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Irrigation Systems for Land Spreading of Olive Oil Mill Wastewater

Antonina Capra* • Vincenzo Tamburino • Santo Marcello Zimbone

Dipartimento di Scienze e Tecnologie Agro-forestali e Ambientali, Facoltà di Agraria, Località Feo di Vito, 89022 Reggio Calabria, Italy

Corresponding author: *acapra@unirc.it

ABSTRACT

Mill wastewater has always created considerable environmental problems for countries producing olive oil. These problems, which are of increasing relevance in relation to the growing interest in protecting water resources, are of technical and economic nature and are mainly due to the quality of the wastewater (which contains a large amount of organic substances and solute or suspended minerals, and is highly fermentable), the seasonal nature of the production process, and the great territorial dislocation of the olive mills. In order to obtain wastewater which complies with current environmental legislation regarding discharge into water supply systems, it is necessary to use treatment plants with high running costs, which can be prohibitive in olive processing activities. Accumulation and subsequent distribution on the soil through irrigation plants may represent a sustainable solution to the various problems connected with olive mill wastewater (OMW) disposal. Besides allowing for a considerable saving in costs, the use of irrigation plants allows optimal distribution of wastewater. With gradual and uniform distribution, phytotoxic organic substances are held and broken down in the surface layer of the soil, far from the roots of the trees and from water tables. Several experiments highlight that the effects of OMW on crops, soils and the environment depend on the quantity of OMW distributed, but very little information on optimal systems and modalities used to spread OMW is available. A gradual, uniform distribution of OMW can be obtained through microirrigation systems. However, some system management problems may occur. In fact, the small orifices of the emitters and the filters used to protect them can be clogged by small particles or growths due to the suspended solid content of OMW, mainly of organic type. The paper discusses both agronomic and operational aspects of OMW spreading. According to the analysis, some practical recommendations for agronomic OMW use by microirrigation systems are made.

Keywords: distribution on soil, filtration, irrigation systems

INTRODUCTION

The olive oil industry is constantly growing, especially in Mediterranean countries, with an average annual growth of *ca*. 5% in world production over the last 15 years (Saadi *et al*. 2007). Olive mill wastewater (OMW) is a liquid by-product generated during olive oil production. The Mediterranean region accounts for 95% of global OMW production (Kapellakis *et al*. 2006). In Italy, an average of 5.8×10^6 t $year^{-1}$ of OMW is produced (Alfano *et al*. 2007).

Although it has been produced since ancient times, during the last four decades the disposal of OMW has created considerable environmental problems for countries producing olive oil. The main reasons for this degradation are: a) an increase in olive oil production; b) the conversion of traditional (pressure-type) olive oil mills (OMs) into modern plants (centrifuge-type) which produce more OMW per ton of olive oil produced; c) the dispersed location of small-sized plants, which leads to an expansion in pollution sources; and d) the exclusion of OM personnel from decision-making processes (Marrara *et al*. 2002; Kapellakis *et al*. 2006).

Different methods based on evaporation ponds, thermal concentration and physico-chemical and biological treatments have been investigated for OMW depollution (Cegarra *et al*. 1996; Rozzi *et al.* 1996; Greco *et al*. 2006; Kapellakis *et al*. 2006; Mechri *et al*. 2007) but most of the systems are in many cases unrealistic and/or uneconomical, and the most suitable procedures are found to involve recycling rather than detoxification of OMW (Cegarra *et al*. 1996). It is also doubtful whether the treated effluents would comply with discharge criteria (Saadi *et al*. 2007). In the absence of feasible OMW treatment solutions, some OMs discharge their wastewater into the environment illegally and without control, with a considerable impact on the receiving soils and waters.

One alternative and economical solution is controlled land application of OMW, also known as land utilisation or agronomic use (Cabrera *et al*. 1996; Sierra *et al*. 2001; Marrara *et al*. 2002; Mechri *et al*. 2007; Saadi *et al*. 2007; Sierra *et al*. 2007). Soils in semi-arid areas have low levels of organic matter content, microbial activity, biomass, and nutrient availability. OMW is rich in organic matter and an important source of nutrients (N, P and K) for plants (Mechri *et al*. 2008). Incorporation of OMW into soil can promote microbiological activity and enhance soil fertility (Sierra *et al*. 2007; Mechri *et al*. 2008).

In organic and sustainable farming, both the nutritional value of OMW and its potential herbicidal activity and ability to induce suppression of soil-borne plant pathogens are of extra value (Saadi *et al*. 2007). OMW does not contain pathogenic microorganisms or great concentrations of heavy metals, but its use may lead to some negative effects on soils and waters, related to acidity, salinity and the accumulation of lipids, organic acids and phenolic compounds (Cegarra *et al*. 1996). For the above-mentioned reasons, great attention has to be paid to both the quantity and methods used to spread OMW on agricultural land in order to avoid or reduce the negative effects on crops, soils and the environment. Accumulation and subsequent distribution through irrigation plants may represent a sustainable solution to the various problems connected with OMW disposal (Marrara *et al*. 2002). Besides allowing for a considerable saving in costs, the use of irrigation plants allows

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optimal (gradual and uniform) distribution of wastewater.

Italian law already permits annual spreading of up to 50 or 80 m^3 ha^{-1} for OMW generated by pressing or the continuous centrifugation method, respectively (Rinaldi *et al.* 2003). The agronomic use of OMW is regulated in Catalonia (Spain) and in Portugal, where an application rate of 30 m^3 ha^{-1} $year^{-1}$ is permitted (Sierra *et al.* 2007).

The paper includes three parts. The first part briefly describes the main effects of the agronomic use of OMW on plants and soils, based on the results of recently published experiments. The different aspects concerning the prospects of an irrigation system for land spreading of OMW, in particular with respect to their suitability, the filtration requirements and the emitter clogging risks, are examined in the second part. Finally, the third part summarises the results of experiments performed on emitters and filters using OMW previously stored in open reservoirs, possibly diluted with rain water.

EFFECTS OF THE AGRONOMIC USE OF OLIVE OIL MILL WASTEWATER

The addition to soil of organic matter is encouraged in Mediterranean agro-ecosystems that are naturally poor in organic soil matter and greatly exposed to risks of erosion and desertification (Brunetti *et al.* 2007). Organic matter can increase water infiltration, water-holding capacity and aggregate stability, improve the mineral nutrient status and growth of plants, and, in saline or sodic soils, can accelerate the leaching of Na, decrease the exchangeable Na percentage (ESP) and the electrical conductivity (EC) (Walker *et al.* 2008). The agronomic use of OMW can represent a strategy in which plant nutrients and organic matter are returned to the soil. However, the modalities adopted and the quantity of OMW to spread on agricultural soil has until now been a subject of controversy in scientific communities. The existing results are sometimes contradictory, not always useful to draw practical conclusions, and they do not seem sufficient to draw definitive conclusions, as shown by the brief review of literature discussed here.

Results of several experiments using OMW showed that the growth and yield of different types of crops were, in general, similar or higher than those of the controls (Saadi *et al.* 2007). The main research discussed in this review is listed in **Table 1**. Cegarra *et al.* (1996) showed that yields of *Beta vulgaris* (sugar beet), *Lactuca sativa* (lettuce), *Hordeum vulgare* (barley) and *Brassica oleracea* (cauliflower) obtained in field and pot experiments using 30 or 60 t ha^{-1} of different types of OMW compost were not significantly different from those obtained with a balanced mineral fertilizer (**Table 1**). However, the concentrations of Fe and Mn in plants and soil were significantly affected by both compost types and application rates, with higher concentrations observed after treatment with OMW compost. Rinaldi *et al.* (2003), based on the results of three years of experiments in South Italy, showed that durum wheat can tolerate OMW spreading during the early growing stage. However, they suggested great care in spreading the OMW uniformly at 50 m^3 ha^{-1} (**Table 1**). Brunetti *et al.* (2007) found that an amendment with 300 or 600 m^3 ha^{-1} of lagooned or catalytically digested OMW positively affected durum wheat grain yield in Mediterranean conditions (Bari, Italy). The enhanced amount of both humified and non-humified soil organic C in amended soils appeared to play a major role in improving wheat yield (**Table 1**), possibly by increasing moisture retention. According to Walker *et al.* (2008), an OMW compost markedly increased the shoot growth (**Table 1**) of salt-tolerant *Beta maritima* L. (sea beet) and *Beta vulgaris* L. (sugar beet). Cultivation of tomato after *B. vulgaris* showed that the impacts of the amendment did not last long.

