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Present and Future Perspectives of Olive Residues Composting in the Mediterranean Basin (CompMed)

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ABSTRACT

For many years, olive mill wastewater (OMW) from oil production plants has been the most pollutant and troublesome waste produced by the olive industry in all Mediterranean countries. Olive wastes (OMW and three-and two-phase olive husks) are generated in large quantities in short periods of time and represent a substantial economic and environmental problem for the sector. Inappropriate management has in the past led to dramatic environmental disasters involving rivers and low-lying farmland in various parts of Europe and across the Mediterranean basin, posing a constant threat to small producers. In addition, either the management of OMW or its disposal by expensive specialised service companies represents a substantial economic burden for the small enterprises that constitute the Mediterranean olive oil sector. The challenge of achieving cost-efficient management of olive wastes has been extensively investigated during the last 50 years without finding a single universally valid solution than may be considered as technically feasible, economically viable and socially acceptable. However, it is well known that olive waste contains valuable resources such as a large proportion of organic matter, a wide range of nutrients and high added-value antioxidants that could be utilised. However, to date, this has not been the case because there are some technological barriers linked to specific processes. This paper reports a synthesis and an overview of recently-developed solutions for the treatment of these wastes, with a special emphasis on olive waste composting as a sustainable solution suitable for small medium-sized agricultural farms and olive mills, which represent the vast majority in Mediterranean agriculture. Furthermore, a review of the Italian and European legal framework on olive waste disposal and treatment is reported.

Keywords: composting, environmental impact, disease-suppressive effect, olive oil, treatment of olive residues, OMW management, olive wastes

Abbreviations: 2-POH, two-phase olive husk; **3-POH**, three-phase olive husk; **CWE**, compost water extract; **OH**, olive husks; **OL**, olive leaves; **OMW**, olive mill waste water, **SME**, small medium enterprise

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INTRODUCTION, SOCIAL AND ECONOMIC BACKGROUND

"The Mediterranean ends where the olive tree no longer grows" (Toussaint-Samat 1987). Despite the famous sentence by the French writer George Duhamel, olive tree cultivation has spread over five continents because of the health benefits (Keys *et al*. 1986; Covas 2007; Yang *et al*. 2007; Covas 2008) and to high profitability on the international market and many other countries, such as Argentina, Australia, Chile, South Africa and the USA, are becoming emergent producers since they are promoting intensive olive tree cultivation (Roig *et al*. 2006).

The olive tree (*Olea europaea* L.) originates from the Mediterranean Basin where it has been closely connected to the development of Mediterranean civilization throughout the ages (Kiritsakis 1998; Di Giovacchino 2000) and is strongly associated with local heritage, the landscape and the environment. In the Mediterranean area approximately 715 million olive trees are cultivated on more than 8.3 million hectares. About 98% of olive oil is produced in this region by more than 30,000 olive mills (**Tables 1, 2**). The

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Invited Review

Table 1 Olive tree cultivated surface area and olive oil productions.

Country	Average surfaces[1] devoted to olive cropping (ha x 1000)			Average production[2] of olive oil (t x 1000)		
	1990/91-1999/00	**2000/01-2006/07**	**Δ (%)**	**1990/91-1999/00**	**2000/01-2008/09**	**Δ (%)**
Cyprus	6.13	11.46	86.80	2.45	6.28	156.24
France	14.12	17.42	23.34	2.62	4.30	64.12
Greece	721.98	782.36	8.36	352.70	379.59	7.62
Italy	1,119.13	1,155.32	3.23	498.93	613.36	22.93
Portugal	341.55	371.39	8.73	38.41	35.68	-7.11
Slovenia	0.36	0.74	101.84	0.0	0.19	--
Spain	2,122.16	2,450.02	15.45	676.81	1,106.46	63.48
EU	4,325.39	4,788.73	10.71	1,571.92	2,145.84	**36.51**
Algeria	164.11	223.09	35.94	31.25	31.39	0.44
Croatia	15.00	15,250.00	1.67	1.55	5.00	222.58
Egypt	22.75	48,752.88	114.25	1.15	4.11	257.49
Iran	5.65	18,775.88	232.26	2.00	3.28	63.89
Iraq	3.48	0.93	-73.38	0.00	0.00	--
Israel	14.44	20.65	43.01	4.55	6.00	31.87
Jordan	52.74	64.35	22.01	13.20	24.50	85.61
Lebanon	45.87	56.99	24.23	5.30	6.11	15.30
Libya	92.50	139.75	51.08	7.25	10.06	38.70
Morocco	426.26	538.89	26.42	52.90	67.78	28.12
Montenegro	0.00	2.60	--	1.60	0.50	-68.75
Syria	423.77	483.35	14.06	83.30	131.78	58.20
Serbia	2.70	2.32	-14.20	0.00	0.00	--
Tunisia	1,412.08	1,188.66	-15.82	172.80	150.78	-12.74
Palestine	88.68	92.80	4.65	8.05	19.78	145.69
Turkey	553.66	620.72	12.11	92.40	123.56	33.72
Tot 1	3,317.43	3,552.39	7.08	477.30	584.61	22.48
Med. Basin	7,642.82	8,353.96	9.14	2,049.22	2,730.45	**33.24**
Argentina	28.58	36.12	26.41	8.95	15.50	73.18
Australia	0.58	2.83	388.23	0.10	6.06	5,955.56
Brazil	0.02	0.009	-58.14	0.00	0.00	--
Chile	3.42	5.94	73.55	0.00	2.22	--
USA	13.17	13.72	4.10	1.30	1.17	-10.26
Mexico	4.82	3.98	-17.40	2.15	1.44	-32.82
Tot 2	64.40	80.57	25.12	22.15	37.61	69.80
World	7,707.22	8,421.70	9.27	2,071.37	2,768.07	**33.63**
EU/Med (%)	56.59	57.32	1.29	76.71	78.59	2.45
EU/World (%)	56.12	56.86	1.32	75.89	77.52	2.15
Med/World (%)	99.16	99.20	0.03	98.93	98.64	-0.29

[1] Source: Elaboration on FAO data 2009.
[2] Source: Elaboration on IOOC data 2009.

Table 2 Olive oil extraction systems distribution mills (Source: IOOC 2009).

Country	Traditional (By animal)*	Press (Discontinuous)	Centrifugation (Continuous 3-P and 2-P)	Total
Cyprus	6		33	39
France	0	80	88	168
Greece		2,590		2,590
Italy				5,744
Slovenia		5	5	10
Spain	440		1,328	1,768
Portugal				1,057
Tot 1 EU	446	2,675	1,454	11,376
Albania	75			75
Algeria	1,400	85	165	1,650
Croatia	15	40	57	112
Egypt		40	15	55
Israel		10	80	90
Jordan		20	81	101
Lebanon	412	13	60	485
Morocco	16,000	468	200	16,668
Syria	61	546	201	808
Tunisia	784	398	335	1,517
Turkey		600	430	1,030
Tot 2	18,747	2,086	1,758	22,591
Med Basin (1+2)	19,193	4,761	3,212	33,967

* Refers to traditional olive presses where the labour force is provided by livestock.

whole olive oil chain is one of the strongest agrifood sectors of Mediterranean countries, both in terms of earnings and employment (Loumou and Giourga 2003; TDC Olive 2004; IOOC 2009).

The olive sector in the EU involves about 2.5 million producers (1,160,000 in Italy, 840,000 in Greece and 380,000 in Spain), providing jobs for more than 800,000 people in Europe, either directly or indirectly. During the winter season, olive production offers the advantage of providing employment in olive farms, olive milling and the processing industry. The sector is characterized by intense fragmentation. 90% of olive mills are small and medium-sized enterprises (SMEs), in many cases they are family-owned with fewer than 10 workers (Niaounakis and Halvadakis 2006). The importance of the sector is underlined by the fact that these olive-growing and -processing SMEs are mostly located in regions that are underdeveloped and deprived in terms of gross domestic production, purchasing power and employment. Therefore, modern and competitive agricultural process and products are crucial to ensure the economic development of the olive sector and to provide social benefit for rural communities.

