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Research Article

Olive Mill Wastewaters Spreading on Agricultural Land: Results and Practical Management

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Abstract

Rich in water (88 to 95%), organic matter (6 to 14%) and mineral matter (1.5 to 4%), the olive mill wastewater or liquid effluent from the olive processing industry represents a certain fertilizer source. Four treatments (Control, 50, 100 and 200 m^3 ha^{-1} of OMWW) with an annual spreading of fresh OMWW, are applied to evaluate the effects of direct spreading of this by-product on the soil and the plant. From the first application, the level of organic matter changed significantly compared to the control soil without OMWW. In fact, three months after spreading, the respective levels of this substance increased from 0.42% in the control plot, to 0.91%, 1.02% and 1.47% respectively, for the spreading doses of 50, 100 or 200 m^3 ha^{-1}. After several years, these same rates are only 0.84%, 0.91% and 0.95% for the respective doses of 50, 100 and 200 m^3 ha^{-1}, indicating an intense activity of mineralization of organic matter under the effect of the soil microflora whose number has increased. The improvement in mineral status consequently improved the growth of olive groves with application doses of 50 and 100 m^3 ha^{-1}. A decline in olive production was recorded with the dose 200 m^3 ha^{-1}, which could be explained by the inhibitory effect probably resulting from a slight toxic action of polyphenols accumulated in the soil. Finally, it should be noted that the results of this research led to the development of Decree No. 1308/2013 of February 26, 2013, authorizing the spreading of 50 m3 ha 1 of fresh vegetable water.

Keywords

Olive Tree, OMWW, Fertilizer, Soil, Microbiology, Polyphenols

1. Introduction

Olive mill wastewater is the liquid effluent produced by oil mills after the olives have been crushed. The quantity produced varies with the crushing process. With conventional extraction systems, processing one ton of olives produces 450 liters of OMWW, while with the 3-phase continuous system, production varies between 800 and 1200 liters. Thus, with an average annual olive production of 850,000 tons over the period 1990 - 2012, OMWW production in Tunisia is estimated at around 680,000 tons per year, 40% of which comes from the pressure system and 60% from the continuous system. These OMWW are characterized by

1. Seasonal production spread over 2 to 5 months per season, depending on the scale of olive production.
2. A high load of organic and mineral matter: the dry

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residue at 105°C varies from 5 to 17% of the fresh weight of the product, depending on the extraction system [1].
3. A polluting power equivalent to the discharge load of a population of 2.5 millions for each day of the campaign, which lasts an average of 100 days a year [2]. In Italy, Amirante [3], estimates that processing one tonne of olives generates 36 kg of BOD_5, corresponding to the daily load of 650 inhabitants, with a correspondence factor of 0.055 kg BOD_5 / inhabitant.
4. What's more, their high organic content means that they cannot be treated industrially as wastewater in urban wastewater treatment plants. As a result, the uncontrolled discharge of OMWW into the environment can present potential environmental pollution risks [4].
5. At present, raw OMWW are discharged annually into open-air storage and drying basins [5]. This solution transforms the liquid OMWW into a solid sludge by evaporation. However, it has harmful effects on the environment, such as the infiltration of OMWW, the release of noxious odors, the disfigurement of the natural environment, and so on. Hence the need to find appropriate, sustainable solutions to the problem posed by this effluent. These solutions may involve reclaiming the OMWW or some of their components [6].

Following the example of Italy, and to a lesser extent Spain and Greece, research into the direct land application of OMWW has been carried out in Tunisia since 1995. This research has attempted to solve several problems and answer several questions, such as:

1. Are OMWW toxic to soil and plants?
2. Do the polyphenols contained in OMWW have a negative effect on soil flora and fauna? Do residual fats affect soil permeability?
3. Do OMWW provide assimilable nutrients?
4. Do OMWW improve soil organic matter levels? What effect do OMWW have on soil fertility?

2. Materials and Methods

In order to study the effects of the direct application of OMWW on the soil and the plant, several experimental plots were set up in various climatic zones of Tunisia: humid zone (Borj el Amri, 2003, olive, apple and pear trees), upper arid zone (Chaâl and Taous in Sfax, 1995 and 2003, olive tree, tomato and maize) and lower arid zone (Zarzis and Sidi Chammekh, 1995 and 2003, olive tree). In each site, four treatments are applied with annual spreading of fresh OMWW during the winter vegetation rest period:

1. Control (T): no OMWW application,
2. Dose 1 (D1): application of 50 m^3 OMWW per hectare
3. Dose 2 (D2): application of 100 m^3 OMWW per hectare
4. Dose 3 (D3): application of 200 m^3 OMWW per hectare.