Other research has explored different aspects related to various chemical, biochemical and physical soil properties and microbial activity. In general, temporary decrease in soil pH, increase in salinity and phenol concentration (Gallardo-Lara *et al.* 1990; Cabrera *et al.* 1996; Zenjari *et al.* 2001), immobilisation of available N (Saviozzi *et al.* 1991) and temporary increase in bulk density with reduced hydraulic conductivity (Colucci *et al.* 2002) have been observed. The main impact of OMW on soil microbial activity was an increase in respiration and microbial biomass (Savi-

Table 1 Review of OMW effects on crops in the literature.

Author	Experiment type	OMW treatment and quality	Crop	Treatments	Yield (% respect to the control)
Cegarra *et al.* 1996	Field and pots	Compost with fresh OMW (SCO)	Sugar beet and lettuce	Control with mineral fertilizer	100
		Compost with OMW sludge and cotton waste (COS)		SC (SCO without OMW) 30 and 60 t ha^{-1}	≅100
		Compost with OMW sludge and maize straw (MOS)		SCO 30 & 60 t ha^{-1}	≅100
		pH= 7.84 (SCO); 8.99 (COS); 8.73 (MOS)	Barley	Control with mineral fertilizer	100
		EC (dS m^{-1})= 7.66 (SCO); 5.01 (COS); 5.03 (MOS)		SC 30 t ha^{-1}	78
		TOC (%)= 29.4 (SCO); 20 (COS); 18.9 (MOS)		SC 60 t ha^{-1}	84
		Total N (%)= 3.1 (SCO); 1.9 (COS); 1.4 (MOS)		SCO 30 t ha^{-1}	62
		Total P (%)= 0.9 (SCO); 0.3 (COS); 0.2 (MOS)		SCO 60 t ha^{-1}	82
		Total K (%)= 2.6 (SCO); 3.7 (COS); 3.2 (MOS)	Cauliflower	Control with mineral fertilizer	100
				COS 30 t ha^{-1}	89
				MOS 30 t ha^{-1}	79
Rinaldi *et al.* 2003	Field	Without pre-treatments pH= 5.2; TOC (g L^{-1})= 43.3; Total N (g L^{-1})= 1.6; Total P (g L^{-1})= 0.83; Total K (g L^{-1})= 1.04	Durum wheat (cv. 'Simeto')	Not treated	100
				Treated 50 t ha^{-1}	97
Brunetti *et al.* 2007	Field	Lagooned 60 days (LW); Catalytically digested 60 days (CW); pH= 4.8 (LW); 5.2 (CW); EC (dS m^{-1})= 10 (LW); 11.2 (CW); TOC (g L^{-1})= 23.6 (LW); 24.6 (CW); Total N (g L^{-1})= 0.28 (LW); 0.31 (CW); Total P (g L^{-1})= 0.24 (LW & CW); Total K (g L^{-1})= 1.99 (LW); 1.96 (CW)	Durum wheat	Non amended	100
				LW 300 m^3ha^{-1}	138
				LW 600 m^3ha^{-1}	157
				CW 300 m^3ha^{-1}	143
				CW 600 m^3ha^{-1}	167
Walker *et al.* 2008	Pot (4.6 kg air-dry soil per pot)	Compost with olive husk and cotton waste (COMC), compared with poultry manure (PM); pH=9.3 (COMC); 7 (PM);EC (dS m^{-1})= 3.3 (COMC); 5.5 (PM); TOC (g kg^{-1})=479 (COMC); 337 (PM); Total N (g kg^{-1})= 24.5 (COMC); 32.1 (PM); Total P (g kg^{-1})= 2.4 (COMC); 15.9 (PM); Total K (g kg^{-1})= 26.7 (COMC); 25.8 (PM)	Sea beet	Non amended	100*
				COMC 20.9 g kg^{-1} dry soil	350
				PM 29.7 g kg^{-1} dry soil	1250
			Sugar beet	Non amended	100
				COMC 20.9 g kg^{-1} dry soil	500
				PM 29.7 g kg^{-1} dry soil	480
			Tomato	Non amended	100
				COMC 20.9 g kg^{-1} dry soil	113
				PM 29.7 g kg^{-1} dry soil	138

* shoot dry matter

Table 2 Review of OMW effects on soil in the literature.

Author	Experiment type	Type and mean characteristics of soil used as control	OMW treatment and quality	Treatment	Effects on soil (with respect to the control) at the end of the experimental period	
					Significantly increased	S. decreased
Piotrowska *et al.* 2006	Laboratory; soil in pots; soil samples analysed 14, 28 and 42 days after OMW application	Sandy Clay Loam; pH= 8.1; EC= 0.28; TOC= 12.5; C/N= 8.7; CEC= 10.9; N_{tot}= 1.4; N_{extr}= 0.04; P_{av}= 0.03; K= 0.99 (meq/100 g)	Without pre-treatments; pH= 4.9; EC= 11.6; K= 3.5 (meq/100 g); Phen.= 3.3	OMW 40 m^3 ha^{-1}	EC, TOC, C/N, N_{tot}, N_{extr}, P_{av}, K, MB-C	
				OMW 80 m^3 ha^{-1}	EC, TOC, C/N, N_{tot}, N_{extr},P_{av}, K, MB-C,	CEC, soil germination capability
Brunetti *et al.* 2007	Field; wheat crop; soil samples analysed 4 months after OMW application	Sandy Loam; pH= 8; EC =0.19; TOC= 10.3; N_{tot}= 1; P_{av}= 33; K_{av}= 186; C/N= 10; TEC= 7.9; (HA+FA)-C= 7; (NH)-C= 0.9; DH= 89; HR= 68; HI= 0.13	OMW lagooned 60 days (LW) or catalytically digested 60 days (CW); characteristics in **Table 1**	LW 300 m^3 ha^{-1}	EC, TOC, P, K, C/N, TEC, (HA+FA)-C, (NH)-C, DH, HR, HI	pH
				LW 600 m^3ha^{-1}	EC, TOC, N, P, K, C/N, TEC, (HA+FA)-C, (NH)-C, HI	pH, DH, HR
				CW 300 m^3 ha^{-1}	EC, TOC, N, P, K, C/N, TEC, (HA+FA)-C, (NH)-C, HI	pH, DH, HR
				CW 600 m^3 ha^{-1}	EC, TOC, N, P, K, C/N, TEC, (HA+FA)-C, (NH)-C, HI	pH, DH, HR
Mechri *et al.* 2007	Field; olive trees; soil samples analysed 30 days after OMW application	Sand (%)= 78.1; Clay (%)= 12.9; Silt (%)= 5.1; pH= 8.53; EC= 0.44; C_{tot} = 3.7; N= 0.42; C/N= 8.33; P= 0.02; K (meq/100 g)= 0.62; Total FAME= 166; B= 39; F= 5; F/B=0.13	OMW without pre-treatments; pH= 5.1; EC= 9.1; COD= 93; N= 1.34; P= 0.72; K = 6.2; Phen.= 8.4	OMW 30 m^3 ha^{-1}	C/N, P, K, Total FAME, B, F, F/B	
				OMW 60 m^3 ha^{-1}	C/N, P, K, Total FAME, B, F, F/B	
				OMW 100 m^3 ha^{-1}	C, CN, P, K, Total FAME, B, F, F/B	pH
				OMW 150 m^3 ha^{-1}	EC, C, C/N, P, K, Total FAME, B, F, F/B	pH
Mechri *et al.* 2008	Field; olive trees; soil samples analysed 1 year after OMW application	As in Mechri *et al.* (2007)	As in Mechri *et al.* (2007)	OMW 30 m^3 ha^{-1}	P, K, F, F/B	
				OMW 60 m^3 ha^{-1}	P, K, F, F/B, AM fungi	
				OMW 100 m^3 ha^{-1}	P, K, F, F/B, AM fungi	B
				OMW 150 m^3 ha^{-1}	EC, C, C/N, P, K, F, F/B, AM fungi	B
Mekki *et al.* 2007	Field; olive trees; soil samples analysed after 4 months and 7 years of OMW application	[(1)] pH=8.3; EC= 1.98; OM= 0.16; Phen.= 0.02	OMW without pre-treatments; pH= 5.1; EC=8.9; COD= 72; TOC= 25; N_{tot}= 0.6; C/N= 43; P= 0.04; K= 8.8; ortho-diphenols= 9.2	OMW 50 m^3 ha^{-1}	EC, OM, Phen.	
				OMW 100 m^3 ha^{-1}	EC, OM, Phen.	
				OMW 200 m^3 ha^{-1}	EC, OM, Phen.	pH
Saadi *et al.* 2007	Field; plum orchard; soil samples analysed 1 and 2 weeks and 3 months after OMW application	Fine Clay	OMW two months stored in a closed tank; pH= 6.6; COD= 91.3; N_{tot}= 2.8; Phen.= 3	OMW 36 m^3 ha^{-1}		
				OMW 72 m^3 ha^{-1}	CFU, F, Microbial respiration (CO_2)	
Sierra *et al.* 2007	Field and laboratory; olive trees; soil samples analysed 10, 30, 60 an 120 days after OMW application	Calcareous Clay Loam; pH= 8; CEC= 15.7; pH= 8	OMW from stabilisation lagoon; pH= 8.5; EC= 11.6; COD= 50; P= 0.18; C/N= 35; Phen.= 1	OMW 30 m^3 ha^{-1}		
				OMW 180 m^3 ha^{-1}	P, adsorbed Phen.	
				OMW 360 m^3 ha^{-1}	EC, P, adsorbed Phen.	
Walker *et al.* 2008	Pot (4.6 kg air-dry soil per pot); soil samples analysed at harvest	Calcareous Clay Loam; pH= 7.7; EC= 1.85; OM= 1.51; N_{tot}= 0.84; C/N= 10.5; K_{tot}= 0.2; CEC (cmol kg^{-1})= 11.2; Bore (mg kg^{-1})= 1.48	Compost with olive husk and cotton waste (COMC); characteristics in **Table 1**	COMC 20.9 g kg^{-1} dry soil		
				Sea beet	CEC, K_{tot}, Bore	
				Sugar beet	CEC, K_{tot}, Bore	
				Poultry manure 29.7 g kg^{-1}		
				Sea beet	CEC, K_{tot}, Bore	
				Sugar beet	CEC, K_{tot}, Bore	

