SCAP
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Soil application of olive oil residues: a sustainable strategy involving olive pomace and composted olive pomace

Aplicação de resíduos oleícolas ao solo: uma abordagem sustentável com bagaço de azeitona e bagaço de azeitona compostado

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ABSTRACT

This study, conducted within the scope of the PRR INOVCIRCOLIVE project, aimed to evaluate the effects of applying olive pomace from a two-phase extraction system, in both composted and raw (untreated) forms, on soil fertility and the development of ryegrass (*Lolium perenne* L.). Two pot trials were carried out, designed into complete randomized blocks, with three replicates, using five application rates of the two materials (0 to 150 t ha^{-1}), applied to two soils with contrasting characteristics: a Podzol and a Luvisol. The application of composted olive pomace significantly improved soil fertility and plant nutrition without compromising biomass production, particularly in the less fertile soil. In contrast, the raw pomace, while showing some potential as an organic soil amendment, exhibited some adverse effects at application rates >50 t ha^{-1}, especially in soils with low buffering capacity and in sensitive crops, due to its instability and potential phytotoxicity. These results highlight the agronomic value of both composted and no-treated two-phase olive mill pomace, providing their application is technically guided, and emphasize the importance of establishing best practices to ensure the safe and sustainable use of these materials in agriculture.

Keywords: Olive mil waste, composting, agricultural valorization, soil fertility, *Lolium perenne*

RESUMO

Este estudo, realizado no âmbito do projeto PRR INOVCIRCOLIVE, teve como objetivo avaliar os efeitos da aplicação de bagaço de azeitona proveniente de um lagar de duas fases, nas formas compostada e em bruto (não tratado), sobre a fertilidade do solo e o desenvolvimento do azevém (*Lolium perenne* L.). Foram conduzidos dois ensaios em vasos, delineados em blocos completos casualizados, com três repetições, utilizando cinco doses dos dois produtos (0 a 150 t ha^{-1}), aplicadas a dois solos com características contrastantes: um Podzol e um Luvissolo. A aplicação de bagaço de azeitona compostado promoveu melhorias significativas na fertilidade do solo e na nutrição vegetal, sem comprometer a produção de biomassa, sobretudo no solo menos fértil. Em contrapartida, o bagaço não tratado, embora apresente algum potencial como corretivo orgânico, revelou alguns efeitos adversos em doses elevadas (>50 t ha^{-1}), especialmente em solos com baixo poder tampão e em culturas sensíveis, devido à sua instabilidade e risco de efeitos fitotóxicos. Estes resultados reforçam o valor agronómico do bagaço de lagares de azeite de duas fases, compostado ou não, desde que a sua aplicação seja tecnicamente orientada, destacando-se a importância da definição de boas práticas para garantir a segurança e a sustentabilidade do seu uso agrícola.

Palavras-chave: Bagaço de azeitona, compostagem, valorização agrícola, fertilidade, *Lolium perenne*

INTRODUCTION

Due to the expansion of highly productive olive groves and the consequent increase in national olive oil production, there is a growing amount of organic waste generated by this agro-industrial sector. Compared to olive mill wastewater, the direct application of olive pomace to agricultural soils has been less extensively studied. This is largely due to the fact that traditional pressing and three-phase extraction systems confer higher economic value to the pomace when it is redirected to the oil and energy production industries. With technological advancements in olive mills, a new by-product emerged from the two-phase extraction system, olive pomace with higher moisture content and organic load, making it more difficult to handle and less suitable for oil extraction processes.

Regarding this by-product, some studies indicate that its agricultural valorization, either in fresh or extracted state, can offer several agronomic benefits when applied properly. These include increases in soil organic carbon (Ilay *et al.*, 2013; López-Piñeiro *et al.*, 2007, 2008, 2011, 2021; Sempiterno, 2007; Ouzounidou *et al*., 2010; Sempiterno and Fernandes, 2010), improved aggregate stability (López-Piñeiro *et al.*, 2008, 2011; Khdair and Abu-Rumman, 2020), enhanced soil enzymatic activity (López-Piñeiro *et al.*, 2011), greater water retention (Brunetti *et al*., 2005; Khdair *et al.*, 2019), elevated potassium content (Brunetti *et al*., 2005; López-Piñeiro *et al.*, 2007, 2008, 2011; Sempiterno, 2007; Regni *et al*., 2017a), increased phosphorus availability (López-Piñeiro *et al*., 2008, 2009, 2011), and nitrogen supply (López-Piñeiro *et al*., 2007, 2008), ultimately contributing to improved crop performance (Brunetti *et al*., 2005; López-Piñeiro *et al.*, 2011; Regni *et al*., 2017).