The treated plots cover an area of 1 hectare per dose of OMWW, with mature olive trees planted at square densities of 24 x 24 meters on sandy soils (to the south) and 10 x 10 m (100 olive trees / ha) to the north (Borj el Amri). To monitor and assess the impact of OMWW on the physico-chemical and microbiological characteristics of the soil, these plots are regularly monitored as follows:

1. Determination of the chemical composition of OMWW on samples taken during spreading and stored in a refrigerator at 5°C.
2. Analysis of the physical, chemical, and biological characteristics of the soil to a depth of over 1 meter for the various treatments. Analyses are carried out just before spreading begins and 3 months after application. The analyses cover: organic matter, pH, electrical conductivity, nitrogen, phosphorus, potassium, calcium, sodium, magnesium, polyphenols, and soil microbiology.
3. Monitoring growth characteristics, crop production and determining the quality of oils produced.

Figure 1. *OMWW spreading.*

3. Result

3.1. Soil Characterization Before OMWW Spreading

The experimental sites of Chaâl (arid) and Borj el Amri (humid) are used as models. The Chaâl site is characterized by sandy soil at the surface and sandy clay at depth. It has relatively high levels of active limestone and very low levels of gypsum. The soil is of the iso humic type, well filtered with a notable capacity for leaching (Table 1). It is very low in organic matter (OM < 0.3%). Its pH is clearly basic (between 8 and 8.5) and its electrical conductivity is very low (0.3 dS m^{-1}). At Borj El Amri in northern Tunisia, the soil has a sandy-silty texture (75% sand and 25% silt) and is richer in organic matter (0.5%).

Table 1. *Granulometric characterization of different soil horizons at the sites of Chaâl and Borj El Amri.*

	Granulometric analysis (%)					
Horizons (cm)	**Clay**		**Silt**		**Sand**	
	Chaâl	**Borj El Amri**	**Chaâl**	**Borj El Amri**	**Chaâl**	**Borj El Amri**
0-20	7.4	0.08	1.3	24.05	94.0	75.87
20-40	3.5	0.16	1.1	24.05	95.4	75.79
40-60	8.3	0.1	4.1	24.41	88.1	75.49
60-80	10.3	3.89	5.7	16.85	84.0	79.26

3.2. Chemical Characteristics of OMWW Used

The OMWW used contain appreciable quantities of organic and mineral elements. During the various test years, the water content of this effluent varied from a maximum of 95.4% to a minimum of 87.9% (Table 2). As a result, its dry extract at 105 ℃ ranged from a minimum of 44.6 g L^{-1} to a maximum of 122 g L^{-1}, composed essentially of organic substances (32.5 to 107 g L^{-1}) and minerals (12.1 to 24 g L^{-1}). The organic fraction consists of sugars (15 g L^{-1}), proteins (12 g L^{-1}), fats (3.2 g L^{-1}) and phenols (1 to 6 g L^{-1}). This high organic matter content explains the relatively high chemical and biological oxygen demand (COD = 64 to 105 g L^{-1} and BOD_5 = 35 to 55 g L^{-1}). Inorganic matter consists mainly of potassium (4 to 7.5 g L^{-1}), sodium (1.15 to 1.31 g L^{-1}), nitrogen (0.44 to 1.4 g L^{-1}), calcium (0.71 to 2.3 g L^{-1}), magnesium (0.65 to 1.05 g L^{-1}), chlorides (0.56 to 1.25 g L^{-1}) and phosphates (0.40 to 1.4 g L^{-1}). In addition, OMWW has a high electrical conductivity (12.4 to 18.6 mS cm^{-1} at 25 ℃) and an acid pH (4.2 to 5.5).

Table 2. *Extreme chemical composition of the OMWW used at the different sites during the study campaigns.*

Parameter	**Values**	
	Minimum	**Maximum**
pH	4.17	5.5
EC (mS cm -1)	12.38	18.6
Water content	95.4	87.9
Dry matter (g L-1)	44.6	122
DCO (g L-1)	63.79	105
DBO5 (g L-1)	34.90	55
Organic matter (g L-1)	32.55	107
Fat (g L-1)	3.18	4.5
Sugars (g L-1)	14.63	15.3
Phenolic compounds (g L-1)	0.99	5.8
Total nitrogen (g L-1)	0.44	1.4
Carbon (g L-1)	1.27	3.74
C/N	2.9	2.7
Mineral matter (g L-1)	12.05	23.7
Phosphorus (g L-1)	0.08	0.32
Potassium (g L-1)	4.37	7.5

