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Short-Term Effect of Different Inputs of Organic Amendments from Olive Oil Industry By-Products on Soil Organic Carbon and Physical Properties

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Abstract: Maintaining adequate levels of soil organic matter in Mediterranean agro-ecosystems is a pressing need due to the increasing evidence of climate change. The use of by-products of the olive oil industry as organic amendments could contribute to this goal. We report the results of a 2-year research carried out in southern Italy on a clay loam soil for evaluating the effects of different olive oil industry by-products on soil organic carbon and other related soil characteristics. The treatments were: (i) Olive mill wastewater (OMW), (ii) compost from olive pomace (CP1), (iii) compost from olive pomace in double quantity (CP2), and (iv) organo-mineral fertilizer (OMF). Soil samples, collected at a depth of 0–20 cm, were analyzed for total organic carbon (TOC), its extractable (TEC) and humic fractions (HC), and aggregate stability (Ist). In addition, soil macroporosity, water retention, and penetration resistance (PR) were evaluated. CP1 induced the largest increase in soil TOC, TEC, and HC content, and a significant improvement in Ist; the addition of a large quantity of organic carbon (CP2) did not determine a proportional increase in soil organic matter content. The aggregate stability of the CP2 was the lowest; nevertheless, the characterization of macroporosity indicated an improvement of soil structure functionality. With respect to control (OMF), OMW had a significant decrease in Ist and an increase in PR of the uppermost soil layer.

Keywords: aggregate stability; compost; olive mill wastewater; olive pomace; organic amendment; soil organic matter; soil penetration resistance; soil porosity; soil water retention

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1. Introduction

The maintenance or increase in soil organic carbon stock in Mediterranean agro-ecosystems is a long-standing agronomic issue [1,2]. It is well known that soil organic carbon (SOC) content is a crucial aspect of soil health since it forms the basis of the "soil food web" and biological activity, as well as being related to other soil functions, such as nutrient, water cycling, and greenhouse gas emissions [3,4]. The intensification of agriculture, mostly in environments with Mediterranean climate, causes its decrease as it promotes the mineralization, leaching, and erosion processes. For all these reasons, the decrease in organic matter in cultivated soils of the Mediterranean region is considered one of the main aspects of soil degradation [5]. Therefore, external sources of organic matter are needed to counteract carbon deficiency. In this regard, returning the organic component of agro-industrial wastes to cultivated soils could be an attractive solution to simultaneously solve problems associated with waste disposal and with the need of reducing production costs.

In the last two decades, an average of about 3 million tons of olive oil have been produced every year in the world [6]. Accordingly, the olive oil industry generates large volumes of by-products, and among these, olive mill wastewater (OMW) and olive pomace (OP) are the main ones [7].

Olive mill wastewater (OMW), the quantitatively greater residual product of the olive oil industry, is a slightly acidic material characterized by high salts and mineral nutrients content, particularly potassium, recalcitrant organic matter, and toxic/phytotoxic compounds [8–10]. These compounds may have adverse effects on soil microbial population [11,12] and aquatic ecosystems [13]. In particular, the processes mediated by nitrifier microorganisms can be altered; therefore, reducing plant nitrogen availability [14]. This effect, however, is short-lived. It has been proven that, after a slowdown in the 4–6 weeks immediately following the spreading of OMW, microbial activity significantly increases compared to untreated soil [15]. OP, the solid fraction obtained after oil extraction, consists of olive pulp, skin, stones, and water. It is an acidic and moist waste, rich in organic matter, potassium, water-soluble carbohydrates, and polyphenols [16].

The compost obtained by mixing OP with appropriate hygroscopic organic wastes (e.g., straw, olive leaves, pruning residues), when applied to soil induces significant increases in total organic carbon and humic substances, without negative effects on plant growth and yield [17,18]. Indeed, the breakdown of these complex substances during composting processes allows for the release of organic and inorganic constituents useful for plants [19].

The organic fraction of the olive oil industry by-products can improve the overall fertility of agricultural soils due to the direct supply of nutrients [20–23], and ensure the provision of valuable soil ecosystem services (e.g., food and biomass production, water, erosion, and climate regulation) [24–26].