However, these and other studies also highlight challenges associated with the management and potential negative impacts of the direct application of two-phases olive pomace to soil. Reported issues include reduced crop productivity (Sempiterno and Fernandes, 2006; Ilay *et al*., 2013), risk of soil salinization (Cabrera *et al*., 2009; López-Piñeiro *et al*., 2011; Regni *et al*., 2017b) alteration of microbial communities (Federici *et al*., 2017; Regni *et al*., 2017b), disturbances in the nitrogen cycle, nutritional imbalances due to the high C/N ratio (Sempiterno, 2007; Sempiterno and Fernandes, 2010; Jimenez, 2015; Khdair and Abu-Rumman, 2020), modifications of soil humic acids (Brunetti *et al*., 2005), increased persistence of pesticides with a potential risk of surface water contamination (Cabrera *et al*., 2009; Peña *et al*., 2013), phosphorus losses due to increased availability (López-Piñeiro *et al*., 2009), and phytotoxicity caused by polyphenols, organic acids, and fatty acids present in the pomace (Alfano *et al*., 2011; Regni *et al*., 2017b; Khdair and Abu-Rumman, 2020; Bouhia *et al*., 2023). These negative effects tend to be more frequent when moist or extracted pomace is applied continuously or at high rates, typically above 15–30 t/ha as indicated by Jiménez (2015), or over 30 t/ha according to López-Piñeiro *et al*. (2011).

Considering that the acidic pH, antimicrobial properties, and high carbon-to-nitrogen (C/N) ratio of olive pomace may temporarily create unfavorable conditions for crop growth, several authors advocate composting as a more suitable strategy prior to soil application (Paredes *et al*., 2002; Kavdır *et al*., 2008; Gigliotti *et al*., 2012; Toscano and Montemurro, 2012; Killi and Kavdır, 2013; Bruzzone *et al*., 2017; Regni *et al*., 2017a, 2020; Sempiterno *et al*., 2022; Černe *et al*., 2023).

Indeed, through composting, organic by-products can be transformed into stabilized, humified, non-phytotoxic, and sanitized soil amendments, facilitating their storage and handling, while offering numerous agronomic benefits. These include enhanced carbon sequestration and improved soil fertility. Additionally, such organic fertilizers increase water-holding capacity, cation exchange capacity, and nutrient availability, factors that collectively strengthen soil resilience, particularly in soils with low buffering capacity (Lal, 1997; Paredes *et al*., 2002; Gigliotti *et al*., 2012; Sempiterno *et al*., 2022).

Co-composting two-phase olive pomace with high-volume lignocellulosic materials such as pruning residues, straw, or olive leaf waste is especially promising due to its operational simplicity and effectiveness in producing a high-quality organic amendment with materials/residues produced in the same region/farm. This process eliminates phytotoxicity and results in an abundance of stabilized organic matter and essential nutrients for plants (Cayuela *et al*., 2010; Buono *et al*., 2011; Ameziane *et al*., 2020).

The need for the establishment of best-practice guidelines for the agronomic valorization of olive mill waste, encompassing treatment, application and management techniques, has been emphasized by several authors (Inglezakis *et al*., 2012; Koutsos *et al*., 2018). Adoption of such practices could transform a waste product into a valuable resource within the context of sustainable agriculture.

The present study aimed to evaluate and compare the effects of applying composted and stabilized two-phase olive pomace (COP), and raw olive pomace (OP), on the fertility of different soil types, as well as on the development and mineral composition of a test forage crop (*Lolium perenne* L.).

MATERIAL AND METHODS

Experimental Design and Crop Management

In line with the objectives of the study, two pot trials – one conducted with a Podzol and the other with a Luvisol - were established, arranged in a randomized complete block design with three replicates. Each trial included nine experimental treatments: one control (T1), with no application of olive pomace (OP) or composted olive pomace (COP); four treatments (T2 to T5) with increasing levels of OP: 25, 50, 100, and 150 t ha^{-1}, fresh-weight basis, corresponding to 15, 30, 60 and 90 g per pot; and four treatments (T6 to T9) with the same increasing levels of COP. The experiments were conducted from May to August 2024, under greenhouse conditions. However, when weather conditions permitted, the pots were placed in a protected outdoor area, which protects them from birds and, at the same time, allows the plants to be exposed to environmental conditions closer to those in the field.

The test crop used was ryegrass (*Lolium perenne* L.), Birtley variety, sown at a density of 0.65 g of seed per pot, distributed across three rows. The pots, with a capacity of 1.5 dm^3, were filled with 2.0 kg of soil previously mixed with varying amounts of OP or COP, depending on the experimental treatment.

In both trials, a basal mineral fertilization was applied using analytical-grade reagents, supplying: 300 mg of nitrogen (N) (divided into three applications), 40 mg of phosphorus (P), 250 mg of potassium (K), 60 mg of magnesium (Mg), 26 mg of calcium (Ca) in the Luvisol (LV) and 169 mg of Ca in the Podzol (PZ), 10 mg each of manganese (Mn) and zinc (Zn), 2 mg of copper (Cu), and 1 mg of boron (B) per pot.

Three harvests (cuts) of ryegrass were carried out. After each cut, the plants were weighed fresh, oven-dried at 65 °C to constant weight, reweighed to determine dry weight, then ground and prepared for chemical analysis.

Total N was determined by dry combustion on a C/N/S Elemental Analyzer. For the analysis of P, K, Ca, Mg, Fe, Mn, Zn, Cu, and B, 500 mg of ground material was ashed in a muffle furnace at (500 ±10) °C for 4 hours. The ashes were solubilized in 3 M hydrochloric acid, and the elements were quantified in the resulting solution by inductively coupled plasma optical emission spectrometry (ICP-OES) (Duarte *et al*., 1998).