OVERVIEW OF OLIVE OIL EXTRACTION PLANTS AND GENERATED WASTES

Oil is produced in olive mesocarp cells and stored in vacuoles (Kapellakis *et al*. 2008). Every cell contains a tiny olive oil droplet. Olive oil extraction is the process of sepa-

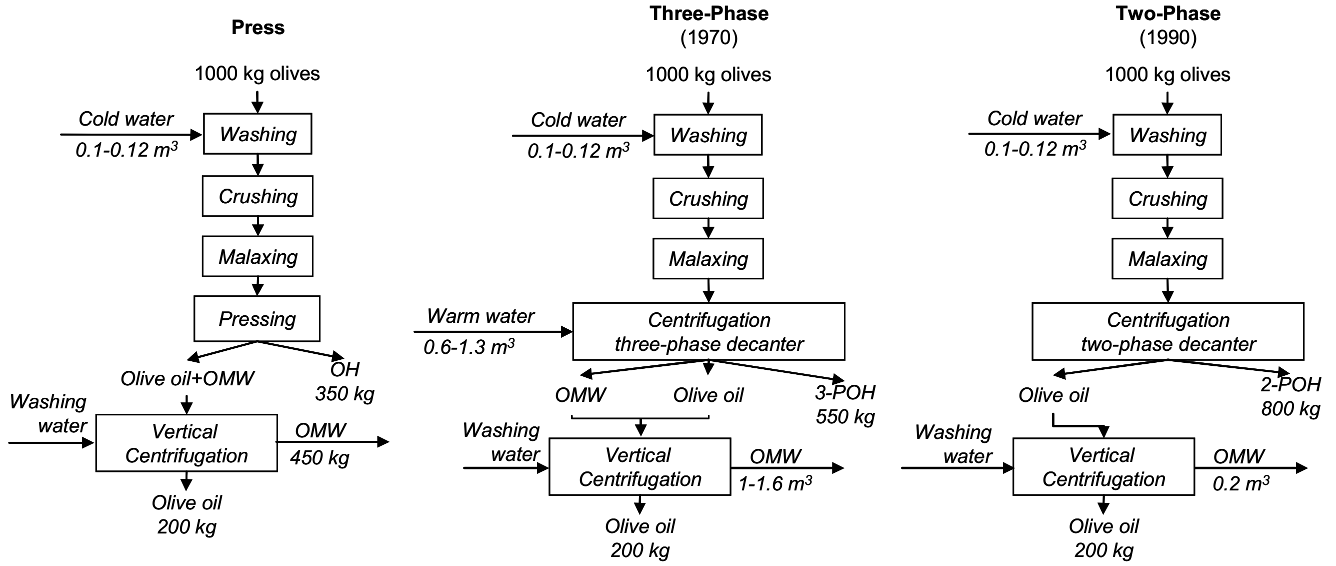

Fig. 1 Comparison of the systems used for olive oil extraction. (Alburquerque *et al*. 2004, modified).

rating the oil from the other fruit contents and it is carried out by physical means alone.

After olive collection from the orchards, the olives are put into a feeding hopper attached to a moving belt which feeds the defoliating and washing machines. Removing leaves, stones and any other foreign material and washing are necessary to avoid damage to machinery and product contamination. For example, the presence of leaves gives a bitter taste to the oil. The olives are ground into a paste to facilitate the release of the oil from the vacuoles. This can be done by using discontinuous millstones in which two or three heavy rotating wheels crush the olives or by using continuous steel drums. The crushed olives are then slowly stirred for 20-30 minutes in special containers called "Malaxators" to increase the percentage of oil available and to facilitate the coalescence of small oil droplets into larger drops, thereby facilitating the separation of the oil from water. Malaxing also helps in breaking up oil-water emulsion. For greater efficiency, malaxators have double walls for circulation of heating water, which should not exceed 30°C to avoid oil oxidation and an increase in acidity. The olive paste is then ready for oil extraction. Currently, traditional pressure and 2- or 3-phase centrifugation systems are the most-commonly used extraction methods (**Fig. 1**). The traditional pressing system has been used for many centuries with only minor adjustments and is based on a separation of liquids from solids phase using hydraulic pressure which is gradually increased to 300-500 kg/cm^2 (Niaounakis and Hakvadakis 2006). The olive paste of 2-3 cm thickness is spread uniformly in oil diaphragms, which are then placed on moving units (trolleys) with a central shaft. A metal tray and a cloth, without paste, are laid every 3-4 diaphragms to obtain uniform application and give a more stable load. Then the moving unit along with its load is placed under a hydraulic pressure unit. When applying pressure, the liquids (oil and water) run through the olive husk (Kapellakis *et al*. 2008). Olive oil is then separated from the liquid using decantation or a vertical centrifuge. This method requires little (3-5 l/100 kg of olives) or no water addition to the olive paste depending on the quality and maturity of the olives. It generates 200 kg of olive oil, 450 kg of Olive Mill Wastewater (OMW) and 350 kg of solid waste called "olive husk" (OH) per ton of olives. However, this technique may only be run in batches and this is leading to the gradual abandonement in favour of more functional continuous centrifuge systems. The use of centrifugation is a relatively new process for separating oil from olive paste. The 3-phase extraction method was developed in the early 1970s in order to reduce labour costs and to increase processing capacity and yield. It is the most widely used and is based on the specific weight differences among the olive paste constituents (olive oil, water and insoluble solids). Separation is accomplished through horizontal-centrifuge separators, known as "decanters".

The oil in the paste is either completely free or is in the form of small droplets inside microgels, or as an emulsion in the aqueous phase. Free olive oil is separated by using the centrifuge, while the oil locked in the microgels is released by adding warm water (Kapellakis *et al*. 2008). The water-thinned paste is rotated at very high speed in the decanters which induces the separation into three phases: olive oil, three-phase olive husk (3-POH) (moisture 46-54%) and a significant amount of OMW (1.0-1.6 m^3 per ton of olive) because of the water added at different stages during the oil extraction process (Alburquerque *et al*. 2004). At this stage the olive oil still contains a small amount of water which is then separated through vertical centrifugation at 6,000-7,000 rpm. The main disadvantages of the 3-phase extraction system are the huge amount of OMW produced, the loss of valuable constituents (e.g. natural antioxidants) from the olive paste into water and the subsequent disposal of the wastewater (Niaounakis and Halvadakis 2006; Kapellakis *et al*. 2008). In the early nineties, problems arising from wastewater disposal led to the introduction of the 2-phase "ecological" centrifuge extraction system which uses no water during the process and delivers the oil as the liquid phase with only one semi-solid or slurry by-product. This by-product is the so-called two-phase olive husk (2-POH). This process lead to the production of husks soaked with OMW and therefore with high water (55-74%) and phenol content (Ranalli *et al*. 2002; Alburquerque *et al*. 2004; Gurbuz *et al*. 2004; Vlyssides *et al*. 2004). In this way, since the process uses no water during oil extraction, there is a dramatic reduction in OMW production, thus solving the mill wastewater problem, which is shifted to the 2-POH.

Pressure and three-phase centrifuge systems produce substantially more OMW than the two-phase centrifuge method. In the past 10 years, the 2-phase system has become prevalent in Spain and Croatia. However, this system has not spread significantly into other olive-oil-producing countries, mainly because of the difficulty in handling the sludge (McNamara *et al*. 2008).

IMPACT OF OLIVE INDUSTRY

Olive tree cultivation and the processing industry produces large quantities of by-products which are essentially: olive leaves and twigs (OL), OH and OMW. The treatment of olive mill by-products is complicated by the seasonal and geographically diffuse nature of olive oil production. It is estimated that around 30 million m^3 of OMW and 20 million tons of OH (Bas Jiménez *et al*. 2000; Boubaker and Ridha 2007) are generated per year in the Mediterranean region, principally from early November to late February. Moreover, olive oil extraction is mostly carried out in small olive mills scattered throughout olive-oil-producing countries (McNamara *et al*. 2008).

Olive mill by-products (especially OMW) are generally recognized as being environmentally troublesome as their disposal without treatment is known to cause serious environmental problem on soil microbial populations (Paredes *et al*. 1987), on aquatic ecosystems (Della Greca *et al*. 2001) and even in the air (Rana *et al*. 2003). The quantity and physical-chemical composition of olive mill waste depends on olive varieties, the climate and environmental conditions (temperature, soil and rainfall), agronomical practices (irrigation, fertilization and time of harvest), olive storage and principally on the oil extraction technology used (Niaounakis and Halvadakis 2006; Roig *et al*. 2006). During olive processing three main residual products are generated.

Olive leaves (OL)

Olive leaves, twigs and branches originate from both the pruning of olive trees as well as the harvesting and cleaning of olives prior to olive extraction. It has been estimated that pruning alone produces approximately 25 kg of twigs and leaves per tree every year, to which 5% of the weight of harvested olives that are collected at the oil mill can be added (Delgado Pertinez *et al.* 1998; Niaounakis and Halvadakis 2006; Molina-Alcaide and Yanez-Ruiz 2008). At present, olive leaf business is substantially limited so as to be almost insignificant, and, in general, olive leaves are burned or composted at the original farms, distributed to ruminants after having been separated from larger branches or landfilled (Molina Alcaide and Nefzaoui 1996). The industrial use of olive leaves is limited to animal feed (Martín García *et al*. 2003) and phytotherapy. But in the near future, several other uses may be feasible (including antioxidants, bioactive compounds, disinfectants, phyto-compounds or energy scopes).

Olive husks (OH)

OH consist of olive pulp, skin, stone and water. The chemical composition varies within very large limits according to type, condition, and origin of the olives, as well as the olive oil extraction process used (Niaounakis and Halvadakis 2006; Alburquerque *et al.* 2004). OH from the traditional press system and 3-POH from the 3-phase centrifuge system have moisture contents of 20-25% and 46-54%, respectively. Whereas, 2-POH, from the 2-phase centrifugation system, has a moisture content in the range of 55-74%. This greater moisture, together with the sugars and fine solids which, in the 3-phase system, remained in the OMW, give 2-POH a doughy consistency and make transport, storage and handling difficult as it cannot be piled and must be kept in large ponds. As a consequence, many OH oil extraction facilities refuse to work with these materials because the energy costs of drying the OH for hexane oil extraction often make the extraction process not cost-effective. Furthermore, due to the addition of OMW, 2-POH contains considerable amounts of polyphenols which together with the lipid content have been related to phytotoxic and antimicrobial effects (Niaounakis and Halvadakis 2006). The 3-phase OH, is usually worked by refineries for further oil extraction with hexane.