In this regard, it is known that organic matter favors the bond between soil particles, the formation of stable aggregates, and improves the overall quality of soil structure [27,28]. Improving the soil structural characteristics means counteracting physical degradation phenomena (e.g., soil crusting, compaction, erosion), but also positively influencing biodiversity by increasing the trophic interactions between the different soil organisms involved in the nutrient cycle [29].

For these reasons, soil structure characterization and evaluation can provide useful information about soil health.

The use of olive mill wastes, raw or composted, could be an effective strategy to improve soil health, and contribute to closing the residue-resource cycle [30–32]. However, the type and quantity of by-products and the way they are used can diversely affect key soil properties and crop response [33–35]. Therefore, the effective use of oil industry by-products as soil amendments or fertilizers requires information, as exhaustive as possible, about the impact they can have on the soil ecosystem.

Although several authors carried out research on the effects of organic amendments derived from the olive oil industry by-products on crop productivity [36–38] or on soil chemical properties [39], few studies investigated and compared the impact of composted olive oil industry by-products with respect to the raw ones on SOC dynamics [35], soil structure characteristics, and related hydrological properties. In this regard, some authors studied the impact of olive mill wastewater alone [24,40,41] or of composted OP [33,42,43] but, especially in the latter case, on a limited set of soil physical characteristics. To help fill this gap, the effects of raw and composted olive mill residual products on soil organic C and on a wide set of physical properties were tested by a field trial carried out in a hilly, clay loam soil under olive.

The tested by-products, OMW, and composted OP (CP), were compared with an organo-mineral fertilizer (OMF) commonly used in organic olive groves. Furthermore, the CP was distributed in two different quantities to evaluate the dose effect.

As a result, the research evaluated the effects of the olive oil industry by-products, comparing treatments with different inputs, both in quantity and type, of organic amendments: (i) Olive mill wastewater (OMW), (ii) compost from olive pomace (CP1), (iii) compost from olive pomace in double dose (CP2), and (iv) organo-mineral fertilizer (OMF) as a control on (i) accumulation of soil organic carbon, (ii) soil aggregate stability, (iii) bulk density, (iv) macroporosity, (v) soil penetration resistance, and (vi) available water capacity.

2. Materials and Methods

2.1. Study Site and Experimental Design

This study was carried out in a rain-fed olive orchard located in the countryside of Matera, southern Italy (40°36′42.84″ N; 16°37′54.55″ E), an area characterized by an "accentuated thermo-mediterranean climate" [44], with a 1991–2020 mean annual temperature and rainfall depth of 15.4 °C and 532 mm, respectively. The soil was a Vertic Calcixeroll [45] with clay loam texture. The main physical and chemical characteristics of soil and biomasses are reported in Table 1.

Table 1. Main physical and chemical characteristics of soil (0–20 cm depth) and applied biomasses.

	Soil	**OMF**	**OMW**	**CP**
Clay (g kg^{-1})	384			
Silt (g kg^{-1})	374			
Sand (g kg^{-1})	242			
pH-H_2O (1:2.5)	8.1		4.9	8.0
Electrical cond. 1:2.5 (µs cm^{-1})	200			
$CaCO_3$ (g kg^{-1})	175.5			
Organic Carbon (g kg^{-1})	11.3	240	25	356
Total N (g kg^{-1})	1.23	60	0.8	21.7
Olsen P (mg kg^{-1})	9.87	50,000 *	300 *	10,000 *
Exchangeable K (mg kg^{-1})	834	130,000 **	2700 **	5000 **
C/N	9.2	4.0	31.3	16.4
Moisture (%)		5		31
Zn (mg kg^{-1})	34	-	3.8	91
Cu (mg kg^{-1})	13.4	-	2	41

OMF: organo-mineral fertilizer; OMW: olive mill wastewater; CP: compost from olive pomace; * Total P; ** Total K.

The experiment consisted of four treatments, randomly assigned to rectangular field plots of 200 m^2 with three replicates. The research was initially set up to evaluate the fertilizing effect of the olive oil industry by-products, comparing treatments with different inputs, both in quantity and type, of organic amendments: (i) Olive mill wastewater (OMW), (ii) compost from olive pomace (CP1), (iii) compost from olive pomace in double dose (CP2), and (iv) organo-mineral fertilizer (OMF) as a control (Table 2).