Following the final cut, representative soil samples were collected from each pot, air dried at <40 °C, sieved to <2 mm, and analyzed for organic carbon (Walkley-Black, Colorimetric determination) (FAO-GSP, 2019), organic matter (C × 1.724), pH (H_2O, 1:2.5 v/v), electrical conductivity (1:2), extractable P and K (AL-Ammonium lactate, Egner-Rhiem method, ICP-OES) (Egnér *et al*., 1960), extractable Mg and exchangeable cations (1M NH_4OAc, pH 7.0), micronutrients (Fe, Mn, Zn, Cu; Acid ammonium acetate-EDTA extraction, Atomic Absorption Spectrometry), B (hot water extraction, ICP-OES) (Motsara & Roy, 2008), and potential acidity (titration). Cation exchange capacity (CEC) was calculated as the sum of exchangeable cations and potential acidity, and base saturation was expressed as (Σ cations × 100) / CEC.

The pots were kept at 70 % field capacity by watering with distilled water to a specified weight.

Soil and organic amendment characteristics

Two soil macro samples were collected from the surface layer (0–0.20 m) of a Luvisol (LV) and a Podzol (PZ) (IUSS Working Group WRB, 2022), which exhibited distinct characteristics, particularly in terms of texture (loamy and sandy, respectively), organic matter content (16.5 and 8.8 g/kg), pH-H_2O (6.7 and 5.7), base saturation (100 % and 50 %), as well as macro- and micronutrient levels.

The raw olive pomace was analyzed immediately after its production at the mill (fresh), and again after six months of storage at 4 °C, prior to its use in the trial.

Composting of the pomace lasted for seven months and was carried out in an open-air windrow using the Turned Windrow Method. Throughout the process, the material, with an initial volume of 33 m^3, was periodically turned and watered as needed to maintain moisture content between 40 % and 60 %. Based on the analytical composition of the materials used - two-phase olive pomace, olive leaf waste, and sheep manure - a mass ratio (m:m:m) of 2.1:1.6:1.0 was initially established to achieve a starting C/N ratio close to 30/1.

The composted pomace was also analyzed for moisture (EN 13040), pH (EN 13037), electrical conductivity (EN 13038), organic matter (EN 13039), and organic carbon (calculated as C = OM × 0.58). Total N was determined according to EN 13654-2; P, K, Ca, Mg, Cu and Zn, according to EN 13650; Phytotoxicity was determined by Zucconi test

Table 1 - Physicochemical characterization of the fresh olive pomace (OP), after cold storage for 6 months, and after composting (COP)

Parameter		OP Fresh	OP after 6 months	COP
Moisture	%	86.6	86.1	41.3
pH (H_2O)		5.6	4.5	9.0
Electrical conductivity	mS cm^{-1}	1.46	1.54	0.87
Organic matter	%	77.8	78.2	36.7
Organic carbon (C)	%	45.1	45.4	21.3
Total nitrogen (N)	%	1.51	1.98	1.91
C/N ratio		30	23	11
Phosphorus (P_2O_5)	%	0.43	-	0.45
Potassium (K_2O)	%	1.78	-	1.16
Calcium (CaO)	%	0.33	-	3.69
Magnesium (MgO)	%	0.27	-	1.15
Copper (Cu)	mg kg^{-1}	15.3	-	21.9
Zinc (Zn)	mg kg^{-1}	54.0	-	117
Phytotoxicity	(GI %)	+ 4.9	- 82.2	- 104.5

Results expressed on a dry matter basis, except for pH, electrical conductivity, and phytotoxicity; GI – Germination Index; the "+" sign indicates the presence of phytotoxicity; the "–" sign indicates the absence of phytotoxicity.

(Zucconi *et al.*, 1981). The number of germinated seeds and the primary rootlength were measured and expressed as a percentage of the control (Germination index). The results are presented in Table 1.

Initially, the olive pomace exhibited phytotoxicity, with a germination index (GI) of only 4.9 %. However, this characteristic was lost after six months of storage at 4 °C, and by the time it was used in the trials, its GI had increased to 82.2%. The analysis of the composted pomace showed that it was properly stabilized, with a low C/N ratio (11) and no signs of phytotoxicity (GI = 104.5 %).

Statistical analysis

For the statistical analysis of the results, the software Statistica 12 was used. A two-way analysis of variance (ANOVA) was performed, followed by Duncan's multiple range test at a 5 % significance level ($p = 0.05$) for post hoc comparison of the means corresponding to the different experimental treatments.

RESULTS E DISCUSSION

Biomass prodution

Ryegrass dry matter production obtained from the three cuts performed in each trial is presented in Table 2. Overall, the analysis of variance revealed a highly significant statistical effect of the experimental treatments on the total aboveground biomass production (i.e., the sum of the three cuts) in the trial conducted with the Luvisol soil ($F[8;16] = 103.1$; $p \leq 0.001$), and a significant effect in the trial with the Podzol soil ($F[8;16] = 2.81$; $p \leq 0.05$). Biomass production proved sensitive to the form and amounts of pomace applied, as well as to soil characteristics.

In the trial conducted with the Luvisol (LV), a soil with better natural fertility, the application of composted olive pomace (COP) did not result in significant differences in biomass production, regardless of the dose applied, suggesting a limited effect when baseline fertility levels are already adequate. In contrast, the application of raw olive pomace

(OP) had a clearly inhibitory effect on crop development, particularly at doses above 50 t ha^{-1}, with this effect being more pronounced at the first cut.