Olive mill waste water (OMW)

OMW is the liquid stream generated by both the pressing and the three-phase extraction systems; it is made up of olive vegetation water in addition to the water added at the various stages of the oil extraction process and olive pulp, mucilage, pectin, oil, etc., suspended in a relatively stable emulsion (Paredes *et al*. 1999a; Alburquerque *et al*. 2004; Roig *et al*. 2006).

OMW is the most abundant olive mill waste produced from oil extraction. The pollutant power of OMW is very high, i.e. BOD 89-100 g l^{-1}, COD 80-200 g l^{-1} (Lucas *et al*. 1999; McNamara *et al*. 2008) as the OMW organic fraction includes, organic acids, lipids, polyalcohols, and noteworthy amounts of aromatic compounds (tannins and polyphenols) that make the OMW a phytotoxic and antimicrobial material, thus representing a serious environmental hazard when not properly managed (Niaounakis and Halvadakis 2006; Roig *et al*. 2006; Alfano *et al*. 2008).

Phenolic compounds present in olive stones and pulp tend to be more soluble in the water phase than in the oil, resulting in concentrations ranging from 0.5 to 25 g l^{-1} in OMW.

The environmental impact of OMW production is considerable. As an example of the scale, it should be noted that 10 million m^3 $year^{-1}$ of OMW from the three-phase system corresponds to an equivalent load of the wastewater generated by about 20 million people. Furthermore, the fact that most olive oil is produced in countries that are deficient in water and energy resources makes the need for effective treatment and reuse of OMW critical (McNamara *et al*. 2008). In addition, high tech techniques to treat OMW are not usually feasible for adoption by olive mill owners (Komilis *et al*. 2005).

OMW phtytoxicity is a complex property, since more than one compound can be responsible for it. Polyphenols are not necessarily the only compounds responsible for the phytotoxic properties of OMW, however, they have been claimed to be the major cause of phytotoxicity (Komilis *et al*. 2005). Generally, phenols, volatile organic acids, alcohols, aldehydes, and other smaller molecules are probable phytotoxic compounds present in OMW (Tomati *et al*. 1996). According to Paredes *et al*. (1999a) phytotoxic properties can also be related to low pH and salts, in addition to the phenols. The same authors mention that alteration of soil properties (competitive sorption capacity) after OMW application to soil can result in phytotoxicity.

Discharge of the OMW directly into the soil may have an impact on the physical and chemical properties of the soil such as porosity, pH and mineral salt content (Niaounakis and Halvadakis 2006; Roig *et al*. 2006). In addition, the presence of phytotoxic phenolics would generally prohibit the use of untreated OMW for irrigation purposes in agricultural production (El Hadrami *et al*. 2004; Mekki *et al*. 2006; Mc Namara *et al*. 2008) as it can inhibit plant seed germination (Mc Namara *et al*. 2008). However, beneficial effects on soils have also been observed in connection with the high nutrient concentrations, especially potassium, and its potential for mobilising soil ions (Roig *et al*. 2006). However, the irrigation of fields with either untreated or pre-treated OMW is a relatively inexpensive technique that could be implemented by small sized three-phase centrifugal olive mills (Komilis *et al*. 2005). OMW also has significant impacts when discharged directly into surface waters (Niaounakis and Halvadakis 2006; Mc Namara *et al*. 2008). The high concentration of darkly-coloured polyphenols can discolour streams and rivers. In addition, the high concentration of reduced sugars can stimulate microbial respiration, lowering dissolved oxygen concentrations, while the high phosphorous content can lead to eutrophication (McNamara *et al*. 2008). In **Table 3** studies of the effects of OMW and OH land spreading by various authors is reported.

OMW discharge into sewers has been reported as causing serious problems because of the acidity and suspended solid content. Due to the high concentration of organic acids (mainly volatile fatty acids), olive mill effluents are very corrosive to sewer pipes. Corrosion phenomena are the main reasons why direct discharge of OMW in sewers has been officially prohibited for many years, although in practice illegal dumping of OMW and sludge in sewers has been

Table 3 Effect of OMW and OH on soil physico-chemical properties.

Parameters	OMW on soil		OH on soil	
	Press	**Centrifuge**	**Press**	**Centrifuge**
Moisture	Increase (Sierra *et al*. 2001)	Increase (Sierra *et al*. 2001)		
pH	Lowering (Sierra *et al*. 2001)	Temporarily lowering (Levi-Minzi *et al.*1992; Kavdir and Killi 2008)		Lowering (de la Fuente *et al*. 2008)
Salinity		Increase (Paredes *et al*. 1987; Sierra *et al*. 2001 Sierra *et al*. 2007; Kavdir and Killi 2008) Temporary increase (Levi-Minzi *et al*. 1992)		
Organic matter	Increase (Sierra *et al*. 2001)	Increase (Sierra *et al*. 2007)		
Total organic carbon		Increase (Piotrowska *et al*. 2006; Kavdir and Killi 2008)	Increase (Lopez-Pineiro *et al*. 2008)	C source/C sequestration (Sánchez-Monedero *et al*. 2008)
Electrical conductivity	Increase (Sierra *et al*. 2001)	Increase (Kavdir and Killi 2008)		
Nitrogen		Increase (Piotrowska *et al*. 2006; Sierra *et al*. 2007; Kavdir and Killi 2008)	Increase (Lopez-Pineiro *et al*. 2008)	
NH_4^+		Increase (Kavdir and Killi 2008)		
NO_3-		Decrease (Kavdir and Killi 2008) Temporarily immobilisation (Sierra *et al*. 2007)		
Phosphorous	Increase (Sierra *et al*. 2001)	Increase (Piotrowska *et al*. 2006; Sierra *et al*. 2007)	Increase (Lopez-Pineiro *et al*. 2008)	
Phenolic compounds	Increase (Sierra *et al*. 2001)	Increase (Piotrowska *et al*. 2006; Sierra *et al*. 2007)		
Potassium		Increase (Gallardo-Lara *et al*. 2000)	Increase (Lopez-Pineiro *et al*. 2008)	
$CaCO_3$	Dissolution and redistributions (Sierra *et al*. 2001)			
Metal		Increase (Piotrowska *et al*. 2006		Changes in speciation (de la Fuente *et al*. 2008)
Water retention				Increase (Abu-Zreig and Al-Widyan 2002)
Aggregate stability		Increase (Le Verge and Bories 2004; Kavdir and Killi 2008)	Increase (Lopez-Pineiro *et al*. 2008)	
Porosity		Decrease (Cox *et al*. 1997; Zenjari and Nejmeddine 2001) Temporarily decrease (Pagliai 1996)		
Dehydrogenase and Urease activity		Increase (Piotrowska *et al*. 2006)		
Microbial biomass		Increase (Piotrowska *et al*. 2006)		
Phospatase, B-glucosidase, nitrate red, diphenol ox.		Decrease (Piotrowska *et al*. 2006)		

a common disposal method for oil mill owners (Rozzi and Malpei 1996).

Thus, its management represented one of the most important limiting factors to the growth of the olive oil sector. The environmental issues led to the introduction in the 1990s of the ecological two-phase extraction system which permitted a remarkable reduction in OMW production, but also led to an increase in 2-POH.

Given the high organic matter and nutrient content of OMW, especially in potassium, it could be recycled as potential fertiliser. In recent years many management options have been proposed for the treatment and valorisation of OMW. Most of these methods aim at the reduction of the phytotoxicity in order to reuse OMW for agricultural purposes, but, more recently, further alternative methods have also been reported (**Table 4**). Furthermore, in some Mediterranean countries traditional olive processing is still based on traditional methods. Morocco has a large number of small traditional extraction plants, called “Maasras”, which are widespread, but have a very low working-capacity. Given the low productivity, these plant are forced to store olives for weeks using salt (NaCl) in order to prevent fermentation processes. It is also believed that salt addition (2-5% w/w) increases oil production. These practices cause even greater pollution because of the salt content of OMW and risk further soil-fertility loss through desertification and the pollution of sources of drinking-water.

Legal framework

The Common Agricultural Policy (CAP) olive oil reform does not provide specific measures on olive processing wastes. Apart from Italy, all the olive oil producing countries do not have specific legislation for olive mill waste. European Community Producer States have national directives on olive oil waste in conformity with European directives on waste, soil and water protection. The general principles are: prevention of waste; recovery of waste (firstly as material, secondly as energy); safe disposal.

***Waste*:** Directive 2006/12/EC of 5th April 2006 on waste, establishes the legislative framework for the handling of the waste in the Community; Directive 2008/98/EC of 19th November 1998 on waste also repeals certain Directives which established management principles such as the “polluter pays principle” or the “waste hierarchy”. COM (1996) 399 final Communication on an updated "Community strategy for waste management", Council Directive 1999/31/EC of 26th April 1999 on landfill of waste (Landfill Directive).

