nine replications were measured for each treatment, three each for the aggregate stability tests: slow wetting (SW), fast wetting (FW) and wet stirring (WS).

Bulk density ρ_b was determined by coating the single, air-dried aggregates with paraffin and measuring their volume in distilled water (Urbanek and Horn, 2006). Four replications were analyzed for each treatment. The particle density ρ_s ($g\,cm^{-3}$) was calculated according to the following empirical equation (Schmidt, 1992):

$$\rho_s = 2.65 - (0.022a) \quad (1)$$

where a is the percentage of organic matter (%).

The aggregate stability was determined using the Le Bissonnais (1996) method, which allows distinguishing the different destruction mechanisms causing aggregate breakdown (Rohošková and Valla, 2004). The experiment was repeated six times for each test and treatment. The soil aggregates were air-dried and gently sieved to separate the macro-aggregates (3–5 mm in size) from the micro-aggregates. The macro-aggregates were then dried at 40 °C for 24 h before the stability analyses. The Le Bissonnais method consists of three tests with different wetting conditions and energies: (i) Slow wetting (SW; wetting by capillarity): This treatment tests the behaviour of dry soils with a low moisture content to moderate rainfall. 5 g of aggregates were placed on a filter paper on a tension table at a matric potential of −30 hPa for 60 min. (ii) Fast wetting (FW; wetting by immersion): This treatment tests the behaviour of dry soils to fast wetting such as irrigation and heavy rainfall. 5 g of aggregates were gently immersed in 50 cm^3 of deionized water for 10 min, then the excess water was sucked off with a pipette. (iii) Mechanical breakdown after stirring of pre-wetted aggregates in ethanol (WS): This treatment tests the behaviour of dry soils to mechanical impacts. 5 g of aggregates were gently immersed in 50 cm^3 of ethanol for 10 min, then the excess ethanol was removed with a pipette and the soil material was transferred to an Erlenmeyer flask filled with 200 cm^3 of deionized water. The Erlenmeyer flask was shaken end over end 20 times, then the excess water was sucked off with a