In the trial with the Podzol (PZ), a poor and acidic soil, a distinct response was observed: at the first cut, the higher doses of COP (100 and 150 t ha^{-1}) induced a reduction in biomass production. However, in the second and third cuts, the effect of COP was positive, with significant increases ($p \leq 0.05$) in production. The best overall performance was recorded in the treatment corresponding to the application of 50 t ha^{-1} of COP, a dose that coincides with the maximum allowed for the application of Class I organic amendments, according to Ordinance No. 185/2022 of July 21. This result suggests the effectiveness of the compost in the recovery of degraded or low-fertility soils, improving the test crop performance.

On the other hand, raw olive pomace (OP) showed initial negative effects on crop growth, mainly at higher doses (>50 t ha^{-1}), but significant reductions in biomass production were only observed at the first cut. This behavior may be associated with microbial nitrogen immobilization, common in materials with a high C/N ratio (Mengel and Kirkby, 2001; Sempiterno, 2007; Sempiterno and Fernandes, 2010; Jimenez, 2015; Khdair and Abu-Rumman, 2020), and/or the presence of phenolic compounds with potential phytotoxicity, as reported by Alfano *et al*. (2011), Bouhia *et al*. (2023), Khdair and Abu-Rumman (2020), Regni *et al*. (2017b) and Sempiterno (2007). Sowing immediately after the incorporation of OP may have further aggravated these effects. However, over successive cuts, a gradual decrease in phytotoxicity was observed, suggesting progressive degradation of inhibitory compounds and mineralization of organic matter, a phenomenon described in other studies with these agro-industrial residues (Abid *et al*., 2010; Cayuela *et al*., 2010; Buono *et al*., 2011; Pinho, 2016, Pinho *et al*., 2017; Ameziane *et al*., 2020; Hernández *et al*., 2022).

Mineral Composition of Plant Material

Tables 3 to 6 show the average concentrations of N, P, K, Ca, Mg, Fe, Mn, Zn, Cu, and B in the first two cuts of ryegrass, for each treatment in the two trials. Nutrient analysis was not done for the third cut due to low biomass, which was usually insufficient for lab tests.

In the Luvisol (LV) trial, treatments had a significant effect ($p \leq 0.05$) on most nutrient levels, except for Mg in the first cut and Mg, Fe and Cu in the second cut. However, not all significant differences may be agronomically relevant.

Nitrogen tended to decrease with higher doses of raw olive pomace (OP) and increase with composted pomace (COP), especially in the first cut. This pattern may be attributed to nitrogen immobilization in the soil, a process commonly associated with the application of organic residues with a high C/N ratio, as in the case of the pomace used.

Table 2 - Aboveground ryegrass biomass production obtained at each cut and total across both trials (g DM pot^{-1})

	1º Cut		2º Cut		3º Cut		Total	
Treatments	**LV**	**PZ**	**LV**	**PZ**	**LV**	**PZ**	**LV**	**PZ**
Control	5.4 a	2.7 a	4.9 a	3.5 de	1.9 a	1.20 c	12.0 a	7.3 abc
25 t OP	5.1 b	2.6 ab	4.8 b	3.4 e	1.7 ab	1.2 bc	11.5 cd	7.1 bc
50 t OP	4.8 c	2.3 abc	4.7 b	3.4 e	1.7 ab	1.2 bc	11.3 d	6.9 bc
100 t OP	4.4 d	2.3 abc	4.5c	3.3e	1.6 bc	1.4 abc	10.4 e	7.0 bc
150 t OP	3.6 e	2.1 bc	4.3 d	3.4 e	1.4 c	1.3 bc	9.3 f	6.8 c
25 t COP	5.5 a	2.6 ab	4.7 b	3.7 cd	1.7 ab	1.4 abc	11.8 bc	7.6 ab
50 t COP	5.5 a	2.3 abc	4.7 b	4.1 a	1.8 a	1.6 ab	12.0 ab	8.0 a
100 t COP	5.3 a	1.9 cd	4.8 ab	4.0 a	1.9 a	1.7 a	12.0 ab	7.5 abc
150 t COP	5.4 a	1.6 d	4.9 a	3.8 bc	1.8 a	1.7 a	12.0 ab	7.0 bc
sm (±)	0.077	0.148	0.054	0.081	1.154	0.108	0.095	0.236
c.v. (%)	2.7	11.3	2.0	3.9	5.8	13.2	1.4	5.6

Values followed by the same letters in the same column do not differ significantly from each other at the 5% significance level. according to Duncan's test; sm – standard deviation of the mean; c.v. – coefficient of variation; LV – Luvisol; PZ – Podzol.

Additionally, the presence of organic compounds that interfere with soil microbial activity, particularly phenolic compounds found at high concentrations in these materials, may cause a temporary inhibition of the nitrification process (Perez & Gallardo-Lara, 1987; Sempiterno & Fernandes, 2010).

Phosphorus changes were statistically significant but small and inconsistent. For example, a slight increase with OP application in the first cut and a decrease in the second.