***Water*:** Directive 2000/60/EC of 23rd October 2000 establishes a framework for Community action in the field of water policy; Council Directive 98/83/EC of 3rd November 1998 on drinking water; Directive 2006/118/EC of 12th December 2006 on the protection of groundwater against pollution and deterioration; Council Directive 91/271/EEC

Table 4 Advantages and disadvantages of methods used for the treatment and disposal of olive mill wastes.

Process	Treatment	Advantages	Disadvantage	EC Projects/ Program	Patents	References
Physical	Dilution	Simple	Large need of water			Boari and Mancini 1990; Niaounakis and Halvadakis 2006
	Sedimentation / Settling	Simple	Slow, needs costly flocculant		ES2116923 1998	Velioglu *et al*. 1987; Al-Malah *et al*. 2000; Khoufi *et al*. 2007
	Filtration		Unsuitable, low filter life		GR1001839 1995; ES2087827 1996; ES2087032 1996; WO2005003037 2005	Mitrakas *et al*. 1996
	Flotation	High oil recovery (30%)	Not feasible		WO9211206 1992;	Mitrakas *et al*. 1996
	Centrifugation	Simple, high COD removal and oil recovery	High costs		ES22091722 1996; WO9728089 1997;	Mitrakas *et al*. 1996
	Membrane technology		High costs, low performances due to membrane fouling, disposal of the retentate and permeate		DE4210413 1993; GR88100203 1989;	Camurati *et al*. 1984; Halet *et al*. 1997; Mameri *et al*. 2000b; Turano *et al*. 2002
Physico-Thermal	Evaporation / Distillation		High energy requirements, batch operations, low pH products, disposal of concentrated paste	EVK1-CT-2002-30028 “SOLARDIST”	GR89100788 1991; ES2021191 1991; IT1211951 1989; ES2043507 1993; EP295722 1988; ES8708149 1987; EP330626 1989; ES2101651 1997	Fiestas Ros de Ursinos and Borja-Padilla 1992; Potoglou *et al*. 2003; Azbar *et al*. 2004
	Drying	High efficiency	High energy demand, Qualified personnel			Arjona *et al*. 1999, 2005
	Lagooning	Simple, cheap	Needs open large areas, Slow, foul odours, insect proliferation, leakages, infiltration			Shammas 1984; Duarte and Neto 1996; Rozzi and Malpei 1996; Azbar *et al*. 2004; Balice *et al*. 1986; Roig *et al*. 2006
Chemical-Thermal	Combustion, Energy recovery	High removal of organic matter, environmentally friendly and biodegradable, energy production, high calorific value (3600-3700 kcal/kg)	High energy cost, high pollution, loss of organic matter, dewatering pre-treatment; Air pollution. (Emission Limit Values for biomass fuels in Italy, Spain and Portugal which limit OH use as biomass fuel)		ES2088340, 1996 ES2032162, 1993 IT1231601, 1991 ES2092444, 1996	Di Giacomo *et al*. 1989, 1991; Mariani *et al*. 1992; Torre *et al*. 1995; Vitolo *et al*. 1999; Dally and Mullinger 2002; TDC Olive 2004; Fokaides and Tsiftes 2007
	Pyrolysis		dewatering pre-treatment, High energy cost		IT1231601, 1991 WO8904355, 1998	Petarca *et al*. 1997; Di Giacomo *et al*. 1989, 1991
Physico-Chemical	Neutralization	Use as fertilizer			ES8706800, 1987 PT85790, 1987	Papaioannou 1988
	Precipitation / Flocculation	Cheap, simple	Not high efficiency; partial removal of organic matter; Disposal of the precipitated; use of flocculants		WO9211206, 1992 IT1191528, 1998 ES2009267, 1989 DE19529404, 1997 CZ941911, 1996 ES820395, 1982 ES8307286, 1983 ES2028497, 1992	Annesini and Gironi 1991; Zouari 1998; Riccardi *et al*. 2000; Lagoudianaki *et al*. 2003; Le Verge and Bories 2004
	Adsorption	Low space requirements; no water pollution, no odour emissions, low cost for adsorbent, use of olive stones and solvent extracted olive pulp for production of activated carbon	Limited adsorption capability, high costs of the adsorbent, high running costs, removal of activated carbon from waste water difficult, absence of regeneration techniques of activated carbon, needs of qualified personnel			Bacaoui *et al*. 1998; Beccari *et a*l. 1998, 1999, 2001, 2002; Gharaibeh *et al*. 1998; Zouari 1998; Al-Malah *et al*. 2000; Mameri *et al*. 2000a; Moreno-Castilla *et al*. 2001; Galiatsatou *et al*. 2001, 2002
	Recovery antioxidants	High antioxidant content	Expensive methods			Brenes *et al.* 2002; Fabiani *et al*. 2002; Visioli and Galli 2002; De Leonardis *et al*. 2008
Chemical	Oxidation	High purification efficiency			ES8607039, 1986; GR88100203, 1989; ES2009267, 1989; WO9211206, 1992	Ranalli 1991; Gonzalez-Lopez *et al*. 1994; Niaounakis and Halvadakis 2006

Table 4 (Cont.)

Process	Treatment	Advantages	Disadvantage	EC Projects/ Program	Patents	References
Biological	Landfills	Easy, cheap	Collection and storage of effluents			Boari *et al*. 1993; Cossu *et al*. 1993; Rozzi and Malpei 1996
	Anaerobic biodegradation	Production of biogas, high removal of organic matter	Needs of inoculum for start up, presence of antimicrobial compounds, possible need of pre-dilution/filtration and addition of n sources, needs large volumes of OMW, avoid cold temperatures, disposal of effluents, special devices are needed, very high costs	AIR3-CT94-1987 "BIOWARE"; FAIR CT-96-1420 "IMPROLIVE"	EP324314 1989 DE19829673, 2000	Aveni 1983, 1984; Boari *et al*. 1984; Carrieri *et al*.1986, 1992; Rigoni Stern *et al*. 1988; Rozzi *et al*. 1988, 1989, 1994; Hamdi 1991, 1992, 1996; Tsonis 1991; Georgacakis and Dalis 1993; Borja-Padilla 1994; Borja-Padilla and Gonzalez 1994; Borja-Padilla *et al*. 1996; Dalis *et al*. 1996; Gavala *et al*. 1996; Zouari and Ellouz 1996; Angelidaki and Ahring 1996, 1997a, 1997b; Angelidaki *et al*. 1997, 2002; Beccari *et al*. 1998; Marques *et al*. 1997, 1998; Tekin and Dalgic 2000; Marques 2001; Mantzavinos and Kalogerakis 2005; Boubaker and Ridha 2007, 2008
	Biofilms	Slow microbial growth rate, less suitable	Removal of metabolic compounds, need of space, odours, insects, expensive		WO9935097, 1999	Bertin *et al*. 2001
	Activated sludge	High removal of BOD_5, residual oil, COD	Presence of non-biodegradable and antimicrobial substances, needs of small plants in rural areas, production of large amounts of biosolids		DE2640156, 1978	Velioglu *et al*. 1992; Borja-Padilla *et al*. 1995
	Sequencing batch reactors	High organic matter removal, suitable for small areas	Complex plant running, expensive, qualified personnel, needs removal of larger particles, production of large amounts of biosolids			Hamdi and Ellouz 1992; Ammary 2005
	Composting	Production of high quality organic fertilizer, nitrogen-rich material, degradation of phytotoxic and anti microbial compounds, hygienic safety, feasible, minimise the emissions, adaptable to SME conditions	Need mix with agricultural waste, woody substrates, bulking agents, pH increase may limit the agricultural use, long maturation period	ETWA-CT92-0006; FAIR5-CT97-3620	HR20010028 2002; IT1244520 1994; GR1003611 2001	Tomati *et al*. 1995, 1996; Cegarra *et al*. 1996a, 1996b; Vlyssides *et al*. 1996, 1999; Paredes *et al*. 1996a, 1996b, 1999a, 2000, 2001, 2002; Galli *et al*. 1997; Improlive 2000; Carter *et al*. 2001; Ranalli *et al*. 2001, 2002; Filippi *et al*. 2002; Principi *et al*. 2003; Roig *et al*. 2004, 2006
	Bioremediation Phytoremedi-ation	Cheap, natural solution, high disposal efficiency, lack of bad smell and insects, limited energy utilization, suitable for SMEs, trees production, low environmental impact	Requires common farming maintenance	ICA3-CT1999-00011 "WAWAROMED"; EVK1-CT-2002-30028 "SOLARDIST"	EP1216963 2002	Skerratt and Ammar 1999; Nikolopoulou and Kalogerakis 2007
	Land spreading/ Irrigation	Beneficial effect of moderate doses, easy, cheap, increase of soil fertility	Odour, presence of phytotoxic and antimicrobial compounds, pollution of groundwater, soil, air, many countries have restrictions on quantities to dispose due to high COD, tree roots may burn	LIFE00 ENV/IT/00023 "TIRSAV"	ES2051242 1994; EP520239 1992; ES2084564 1996; FR27249222 1996	Ramos *et al*. 1995; Cabrera *et al*. 1996; Garcia-Ortiz *et al*. 1999; Paredes *et al*. 1999a, 1999b; Marques 2001; Zenjari and Nejmeddine 2001; Rana *et al* 2003; Rinaldi *et al*. 2003; Saadi *et al* 2007; Mechri *et al*. 2008
	Animal feed	Cheap	Low protein content, lysine deficient, high cellulose content, bitter (non feed able)			Molina-Alcaide and Nefzaoui 1996; Clemente *et al*. 1997

of 21st May 1991 concerns urban waste-water treatment, amended by the Commission Directive 98/15/EC of 27th February 1998 concerning certain requirements established in Annex I thereof; Council Directive 91/676/EEC of 12th December 1991 concerns the protection of water against pollution caused by nitrates from agricultural sources.