Parameter	Values	
	Minimum	Maximum
Sodium (g L-1)	1.15	1.31
Calcium (g L-1)	0.71	2.3
Magnesium (g L-1)	0.65	1.05
Chlorides (g L-1)	0.56	1.25

3.3. Effect of Spreading OMWW on Soil Fertility

Given the relative richness of OMWW in organic and mineral elements, it seems clear that spreading this effluent on the soil will have an effect on soil fertility [7]. Depending on the dose applied, OMWW can provide the soil with an average between 6 and 24T $ha^{-1}year^{-1}$ of organic matter, 37 to 140 Kg of nitrogen, 16 to *64* Kg of phosphorus and 75 to 1100 Kg of potassium $ha^{-1}year^{-1}$. The results obtained for these parameters are reported in Table 3.

Table 3. *Dry residues, organic matter, total minerals and NPK provided by OMWW as a function of the dose applied to the soil (Unit: kg per hectare).*

Doses	Dry residue 105 °C	Organic matter	Mineral matter	N	P	K
50 m^3	6035	5350	685	37	16	275
100 m^3	12070	10700	1370	74	32	550
200 m^3	24140	21400	2740	148	64	1100

3.3.1. Effect on Electrical Conductivity

Despite the relatively high mineral element content of OMWW (12 to 23 g L^{-1}), the high permeability of sandy soils and the consequent high leaching rate seem to prevent electrical conductivity values from increasing excessively (Table 4). In fact, despite 12 consecutive applications in the arid climate of Chaâl, where average rainfall is 200 mm year $^{-1}$, and with OMWW, electrical conductivity values initially ranged between 0.4 and 0.5 dS m^{-1}, but only reached 0.69 with the 50 m^3 dose and 3.9 dS m^{-1} with the 200 m^3 dose, thus remaining acceptable. At Borj El Amri, after 4 successive applications, C. E. values only reached 1.81 dS m^{-1} with the highest dose. This was due to leaching, which drained the salts deep into the soil, and to the consumption of some of the mineral elements by plants and soil fauna. As a result, some of the minerals are exported, while others are transformed into organic matter (Table 4).

Table 4. *Soil chemical composition (surface horizon) at the Chaâl site following 13 consecutive years of OMWW application (Sept. 2007) and at the Borj El Amri site (after 4 applications).*

Parameter	Control		50 m^3		100 m^3		200 m^3	
	Chaâl	Borj El Amri	Chaâl	Borj El Amri	Chaâl	Borj El Amri	Chaâl	Borj El Amri
pH	8.14	8.34	8.42	7.94	7.96	7.96	8.81	7.85
EC	0.45	0.53	0.58	0.69	0.67	0.67	3.90	1.81
MO (%)	0.20	0.48	0.34	0.55	0.79	0.79	0.83	1.10
N (ppm)	420	714	420	1001	795	795	620	697

Parameter	Control		50 m^3		100 m^3		200 m^3	
	Chaâl	Borj El Amri	Chaâl	Borj El Amri	Chaâl	Borj El Amri	Chaâl	Borj El Amri
P (ppm)	24.1	31	34.7	33	64	63.1	61.4	65
K (ppm)	77.0	72.5	750	660	1075	1075	1100	1400
Na (ppm)	11	44	44	131	114	114	71	94

We would also like to point out that the absence of OMWW for two successive years has led to a drop in electrical conductivity values because of salts leaching out and migrating deep into the sandy soil of the Chaâl site.

3.3.2. Effect on Organic Matter Content

Relatively rich in organic substances (annual contribution of 5.3 to 21T/ha depending on the dose applied), the OMWW applied rapidly improves the soil's organic matter content [8]. At Borj El Amri, after the first application, the initially low level of organic matter was at least doubled for the different doses applied. Its values rose from 0.45 to 0.68% with the 50 m^3 dose, from 0.46 to 0.91% with the 100 m^3 dose and from 0.48 to 1.26% with the 200 m^3 dose. After four successive applications, these respective rates become: 0.55%, 0.79% and 1.1% for doses of 50, 100 and 200 m^3 (0.48% in the soil of the control plot). In the Chaâl soil, where organic matter was almost non-existent 12 years ago (from 0.05 to 0.2%), its levels have become excellent for the degraded soils of the arid region, since they are equal to 0.34%, 0.79% and 0.83% depending on whether the doses of OMWW are 50, 100 or 200 m^3. These values testify to a restoration of soil fertility resulting from its significant enrichment in organic compounds, leading to improvements in soil fertility and water retention capacity, micro-organism activity and, consequently, tree growth and fruiting.