Potassium levels decreased in the second cut with higher doses of OP and with COP in both cuts, which was unexpected. Still, K levels were above the recommended values for this crop (Benton-Jones *et al.*, 1991; Rengel *et al.*, 2022).

Calcium levels were higher in COP treatments than in OP, matching the higher Ca content in the composted material (3.69 % in COP vs. 0.33 % in OP).

For micronutrients, Mn and Zn levels dropped with the highest COP doses, likely due to the compost raising soil pH and reducing availability. Boron increased in the first cut with raw pomace.

In the first two cuts of ryegrass conducted in the trial with the Podzol (PZ) soil, the experimental treatments had a statistically significant effect (p ≤

Table 3 - Mean concentrations of macro and micronutrients in the biomass from the 1st cut of ryegrass in the trial with LV

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
	%					mg kg^{-1}				
Control	3.4 d	0.40 d	5.6 a	0.62 d	0.35 a	83 d	81 ab	55 a	11.9 c	22 cd
25 t OP	3.4 d	0.44 bcd	5.6 a	0.66 cd	0.37 a	88 cd	78 ab	55 a	11.7 cd	22 cd
50 t OP	3.1 e	0.45 bc	5.6 a	0.68 cd	0.38 a	86 cd	81 a	54 a	10.8 cde	24 c
100 t OP	2.5 f	0.49 ab	5.8 a	0.70 bc	0.38 a	89 cd	85 a	55 a	9.8 c	29 b
150 t OP	2.4 f	0.52 a	5.5 a	0.69 bcd	0.37 a	80 d	82 a	55 a	9.9 de	33 a
25 t COP	3.8 c	0.48 ab	5.6 a	0.78 a	0.40 a	97 bc	73 bc	56 a	12.2 bc	22 cd
50 t COP	3.8 c	0.47 b	5.5 a	0.76 ab	0.39 a	109 ab	69 c	55 a	13.9 ab	22 cd
100 t COP	4.1 b	0.41 cd	5.1 b	0.70 bc	0.36 a	109 ab	58 d	49 b	11.3 cde	20 d
150 t COP	4.4 a	0.43 cd	5.2 b	0.73 abc	0.37 a	111 a	56 d	49 b	14.5 a	21 d
sm (±)	0.078	0.014	0.10	0.022	0.011	4.1	2.7	0.9	0.57	0.6
c.v. (%)	3.4	5.1	3.3	5.5	4.9	7.6	6.1	3.0	8.3	4.8

Results expressed on a dry matter basis at 100–105 ºC; sm – standard deviation of the mean; c.v. – coefficient of variation; Values in the same column followed by the same letters do not differ significantly from each other at the 5 % significance level.

Table 4 - Mean concentrations of macro- and micronutrients in the biomass from the 2nd cut of ryegrass in the trial with LV

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
	%					mg kg^{-1}				
Control	2.4 ab	0.51 abc	5.0 a	0.60 b	0.40 a	66 a	149 a	65 de	8.36 a	15 abc
25 t OP	2.3 bc	0.52 ab	4.9 abc	0.57 bc	0.39 a	60 a	151 a	68 bcd	4.92 a	12 c
50 t OP	2.2 cd	0.50 abc	4.7 bcd	0.55 cd	0.40 a	58 a	149 a	69 bc	6.27 a	14 bc
100 t OP	2.1 de	0.48 c	4.5 de	0.52 de	0.41 a	53 a	156 a	72 abc	6.78 a	16 ab
150 t OP	2.0 e	0.44 d	4.4 e	0.49 e	0.37 a	51 a	141 b	73 ab	6.08 a	16 ab
25 t COP	2.4 ab	0.50 abc	4.9 ab	0.60 b	0.37 a	61 a	123 c	79 a	6.65 a	17 ab
50 t COP	2.3 bc	0.48 bc	4.6 de	0.59 bc	0.36 a	56 a	102 d	67 bcd	6.69 a	17 a
100 t COP	2.3 bc	0.49 bc	4.5 de	0.62 b	0.37 a	52 a	86 e	60 e	7.14 a	17 ab
150 t COP	2.5 a	0.53 a	4.7 cd	0.68 a	0.39 a	66 a	78 f	66 bcd	8.23 a	15 abc
sm (±)	0.05	0.012	0.08	0.016	0.01	3.8	2.4	2.4	0.869	0.9
c.v. (%)	4.0	4.1	3.0	4.7	5.2	11.2	3.3	6.2	22.2	10.6

Results expressed on a dry matter basis at 100–105 ºC; sm – standard deviation of the mean; c.v. – coefficient of variation; Values in the same column followed by the same letters do not differ significantly from each other at the 5 % significance level.

0.05) on most of the analyzed nutrients, except for Cu in the first cut and Fe and Cu in the second cut.

Nitrogen content in ryegrass showed, similarly to the results observed in the Luvisol trial, a significant tendency to decrease with increasing doses of raw pomace and to increase with the application of composted pomace in both cuts. This situation may also explain the reduced vegetative growth observed at the beginning of the trial and the low N content in plant tissues collected in the first cut - especially in treatments with OP - in both trials. However, other possible causes for the reduced productivity should not be excluded, such as potential phytotoxicity phenomena caused by the presence of potentially inhibitory organic compounds, notably phenolic compounds, associated with the recent application of pomace without a prior stabilization period in the soil.