***Soil*:** Directive 2004/35/CE of 21st April 2004 on environmental liability with regard to the prevention and remedying of environmental damage; the Soil Thematic Strategy COM(2006)231 and the proposal for a Soil Framework Directive COM(2006)232 of 22nd September 2006 have the objective of protecting soil across the EU.

Other important EU legislation on sludge, wastewater and water management

Directive 2008/1/EC of 15th January 2008 on integrated pollution and prevention and control (IPPC), Council Directive 94/67/EC of 16 December 1994 on the incineration of Hazardous Waste.

Every producing country has its own legislation and or regulations that often vary greatly with consequent non-uniform application of generally accepted guidelines. In many cases, land configuration, geographical distribution and size of olive mills pose technical and economic limitations to the use of valorisation/disposal methods proposed by many authors. In a similar context, the most widely-used disposal strategy for olive liquid residue mainly uses evaporation ponds and spreading on olive plantations, especially in the case of small olive mills, which often represents the only affordable economic solution (Niaounakis and Halvadakis 2006).

The case of Italy

Italy is the only olive oil producing country with specific legislation for the disposal and/or recycling of olive processing wastes. Crude OH has always been recognised by the law as a by-product, while OMW has been considered as waste. Law no 574/96 of 11th November 1996 entitled "Regulations pertaining to the agronomic use of olive oil vegetation water and olive mill effluents", permitted agronomic use of OMW and OH. Legislative decree no. 22 of February 1997 no longer considered OMW as waste and permitted its use for fertirrigation due to the organic matter content and fertilization potential. The OMW from traditional press and centrifuge systems can be used at a concentration of 50 and 80 m^3/ha/year, respectively.

Notification of spreading operations must be communicated to the major 30 days before operations begin. The communication must include details of the spreading system, the spreading time, soil analysis and hydrological conditions. The major can prohibit spreading operations if there is a chance of damage to the environment. OMW and OH soil distribution must be uniform and by products must be ploughed in. Moreover, during spreading operations OMW run-off must be avoided. OMW Spreading is forbidden within 300 m of groundwater drainage areas, within 200 m of built-up areas, in soil with growing vegetables, in soils where the water table depth is less than 10 m and in soil where percolation water could reach the water table. Moreover, the law establishes that OMW can be stored for up to 30 days in water-proof containers and that the major must be notified of the storage location.

However, it is widely recognised that law 574/96 needs some technical improvement, it should, for example, distinguish between the water used for washing olives and the water added to the olive paste for oil separation. Moreover, the diverse national, European and international regulations on liquid effluents, wastewaters, fertirrigation and dumping should be harmonized.

OLIVE MILL WASTE MANAGEMENT

Olive mill wastewater, generated by both the pressing and three-phase systems, has been illegally dumped onto the soil or into nearby streams or rivers for many years with some serious negative effects: (i) during autumn and winter, a period of high rainfall, the application of OMW can lead to detrimental stagnation and the formation of anaerobic microsites; (ii) the percolation of the wastewaters into superficial aquifers can cause aquifer pollution (Filidei *et al.* 2003); (iii) the fatty acid, phenol and tannin content (highly phytotoxic compounds) of crude OH precludes their use as fertiliser (Ranalli *et al.* 2002) as this would lead temporary critical soil conditions (Amirante and Montel 2000).

The continuous dumping and the rapid increase in the amount of waste produced have brought serious environmental problems to the Mediterranean area. To avoid these environmentally detrimental effects, olive mills were obliged to treat or eliminate their own waste.

Many different methods have been proposed to treat solid, semi-solid and liquid olive residues (**Table 4**): lagoons (Niaounakis and Halvadakis 2004), flocculation-clarification (Zouari 1998; Roig *et al.* 2006), ultrafiltration/reverse osmosis (Niaounakis and Halvadakis 2004), thermal concentration and evaporation (Netty and Wlassics 1995; Vitolo *et al.* 1999), incineration and combustion (Vitolo *et al.* 1999) for OMW, and combustion and gasification for mixed OMW and OH (Caputo *et al.* 2003). All are generally very expensive and or unable to completely solve the problem because of the need to dispose of a sludge deriving from the process (Paredes *et al.* 2002). Anaerobic digestion treatments (Filidei *et al.* 2003; Marques 2001; Hamdi 1996) have been carried out successfully on OMW: they result in biogas production and much less waste sludge (Rozzi and Malpei 1996), but their high costs makes them uneconomical for small scale olive mills.

On the other hand, at small mills, the composting of their residues could allow recovery of the effluents that could then be re-used in agriculture as eco-compatible, good quality organic amenders and fertilizers. Furthermore, composting is a favourable technology, which is economically applicable in small/medium size olive mill farms (< 1000 t y^{-1}), like those found throughout Italy and Greece (Alfano *et al.* 2008).

One of the most widely-accepted management options is through natural evaporation in storage ponds in the open because of the low investment required and the favourable climatic conditions in Mediterranean countries. This method produces a solid phase which can be spread or composted. However, use of this method requires a large area and has various associated problems such as bas odour, infiltration and insect proliferation. This management procedure is used in Spain, Greece, Tunisia, Cyprus and Morocco. However, the experiences performed at a full scale plant showed some inconvenient aspects: long-term storage of OMW in large lagoons led to a significant reduction in the evaporation of wastewaters, due to the formation of an oil patina on the surface. In other olive oil producing countries such as Italy, Turkey, Portugal, France, Croatia, Malta and Egypt olive residues can be directly spread onto fields as amenders of fertilizers.

More recently, specific wastewater treatment plants were developed. However, they did not consolidate in the olive oil sector for technical and economic reasons. Several research groups have been working on the alternative use of these organic residues and the recovery of valuable substances. By using adequate technology, olive mill waste can be converted into products with additional value. Alternative uses are highlighted by two possible applications: the recovery of natural constituents and bioconversion into useful products.

Recovery of phenolic compounds

The fruit of the olive contains a wide variety of phenolic compounds which are strong antioxidants and play an important role in the chemical, organoleptic and nutritional properties of the olive oil. The main phenolic compounds present in olive oil are tyrosol, hydroxytyrosol, their secoiroids and conjugate foms (oleuropein, ligustroside, verbascoside) and lignans (pinoresinol and acetopinoresinol) (Brenes *et al.* 2002; De Leonardis *et al.* 2008).

During the olive oil mechanical extraction process, the majority of the phenolic compounds are found in the aqueous phase, while only a very small percentage (<1%) are located in the olive oil (Vierhuis *et al.* 2001). More than 30 different phenolic compounds have been identified in OMW and the types and concentrations of phenolics reported in OMW vary tremendously (McNamara *et al.* 2008). Hydroxytyrosol is one of the major phenolic compounds present in olives, olive oil and OMW. It has been revealed to be the most interesting, because of its remarkable pharmacological and antioxidant activity (Fabiani *et al.* 2002; Visioli and Galli 2002). Although further study is required, even OL have an appreciable polyphenol content, which could range from 1.5 to 7.0 g per 100 g of fresh leaves (Niaounakis and Halvadakis 2006). Oleuropein and other secoiridoids are the principal compounds present in OL, while simple phenols and enclosed hydroxytyrosol are present but in lower quantities (Tuck and Hayball 2002).

Interest in natural antioxidants is increasing because of the growing body of evidence indicating the involvement of oxygen-derived free radicals in several pathologic processes, such as cancer and atherosclerosis (Manna *et al.* 1999). Indeed, olive leaf polyphenols are bio-active compounds and have been reported to show antiviral (Lee-Huang *et al.* 2003), antibiotic with both antimicrobial and antifungal (Niaounakis and Halvadakis 2006), antioxidant and anti-inflammatory (Manna *et al.* 1999; Briante *et al.* 2002) properties, atherosclerosis inhibition and hypotensive action, anti-carcinogenic properties that lead to the prevention of some cancers and, finally, stimulation of the thyroid (De Leonardis *et al.* 2008).

So, it would be desirable to have processes for the extraction of these components from olive-based starting materials for the development of chemicals, nutrition supplements, skin cosmetics, detergents, rinsing and cleaning agents.