EC = electrical conductivity (dS m^{-1}); TOC = total organic C (g kg^{-1}); CEC= cation exchange capacity (meq/100 g of soil); COD = chemical oxygen demand (g L^{-1}); N, P, K = in soil (g kg^{-1}) and in water (g L^{-1}); tot = total; av = available; extr = extractable; Phen.= phenolic compounds in soil (g kg^{-1}) and in water (g L^{-1}); MB-C = microbial biomass Carbon; TEC = total extractable C (g kg^{-1}); (HA+FA)-C = humified content (g kg^{-1}); (NH)-C= non-humified content (g kg^{-1}); DH = degree of humification (%); HR= humification rate (%); HI = humification index (%); FAME = fatty acids (µg kg-1); B = bacteria (µg kg^{-1}); F = fungi (µg kg^{-1}); AM fungi = arbuscular mycorrhizal fungi (µg kg^{-1}); CFU = colony forming units; OM= organic matter (%); [(1)] at 0.5 m of depth.

ozzi *et al*. 1991; Alianiello *et al*. 1998; Gamba *et al*. 2005).

Table 2 shows some details of recent experiments which confirm the above-mentioned general considerations. Increasing rates of lagooned OMW (from 30 to 360 m^3 ha^{-1}) notably enhanced the fertility of a Typic Xerorthent soil in Tarragona (Spain) (Sierra *et al*. 2007). The authors suggest rates no higher than 180 m^3 ha^{-1} per year to control the temporal immobilisation of nitrates and the increase in salinity and phenolic compound concentrations (**Table 2**).

Organic C content, C/N ratio and exchangeable P and K were greater in soil amended with 30-150 m^3 ha^{-1} of OMW in a field of olive trees located in Tunisia (**Table 2**) (Mechri *et al*. 2007, 2008). Olive mill wastewater spreading stimulated the fungal and actinomycetes communities (**Table 2**). The increase in fungi can help to degradate the phenolic and non-phenolic aromatic pollutants in OMW, and the partial delignification of OMW used as a substrate can exert a positive effect on the growth of other soil microorganisms, including those contributing to the total degradation of recalcitrant pollutants (Mechri *et al*. 2007). However, Mechri *et al*. (2008) observed a parallel decline in the arbuscular mycorrhizal fungi (**Table 2**) formed by the olive plants. Mycorrhizal fungi increase the potential for nutrient and possibly water uptake and play an essential role in supporting plants under biotic or abiotic stress. Mechri *et al*. (2008) suggest that the altering functioning of arbuscular mycorrhizae should be considered as potential factor mediating olive tree responses to agronomic application of OMW when the dose applied is higher than 30 m^3 ha^{-1}.

A high fungi/bacteria quotient was also observed by Piotrowska *et al*. (2006) during investigations into the short-term influence of OMW on several chemical and biochemical properties of a soil from a continental semi-arid Mediterranean region (Morocco). During the experiments a potted sandy clay loam soil was amended with 40 or 80 m^3 ha^{-1} of OMW. They showed that the impact of OMW on soil properties was the result of opposite effects (positive-negative) depending on the relative amounts of beneficial and toxic organic and inorganic compounds present. In particular, a sudden increase in total organic C, extractable N and C, available P and the microbial biomass of OMW-amended soils occurred (**Table 2**). In contrast, the soil became highly phytotoxic after the addition of 80 m^3 ha^{-1} OMW: soil germination capability of almost 60% and a residual phytotoxicity of about 30% were observed after 42 days' incubation. However, complete recovery of the soil germination capability was instead observed with 40 m^3 ha^{-1} of OMW.

The amendment of a sandy soil (about 90% of sand) located in Châal (Tunisia) with 50-200 m^3 ha^{-1} of unprocessed OMW showed the presence of phenolic compounds at different soil depths four months after spreading and in the 7th consecutive year of irrigation by OMW (Mekki *et al*. 2007). The phytotoxic phenolic monomers tend to disappear from the upper layer of soil after some time, due to degradation or polymerization or to significant leaching to the deeper soil layers, which may provoke contamination of the ground water in the long term.

Saadi *et al*. (2007) carried out a field experiment in an organic orchard of plum trees located on a Vertisol-type soil in Jezre'el Valley (Israel), spreading 36 or 72 m^3 ha^{-1} of OMW (**Table 2**). The OMW was spread in three applications during three months (from December to February). The results of this study show that OMW potentially stimulates soil microbial activity and is not harmful to soil microflora in general and not necessarily detrimental to soil fertility. The rates of mineralization proved the biodegradability potential of OMW, and the absence of a detrimental effect on soil activity. Pure OMW (100%) was highly toxic to germinating cress (*Lepidium sativum* L.) seeds. The authors also showed the practical relevance of alterations in OMW properties stored for a period of three months. The COD, BOD and dissolved organic carbon (DOC) decreased by about 10%. Total nitrogen decreased by almost 50% and total phenols by 20%, whereas pH increased from 4.5 to 6.6. Dealing with this aspect, Marrara *et al*. (2002) suggested that besides providing the spreading system with a useful flexibility, OMW storage could play the role of effluent pretreatment. They observed an almost 50% decrease in BOD and COD during 140 days of storage.

Walker *et al*. (2008) evaluated the effects of OMW compost on mineral ion solubility and exchangeability in a highly saline agricultural soil in Murcia (Spain). Organic amendment with 20.9 g kg^{-1} of dried soil compost increased the soluble K and the cation exchange capacity, and did not significantly change the soil EC or the soluble Na, Ca or Mg.