Table 2. Quantity of amendment supplied for each plant and corresponding N_input and OC_input per hectare.

Treatment	**Plants (n.)**	**Quantity**	**N_Input (kg ha^{-1} y^{-1})**	**OC_Input (Mg ha^{-1} y^{-1})**
OMW	6	800 L	64	2
OMF	6	15 kg	90	0.36
CP1	6	60 kg	90	1.48
CP2	6	120 kg	180	2.96

The quantity of applied OMW was equal to the maximum allowed by the Italian law (80 m^3 ha^{-1}), while the amount of CP1 and OMF was quantified on the basis of the average annual quantity of nitrogen removed by the olive trees [46]. All amendments were distributed every year at the end of December and incorporated into the soil by shallow plowing (0–20 cm). According to the dry farming techniques usually used in the study area to reduce water loss by capillary rise, three surface harrowing (0–10 cm) were carried out every year in the period from May to October.

2.2. Soil Sampling and Analyses

Before starting the investigation, the selected olive orchard was uniformly managed with organic farming practices. In particular, as for fertilizer strategy, in the previous 4 years, green manure of horse bean was used. During a trial period of 2 years, two soil samplings per year were made in April and September to evaluate the dynamics of organic carbon. Aggregate stability analyses were performed on soil samples collected in September of both years. All the other soil physical properties were determined in the second year. Specifically, in spring, 3 months after the last supply of organic matter and before tillage operations, undisturbed soil samples for bulk density, macroporosity, and available water capacity determination were collected, and penetration resistance was measured. Soil samples for organic carbon fractionation were collected in the late summer of the second year only.

2.2.1. Chemical Analyses

Soil total organic carbon (TOC) was determined by oxidation at 170 °C, with potassium dichromate in the presence of sulphuric acid, followed by the excess potassium dichromate titration with Möhr salt [47]. The organic C fractionation was performed according to the Italian Official method [48]. Total extractable carbon (TEC) was obtained by 0.1 M NaOH + 0.1 M Na4P2O7 (1:10 soil to solution ratio) at 65 °C for 24 h. Humic and fulvic acids (HA and FA, respectively) were separated from the extract by acidification to pH 2.0 with H2SO4. The purification of FA from non-humic substances was carried out by adsorption onto polyvinylpyrrolidone columns. The purified FA fraction was then combined with the HA fraction to give the humified carbon (HC). The quantification of TEC and HC in the extracts was performed by K2Cr2O7 + H2SO4 hot oxidation [47].

2.2.2. Evaluation of Carbon Storage Effect and Efficiency

For each treatment, the organic carbon stock (SOC_{ST} in Mg C ha^{-1}) in the upper 20 cm was determined by applying the following equation:

$$SOC_{ST} = 10,000\frac{TOC}{1000}\cdot BD\cdot\frac{20}{100} \quad (1)$$

where TOC is expressed in g kg^{-1} and the bulk density (BD) in g cm^{-3}.

To compare the different amendments, two indicators were computed: the organic carbon storage increase in each treatment (ΔSOC_{ST}), assessed as the percentage of the difference between SOC_{STf} computed at the end of the trial and the initial SOC_{STi} value (equal for all the plots), with respect to the latter.

$$\Delta SOC_{ST} = \frac{\left(SOC_{STf\_}SOC_{STi}\right)}{SOC_{STi}}\cdot 100 \quad (2)$$

Provided that the former quantity does not effectively consider the total carbon input added to the soil by each amendment, it is defined as another indicator, the efficiency (EF_{OC}), calculated for each treatment through the following equation:

$$EF_{OC} = \frac{\left(SOC_{STf\_}SOC_{STi}\right)}{OC\_input} \quad (3)$$

where OC_input is the total carbon added to the soil at the end of the trial and expressed as Mg ha^{-1}.