Comparison of these values with the results obtained 8 years previously (after the sixth application, Table 4) shows similar values for the 50 and 100 m^3 doses (0.41 and 0.71% organic matter, respectively) and a regression in the content of this substance to 0.83%; whereas it was equal to 1.27% during the 2000/2001 campaign. This regression is probably due to the growth of an intense flora of microorganisms responsible for the mineralization of organic matter.

3.3.3. Effect on Phenolic Compound Content

Given the high phenolic content of OMWW (4 to 6 g L^{-1}), which is potentially toxic and inhibits the development of microorganisms [9], spreading this effluent on the soil is likely to have a depressive impact on flora and fauna. To this end, an in-depth study of the impact of these substances, both in situ and in the laboratory, is being carried out.

After 3 months of spreading, the polyphenol contents in the soil, at depths ranging from 0 to 80 cm, are substantially comparable for the different doses of OMWW except for that 100 m^3 ha^{-1}, which presents the values the highest (Table 5). Furthermore, it should be noted that there are no significant differences between the two treatments 100 and 200 $m^3 ha^{-1}$.

The identification of phenolic compounds by gas chromatography coupled with mass spectrometry after extraction with methanol carried out 9 months after the application of OMWW, in the soil having received the highest dose of OMWW (200 m^3 ha^{-1}), gave the following chromatogram (Figure 2).

Table 5. *Effect of the addition of OMWW on the soil content of phenolic compounds in the Chaâl site after 12 successive years of spreading (in ppm)*

Dose	0-20 cm	20-40 cm	40-60 cm	60-80 cm
Control	1155	1301	1082	1514
50 m^3 ha^{-1}	997	1176	1440	1127
100 m^3 ha^{-1}	1858	1880	1384	2007
200 m^3 ha^{-1}	1476	1221	1298	1374

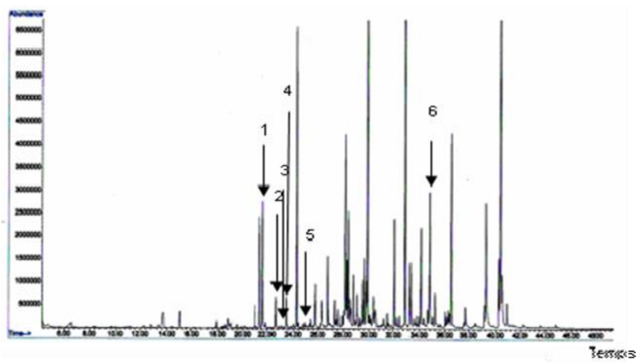

Figure 2. *Chromatogram of the soil extract receiving the dose of 200 m3 ha-1 (Layer 0-40 cm).*

The identification of these polyphenols revealed the presence of the following six compounds: vanillic acid (1), 4 hydroxyphenylethanol (tyrosol) acid (2), 4-hydroxybenzoic acid (3), 4-hydroxyphenylethanol acid (4), hydroxyphenylacetic acid (5) and ferrulic acid (6).

3.3.4. Effect of Spreading OMWW on Soil Microflora

The enumeration of the total flora 3 months after spreading revealed that the addition of OMWW is accompanied by an increase in the number of microorganisms in the soil compared to the control [10], (Figure 3). This increase depends on the dose provided and is remarkable for the two superficial layers going from the surface to 40cm depth. This is due to the contribution of organic matter and indigenous microorganisms to the OMWW.

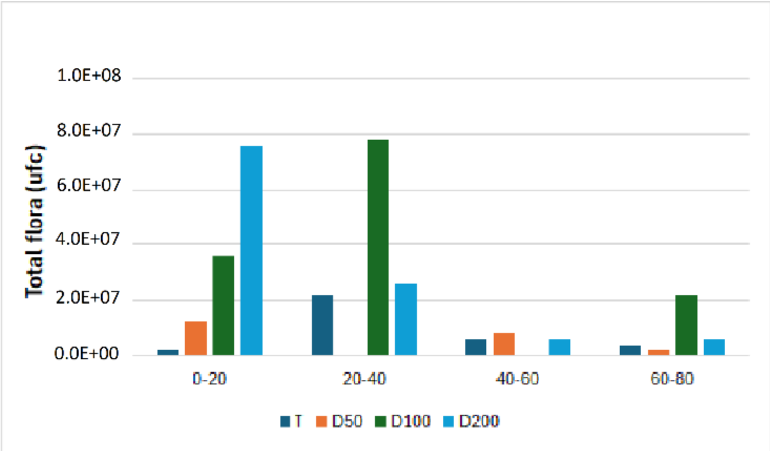

Figure 3. *Effect of the addition of OMWW on the total soil flora, 3 months after spreading (cfu = colony forming unit).*