Regarding P, the greatest variations occurred in the first cut, with significantly higher levels observed in treatments with higher doses of OP as well as in all treatments with COP.

In this trial, K concentrations in plant tissues increased significantly and markedly with the application of both products, consistent with the high concentration of this nutrient in the applied materials (1.78 % K_2O in OP and 1.16 % in COP).

Conversely, Ca concentrations were significantly lower in treatments with the highest doses of both forms of olive pomace. This behavior may result from antagonistic interactions caused by elevated levels of other cations, such as K^+ or Mg^{2+}, limiting Ca uptake, a phenomenon widely documented under ionic competition conditions (Mengel & Kirkby, 2001; Bryson & Mills, 2014; Rengel *et al.*, 2023).

It is noteworthy that in this trial, the base fertilization applied to all experimental treatments contained a higher Ca content than that used in the Luvisol trial. This difference is due to the substitution of ammonium nitrate by calcium nitrate, justified by the soil acidity, which resulted in higher Ca values observed in the control treatment.

Concerning micronutrients, as observed in the Luvisol trial, a significant reduction in Mn and Zn concentrations occurred with the application of the highest doses of COP. This effect may be related to the pH increase caused by the compost, which reduces the solubility and thus availability of these elements (Kabata-Pendias, 2010). An increase in B levels was also observed in the first cut with the application OP.

However, contrary to what was observed in the Luvisol trial, in this soil (PZ), B concentrations decreased significantly with COP application in both cuts. This behavior may indicate possible fixation or complexation of B into less available forms or may be related to the marked reduction in B uptake rates by plants under higher soil solution pH conditions (Rengel *et al.*, 2022).

Table 5 - Mean concentrations of macro and micronutrients in the biomass from the 1st cut of ryegrass in the trial with PZ

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
	%					mg kg^{-1}				
Control	5.8 bc	0.32 d	4.6 d	1.17 a	0.53 a	90 b	409 a	150 a	19.1 a	84 a
25 t OP	5.7 cd	0.35 cd	5.1 cd	0.85 b	0.41 bc	82 b	388 ab	131 b	15.1 a	71 ab
50 t OP	6.0 bc	0.39 bc	5.7 bc	0.87 b	0.43 b	87 b	415 a	123 b	16.4 a	81 a
100 t OP	5.4 d	0.44 ab	6.2 ab	0.58 de	0.37 cd	102 ab	349 bc	103 c	16.2 a	65 bc
150 t OP	4.7 e	0.46 a	6.2 ab	0.44 e	0.32 d	79 b	302 c	101 cd	16.5 a	57 c
25 t COP	6.0 b	0.43 ab	6.0 ab	0.88 b	0.41 bc	85 b	210 d	93 cde	14.4 a	60 bc
50 t COP	6.3 a	0.44 ab	6.0 ab	0.73 bc	0.36 cd	86 b	165 de	84 de	13.0 a	42 d
100 t COP	6.5 a	0.48 a	6.7 a	0.62 cd	0.33 d	125 a	139 e	78 e	14.1 a	29 d
150 t COP	6.4 a	0.43 ab	6.4 ab	0.67 cd	0.34 d	129 a	120 e	77 e	14.8 a	30 d
sm (±)	0.090	0.019	0.223	0.046	0.018	7.347	16.768	5.454	1.115	4.383
c.v. (%)	2.7	7.6	6.6	10.6	7.9	13.4	10.5	9.0	12.4	13.1

Results expressed on a dry matter basis at 100–105ºC; sm – standard deviation of the mean; c.v. – coefficient of variation; Values in the same column followed by the same letters do not differ significantly from each other at the 5% significance level.

Table 6 - Mean concentrations of macro and micronutrients in the biomass from the 2nd cut of ryegrass in the trial with PZ

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
	%					mg kg-1				
Control	3.6 bc	0.26 b	1.6 e	1.35 a	0.56 a	87 a	331 c	148 a	12.5 a	28 bc
25 t OP	3.4 bc	0.29 b	2.8 d	1.12 b	0.54 a	73 a	502 a	132 abc	12.9 a	36 a
50 t OP	3.6 bc	0.29 b	3.4 d	0.96 c	0.48 b	85 a	455 ab	135 ab	13.7 a	33 ab
100 t OP	3.3 c	0.27 b	4.2 bc	0.76 ef	0.41 c	69 a	447 b	128 abc	11.2 a	37 a
150 t OP	3.3 c	0.31 ab	4.8 ab	0.66 f	0.40 c	67 a	358 c	140 a	14.1 a	37 a
25 t COP	3.8 bc	0.31 ab	3.3 d	0.88 cd	0.41 c	77 a	198 d	121 abc	15.1 a	29 bc
50 t COP	4.0 b	0.35 a	4.1 c	0.79 de	0.39 c	64 a	175 de	109 bc	12.9 a	25 c
100 t COP	4.7 a	0.36 a	5.0 a	0.70 ef	0.37 c	82 a	153 de	108 bc	13.0 a	18 d
150 t COP	5.3 a	0.35 a	5.2 a	0.69 ef	0.37 c	80 a	130 e	102 c	13.4 a	16 d
sm (±)	0.20	0.017	0.20	0.032	0.017	10.6	15.6	8.9	1.46	1.8
c.v. (%)	8.9	9.2	8.7	6.5	6.9	19.5	35.8	12.5	10.2	10.8

Results expressed on a dry matter basis at 100–105ºC; sm – standard deviation of the mean; c.v. – coefficient of variation; Values in the same column followed by the same letters do not differ significantly from each other at the 5% significance level.