2.2.3. Physical Analyses

Soil aggregate stability was evaluated by quantification of dispersible clay using the turbidimetric technique [49,50]. Ten g of air-dry aggregates (1–2 mm) were put in a 300 mL bottle containing 250 mL of deionized water. The bottles were horizontally shaken for

1, 10, and 100 min and then left at constant laboratory temperature, leaving only clay in suspension. A 30 mL sample was placed in the turbidity measuring instrument (WTW—Turb 550IR). The turbidity readings, expressed as nephelometric turbidity units (NTU), were normalized by dividing by the dry weight of the sample. The aggregate stability index (Ist) was obtained according to the following equation:

$$Ist = \frac{(NTU_{tot} - NTU_{tx})}{NTU_{tot}} \quad (4)$$

where NTU_{tot} is the value corresponding to the total dispersed clay measured on a sample of the same weight (±0.1 g) after addition of 10 mL of sodium hexametaphosphate solution (0.2% vol.), and NTU_{tx} is the quantity of dispersed clay after shaking times (tx) of 1, 10, and 100 min. The application of different shaking times, resulting in different levels of applied energy, allows us to identify the time in which the differences between the treatments are most evident. All the analyses were performed in triplicate.

Soil bulk density (BD) was measured by oven-drying to constant weight undisturbed samples (100 cm^3) collected at 5–15 cm depth according to the core method [51].

Soil macroporosity was evaluated by the micro-morphometric method [52], that allows for the quantification of total macroporosity (pores > 50 μm) by image analysis of thin sections obtained from undisturbed soil samples. Total macroporosity and pore distribution were calculated from measurements of pore shape and size [52]. Based on their function, pores of 50–500 μm were described as transmission pores, and those >500 μm as fissures [53].

Soil penetration resistance (PR) up to a depth of 80 cm, at 10 mm intervals, was measured according to the ASAE standards [54] using a hand-held electronic penetrometer (Eijkelkamp Penetrologger 06.15.SA) with a 1 cm^2 base area conical tip and opening angle of 30°.

To determine soil water retention properties, 12 undisturbed soil samples were collected at 0–20 cm depth. Metal cylinders of 122 cm^3 were used and retention measurements at the matric potentials of −10 and −1500 kPa were performed by sandbox apparatus and pressure plate extractors, respectively [55]. The moisture content at each matric potential, expressed as percentage by weight of the dry soil, was then converted on a volumetric basis [56]. The retention data at field capacity (FC) (−10 kPa) and wilting point (WP) (−1500 kPa) were used to determine the available water capacity (AWC = FC-WP) of the soil.

2.3. Statistical Analysis

Soil physical and chemical data were analyzed by a one-way analysis of variance (ANOVA). Post-hoc mean separation was performed by Duncan's multiple range test at the $p \leq 0.05$ significance level. Additionally, Pearson correlation analysis was employed to identify the relationship between soil physico-chemical properties. All analyses were carried out using the StatSoft Statistica 10.0 software package (StatSoft, Tulsa, OK, USA).

3. Results

3.1. TOC Dynamics

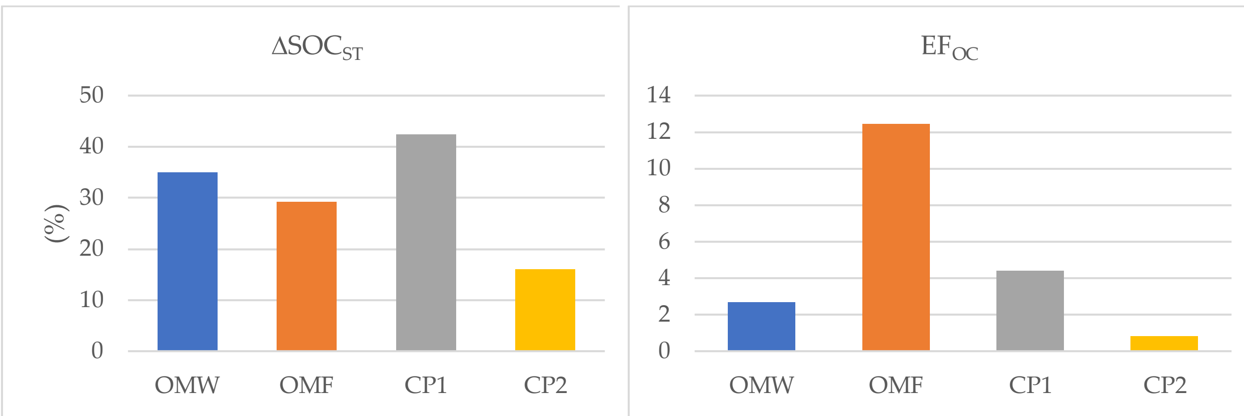
The soil TOC content always showed significant differences between treatments during the trial period (Table 3). Furthermore, a marked carbon dynamic was observed both during the year and between the 2 years of experimentation. Regardless of the amount of organic carbon supplied, CP2 always showed the lowest TOC values. On the contrary, CP1 exhibited the highest content except for September of the first year in which, although not statistically different from OMW, the latter had the highest TOC content. The fractionation of organic matter carried out on soil samples collected at the end of the trial period showed that CP1 soil, besides the highest TOC, also had the highest TEC and HC content (Table 3). OMF and OMW exhibited a similar behavior, with the only exception for HC content, which was significantly lower in OMW. Significantly lower HC values were always observed in the CP2 plots.