3.3.5. Effect of Spreading OMWW on the Physical Characteristics of the Soil

The spreading of OMWW modifies the physical structure of the soil [11]. Thanks to its binding power, the addition over the years of this effluent induces a conglomeration of fine earth composed of particles having a diameter less than 2mm. The rate of this fraction increases from a rate of around 100% at the start of the experiments, to values of 96.5%, 90.7% and 74.5% for doses of 50, 100 or 200 m^3 ha^{-1} respectively. This action improves the structural stability of the soil by consolidating its aggregates made up of fine earth and consequently its water reserves, without however making it impermeable (Figure 3).

These results corroborate those of Mellouli [12], who reports that OMWW, thanks to its hydrophobic and binding powers, promotes the formation of a more effective mulch than the natural one (sand alone) whose porosity and structure play the role of role of a barrier against evaporation. Furthermore, they can be compared to those of Gabriels et al. [13] obtained in sandy soil treated with bituminous emulsions and which demonstrate the effectiveness of mulch made up of aggregates having a thickness less than 5.35 mm allowing better soil stability and a substantial reduction in evaporation.

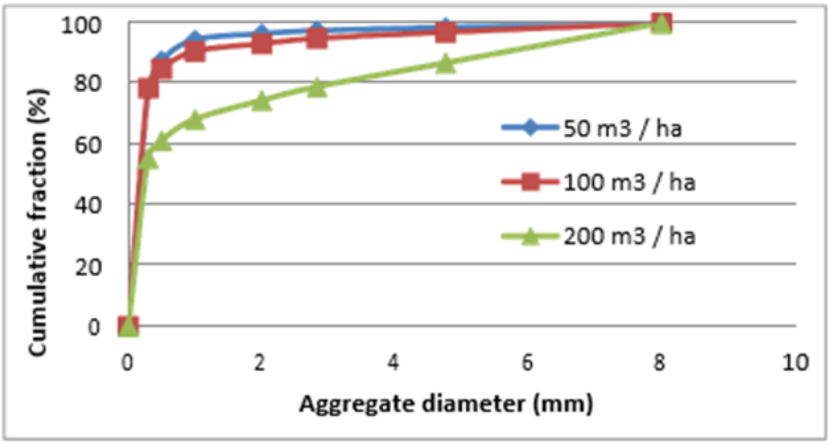

Figure 4. *Structural stability of the soil expressed in%.*

Studying the effect of OMWW on the wind transport of fine particles of sandy soil vulnerable to erosion (87.5% are of a diameter <0.3mm), we found that the contribution of this effluent protects the soil by delaying the departure of its very fine particles. Indeed, if the departure of the first particles is observed at a wind speed equal to 8.50m s^{-1} (i.e. 30.6 Km h^{-1}) on the control soil, it only appears at respective speeds of 10 .26m s^{-1} and 12.16 m s^{-1} for soils having received 100 and 200 m^3 ha^{-1} (Figure 5).

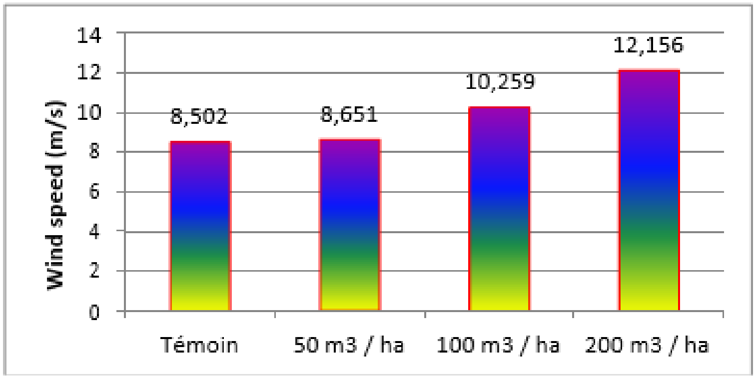

Figure 5. *Wind speed causing the start of the phenomenon of transport of soil particles by wind erosion depending on the dose of OMWW.*

3.3.6. Effect of OMWW Spreading on the Growth and Production of Olive Tree

In adult olive groves, the winter application, at the time of the vegetative shutdown, of increasing quantities of OMWW did not cause any phytotoxic effect on the trees. On the contrary, it resulted an improvement in their growth and fruiting bodies which were increased for the different doses compared to the control without intake [14] (Table 6).