Soil Chemical Composition

Tables 7 and 8 show the average values of several soil parameters measured at the end of the trials, for each experimental treatment.

In the Luvisol trial, the treatments had a statistically significant effect ($p \leq 0.05$) on several soil parameters, including: pH, organic matter (OM), total N, extractable K (Ext. K), exchangeable K, exchangeable Na, base saturation percentage (BS%), Zn, Cu, and B.

COP application increased soil pH from slightly acidic in the control to neutral, due to its high pH (9.0). Organic matter also increased, from low to medium levels, especially with COP, which is a very positive effect on the soils of the Medditerranean region, usually poor in organic matter.

Extractable K, already high in the control, increased further with both OP and COP. The highest value was observed with 150 t ha^{-1} of OP. Exchangeable K followed the same trend.

Exchangeable Na also increased, but remained in the low range (0.10–0.25 cmol(+) kg^{-1}). Base Saturation, already high in the control, rose slightly with COP. Zinc increased from medium to high levels with both materials. Copper increased with COP but stayed within the medium range.

Neither OP nor COP had a significant effect on electrical conductivity of the Luvisoil, that remained with a low salinity even on the higher application rates.

In the Podzol trial, more soil parameters were affected by the treatments: pH, OM, total N, Ext. P, Ext. K, Ext. Mg, exchangeable Ca, Mg, K, Na, BS, Mn, Cu, and B. Overall, effects were stronger than in the Luvisol, reflecting the lower buffer capacity of this soil.

Soil pH rose with COP, reaching neutral levels. Organic matter increased with both products, though it remained in the low range for coarse soils.

Extractable P increased from very low to medium levels with 150 t ha^{-1} of COP. Extractable K also rose, from very low in the control to low or medium levels depending on dose and product used. Magnesium increased especially with COP. Exchangeable cations Ca, Mg, K and Na increased, especially with 150 t ha^{-1} of COP, but remained in the very low range. In turn exchangeable acidity decreased. Consequently, cation exchange capacity, and base saturation also rose. BS% went from medium (41–60%) in the control to high (61–80%) with OP and very high (>80%) with higher COP doses, mainly due to the high pH (9.0) and Ca levels (3.69 %) in COP.

Table 7 - Mean effects of the experimental treatments on selected soil properties – trial with the LV

Parameters		Units	Control	25 t OP	50 t OP	100 t OP	150 t OP	25 t COP	50 t COP	100 t COP	150 t COP	sm (±)	c.v. (%)
pH (H_2O)			6.1 e	6.1 e	6.2 de	6.2 de	6.4 c	6.3 cd	6.4 c	6.7 b	7.0 a	0.05	1.3
EC		dS m^{-1}	0.16 a	0.17 a	0.15 a	0.16 a	0.15 a	0.17 a	0.15 a	0.20 a	0.21 a	0.023	23.7
OM		%	2.05 c	2.15 c	2.1 c	2.26 bc	2.31 bc	2.12 c	2.29 bc	2.49 ab	2.59 a	0.084	6.4
Total-N		mg g^{-1}	0.11 b	0.12 b	0.12 b	0.13 b	0.13 b	0.13 b	0.12 b	0.13 b	0.16 a	0.005	6.4
NO_3-N		mg g^{-1}	2.9 a	3.0 a	2.9 a	3.0 a	3.2 a	3.0 a	3.1 a	3.2a	3.4 a	0.12	6.8
Ext. P (P_2O_5)		mg kg^{-1}	132 a	125 a	125 a	136 a	138 a	148 a	155 a	190 a	179 a	15.4	18.1
Ext. K (K_2O)		mg kg^{-1}	173 f	176 ef	180 de	192 bc	206 a	181 de	178 ef	186 cd	194 b	2.1	2.0
Ext. Mg		mg kg^{-1}	391 a	384 a	363 a	382 a	377 a	378 a	380 a	388 a	377 a	6.9	3.1
	Ca	cmol kg^{-1}	7.6 a	7.7 a	7.6 a	7.6 a	8.3 a	8.2 a	8.7 a	8.5 a	8.8 a	0.38	8.2
Exch.	Mg	cmol kg^{-1}	2.0 a	2.1 a	2.0 a	2.1 a	2.1 a	2.1 a	2.1 a	2.1 a	2.2 a	0.08	6.6
cat	K	cmol kg^{-1}	0.34 d	0.34 d	0.34 d	0.37 bc	0.42 a	0.33 d	0.33 d	0.34 cd	0.38 b	0.075	3.7
	Na	cmol kg^{-1}	0.11 d	0.12 cd	0.12 cd	0.14 cd	0.15 c	0.13 cd	0.14 c	0.20 b	0.23 a	0.008	9.3
BS		%	90 c	91 c	91 c	91 c	92 bc	91 c	93 bc	94 b	99 a	0.8	1.5
Ext. Mn		mg kg^{-1}	255 a	255 a	240 a	215 a	324 a	255 a	250 a	287 a	248 a	30.4	20.5
Ext. Zn		mg kg^{-1}	3.3 c	3.2 c	2. 9c	3.7 bc	3.6 bc	3.5 bc	4.2 b	5.1 a	5.3 a	0.24	10.9
Ext. Cu		mg kg^{-1}	1.4 d	1.5 d	2.0d	1.8 d	1.3 d	2.1 d	2.9 c	3.8 b	4.8 a	0.26	18.6
Ext. B		mg kg^{-1}	0.5 c	0.5 c	0.5 bc	0.6 bc	0.6 b	0.6 bc	0.6 b	0.7 a	0.7 a	0.01	8.3