Table 3. Soil TOC content (g kg^{-1}) for each sampling date in the different treatments; in each column, values marked with the same letter are not significantly different ($p \leq 0.05$) according to Duncan's test.

Treatment	Apr_Y1	Sep_Y1	Apr_Y2	Sep_Y2		
				TOC	TEC	HC
	g kg^{-1}					
OMW	13.0 bc	12.2 a	16.2 b	15.0 b	7.7 b	4.0 c
OMF	13.2 ab	11.1 b	15.7 b	14.9 b	7.6 b	4.8 b
CP1	13.9 a	11.8 ab	17.7 a	16.3 a	8.8 a	5.8 a
CP2	12.4 c	9.9 c	13.0 c	12.9 c	5.9 c	2.4 d

Y1 = First year of trial; Y2 = Second year of trial.

The results illustrated in Figure 1 show that CP1 induced the highest increase in SOC_{ST} (Figure 1a), and a higher storage efficiency with respect to OMW and CP2 (Figure 1b).



(**a**) (**b**)

Figure 1. (**a**) Percentage increase in carbon storage in the different treatments with respect to the initial soil conditions; (**b**) storage efficiency with respect to the total OC input.

3.2. Effects on Soil Physical Properties

Table 4 shows the Ist values determined in both years after applying different shaking times: CP1 always showed the highest aggregate stability values except after 100′ of shaking; however, only in the second year and after agitation of 1′ and 10′, CP1 was significantly higher than OMF. Conversely, CP2 showed the lowest Ist values, significantly different from the others after 10′ of shaking; OMW exhibited a lower Ist value with respect to CP1 and OMF, except for the highest shaking time.

Soil bulk density (BD) and available water capacity (AWC) did not show significant differences between treatments (Table 5). Total macroporosity, instead, exhibited an increase when composted materials (CP1 and CP2) were distributed. This improvement is mainly due to the increase in regular pores and, in the case of CP2, of elongated ones of the 50–500 µm size class (transmission pores).

Table 4. Dynamics of 1–2 mm aggregate stability index (Ist) with increasing applied energy (shaking times: 1, 10, and 100 min). In each column, single-year values marked with the same letter are not significantly different ($p \leq 0.05$) according to Duncan's test.

Year	Treatment	Ist 1′	Ist 10′	Ist 100′
1	OMW	0.973 b	0.938 b	0.890 a
	OMF	0.982 a	0.953 a	0.900 a
	CP1	0.983 a	0.956 a	0.865 b
	CP2	0.971 b	0.930 c	0.862 b
2	OMW	0.980 c	0.937 c	0.854 a
	OMF	0.984 b	0.949 b	0.868 a
	CP1	0.987 a	0.956 a	0.864 a
	CP2	0.982 bc	0.930 d	0.814 b

Table 5. Soil bulk density (BD), macroporosity (pores > 50 µm), and available water capacity (AWC) measured 3 months after the last supply of organic matter. In each column, values marked with the same letter are not significantly different ($p \leq 0.05$) according to Duncan's test.