Table 6. *Average annual production of the last 3 campaigns 2005/2006 - 2007/2008 and average production of the 12 years of observation depending on the dose of OMWW (in kg per hectare). Chaâl experimental plots.*

Dose	Production 2005/2006 (kg/ha)	Production 2006/2007 (kg/ha)	Production 2007/2008 (kg/ha)	Average production over the 12 years (kg/ha)	Growth / Control during the 12 campaigns (%)
Control	799	255	1658	746,8	-
50 m^3 ha^{-1}	867	374	1709	799,7	+ 7%
100 m^3 ha^{-1}	986	391	1989	950,5	+ 27%
200 m^3 ha^{-1}	884	323	1615	800,4	+ 7%

The results representing the production of the three past seasons (2005/06, 2006/07 and 2007/08) show significant fluctuations resulting from the irregularity of rainfall, the importance of growth and flowering and the productive antecedent of the plot (physiological alternation). The average production shows a positive effect of the contribution of OMWW. Thanks to its fertilizing effect and the improvement of soil water reserves, the OMWW applied at doses of 50 and 100 m^3 ha^{-1} allows an increase in the vigor of the olive trees and the development of fruiting shoots that are longer and bear more leaves than those of the control, resulting in a positive effect on the level of flowering and fruiting expressed by the number of clusters and set fruits. The differences between the control and the treated plots persist until harvest by obtaining larger fruits (1.58 g for the 100 m^3 dose compared to only 1.17g in the control). The average of the 13 years of production is 746Kg ha^{-1} in the plot without OMWW and an increase in production varying between +7% and 27% depending on whether the dose provided is 50 or 100 m^3 ha^{-1} is recorded (respectively, 800 and 951 kg ha^{-1}). With the dose 200 m^3 ha^{-1}, this production is on average 800Kg ha^{-1} (i.e. an increase of 7% compared to the control).

3.3.7. Effect of Spreading OMWW on the Quality of Fruits and Oil

The results recorded in Table 7 show that OMWW does not in any way affect the quality of the fruits and the oil produced. On the contrary, thanks to its positive effects on soil fertility and its water status, OMWW improves the quality of olive production. The fruits are generally of a larger size and their oil content is not affected (either in their fresh or dry weight). These same results indicate that the quality of the oil, judged by its acidity and its composition of fatty acids, chlorophylls and polyphenols, is not affected. On the contrary, OMWW has a positive effect on this quality and makes the oil more stable. Being richer in polyphenols, the oil from olives harvested in the plots having received 100 and 200m^3 ha^{-1} has an oxidative stability of 5.6 hours compared to only 3 hours for the control.

Table 7. *Effect of the dose of OMWW on the quality of olives and the oil produced.*

Treatment	Control	50 m^3 ha^{-1}	100 m^3 ha^{-1}	200 m^3 ha^{-1}
Fruit characteristics				
Average weight of a fruit (g)	1.17	1.22	1.58	1.35
Fat / fresh weight (%)	29.02	28.36	23.24	27.49
Fat / dry weight (%)	55.63	55.21	54.64	54.91
Acidity of the oil produced	0.26	0.28	0.24	0.27
Acidic composition of the oil produced (%)				
Palmitic ac. C16:0	20.23	19.61	19.27	19.68
Palmitoleic ac. C16:1	2.45	2.28	2.31	2.50
Stearic ac. C18:0	1.91	2.07	2.20	2.00
Oleic ac. C18:1	57.20	57.82	59.40	59.04
Linoleic ac. C18:2	17.14	17.10	15.81	15.70
Linolenic ac. C18:3	0.58	0.60	0.44	0.58
Arachidic ac. C20:0	0.33	0.33	0.40	0.33
Gadoleic ac. C20:1	0.13	0.15	0.15	0.13
Light-specific extinguishing				
K232	1.88	1.87	2.10	2.01
K270	0.13	0.11	0.14	0.13
Chlorophyll contents (ppm)	0.24	0.33	0.47	0.48
Polyphenol contents (ppm)	28.94	23.81	91.23	129.17
Oxidative stability of the oil by rancimat (Hours)	3.03	3.03	5.67	5.65