SUITABILITY OF IRRIGATION METHODS FOR OLIVE OIL MILL WASTEWATER SPREADING

Although several of the papers commented on above highlight that the effects of OMW on crops, soils and the environment depend on the quantity of OMW distributed, very little information on the systems and modalities used to spread OMW is available. The lack of attention to this aspect is probably due to the fact that interest in the rational agronomic use of OMW and the experimental nature of the experiences described in the literature is very recent.

A gradual, uniform distribution of low amounts of OMW (e.g. 50-80 m^3 ha^{-1} $year^{-1}$) can be obtained through irrigation systems (Marrara *et al*. 2002; Capra *et al*. 2007a). It allows for a considerable saving in costs, mainly when an irrigation system already exists. OMW could be used in olive groves, usually located in the area of OMW production, and in other arboreous crops, mainly in those farmed using traditional cultivation methods in which the surface soil layer (0.15-0.20 m deep) is regularly cultivated. In this case, in fact, the small amounts of OMW can be spread far from the active roots of the trees.

In areas with a Mediterranean climate, characterized by little or no rainfall during the most critical phenological phases for yield formation, intensive olive growing is barely feasible without irrigation (Pérez-López *et al*. 2008). Furthermore, the introduction of olive oil via the Mediterranean diet and its associated health properties has induced an increase in olive crop areas throughout the world. This has led to a situation in which some of the traditional olive groves, and the majority of the new ones, are being adapted to irrigation techniques (Gómez-Rico 2007). Olive orchards in Greece, Israel, Italy, Spain, Turkey and other Mediterranean countries, Argentina, Australia and California are irrigated with a variety of microirrigation systems (drip, microtubes, microjets) (Beede *et al*. 1994; Michelakis *et al*. 1996; Çetin *et al*. 2004; Government of South Australia 2006; Rousseaux *et al*. 2008).

The irrigation method used for spreading OMW has to have specific characteristics which minimise the risks of plant toxicity due to direct contact between roots and leaves and water, and water body contamination due to excessive water loss by runoff and percolation. From these points of view, microirrigation is the most suitable method for safe OMW distribution.

Microirrigation systems include use of line-source lateral drip tubes, microsprayers, microsprinklers, spaghetti tubes, capillary mats, and numerous other emitter devices and systems (Keller *et al*. 1990; Capra *et al*. 2007b). These systems apply water at low rates to localized zones and allow precise and controlled irrigation applications. Microsprayers and drippers are the most common emitters used in olive groves and on other orchard crops. These emitters operate with a low water application rate (4-200 l/h per emitter) and low operating pressure requirements (100-150 kPa). Pumping power requirements are generally low.

The maintenance of microirrigation systems is more complicated than sprinkler irrigation. The small orifices and openings of these systems can be clogged by small particles or growths. Emitter clogging is the largest management problem with drip systems (Keller *et al*. 1990; Capra *et al*. 2007b). Partial or complete clogging reduces emission uniformity which, in turn, reduces water distribution uniformity (Capra *et al*. 2007c).

Filtering is the main defence against clogging. The main filter types are screen, disk and gravel-sand media filters. The most commonly used in irrigation are screen and disk filters; they are simple, economical and easy to manage. Gravel-sand media filters are particularly suitable for water with a high suspended solids content, but they are relatively more complex and expensive.

Clogging and mitigation procedures are closely related to the quality of the water used. High levels of suspended solids (TSS), organic matter, calcium, bicarbonates, iron and sulfates may clog emitters. At present, analytical methods to forecast the clogging risk do not exist. Nakayama *et al.* (1991) and Capra *et al.* (1998) classified the respective clogging risks for common drippers (discharge from 2 to 4 l h^{-1}), large-size drippers (discharge from 8 to 16 l h^{-1}) and sprayers using clean water.

Despite great experience with other types of non-conventional water, above all urban wastewater (see, among others, Scischa *et al.* 1996; Capra *et al.* 2004, 2005), very few tests have been carried out on OMW. The authors performed field tests (Capra *et al.* 2005, 2007a) with stored dilute and non-dilute olive wastewater on the performance of different kinds of mini-sprayers and drippers, and different kinds of filters, both commonly installed in olive grove and orchard irrigation systems.

EXPERIMENTAL TESTS ON MICROIRRIGATION SYSTEMS

Materials and methods

1. Experimental systems

The tests were carried out using wastewater from an oil mill with a three-phase continuous-cycle extraction plant, located on a farm in the Lamezia Terme (Italy) area; the water was collected in a 180 m^3 uncovered concrete tank.

Three cycles of tests were carried out using OMW after a 4- to 5-month sedimentation period; in the first (2001) and third (2007) cycle (henceforward referred to as Trial 1 and Trial 3) the water was diluted with about 50% rain water before the experiment, whereas in the second (Trial 2, in 2004) it was not diluted. The water characteristics useful for clogging risk classification were determined by periodical analysis of TSS, EC and COD (three times – at the start, middle and end of the test).

Table 3 synthesises the experimental layout (OMW, filters and emitters tested during the trials).

The emitters tested in Trials 1 and 2 (**Table 3**) were static sprayers from different manufacturers and with different flow rates, all with a flow rate/pressure index *x* of about 0.5. Those tested in Trial 1 were Microfix 90 l h^{-1} and Tornado 80 l h^{-1}; those in Trial 2 Imago 35, 70 and 90 l h^{-1}. Line-source lateral drip tubes were used in Trial 3. The emitters were labyrinth drippers with different emitter sizes and flow rates (**Tables 3** and **4**) manufactured by Irritec-Siplast in a polyethylene pipe with external and internal diameters of 20.1 and 17.7 mm, respectively. These drippers are particularly suitable for use with water of poor quality as they have a microfilter inserted at the inlet of the water into the labyrinth and a labyrinth shape that is suitable for self-cleaning; the microfilter surface areas are 19, 30 and 60 mm^2 for the 3.8, 7 and 15 l h^{-1} drippers, respectively.

Table 3 Experimental layout.

Trial	OMW	Filter		Emitters
		Commercial name	Abbreviation	
1	W1	Arkal Disk 40	D40	Tornado
		Arkal Disk 80	D80	sprayer 80,
		JP Screen 50	RJP50	Microfix
		JP Screen 75	RJP75	sprayer 90
2	W2	Arkal Disk 40	D40	Imago sprayer
		Arkal Disk 80	D80	35, 70, 90
		Arkal Disk 120	D120	
		Arkal Disk 140	D140	
		Valducci Screen 75	R75	
		Valducci Screen 120	R120	
		Valducci Screen 150	R150	
		Valducci Screen 180	R180	
3	W3	Arkal Disk 40	D40	Irritec dripper
		Arkal Disk 80	D80	3.8, 7, 15
		Arkal Disk 120	D120	
		Valducci Screen 50	R50	
		Valducci Screen 75	R75	
		Valducci Screen 120	R120	
		Valducci Screen 180	R180	

Table 4 Characteristics of drippers tested in Trial 3.

Nominal flow rate (l h^{-1})	Labyrinth size (mm)			Flow rate-pressure equation*	
	Depth	Width	Length	k	x
3.8	1.4	1.4	252	1.38	0.43
7	1.5	1.5	125	2.13	0.53
15	1.5	1.5	63	5.19	0.44

* q = k H^x, where q = flow rate, l h^{-1}; H = pressure head, m; k and x obtained by regression analysis using the four pressure values and the corresponding flow rate values published in the Siplast catalogue (Siplast 2007).

Table 5 Characteristics of filters tested.

Type	Surface area (m^2)	Filtration dimension, mesh (mm)
D40	0.069	40 (0.42)
D80	0.069	80 (0.18)
D120	0.069	120 (0.13)
D140	0.069	140 (0.11)
RJP50	0.12	50 (0.31)
RJP75	0.12	75 (0.21)
R50	0.081	50 (0.31)
R75	0.081	75 (0.21)
R120	0.081	120 (0.13)
R150	0.081	150 (0.11)
R180	0.081	180 (0.09)

Fig. 1 Experimental irrigation system.