Treatment	BD	Macroporosity					AWC
		Regular	Irregular	Elongated 50–500 µm	Elongated >500 µm	Total	
	(g cm^{-3})	(%)					(% vol.)
OMW	1.38	1.3 b	4.0	5.2 b	12.5	22.9 b	14.3
OMF	1.33	1.3 b	4.3	6.8 b	10.3	22.7 b	14.4
CP1	1.34	1.5 ab	5.2	6.1 b	13.6	26.2 ab	14.1
CP2	1.38	1.7 a	5.5	9.0 a	11.5	27.7 a	15.2

With respect to PR, the results of the field tests show that some significant differences between the treatments were detected only in the tilled soil layer (0–20 cm depth). At greater depth (20–50 cm), neither significant differences between the theses were observed, nor were the recorded PR values able to limit root growth (>5.0 MPa) [57] (Figure 2). In general terms, the CP1 and OMF treatments always showed a similar behavior displaying the lowest PR values, while CP2 exhibited the highest PR value, with the only exception of the surface soil layer (0–5 cm).

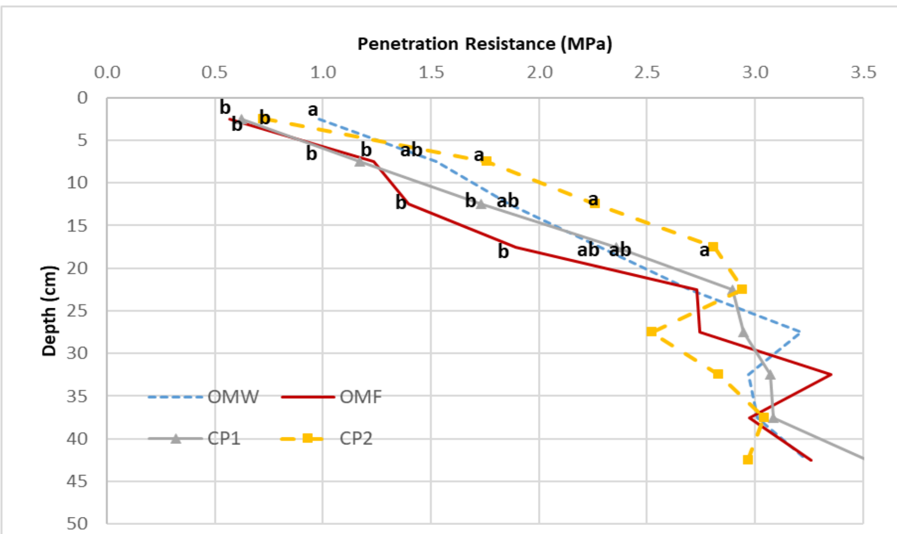


Figure 2. Soil penetration resistance (MPa) versus depth under different treatments. At each depth, different letters indicate significantly different ($p \leq 0.05$) PR values according to Duncan's test.

4. Discussion

The dynamics of TOC under the studied pedoclimatic conditions appear very marked; the seasonal variations which highlight a decrease in the TOC content in September with respect to April (Table 3) agree with the dry farming techniques applied during the summer. When a soil is tilled, the mineralization of organic matter is faster, resulting in the formation of less stable humus, increased release in CO_2 to the atmosphere, and thus in a reduction in TOC content.

Although the study area is located within a Mediterranean climate particularly prone to mineralization, the observed annual increase in TOC content shows how this type of soil is benefited in a different way by the availability of organic matter according to the qualitative and quantitative characteristics of the doses supplied. Actually, the tested organic amendments exhibited different ΔSOC_{ST} and EF_{OC} (Figure 1). These results suggested that the different nature of the added carbon influences its residence time [58]. Nevertheless, after 2 years of amendments addition, only CP1 and OMW showed a better carbon storage capacity compared to OMF. The CP2 soil, added with organic carbon of the same nature as CP1, showed the worst results. Some authors [59–61] have found a direct relationship between OM application rates and final SOC content. Conversely, other research has highlighted a non-linear relationship between these two parameters [62–64]. Indeed, the behavior observed in CP2 is not easy to explain; despite the higher carbon input, this soil shows the lowest TOC value, not very different from the initial content.