Olive mill by-products (especially OMW) represent a potentially rich source of antioxidant compounds, which have not been effectively exploited, due to the impracticability of extracting usable amounts of antioxidant compounds using conventional technology (Visioli *et al.* 1995). Fewer references have been made to the use of 3-POH and 2-POH as a substrate for the recovery of polyphenols (Niaounakis and Halvadakis 2006).

In conclusion, OMW has powerful antioxidant properties and this might be a cheap source of natural antioxidants.

Composting

Composting of olive solid, semi-solid and liquid olive residues has been extensively examined as a potential bioremediation treatment of these wastes. By using this method, it is possible to transform either fresh OMW or sludge from pond-stored OMW mixed with appropriate plant waste materials into organic fertilizers. It permits the return of nutrients to cropland avoiding the negative effects of wastes when directly applied to soil. Olive mill waste composts may play an important role in organic agriculture. The high purity of olive mill wastes (lacking in recalcitrant toxic substances and hazardous micro-organisms) ensures the quality and competitiveness of composts made from the biological transformation of these residues (Roig *et al.* 2006).

Some authors have demonstrated that composting may be a suitable low-cost strategy for recycling of olive mill wastes within agricultural SMEs (Cayuela *et al.* 2006; Alfano *et al.* 2008). Cayuela *et al.* (2004) proposed composting with manure as a good method to revalorise this residue in the area surrounding the olive mills.

During the process, the organic fraction is partially aerobically degraded by microorganisms to carbon dioxide and water, whereas the other part undergoes a humification process which results in a stable compost possessing suitable characteristics to be used as bio-fertilizer (Tomati *et al.* 1996; Vlyssides *et al.* 1996; Paredes *et al.* 2000; Baeta-Hall *et al.* 2005). However, the composting process, and thus the operating strategies, should be designed taking into account both product quality and environmental protection (Savage 1996; Tiquia *et al.* 2000; Baeta-Hall *et al.* 2005). Proper evaluation of the system is required if an acceptable product is to be generated, and the system efficiency is to be maximized (Tiquia and Tam 2002; Baeta-Hall *et al.* 2005).

The aerobic composting technologies are windrow (turned pile), aerated static pile and in-vessel, of which the first two are the most-commonly used. Several solutions have been proposed for composting of olive mill residues from three or two-phase extraction systems: Rutgers static-pile with on-demand aeration or forced ventilation (Paredes *et al.* 2002; Ranalli *et al.* 2002), dynamic turned pile (Sciancalepore *et al.* 1996; Ranalli *et al.* 2001), in a pit or in a bioreactor (Principi *et al.* 2003).

The technologies vary in the method of air supply used, temperature control, mixing/turning of the material and the time required for composting. The corresponding capital and operating costs also vary considerably. The efficiency of olive mill waste composting under different aeration and/or mixing methods was tested using olive mill wastes mixed with different types of organic material.

Due to the physical nature (liquid or semi-solid) of OMW and 2-POH, they need to be adsorbed in a solid substrate such as lignicellulosic waste before proceeding with the composting, the former mixed and the latter co-composted with other agricultural wastes. Several authors studied the co-composting of OMW or 2-POH with the addition of some suitable material as bulking agents, using straw (Madejon *et al.* 1998), cotton waste (Alburquerque *et al.* 2006), poplar sawdust and bark chips (Filippi *et al.* 2002), grape stalks (Baeta-Hall *et al.* 2005), olive leaves (Alfano *et al.* 2008), rice husks and dairy sludge (Ranalli *et al.* 2001), animal manure (Sciancalepore *et al.* 1996; Ranalli *et al.* 2002; Alfano *et al.* 2008) corn stalks (Ranalli *et al.* 2002) agricultural by-products and urban wastes (Tomati *et al.* 1995; Paredes *et al.* 2000) and fertilizers with high levels of humification and no phytotoxic effects were obtained. Similar or increased yields of horticultural and other crops, compared with those obtained using mineral fertilisers, were observed after application of OMW compost (Cegarra *et al.* 1996a, 1996b).

Static, non-aerated composting of 2-POH recently proved not to be suitable for degradation, detoxification and stabilization of organic matter (Alfano *et al.* 2008). Furthermore, several authors reported that even forced-aeration systems for static composting of 2-POH presents several drawbacks because of the oily consistency, the lack of porosity and preferential air-flow paths which negatively affected the degree of humification and the Nitrogen content in the final compost (Cayuela *et al.* 2006; Roig *et al.* 2006).

Better composting performance was obtained mixing 2-POH with bulking agents and using mechanically-turned pile technology. In this way, higher temperatures accelerated the process and provided a higher degree of organic matter humification (Cayuela *et al.* 2006; Roig *et al.* 2006; Alfano *et al.* 2008).

Where OMW or 2-POH were properly composted, the final product showed a high degree of humification, no phytotoxic effect and considerable quantities of mineral nutrients. It has been suggested that composting may be a suitable low-cost strategy for the recycling of olive oil by-products with complete detoxification of starting materials (Baeta-Hall *et al.* 2005).

Olive by-product composts have been tested as fertilizers in horticultural crops (Madejon *et al.* 2001). However, the high pH reached during the composting of 2-POH with other agricultural wastes may represent a limitation for its

Table 5 Composting trials carried out on olive oil mill wastes in the last decade (DISTAAM-DISTAT, UNIMOL, Italy).

Composting trials	Olive oil campaign	Residues	Inoculum	Composting plant	Plant scale	Turnover	Final use
Mafalda (CB)	1997/98 1998/99	2-POH OL	--	Confined, roof covered	Pilot	Static pile; Simplified manual	Agronomical
Mafalda (CB)	2003/04 2004/05 2005/06 2006/07	2-POH 3-POH OL	Composted husks, Sheep manure	Confined, roof covered	Pilot	Static pile, Simplified manual	Agronomical
Moscufo (PE)	2003/04	2-POH OL	--	Open space	Pilot	Simplified manual	Agronomical
Moscufo (PE)	2003/04	2-POH OL Wheat straw	--	Open space	Pilot	Simplified manual	Agronomical
Torrevecchia (CH)	2003/04	2-POH Vegetables residues Rotten fruits	--	Confined, roof covered	Pilot	Simplified manual	Agronomical
Verona (VR)	2003/04 2004/05	3-POH Public Park residues	Municipal sludge	Confined, roof covered	Industrial	Automated	Market
Sulmona (AQ)	2005/06	2-POH Wheat straw	--	Confined	Pilot	Simplified manual	Agronomical
Sulmona (AQ)	2005/06	2-POH Wheat straw OL	Horse manure	Confined	Pilot	Simplified manual	Agronomical
Ururi (CB)	2006/07 2007/08 2008/09	3-POH OL Chopped pruning	Sheep litter	Confined, roof covered	Pilot	Simplified manual	Agronomical, Pellet - Fuel

application on soil. In order to solve this problem, Roig *et al*. (2004) suggested the addition of elemental sulphur as a suitable strategy for pH control during the composting process under the organic farming regulations. Additionally there is evidence in the literature which shows that composts possess plant growth regulators and properties which suppress soil-borne plant pathogens (Lumsden *et al*. 1986; Hoitink *et al*. 1997; Hoitink and Boehm 1999; Abbasi *et al*. 2002).

Research activity over the last few decades has been focussing on olive waste composting as an ecologically compatible and economically sustainable solution to be specially adapted/adopted by small medium-sized agricultural farms, which constitute the great majority of the Italian agricultural context and very often do not have significant labour or economic resources. Many composting trials on olive oil mill residues, coming from both three and two-phase extraction systems, were carried out in several pilot scale plants in central Italy (Regions of Abruzzo and Molise) and at an industrial scale plant in northern Italy (Region of Veneto) (**Table 5, Fig. 2**). Several technological solutions have been tested in order to find effective solutions for the treatment and valorisation of OMW, 2-POH, 3-POH and OL. As a result of the diffusion of the two-phase extraction systems, experimentation has focused mainly on 2-POH which poses a greater environmental threat than 3-POH.

To this extent, under the research project "Husks" (FAIR5-CT97-3620) funded by the EC, several 2-POH composting trials were performed by the authors; in these cases ATP content and the activity of a pool of 19 enzymes proved to be quick and useful bioindicators of microbial activity during the composting process (Ranalli *et al*. 2002).

In the last ten years, many composting experiments have been carried out in small and medium sized olive mills and agricultural farms by suitable pilot scale composting plants built in confined spaces, on concrete platforms covered with a fixed roof (**Fig. 2A, 2B**), or in open spaces on compressed soil and with a leached water-recovery system (**Fig. 2C, 2D**). 2-POH were mixed with lignocellulosic agricultural residues such as corn stalks, wheat and rice straw, olive leaves, pruning residues and livestock by-products such as cow, sheep and horse manure to improve the start-up of the process and to balance the C/N ratio (Ranalli *et al*. 2002; Principi *et al*. 2003; Alfano *et al*. 2008).

Furthermore, other tests were carried out on OMW and 3-POH. Lignocellulosic agricultural residues including corn stalks, wheat and rice straw, olive leaves, pruning residues and livestock by-products such as animal manure, to improve the start-up of the process, were drenched with OMW and added or not to 3-POH. Further, OMW was also used to water the composting piles during the first stages and the thermophilic phase of the process (Alfano *et al*. 2003).