In Trial 1, two types of filter (disk and screen) and two filter sizes for each type were tested; in Trial 2, two types of filter and 4 filter sizes; and, in Trial 3, two types of filter and three filtration sizes (**Table 3**). All the filters tested had a theoretical flow-rate of 5 l s^{-1}. **Table 5** lists the features of the filters tested.

The experimental plants (**Fig. 1**) were divided into sectors, one for each type of filter. Each sector comprised a filter; two pressure gauges, one before and one after the filter; a ½″ volume counter; a digital differential pressure gauge, and polyethylene pipes with external diameters of 32 or 20.1 mm (for sprayers and drippers, respectively). Twenty-five emitters for each type spaced at 0.2 m intervals were tested. The irrigation system was run by a 4 KW electric pump.

2. Experimental procedure

Eight test sessions per Trial were performed about once a week between May and July, each lasting about 4 hours, for a total of 32 hours, to simulate the distribution of OMW amounts similar to those permitted by Italian law. The filters were cleaned manually at the end of each session using clean water and domestic detergents.

The following measurements were taken during each session: the flow rate for 8 emitters per type equally distributed along the pipe, at the end of each session; the difference in pressure due to head loss in each filter type; the total volume emitted by each sector; and the number of totally clogged emitters (zero flow rate) at the end of the session. To measure the flow rate, the flow emitted by emitters in a fixed time was collected in cylinders graduated every 20 ml.

Total clogging is expressed as the percentage of emitters totally clogged. Partial clogging is obtained by comparing the flow rate measured with that of new, unclogged emitters, at the operating pressure measured during the tests, and calculated using the flow-rate/pressure equation of new, unclogged emitters. Partial clogging was thus expressed by means of the flow rate ratio (R_q, %):

$$R_q = 100\ (q_m / q_c) \qquad (1)$$

where q_m = measured flow rate, l h^{-1}, q_c = calculated flow rate, l h^{-1}.

The lower the value of R_q, the higher the level of clogging is.

The measured flow rates were also used to calculate the emission uniformity coefficient, EU (Keller *et al*. 1990):

$$EU = 100\ (q_{1/4\ min} / q_m) \qquad (2)$$

where $q_{1/4\ min}$ = mean of the low quarter of the flow rates, l h^{-1} ; q_m = mean of all flow rates, l h^{-1}.

The feasibility of homogeneous OMW distribution is obtained with high values of *EU* (>80%).

Filter performance was evaluated in terms of the time pressure was maintained after the filters, and the head losses occurring during the test sessions.

The number of treatments (kind of water × kind of filters × kind of emitters) is 53 (see **Table 3**), with 8 repetitions (8 emitters of the same kind). Using Microsoft Office Excel 2003, the parameters expressing the emitter performance (D_r, *EU* and the percentage of totally clogged emitters) were subjected to variance analysis and the differences between the means were determined using the *t*-test at P≤0.05. The analysis of variance was applied pooling 64 data (8 emitters × 8 test sessions) for each treatment. The comparison is between homogeneous groups (e.g. between treatments and grouping treatments with the same filter kind).

RESULTS

Water quality

As is evident in **Table 6**, the OMW used in Trial 2 was the worst for both chemical oxygen demand (COD) and EC, whereas TSS was higher for the OMW used in Trial 3. As regards emitter clogging, the water used in Trial 1 can be classified (Nakayama *et al*. 1991; Capra *et al*. 1998) as low-risk for TSS and moderate for EC, that used in Trial 2 as moderate-risk for TSS and high-risk for EC, and that used in Trail 3 as high-risk for TSS and moderate-risk for EC. The waters were classified for COD according to the classification for BOD_5 (Capra *et al*. 2004, 2005), as no classification based on COD exists.

Emitter performance

The various emitters behaved differently in the different trials. During Trial 1, although the drop in flow rate (expressed by *Rq*) was less for Tornado emitters, or similar in the two types of emitters (**Table 7**), only Microfix gave close to optimal *EU* values (almost 90%), at least with disk filters (**Table 8**). Total clogging was very rare and temporary.

During Trial 2, emitter performance generally depended on emitter discharge and filter size. 35 l h^{-1} emitters, those with the smallest discharge and size, did not perform satisfactorily (low values of both R_q and *EU*, **Tables 7** and **8**); moderately good results were obtained with 70 l h^{-1} emitters; 90 l h^{-1}, emitters gave the best performance, with a few exceptions, mainly for *EU* and disk filters. A high percentage of totally clogged emitters was observed for 35 l h^{-1} emitters, whereas total clogging was rare for 90 l h^{-1} emitters (**Table 9**). Optimal *EU* values (close or equal to 90%) were obtained with 70 l h^{-1} emitters and 40 and 120 mesh disk filters; with 90 l h^{-1} emitters and 40, 80 and 120 mesh disk filters, and with a 75 mesh screen filter (**Table**

Table 6 Characteristics of olive mill wastewater used in the trials (M= mean; SD= standard deviation; CR= clogging risk).

	W1			W2			W3		
	M	**SD**	**CR**	**M**	**SD**	**CR**	**M**	**SD**	**CR**
Total suspended solids, TSS (mg l^{-1})	68	89	Low	551	306	Medium	942	92	High
Electrical conductivity, EC (dS m^{-1})	2.91	0.03	Medium	7.07	1.05	High	2.22	0.02	Medium
COD (mg l^{-1} O_2)	14723	468	High	21539	642	High	6500	120	High

Table 7 Flow rate ratio (*Rq*, %) during Trials 1 and 2 (M= mean; SD= standard deviation).

Trial	Filter	M	SD	M	SD	M	SD
1		**Sprayers Tornado 80 l h^{-1}**		**Sprayers Microfix 90 l h^{-1}**			
	D40	96	6	89	4		
	D80	100	4	93	7		
	Mean D	98	5	91	6		
	SJP50	83a	5	83a	5		
	SJP75	93a	9	93a	3		
	Mean S	88a	7	88a	4		
	Mean trial	93a	6	90a	5		
2		**Sprayers Imago 35 l h^{-1}**		**Sprayers Imago 70 l h^{-1}**		**Sprayers Imago 90 l h^{-1}**	
	D40	83	27	98	27	91A	13
	D80	62A	55	89	26	92A	15
	D120	88	20	99	11	91A	16
	D140	61A	42	70A	29	79B	29
	Mean D	74	36	89a	23	88a	18
	S75	47B	42	67	44	70	30
	S120	46B	25	70A	36	81B	28
	S150	72	29	75a	19	74a	11
	Mean S	55	38	71	36	77	12
	Mean trial	66	47	81a	30	82a	25

D= disk; S= screen; Means followed within the same row by the same small letter or by the same capital letter within the same column are not statistically different by *t*-test (P≤0.05); the comparison within the same column is between homogeneous groups (e.g. treatments or Means).

Table 8 Emission uniformity coefficient (*EU*, %) (M = mean; SD = standard deviation)

Trial	Filter	M	SD	M	SD	M	SD
1		Sprayers Tornado 80 l h^{-1}		Sprayers Microfix 90 l h^{-1}			
	D40	79	3	89AB	5		
	D80	87	5	91A	9		
	Mean D	83	4	90	7		
	SJP50	47	10	76	6		
	SJP75	68	6	88B	8		
	MeanS	58	8	82	7		
	Mean trial	70	6	86	7		
2		Sprayers Imago 35 l h^{-1}		Sprayers Imago 70 l h^{-1}		Sprayers Imago 90 l h^{-1}	
	D40	52	13	88	15	89A	15
	D80	7	13	79	10	88A	9
	D120	73	14	90	9	89A	8
	D140	11	16	54	7	80	4
	Mean D	36	14	78	10	87A	9
	S75	0	0	11	3	94	6
	S120	33	14	36	9	52B	18
	S150	53a	28	65	11	53aB	16
	Mean S	29	21	37	8	66	13
	Mean trial	32	14	55	9	77	11
3		Drippers 3.8 l h^{-1}		Drippers 7 l h^{-1}		Drippers 15 l h^{-1}	
	D40	88A	10	86	7	81	17
	D80	85a	12	88A	7	86a	10
	D120	91	6	88A	7	89	7
	Mean D	87a	10	87aB	6	84A	11
	S50	88A	6	89A	9	83	12
	S75	82	12	90A	4	84	12
	S120	87	6	85	10	89	8
	Mean S	85a	8	88B	7	85aA	11
	Mean trial	86a	9	87a	6	85	11

D= disk; S= screen; Means followed within the same row by the same small letter or by the same capital letter within the same column are not statistically different by *t*-test (P≤0.05); the comparison within the same column is between homogeneous groups (e.g. treatments or Means).