3.4. Effect of OMWW on Apple and Pear Production

As with the olive tree, the addition of increasing quantities of OMWW has substantially improved the production of apples and pears trees. Compared to the production of the control which is 13.175 tonnes ha^{-1}, the observation of apple production in the trees receiving this type of fertilizer shows an improvement in production ranging from 3.875 T ha^{-1} in the trees in the plot having received 50 m^3 ha^{-1} to 6.875T ha^{-1} for the 100m^3 ha^{-1} dose (respectively, 17 T and 20.4T ha^{-1}. With the 200 m^3 ha^{-1} dose, this production is only 10.625 T ha^{-1}, i.e. a reduction of 2,550T ha^{-1} compared to the control and almost 10 tonnes compared to the dose 100 m^3 ha^{-1}.

With the pear tree, the evolution of production is similar to that of the apple tree. Indeed, from 32.5T ha^{-1} in the control, this production reached 50.3T ha^{-1} with the dose of 100 m^3 ha^{-1} to decline by 10 T (42.2 T ha^{-1}) with the dose of 200 m^3 ha^{-1}.

Table 8. Production of apples recorded in June 2007 and pears harvested in August 2007 in the different plots having received OMWW in the SODEXA area of Borj El Amri (Unit: ton per hectare).

Crops	Planting density (tree ha^{-1})	Control	50 m^3 ha^{-1}	100 m^3 ha^{-1}	200 m^3 ha^{-1}
Pear tree	1624	32.480	35.728	50.344	42.224
Apple tree	850	13.175	17.000	20.400	10.625

3.5. Effect of OMWW on Tomato and Fodder Corn Production

Examination of the results recorded in Table 9, relating to the production of tomato and fodder corn (cut green at the start of heading), shows controversial values. If the doses of 5 and 10 liters of OMWW m^2 (equivalent to 50 and 100 m3/ha) induce substantial improvements, the doses 15 and 20 L/m^2 gave values similar if not lower than those recorded in the control plots.

Table 9. Evolution of tomato and green-cut fodder corn production in relation to the dose of OMWW

Crops	Number of plants / hectare	Control (T ha -1)	5 l / m ²(T ha -1)	10 l/m ²(T ha -1)	15 l/m ²(T ha -1)	20 l/m ²(T ha -1)
Fodder corn	40.000	15.0*	13.8	16.9	12.0	12.0
Tomato	25.000	14.450*	19.500	18.400	18.500	14.250

* The plots of bare soil did not receive any fertilization other than OMWW.

4. Conclusion

The experiments carried out for twelve years on the agricultural use of raw OMWW in olive orchards have made it possible to demonstrate that their annual spreading under well-defined conditions (dose and period of spreading), is accompanied by an improvement in the physicochemical properties of the soil, its water retention capacity and its biological activity. Despite an acidic pH of the OMWW, the pH of the soil remains practically unchanged compared to the control whatever the dose used. As for salinity, it remains very close to that of the control at a dose of 50 m^3 ha^{-1} and shows a slight increase with higher doses while remaining within acceptable limits. As for soil fertility, it is undeniably improved by the addition of OMWW, particularly in terms of organic matter and potassium content. In fact, the spreading of 1 m^3 of OMWW brings to the soil on average 107 kg of organic matter and 13 kg of mineral matter including 7.5 kg of potassium. Thus the organic matter content is multiplied by 4 to 10 times compared to the initial situation by going from the dose of 50 to 200 m^3 after 4 and 12 successive spreadings. The content of assimilable potassium increases significantly with the dose but remains without risk of pollution by soil salification up to 100 m^3 ha^{-1}. Monitoring the evolution of polyphenols in the soil up to 80 cm depth revealed that the contents of these compounds are comparable to those of the control whatever the depth (1000 to 1440 ppm) except for the dose of 200 m^3 ha^{-1} where the content is slightly higher (1800 to 2020 ppm). The analysis of these compounds highlighted the abundance of hydroxytyrosol and tyrosol which are products of the degradation of oleuropein. The spreading of OMWW, contrary to what one might think, promotes the soil microflora whose activity is improved by the enrichment of the soil with organic matter associated with the degradation of polyphenols.

Regarding their impact on the physical characteristics of the soil, we note that OMWW improve the structure of sandy soil by binding its fine particles, which cannot be without consequences on its stability and water properties. On a practical level, the valorization of OMWW by direct spreading can be recommended at doses of 50 and 100 m^3 ha^{-1} in order to avoid any risk of abuse and overdose. This valorization can contribute to the promotion of organic olive growing in traditional production areas that are easily convertible to organic cultivation. Finally, it should be noted that the results of this research led to the development of Decree No. 1308/2013 of February 26, 2013, authorizing the spreading of 50 m^3 ha^{-1} of fresh olive mill wastewater.