This could be explained by the fact that a very high dose of soil conditioner poorly interacted with the soil mineral matrix and the occurrence of intense rainfalls in the early spring of both years (Figure S1) has favored the removal of the amendment at soil surface by erosion.

Another hypothesis could be that CP distributed in higher dose proportionally increased the mineralization of the added C, as also evidenced by Mendoza et al. [65]. It is reasonable to believe that a higher dose of CP brought a proportionally higher quantity of microorganisms to the soil and in an aerobic environment, as evidenced by the macroporosity data (Table 5), the mineralization process prevailed over the stabilization one. A more intense biological activity in the treatments with the addition of compost is evidenced by the statistically significant increase in regular pores (Table 5) [52]. However, both in terms of total macropores and regular pores, there are no significant differences between CP2 and CP1. A lower CO stabilization capacity of CP2 compared to CP1 is evidenced by the HC values (Table 3) which appear to represent respectively 19% and 36% of the TOC. However, as reported by Wang et al. [64], increasing C input to soil has been widely advocated with a view to maximizing carbon sequestration in agricultural soil. At the same time, understanding the processes underlying the spatio-temporal dynamics of SOC in response to different qualities and quantities of added C input is very challenging. This is especially true in field experiments, in which the effects of soil, climate, and management systems are interconnected, and therefore not easy to understand and predict.

Considering the SOC/Clay value to indicate the quality of the structural conditions [66,67], the investigated soil is classified as "degraded" (SOC/Clay < 1/13). After 2 years of exogeneous organic matter addition, this index improved but remained under this threshold ratio. The aggregate stability, considered an effective indicator of soil health, being very sensitive to land use and management practices changes [68], highlighted statistical differences between different treatments. The values obtained generally indicate a very high stability; however, this result could have been influenced by the fact that the test, based on the quantification of the dispersed clay, was performed on air-dried aggregates and not at field moisture content; indeed, it is known that the amount of dispersible clay decreases as soil dries [69–71]. This choice was made to standardize the measurement within the trial and identify a trend between the different sampling periods, since the main purpose was the comparison between the different treatments and not the identification of a univocal stability value. The distribution of amendments induces significant effects starting from the first year and the differences between the various treatments increase in the second year. In both years, the applied mechanical energy which best differentiates the behavior of the various treatments was that set at 10′ of agitation. At the end of the test, each treatment differs statistically from the other and the measured stability values are positively correlated with TOC data, and even more significantly with HC, the most stable fraction of the organic matter (Figure 3). After CP2, OMW is the treatment that showed the lowest aggregate stability values. This may have been due to both the chemical composition of OMW, and the time elapsed between the distribution of the amendment and the soil sampling. Barbera et al. [34] reports a short-term increase in aggregate stability, which however decreases about 4 months after the spreading of OMW. This dynamic was attributed to the cementing action of the polysaccharides contained in OMW, while the successive decomposition reduces their stabilizing effect.