In an industrial scale plant trial carried out in 2005 in the Veneto Region, a pile was made mixing 3-POH to pruned branches and green residues from park maintenance and municipal sludge from the wastewater treatment plant in Verona; this last fraction was added as inoculum and to balance the C/N ratio. The pile (60 m long × 2.5 m wide × 1.5 m high) was mechanically turned over (**Fig. 2E**). The composting process lasted between 3 and 4 months. Generally, 60 days of active bio-oxidation followed by 1 or 2 months of curing.

Different pile aeration/turning systems were tested and compared (Ranalli *et al*. 2002; Principi *et al*. 2003). Preliminary tests were carried out with a front end loader, while the subsequent tests were carried out with more efficient pile aeration/turning systems. In these trials piles were aerated with air-blowers inside the piles, which, however, presented some drawbacks because of the preferential air-flow paths. When 2-POH were composted in an elliptical tank (bioreactor) equipped with auger-type turning equipment the turning of the composting mass was guaranteed simultaneously along the vertical and horizontal axes. The bioreactor, even if prohibitively expensive, proved to be suitable and produced high-quality, cured, composted residues (Principi *et al*. 2003). In order to make the process affordable for small olive mills and farms, a low cost simplified turning machine was realized (**Fig. 2F**), and, in addition, old forage, mixing/grinding machines (Seko, mod. Samurai Double Mix, Curtarolo, Italy), used in the past for the preparation of cattle forage, were also recovered and used (**Fig. 2D, 2G**). Both these turning systems proved to be reliable and led to olive waste composted residues with no phytotoxic and antimicrobial effects which were hygienically-safe despite the presence of animal manures used as inoculum.

Cured composted residues were tested *in vitro* and *in vivo* for their disease suppressive effect. Composted olive waste proved to be suppressive in preliminary *in vitro* tests against several soil-borne fungal plant pathogens (**Fig. 2H**), and microbiological characterization showed the biotic

Fig. 2 Images of composting processes carried out in the last decade. (**A**) Composting process carried out on 2-POH in pilot scale plant. (**B**) 2-POH composting carried out in confined pilot scale plant. (**C**) Composting of 3-POH carried out in open air pilot scal plant. (**D**) Composting pilot plant and turning/grinding machine. (**E**) OH composting carried out in industrial scale plant. (**F**) Prototype of the turning machine realized. (**G**) Olive mill and agricultural residues turning and grinding. (**H**) *In vitro* suppressive test on *Verticillium dahliae*. (**I**) SEM observation (7500 x) of a sample of composted OH. (**J**) *In vitro* activity of antagonistic bacteria isolated from compost. (**K**) *In vivo* suppressive trials carried out in a nursery on young olive plants. (**L**) Agronomical trials carried out in open field on sunflower.

factor of disease suppressive effect in greater detail (**Fig. 2I**). Several specific microbial strains with notable suppressive activity were selected and tested *in vitro* and *in vivo* against several soil-borne, fungal plant pathogens (**Fig. 2J**). Suppressive composted olive waste was also tested in a nursery against *Verticillium* spp. olive tree wilt (**Fig. 2K**) (Alfano *et al*. 2004; Lima *et al*. 2008a). Furthermore, composted olive waste proved to have negligible agricultural value when used as soil conditioner, amender and fertilizer (**Fig. 2L**).

Over the experiments, several plant and technological solutions have been tested in order to select the most appropriate for small-medium sized olive mills and agricultural farms or at an industrial-scale plant. The low-cost, simplified technologies which have demonstrated greater reliability have been selected. These promising low-cost, simplified technologies could largely find applications in olive-oil-producing countries, especially taking into account the agricultural, structural and economic scenario in Italy and other olive-oil-producing countries in the Mediterranean basin.

DISEASE-SUPPRESSIVE EFFECT OF COMPOST

Green waste, organic amendments and composts may have the natural ability to control the incidence of plant diseases.

The biological control of plant pathogen diseases, referred to as "disease suppression", may possess other advantages over conventional pesticides, in addition to their non-hazardous nature. They could lead to the reduction or replacement of the application of pesticides, fungicides and nematicides, which can adversely affect water resources, food safety and worker safety (Hoitink and Boehm 1999; Shilev *et al*. 2007). Most fungicides have only a temporary effect and usually require repeated applications during the growth season. Biological control agents have the ability to reproduce, to establish themselves in the soil ecosystem and to colonize seeds, the spermosphere, the rhizosphere, the rhizoplane, and foliage (Hoitink and Boehm 1999). Furthermore biocontrol strategies are highly compatible with the sustainable agricultural practices that are required for conserving the fundamental natural resources of agriculture (Sivan and Chet 1992; Hoitink and Boehm 1999).

Addition of organic amendments to soils can suppress several, economically-relevant greenhouse and crop diseases (Rotenberg *et al*. 2005). Composted organic amendments can reduce the severity of soil-borne diseases; primarily those caused by root-rot pathogens in container systems (Stephens *et al*. 1981; Hoitink *et al*. 1999) and in the field (Lewis *et al*. 1992; Drinkwater *et al*. 1995; Stone *et al*. 2003). The nature of organic-matter-mediated, root-rot suppression is based mainly on the interaction associated with high overall microbial activity (Zhang *et al*. 1998), organic matter decomposition (Boehm *et al*. 1993; Stone *et al*. 2001), and the sequestering (McKellar and Nelson 2003) and availability of carbon substrates that sustain high-microbial activity (Chen *et al*. 1988; Hu *et al*. 1997; Hoitink and Boehm 1999). There are fewer examples of foliar disease suppression with the use of organic amendments. Although composted organic by-products have been shown to suppress foliar disease caused by aerial bacteria and fungi (Stone *et al*. 2003; Khan *et al*. 2004), their efficacy has been more variable (Zhang *et al*. 1996, 1998; Abbasi *et al*. 2002; Krause *et al*. 2003) and therefore, less predictable (Rotenberg *et al*. 2005).

Compost prepared from heterogeneous wastes and used in container media or as soil amendments may have highly-suppressive effects against diseases caused by many soil-borne plant pathogens such as *Pythium* spp. (Mandelbaum and Hadar 1990; Boehm and Hoitink 1992; Zhang *et al*. 1996; Pascual *et al*. 2000); *Phytophtora* spp. (Hoitink and Boehm 1999; Widmer *et al*. 1999; Chae *et al*. 2006; Termorshuizen *et al*. 2006), *Fusarium* spp. (Chef *et al*. 1983; Trillas-Gay *et al*. 1986; Cotxarrera *et al*. 2002; Pharand *et al*. 2002; Reuveni *et al*. 2002; Termorshuizen *et al*. 2006), *Rhizoctonia* spp. (Kuter *et al*. 1983; Tuitert *et al*. 1998; Termorshuizen *et al*. 2006) *Botrytis cinerea* (Horst *et al.* 2005), *Sclerotium rolfsii* (Hadar and Gorodecki 1991), *Verticillium dahliae*, *Cycndrocladium spathiphylli* and *Spathiphyllum* spp. (Termorshuizen *et al*. 2006), *Colletotrichum orbiculare* and *Pseudomonas syringae* pv. *maculicola* (Zhang *et al*. 1996, 1998). Even foliar sprays of compost extracts have been reported to significantly reduce the bacterial spots on tomato fruit caused by *Xanthomonas vesicatoria* (Al-Dahmani *et al*. 2003, 2005).

Edaphic microorganisms stimulated by these amendments contribute to the suppressive activity of the amended soils through all four principal mechanisms of biological control: 1) competition, 2) antibiosis, 3) parasitism/predation, and 4) systemic induced resistance (Lockwood, 1988). This type of control is based on the activities of biological control agents within the context of microbial communities and their response to soil and plant-introduced energy reserves. The concentration and availability of nutrients (carbohydrates in lignocellulosic substances, chitin, lipids, etc.) within the soil organic matter play a critical role in regulating these activities (Baker and Cook 1974; Hoitink *et al*. 1997; Cohen *et al*. 1998; Stone *et al*. 2001; Rotenberg *et al*. 2005). Organic amendments such as green manures, stable manures, and composts can provide this food base and have long been recognized to facilitate biological control if applied well in advance of planting (Baker and Cook 1974; Hodges and Scofield 1983; Lumsden *et al*. 1983).

From a theoretical point of view, both the abiotic characteristics and the biological properties can affect compost disease suppression. However in most cases, suppressive effect is fundamentally-based on the beneficial microflora selected throughout the composting process (Hoitink and Fahy 1986; Hoitink *et al*. 1993; Cotxarrera *et al*. 2002; Alabouvette and Steinberg 2006; Lima *et al*. 2008a). In fact, the suppressive effect disappears after sterilization treatments (Alabouvette and Steinberg 2006; Lima *et al*. 2008a).

The composting process involves the complete or partial degradation of a variety of chemical compounds by a consortium of micro-organisms, the composition of which changes as composting progresses. Characteristics of the microbial population and their rate of change depend on the substrate and physical conditions under which composting is taking place (Boulter *et al*. 2000).