Table 9 Percentage of totally clogged emitters during Trial 2.

Filter type	Sprayers Imago 35 l h^{-1}		Sprayers Imago 70 l h^{-1}		Sprayers Imago 90 l h^{-1}	
	M	SD	M	SD	M	SD
D40	0.00		0.00		0.00	
D80	10.63	4.96	0.00		0.00	
D120	0.00		0.00		0.00	
D140	20.71	10.18	0.00		5.00	0.00
Mean D	7.83	7.57	0.00		1.25	0.00
S75	16.25	2.31	7.50	2.67	0.00	
S120	6.88	1.77	4.38	1.77	0.00	
S150	16.25	12.50	5.00	0.00	0.00	
Mean S	13.13	5.53	5.63	1.48	0.00	
Mean trial	10.48	6.55	2.81	1.48	0.63	0.00

D= disk; S= screen.

8). Data for the 180 mesh screen filter are omitted because, as will be discussed below, this filter only worked in the first three trials.

During the Trial 3, some values of the flow rate ratio *Rq* were not very convincing because they were equal to or higher than 100 (which means that the measured rates were higher than calculated). This was probably due to an incorrect flow rate-pressure ratio, estimated on the basis of the ratio supplied by the manufacturer.

Emission uniformity values (*EU*) were higher for 3.8 and 7 l h^{-1} emitters (**Table 8**). This means that 3.8 and 7 l h^{-1} drippers were less sensitive to clogging than 15 l h^{-1}. This may be accounted for by the higher labyrinth length in these drippers (**Table 4**), which permits greater particle deposits. This result seems to contrast with that of the previous trials (1 and 2), but the contrast is only apparent. In fact, the different flow rates of the drippers tested are mainly due to a different labyrinth length, and not to a different passage size (see **Table 4**) as in the sprayers.

Few drippers were totally clogged (flow rate equal to zero), only during the first session and only in the sectors with 120 mesh filters, which presented anomalous performance as will be analysed below.

Filter performance

During Trial 1, the best emitter performance was with disk filters, above all in terms of emission uniformity (*EU*) which differs significantly from screen filters (**Tables 8, 9**). A 50 mesh screen filter (SJP50) does not appear to protect emitters adequately, as shown by the low mean flow rate and emission uniformity values (**Tables 7, 8**). D40 and SJP75 only performed well with the Microfix emitter.

In Trial 2 also, disk filters were generally more efficient than screen filters. More specifically, comparing pairs of filters of different types but similar sizes (80 mesh disk with 75 mesh screen and the two 120 mesh filters), when disk filters were used total clogging of emitters only occurred in small size emitters (35 l h^{-1}), whereas when screen filters were used, total clogging occurred in both 35 and 70 l h^{-1} emitters with both 75 (S75) 120 mesh (S120) and 150 (S150) filters (**Table 9**).

During Trial 3, the emission uniformity coefficients (*EU*) showed similar values for the different filter types and filtration dimensions (**Table 8**).

During Trial 1 head losses were very low, always below 1 m (**Fig. 2**). The interval between two filter cleaning operations, 4 hours, was thus sufficient for acceptable head loss levels. The volumes filtered per surface filtering unit in this interval were 120 (screen filters) and 209 (disk filters) m^3 m^{-2}. The filtration speeds for the screen and disk filters were about 8 and 15 l s^{-1} m^{-2}, respectively. The high head loss values in the third session were caused by problems of pre-filtration prior to pumping. Malfunctioning of the pump, counters and differential pressure gauge during this session suggested improving pre-filtration; this was achieved by placing a wide mesh screen around the valve, using a purpose-built wire netting cage (mesh size 1.2 × 1.7

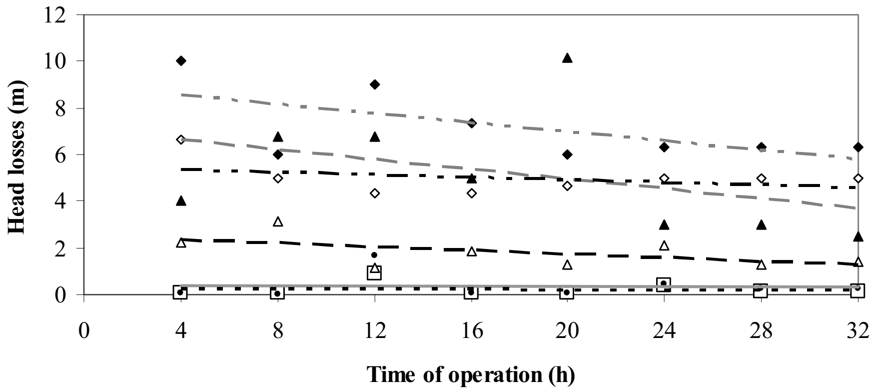

Fig. 2 Head losses in the different trials (T) and filter types (D= disk; S= screen). □ Mean T1-D, ∗ Mean T1-S, △ Mean T2-D, ▲ Mean T2-S, ◇ Mean T3-D, ◆ Mean T3-S.

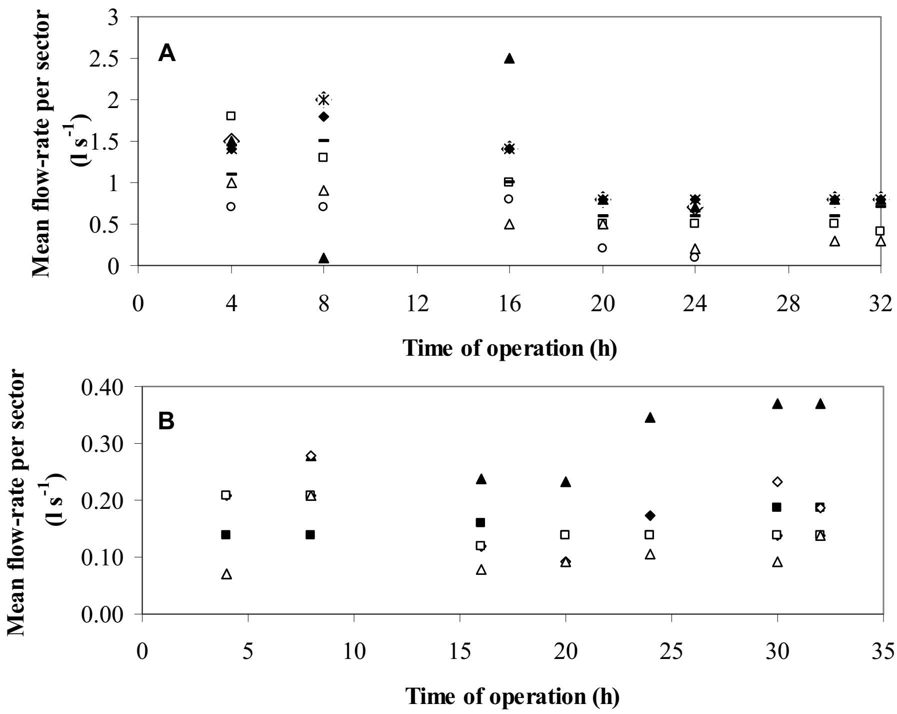

Fig. 3 Mean flow-rate per sector during Trial 2 (**A**), ◇ T2-S75, □ T2-S120, △ T2-S150,○ T2-S180, ∗ T2-D40, ◆ T2-D80, ▲ T2-D120,‒T2-D140, and Trial 3 (**B**), ◆ T3-D40, ■ T3-D80, ▲ T3-D120, ◇ T3-S50, △ T3-S120.

mm) with a large filtering surface (1.5 m^2).