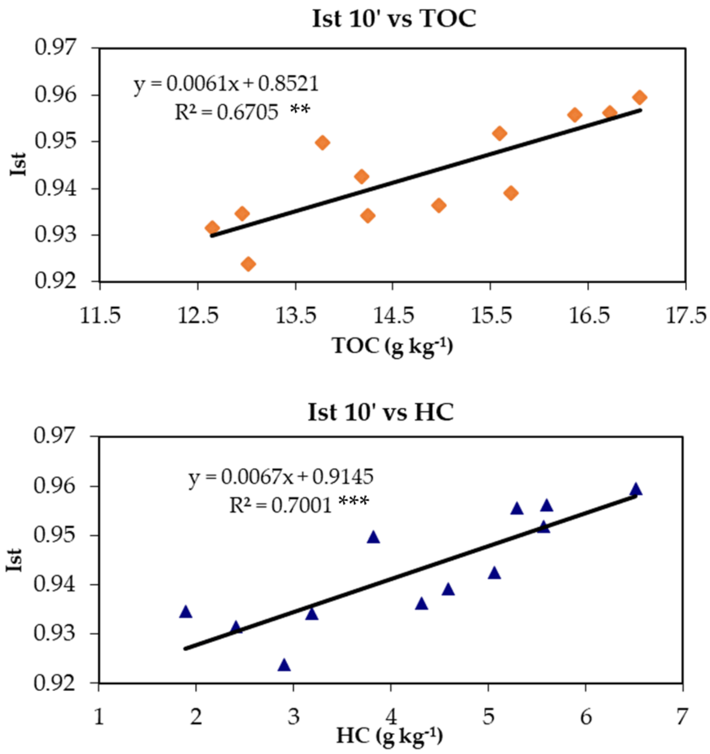


Figure 3. Relationships between soil TOC and HC content (g kg^{-1}), and aggregate stability after 10 min of shaking (** $p \leq 0.01$, *** $p \leq 0.001$).

The results confirm the relevance of quantity and quality of organic matter in the stabilization process [27]. However, this type of soil, due to its mineralogical characteristics, has inherent good structural dynamics. Moreover, the high content of calcium carbonate further favors the formation of stable aggregates, and this may have contributed to carbon sequestration due to the increase in physical protection of organic matter [72].

Another important physical characteristic, indicator of soil health, is the BD. As previously stated, there are no significant differences between the various treatments. In any case, the measured BD values are not critical [73], as are not those of total macroporosity. According to the micro-morphometric method [74], the soils in which compost has been added can be classified as "highly porous" (25–40% macropores), while those treated with OMW and OMF as "moderately porous" (10–25%).

Overall, the results relating to the quantification and characterization of macroporosity, unlike those discussed to date, indicate an improvement of the soil structure in CP2. This treatment differs from OMF and OMW not only in terms of total macroporosity, but also in relation to the increase in regular pores, typically associated with biological activity [52], and in elongated transmission pores of the 50–500 μm size class, crucial in regulating plant-soil-water relationships and, more in general, in maintaining good soil structure conditions [53].

Moreover, in the case of AWC, a crucial property for evaluating the provided ecosystem services, no significant differences between treatments were recorded. CP2 soil, even if only as a trend, shows the highest volumes of available water (AWC > 15%), while the other treatments do not exceed 15%, a value considered the threshold between a "good" and a "limited" AWC [75].

As for other examined parameters, the trend of PR in CP2 soil appears somewhat surprising. In this thesis, except for the 0–5 cm soil layer, significantly higher PR values were recorded compared to OMF. Despite the high quantity of compost supplied, there were no positive effects on PR. The fact that the same behavior was observed for other investigated properties (TOC and aggregate stability) suggests that this high amount of organic material difficultly interacted with the mineral soil fraction and, consequently, poorly affected structure-related soil properties. It seems that in a soil under this thermo-pluviometric regime, the evenness of amendments incorporation into the soil plays a more important role with respect to the supplied quantity.

5. Conclusions

The recycling of exogenous organic matter in soils is strongly encouraged by the European Union to promote the circular economy in the agricultural sector. However, the recycling of organic residues is only possible if their use is not harmful to the soil, crops, and the environment.

The results of this 2-year study, while generally confirming the well-known positive effects of organic amendments on soil physical properties, also provide new useful information for their effective use.

The by-products of the olive oil industry that gave the best results are the composted ones. In the considered pedoclimatic environment, the increase in quantity and residence times of soil organic carbon is the main aim to be pursued, and to this end, CP1 gave the best results since it induced the largest increase in soil TOC, TEC, and HC content; a significant improvement in aggregate stability was also observed. Furthermore, its use has never induced pejorative effects on the other physical properties compared to control (OMF). The same cannot be stated for OMW which appears to have worsened the aggregate stability and increased the penetration resistance of the uppermost soil layer. Contrary to expectations, the addition of a large quantity of organic carbon (CP2) did not induce a proportional increase in soil organic matter content. However, there were some improvements in soil physical properties, notably a significant increase in transmission pores and, at the trend level, in AWC.

The hypotheses put forward to understand what the fate was of the applied organic matter could both be plausible and, given the results, it is possible that there was a concurrence of actions. Further research is needed to evaluate the dose effect in a wider range of pedoclimatic environment and after a longer period of application.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12081628/s1. Figure S1: Ombrotermic diagrams [76].

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