The duration of suppressiveness capacity and the degree and efficacy are critically affected by a number of compost and soil factors includibg: i) feedstock from which the compost is prepared; ii) the composting process; iii) the salinity of the compost; iv) the compost maturity and stability; v) microorganisms that colonize the composts after peak-heating or before planting in the soil; vi) the nutrient content of the compost; vii) the rate and timing of compost application; viii) the character of soil organic matter. In many cases the quality of the product composted cannot be standardized. This has been a major limitation in recommending compost for disease control. Production issues need further research. To enhance the suppressive potential of composted residues and thus to improve the efficacy of disease control, inoculation of composting samples after peak-heating with specific strains of biological control agents has been proposed. Although promising, this strategy has not yet been successfully applied. In fact, as for every type of soil, every compost has a certain level of suppressiveness towards introduced micro-organisms. Thus, it is not easy to establish biological control agents in composts even after peak heating (Hoitink and Boehm 1999; Alabouvette and Steinberg 2006).

A number of micro-organisms, including *Pseudomonas* spp., *Pantoea agglomerans* (former *Enterobacter agglomerans*), *Bacillus* spp., *Burkholderia* spp., *Klebsiella* spp., *Enterobacter* spp., *Serratia* spp., *Flavobacterium* spp, *Streptomyces* spp., *Trichoderma* spp., non-pathogenic strains of *Fusarium* spp., *Penicillium* spp. were isolated and tested as biocontrol agents for their ability to induce suppression (Boehm *et al*. 1993; Boulter *et al*. 2002; Georgakopoulos *et al*. 2002; Krause *et al*. 2003; Suárez-Estrella *et al*. 2007).

Composts contribute to disease suppression in a complex manner, involving all the above-mentioned mechanisms. Therefore, generally applicable predictive variables for pathogen suppression based on simple compost physical-chemical and/or biological characteristics are hard to determine. As a consequence of the different mechanisms involved, disease protection properties may differ dramatically among composts (Termorshuizen *et al*. 2006).

So far very few studies are available on the disease-suppressive effect of composted olive waste. Lima *et al* (2008a) demonstrated the disease-suppressive effect of composted 2-POH against fungal plant pathogens. The *in vitro* growth of *Verticillium dahliae* and another 6 significant fungal plant pathogens was consistently inhibited by water extract from composted 2-POH (CWEs). Suppressive effect decreased or disappeared when CWEs were autoclaved before use. These results suggest that the suppressive effect is probably correlated to the beneficial residual microbial population in composted residues. Moreover, the growth of *Pyrenochaeta lycopersici*, *Verticillium albo-atrum* and *V. dahliae* was also reduced by the application of autoclaved CWEs, and this positive effect could be due to the antifungal effect of residual phenolics and fatty acids. *In vivo* tests carried out both in growth chambers and nursery on 2-year-old olive plants, grown in potting mixes amended with 2-POH compost (15% v/v), showed that the recovery of *V. dahliae* microsclerotia was significantly reduced (Lima *et al*. 2008a, 2008b).

Ntougias *et al*. (2008) studied the disease-suppressive effect of nine composts prepared from agro-industrial wastes abundant in the Mediterranean basin. Grape marc, spent mushroom and OL were composted alone or mixed with OMW, 3-POH, and extracted olive press cake. All the composts demonstrated high levels of suppression of *Phytophtora nicotianae* in tomato plants, although this effect was negatively affected by prolonged compost storage. The same composts exerted highly-variable suppressive effects on *Fusarium oxysporum* f. sp. *radicis-lycopersici*. The authors suggest that suppression of disease caused by *Phytophtora* spp. may be related to general microbial activity and changes in the microbial community structure in the growth media while suppression of *Fusarium* may be induced by specific biological agents. Three of the composts conferred induced systemic resistance against the foliar pathogen *Septoria lycopersici*. The comparative evaluation of the nine composts revealed no common critical biotic or abiotic variable determining their suppressive effects on soil-borne diseases. Cayuela *et al*. (2008) demonstrated the high potential of sterile water extracts of raw and composted 2-POH as bio-based potential pesticide against several species of fungi, weeds and nematodes. 2-POH extracts *in vitro* strongly inhibited *Phytophtora capsici*. In contrast, suppression of *Pythium ultimum* and *Botrytis cinerea* by the extracts was variable and not as strong as for *P. capsici*. Mature 2-POH CWE totally and significantly inhibited the growth of *P. capsici* and *B. cinerea*, respectively, while the growth of the basidiomycete root-rot agent *Rhizoctonia solani* was not inhibited by any 2-POH or 2-POH CWE. 2-POH and immature 2-POH CWE substantially inhibited germination of the highly invasive weeds *Amaranthus retroflexus* and *Solanum nigrum*, whereas mature CWE only partially reduced the germination of *S. nigrum*. Moreover, 2-POH extracts were found to strongly inhibit egg hatching and second-stage juvenile motility of the root-knot nematode *Meloidogyne incognita*. The study shows the abiotic suppressive capability produced by chemical compounds of raw and composted 2-POH. However, the use of non-sterilized samples and compost teas would also imply biological mechanisms which could, in many cases, result in an increase in disease control (Cayuela *et al*. 2008). Similarly, Nico *et al*. (2004) found that root-galling and the final population of *Meloidogyne incognita* and *Meloidogyne javanica* in tomato and olive plants was reduced by compost amendments of potting mixes. However, compost from OH did not show any suppressive effect of root-galling and final nematode population. Koutsou *et al*. (2004) found that *Rhizoctonia solani* damping-off of lettuce was significantly reduced in soil that has been previously treated with OMW. But when OMW bioremediated using *Azotobacter vinelandii* was added to the soil, suppressive effect was not found to be significant. Similarly, in another study by Yangui *et al*. (2008), OMW displayed a high level of antibacterial activity against the agent of crown gall disease of bitter almond *Agrobacterium tumefaciens in vitro* and *in planta*. Five indigenous bacteria isolated from OMW exhibited an antagonistic effect against *A. tumefaciens*. According to the authors, the significant reduction of crown gall incidence on bitter almond trees using the OMW amendment was attributed to the effect of polyphenols and probably other chemical compounds. Moreover, it is possible that OMW indigenous bacteria played a major role in the suppression of *A. tumefaciens*.

The results of these investigations indicate that composted olive by-products could be effectively used in eco-compatible agriculture systems, not only because of their positive agronomic properties, but also because of the suppressive effect against fungal plant pathogens, weeds, nematodes of olive and other several important vegetal crops. However, further research is required to clarify the nature and the variability of the biocontrol effect and its correlation to the particular biotic and abiotic properties of olive mill by-products and to compost quality, maturity, stability and application practices. This could lead to the production of composts with specific properties and effects for specific uses: "Tailored Composts".

CONCLUSIONS

This work discusses the latest developments in olive-residue composting in the Mediterranean Basin. Olive mill wastes (OMW, 2-POH, 3-POH) are of great concern worldwide due to their high-pollution potential and their management represents a significant economic and environmental problem that has often hindered the growth of the olive oil sector. OMW, 2-POH, 3-POH appear to be more of a resource than to be actually waste and their recovery, in terms of both energy and organic matter applications, appears to have great potential. Many of the most-commonly accepted disposal methods (lagooning, combustion, wastewater treatment) are currently causing the loss of important resources without preventing harmful effects on soil, water and the air, especially in those countries where resources are scarce.

The lack of a common legal framework and olive-waste-management guidelines among European and Mediterranean countries is aggravating the situation and is contributing to the further loss of resources. An integrated approach by the olive-oil-producing countries of the Mediterranean basin would be highly desirable.

Research over the last few decades has been focussing on the composting of olive waste as an ecologically-compatible and economically-sustainable solution to be specially adapted/adopted by the small and medium-sized agricultural farms which constitute the vast majority of the Mediterranean agricultural context and very often do not have significant labour or economic resources.

The composting process may be considered to be one of the most environmentally-friendly options for valorisation of by-products because of the potential to produce high-quality organic amendments without phytotoxic and anti-microbial effects. Composted olive waste can be used in agriculture as high-quality, eco-compatible, organic amenders and fertilizers, which, in addition, may considerably provide plant-pathogen control through its disease-suppressive effect. The disease-suppressive effect seems to be fundamentally based on the beneficial microflora selected throughout the composting process. However, further research is required to clarify the nature and the variability of the biocontrol effect and its correlation to the particular biotic and abiotic properties of olive mill by-products and to compost quality, maturity, stability and application practices. This could lead to the production of composted residues with specific properties and effects for specific uses: "Tailored Composts".

The application of cured composts for the control of fungal pathogens in olive and in other crops in organic agriculture systems seem to be a very promising strategy. This would be particularly important to close the cycle of residue-resource and to find alternatives to the chemical control of plant diseases.

Low-cost simplified technologies which have demonstrated greater reliability have been selected. These promising, low-cost, simplified technologies could largely find application in the olive-oil-producing countries, especially taking into account the agricultural, structural and economic scenarios in the large number of olive-oil-producing countries in the Mediterranean basin.

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