In Trial 2, cleaning operations after 4 hours of operating were sufficient to keep head losses within about 3 m (this value should normally not be any higher for the irrigation plant to function properly) for disk filters (D) (**Fig. 2**). On average, head losses exceeded 3 m after about 1 and 2 hours of operation for 120 and 150 mesh screen filters respectively, and after only a few minutes for the 180 mesh screen filter. The volumes filtered per surface unit were on average 23, 77 and 202 m^3 m^{-2} respectively for 150, 120 and 75 mesh screen filters, and 131, 153, 166 and 167 m^3 m^{-2} respectively for 140, 120, 80 and 40 mesh disk filters. The corresponding filtration speeds were about 6, 11 and 14 l s^{-1} m^{-2} for screen filters (as opposed to the manufacturers' specifications of 62 l s^{-1} m^{-2}) and 11, 13, 14 and 14 l s^{-1} m^{-2} for disk filters (recommended speed 53 l s^{-1} m^{-2}).

In Trial 3, cleaning operations after 4 hours of operation were generally sufficient to keep head losses within about 4 m for disk filters (**Fig. 2**). For the other filters the head losses exceeded these values, sometimes up to 10 m (*ca.* 100 kPa), right from the start of the test sessions despite cleaning after each session. The volumes emitted were similar for the different filter types, with the exception of the 120 mesh; in fact, the volume filtered by the 120 mesh disk filter was almost double that of the other filters, while the volume filtered by the 120 mesh screen filter was the lowest. The volumes filtered per surface unit were on average almost 235 m^3 m^{-2} for the S120 filter, 310 m^3 m^{-2} for S75, 370 m^3 m^{-2} for the D40, D80 and S50 filters, and 680 m^3 m^{-2} for the D120 filter. The corresponding filtration speeds were almost 2 s^{-1} m^{-2} for the S120 filter, 3 l s^{-1} m^{-2} for the D40, D80 and S50 filters, 2.7 l s^{-1} m^{-2} for the S75 filters, and 6 l s^{-1} m^{-2} for D120. These speeds were very low if compared with the manufacturers' specifications (62 l s^{-1} m^{-2} for screen filters and 53 l s^{-1} m^{-2} for disk filters).

System performance

Apart from a certain variability to be expected when wastewater is used, the operating parameters showed no systematic trends during Trial 1. Only a slight decrease in the sector flow-rate was observed until the last test session.

During Trial 2, the flow-rate decreased in all the sectors, mainly in those with screen filters (**Fig. 3A**). After 20 hours of operation the decrease was almost 40% of the initial flow-rate in the sectors with disk filters and 46, 60, 63 and 86% in those with S75, S120, S150 and S180 screen filters, respectively. The flow rate was halved after 24 hours of operation in the S180 sector.

In Trial 3, all filters permitted the system to discharge water throughout the tests. The mean flow rates were almost constant for all the sectors, with the exception of the S75 sector, in which the flow-rate decreased by almost 20%, and the D120 sector, where the flow-rate recovered after some initial functioning anomalies.

DISCUSSION

It is evident from the results given above that the distribution on the soil of OMW through common microirrigation systems is a realistic solution to the problems of OMW disposal, but the water characteristics play a significant role in assessing the possibility of distributing OMW through existing irrigation plants or in choosing suitable emitters and filters when designing a plant with the dual function of irrigating and distributing OMW.

In Trial 1, carried out using water with TSS<100 mg l^{-1}, EC < 3 dS m^{-1} and COD< 15,000 mg l^{-1} O_2, and spray emitters, there were no cases of totally clogged emitters, the emission uniformity was satisfactory for most of the filters and emitters tested, and no filter management problems occurred. Excellent results were obtained using a good-quality emitter like Microfix and 80 mesh disk filters.

In Trial 2, carried out using water of decidedly worse quality (mean TSS, EC and COD values of about 550 mg l^{-1}, 7 dS m^{-1} and 21,500 mg l^{-1} O_2, respectively), spray emitters with a nominal flow rate of 35 and 70 l h^{-1} were in most cases inadequate as they were affected by significant partial and total clogging. 90 l h^{-1} emitters, on the other hand, gave an acceptable emission uniformity, although the mean flow rate was about 25% lower than the theoretical rate for new, unclogged emitters. For 90 l h^{-1} emitters, the optimal filter size, i.e. the one that guaranteed the best trade-off between protecting emitters from clogging and ensuring adequate operating times between cleaning operations, was 75 mesh for screen filters, and 40 and 80 mesh for disk filters.

With OMW of poor quality (TSS equal to 942 mg l^{-1} and COD equal to 6500 mg l^{-1}), all the drippers and the filters tested were sufficiently adequate for OMW distribution, with the exception of the 120 mesch screen filter which showed some operating problems right from the start of the test. The best performance was obtained with the dripper with the highest labyrinth length (flow rate equal to 3.8 and 7 l h^{-1} at a pressure head of *ca.* 100 kPa) and with disk filters. During the trial there were no cases of totally clogged drippers and the emission uniformity was satisfactory (equal to or over 80%), for unconventional water, for most of the filters and emitters tested. All the measured performance indices (mean flow rate, flow rate ratios, emission uniformity, head losses in the filters) showed a high variability during the trials. This variability diminished after the 3^{rd}-4^{th} session of the test, showing a certain capacity on the part of the irrigation system to find an equilibrium with the quality of the water, mainly due to the good characteristics of the drippers whose labyrinths are designed to be self-cleaning. Disk filters with a filtration size of 40 and 80 mesh allowed the system to operate with head losses of less than 4 m during an operating time of 4 hours.

It emerged from the tests that when these types of water are used filters should be sized for a flow rate lower than that recommended by the manufacturers. This does not represent a problem considering the low volumes of OMW to be distributed as compared with the amount of clean irrigation water distributed during normal irrigation.

In all cases pre-filtering before the water was pumped appeared indispensable to protect the pump and other equipment such as counters, pressure gauges, etc.; performance improved considerably after installing a purpose-built wire netting cage with a large filtering surface.

Finally, it will be interesting to test the capacity of the irrigation system to recover initial performance levels after OMW distribution, in order to be used for normal irrigation.

CONCLUSIONS

The agronomic use of OMW, which is an abundant by-product of the olive oil industry, can represent a strategy in which plant nutrients and organic matter are returned to the soil. However, due to some detrimental effects on soil fertility and water body pollution, the practice of OMW spreading on agricultural soil has until now caused controversy in the scientific community. Although the existing results are sometimes contradictory, and do not seem sufficient to draw definitive conclusions, the most suitable procedures found to depollute OMW involve recycling rather than detoxification of OMW.

The effects of OMW on crops, soils and the environment depend on the quantity of OMW distributed. A gradual, uniform distribution of OMW can be obtained through microirrigation systems. However, some system management problems can occur. The small orifices of the emitters and the filters used to protect them can be clogged by small particles or growths due to the suspended solid content of OMW, mainly of organic type.

In summary the following recommendations for OMW agronomic use by micro irrigation systems can be made:

– OMW could be used in olive groves, usually located in the area of OMW production, and in other arboreous orchards, mainly in those where traditional cultivation methods are used and in which OMW can be spread far from the active roots of the trees;

– great attention should be paid to the quantity of OMW distributed; the amounts fixed by Italian law (until 80 m^3 ha^{-1}) seem sufficiently safe;

– storage of OMW before spreading provides the spreading system with a useful flexibility and acts as effluent pre-treatment;

– microirrigation systems are suitable for safe agronomic use of OMW; by allowing a precise, gradual and uniform distribution, they minimise the risks of plant toxicity and water body contamination;

– storage and dilution with clean water (e.g. rain water) can be useful to reduce the system management problems due to emitter and filter clogging;

– microsprayers with a relatively large emitter size (e.g. 90 l h^{-1} flow-rate) and self-cleaning and long labyrinth drippers (e.g. labyrinth length $\geq$ 250 mm) allow OMW to be spread with an acceptable emission uniformity (EU ≥ 80%);

– disk filters with a medium filtration size (e.g. 40 and 80 mesh) can allow the system to operate with head losses of less than 4 m; in these conditions an interval between two filter cleaning operations of 4 hours seems sufficient;

– pre-filtering before the OMW was pumped (e.g. with a large surface wide mesh screen around the valve), is necessary to protect the pump and other equipment such as counters, pressure gauges, etc.;

– cleaning of the pipes with clean water after OMW distribution could be useful to avoid organic matter deposits and bacterial growth in the irrigation system.