Abbreviations

OMWW: Olive Mill Wastewater
pH: Hydrogen Potential
EC: Electrical Conductivity
DCO: Chemical Oxygen Demand
DBO_5: Biological Oxygen Demand

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Chatzistathis T & Koutsos, T. Olive mill wastewater as a source of organic matter, water and nutrients for restoration of degraded soils and for crops managed with sustainable systems. *Agricultural Water Management*, 2017, *190*, 55-64. https://doi.org/10.1016/j.agwat.2017.05.008

[2] Ministry of the Environment and Regional Planning (MEAT) Mediterranean experiences in the treatment and elimination of wastewater from olive oil mills, 1996, 380 p.

[3] Amirante P. Treatment and use of by-products. International seminar on scientific innovations and their application in olive growing and oil technology. Florence. Italy. Eds COI 1999. 44 p.

[4] Gudiña E. J., Rodrigues A. I., de Freitas V., Azevedo Z., Teixeira J. A., Rodrigues, L. R. Valorization of agro-industrial wastes towards the production of rhamnolipids. *Bioresource technology*, 216, *212*, 144-150. https://doi.org/10.1016/j.biortech.2016.04.027

[5] Fki I, Allouche N., Sayadi S. The use of polyphenolic extract, purified hydroxytyrosol and 3, 4-dihydroxyphenyl acetic acid from olive mill wastewater for the stabilization of refined oils: a potential alternative to synthetic antioxidants. *Food Chemistry*, 2005, *93*(2), 197-204. https://doi.org/10.1016/j.foodchem.2004.09.014

[6] Souilem S., El-Abbassi A., Kiai H., Hafidi A., Sayadi S., Galanakis C. M. Olive oil production sector: Environmental effects and sustainability challenges. In *Olive mill waste* (pp. 1-28). Academic Press, 2017, https://doi.org/10.1016/B978-0-12-805314-0.00001-7/

[7] Tosti S., Accetta C., Fabbricino M., Sansovini M., Pontoni L. Reforming of olive mill wastewater through a Pd-membrane reactor. *International journal of hydrogen energy*, 2013, *38*(25), 10252-10259. https://doi.org/10.1016/j.ijhydene.2013.06.027

[8] Regni L., Gigliotti G., Nasini L., Agrafioti E., Galanakis C. M., Proietti P. Reuse of olive mill waste as soil amendment. In *Olive mill waste* (pp. 97-117). Academic Press, 2017, https://doi.org/10.1016/B978-0-12-805314-0.00005-4

[9] Ayed L., Bouguerra A., Charef A., Bakhrouf A., Mzoughi R. E. Biodegradation of Olive Mill Wastewater by a newly isolated novel bacterial consortium under RSM optimized culture conditions. *Journal of Water Process Engineering*, 2019, *32*, 100986. https://doi.org/10.1016/j.jwpe.2019.100986

[10] Abdennbi S., Chaieb M., Mekki A. Long-term effects of olive mill waste waters spreading on the soil rhizospheric properties of olive trees grown under Mediterranean arid climate. *Soil Research*, 2023, *62*(1). https://doi.org/10.1071/SR23102

[11] Mekki A., Dhouib A., Sayadi S. Polyphenols dynamics and phytotoxicity in a soil amended by olive mill wastewaters. *Journal of Environmental Management*, 2007, *84*(2), 134-140. https://doi.org/10.1016/j.jenvman.2006.05.015

[12] Mellouli H. J. Modifications of the physical characteristics of a silty sand by olive mill wastewaters: effects on evaporation. State thesis from the University of Gent, 1996, p255.

[13] Gabriels D., Moldenhauer W. C. and Kirklham D. Infiltration. hydraulic conductivity and resistance to water-drop impact of cold beds as affected by chemical treatment. Soil. Sci. Soc. Am. Proc, 1973, 37. pp 634-637. https://doi.org/10.2136/sssaj1973.03615995003700040043x

[14] Bargougui L., Guergueb Z., Chaieb M., Braham M., Mekki, A. Agro-physiological and biochemical responses of Sorghum bicolor in soil amended by olive mill wastewater. *Agricultural Water Management*, 2019, *212*, 60-67. https://doi.org/10.1016/j.agwat.2018.08.011