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REFERENCES

Alfano G, Belli C, Lustrato G, Vitullo D, Piedimonte D, Lima G, Ranalli G (2007) Modern strategies for oil mill residues exploitation: environmental and energetical opportunities. *International Conference: New Technologies for the Treatment and Valorization of Agro By-Products*, Terni, Italy

Alianiello F, Dell'Orco S, Pinzari F, Benedetti A (1998) Effects of olive mill waste water on microbial activity of agricultural soils. *Fresenius Environmental Bulletin* **7**, 764-771

Beede RH, Goldhamer DA (1994) Olive irrigation management. In: Ferguson L, Sibbett GS, Martin GC (Eds) *Olive Production Manual*, University of California, Publication 3353, pp 61-68

Brunetti G, Senesi N, Plaza C (2007) Effects of amendment with treated and untreated olive oil mill wastewater on soil properties, soil humic substances and wheat yield. *Geoderma* **138**, 144-152

Cabrera F, López R, Martinez-Bordiú A, Dupuy de Lome E, Murillo JM (1996) Land treatment of olive oil mill wastewater. *International Biodeterioration and Biodegradation* **38**, 215-225

Capra A, Scicolone B (1998) Water quality and distribution uniformity in drip/trickle irrigation systems. *Journal of Agricultural Engineering Research* **70**, 355-365

Capra A, Scicolone B (2004) Emitter and filter tests for wastewater reuse by drip irrigation. *Agricultural Water Management* **68 (2)**, 135-149

Capra A, Scicolone B (2005) Assessing dripper clogging and filtering performance using municipal wastewater. *Irrigation and Drainage* **54 (Suppl.)**, S571-S580

Capra A, Andiloro S, Tamburino V, Zimbone SM (2007a) Distribution of olive mill wastewater on soil by irrigation systems. *International Conference: New Technologies for the Treatment and Valorization of Agro By-Products*, Terni, Italy

Capra A, Scicolone B (2007b) Recycling of poor quality urban wastewater by drip irrigation systems. *Journal of Cleaner Production* **15**, 1529-1534

Capra A, Scicolone B (2007c) *Progettazione e Gestione Degli Impianti di Irrigazione. Criteri di Impiego e Valorizzazione delle Acque per Uso Irriguo (Irrigation Systems Design and Management)*, Edizioni agricole de Il sole 24 Ore Editoria specializzata, Bologna, Italy, 297 pp

Cegarra J, Paredes C, Roig A, Bernal MP, García D (1996) Use of olive mill wastewater compost for crop production. *International Biodeterioration and Biodegradation* **38 (3-4)**, 193-203

Çetin B, Yazgan S, Tipia T (2004) Economics of drip irrigation of olives in Turkey. *Agricultural Water Management* **66**, 145-151

Colucci R, Bari VD, Ventrella D, Marrone G, Mastrorilli M (2002) The effect of oil mill effluents on soil aggregation properties. In: Jones R (Ed) *Sustainable Land Management-Environmental Protection. A Soil Physical Approach*, *Advances in Geoecology* **35**, pp 91-100

Gallardo-Lara F, Perez JD (1990) Direct, delayed and residual effects of applied wastewater from olive processing on nitrogen and phosphorous availability in the soil-plant system. *Journal of Environmental Science and Health* **B25**, 379-394

Gamba C, Piovanelli C, Papini R, Pezzarossa B, Ceccarini L, Bonari E (2005) Soil microbial characteristics and mineral nitrogen availability as affected by olive oil waste water applied to cultivated soil. *Communications in Soil Science and Plant Analysis* **36**, 937-950

Gómez-Rico A, Desamparados S, Moriana A, David Pérez C (2007) Influence of different irrigation strategies in a traditional Cornicabra cv. olive orchard on virgin olive oil composition and quality. *Food Chemistry* **100**, 568-578

Government of South Australia (2006) Olives may be grown under full or partial cover low-level sprinkler irrigation, or under drip irrigation. *Factsheet 17/06*, Available online: www.pir.sa.gov.au/factsheets

Greco G, Colarieti ML, Toscano G, Iamarino G, Rao MA, Gianfreda L (2006) Mitigation of olive mill wastewater toxicology. *Journal of Agricultural and Food Chemistry* **54 (18)**, 6776-6782

Kapellakis IE, Tsagarakis KP, Avramaki Ch, Angelakis AN (2006) Olive mill wastewater management in river basins: A case study in Greece. *Agricultural Water Management* **82**, 354-370

Keller J, Bliesner D (1990) *Sprinkle and Trickle Irrigation*, AVI Book, New York, 652 pp

Marrara G, Tamburino V, Zimbone SM (2002) Storage and land application of olive mill wastewater: experiences in Calabria. *ASAE Annual International Meeting/CIGR XVth World Congress*, Chicago, Illinois, USA

Mechri B, Echbili A, Issaoui M, Baham M, Elhadj SB, Hammami M (2007) Short-term effects in soil microbial community following agronomic application of olive mill wastewaters in a field of olive trees. *Applied Soil Ecology* **36**, 216-223

Mechri B, Mariem FB, Baham M, Elhadj SB, Hammami M (2008) Change in soil properties and the soil microbial community following land spreading of olive mill wastewater affects olive trees key physiological parameters and the abundance of arbuscular mycorrhizal fungi. *Soil Biology and Biochemistry* **40**, 152-161

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

Michelakis N, Vouyoukalou E, Clapaki G (1996) Water use and soil moisture depletion by olive trees under different irrigation conditions. *Agricultural Water Management* **29**, 315-325

Nakayama FS, Bucks DA (1991) Water quality in drip/trickle irrigation: a review. *Irrigation Science* **12 (4)**, 187-192

Pérez-López D, Gijón MC, Moriana A (2008) Influence of irrigation rate on the rehydration of olive tree plantlets. *Agricultural Water Management* **95**, 1161-1166

Piotrowska A, Iamarino G, Rao MA, 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**, 600-610

Rinaldi M, Rana G, Introna M (2003) Olive-mill wastewater spreading in Southern Italy: effects on a durum wheat crop. *Field Crop Research* **84**, 319-326

Rousseaux MC, Figuerola PI, Correa-Tedesco G, Searles PS (2009) Seasonal variations in sap flow and soil evaporation in an olive (*Olea europaea*) grove under two irrigation regimes in an arid region of Argentina. *Agricultural Water Management* **96**, 1037-1044

Rozzi A, Malpei F (1996) Treatment and disposal of olive mill effluent. *International Biodeterioration and Biodegradation* **38**, 135-144

Saadi I, Laor Y, Raviv Medina S (2007) Land spreading of olive mill wastewater: effects on soil microbial activity and potential phytotoxicity. *Chemosphere* **66**, 75-83

Saviozzi A, Levi-Minzi R, Cardelli R, Biasci A, Riffaldi R (1991) Suitability of moist olive pomace as soil amendment. *Water, Air, and Soil Pollution* **128**, 13-22

Scischa A, Ravina I, Sagi G, Paz E, Yechiely Z, Alkon A, Schramm G, Sofer Z, Marcu A, Lev Y (1996) Clogging control in drip irrigation systems using reclaimed wastewater – The Platform trials. *7th International Conference on Water and Irrigation*, Tel Aviv, Israel, pp 104-114

Sierra J, Martí E, Montserrat G, Cruañas R, Garau MA (2001) Characteristics and evolution of a soil affected by olive oil mill wastewater disposal. *The Science of the Total Environment* **279**, 207-214

Sierra J, Martí E, Garau MA, Cruañas R (2007) Effects of the agronomic use of olive oil mill wastewater: field experiment. *The Science of the Total Environment* **378**, 90-94

Walker DJ, Bernal MP (2008) The effects of olive mill waste compost and poultry manure on the availability and plant uptake of nutrients in a highly saline soil. *Bioresource Technology* **99**, 396-403

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