Values followed by the same letters in the same row do not differ significantly from each other at the 5% significance level; sm – standard deviation of the mean; c.v. – coefficient of variation; ext. – extractable; BS – base saturation

Table 8 - Mean effects of the experimental treatments on selected soil properties – trial with the PZ

Parameters		Units	Control	25 t OP	50 t OP	100 t OP	150 t OP	25 t COP	50 t COP	100 t COP	150 t COP	sm (±)	c.v. (%)
pH (H_2O)			5.9 c	5.9 c	5.9 c	6.0 c	6.1 c	6.4 bc	6.7 ab	7.2 a	7.0 a	0.16	4.4
EC		dS m^{-1}	0.08 a	0.08 a	0.08 a	0.10 a	0.12 a	0.10 a	0.12 a	0.15 a	0.14 a	0.016	26.1
OM		%	0.99 bc	0.99 bc	0.90 c	1.15 abc	1.06 bc	0.83 c	1.00 bc	1.25 ab	1.44 a	0.095	15.4
Total-N		mg g^{-1}	0.01 cd	<0.013 d	0.03 ab	0.03 ab	0.02 bc	0.02 bc	0.03 ab	0.04 ab	0.05 a	0.006	41.1
NO_3-N		mg g^{-1}	3.0 a	3.1 a	2.7 a	2.7 a	2.9 a	3.0 a	3.0 a	3.0 a	3.1 a	0.19	11.5
Ext. P (P_2O_5)		mg kg^{-1}	17 d	12 d	15 d	16 d	16 d	24 cd	31 c	48 b	78 a	3.82	23.3
Ext. K (K_2O)		mg kg^{-1}	5 c	6 c	11 c	18 c	40 b	6 c	10 c	39 b	83 a	4.4	30.9
Ext. Mg		mg kg^{-1}	28 b	24 b	27 b	29 b	34 b	32 b	35 b	49 a	51 a	4.2	21.2
	Ca	cmol kg^{-1} kg^{-1}	0. 9e	1.1 cde	1.0 de	1.2 cde	1.6 bcd	1.4 cde	1.6 bc	2.0 ab	2.4 a	0.163	19.1
Exch.	Mg	cmol kg^{-1}	0.10 e	0.13 de	0.14 de	0.18 cd	0.20 c	0.18 c	0.2 0c	0.27 b	0.3 3a	0.013	11.6
cat	K	cmol kg^{-1}	0.01 c	0.02 c	0.02 c	0.04 c	0.08 b	0.01 c	0.02 c	0.09 b	0.2 1a	0.011	33.6
	Na	cmol kg^{-1}	0.01 f	0.02 ef	0.03 def	0.04 cd	0.05 bc	0.03 def	0.03 de	0.05 b	0.07 a	0.004	17.0
BS		%	49 d	55 d	53 d	58 cd	66 c	68 c	80 b	100 a	91 a	3.6	8.9
Ext. Mn		mg kg^{-1}	7 bc	6 cd	5 d	7 bcd	8 ab	9 a	8 ab	8 ab	8 ab	0.5	12.6
Ext. Zn		mg kg^{-1}	4.1 a	3.1 a	3.4 a	4.3 a	3.9 a	3.4 a	3.3 a	3.7 a	4.5 a	0.50	23.1
Ext. Cu		mg kg^{-1}	0.9 cd	0.6 d	0.7 cd	1.1 bc	0.8 cd	1.0 bc	1.4 b	2.0 a	2.2 a	0.136	18.3
Ext. B		mg kg^{-1}	0.1 cd	0.1 d	0.1 d	0.1 cd	0.1 cd	0.1 cd	0.2 c	0.3 b	0.3 a	0.028	18.5

Values followed by the same letters in the same row do not differ significantly from each other at the 5% significance level; sm – standard deviation of the mean; c.v. – coefficient of variation; ext. – extractable; BS – base saturation

Among micronutrients, only Zn did not respond to treatments. Copper increased from low to medium, especially with COP. Manganese remained very low overall. Boron increased from very low to low with higher COP doses.

These results show that both raw and composted olive pomace can improve soil fertility. COP had stronger and more consistent effects, especially in the nutrient-poor, coarse-textured Podzol. It improved pH, OM, nutrient levels (P, K, Ca, Mg, Cu, B), and CEC.

Raw pomace also showed potential, but should be used carefully, especially in sensitive soils and crops. Being fresh and not stabilized, it may temporarily reduce N availability, cause phytotoxic effects (due to phenolics and organic acids), and lead to unpredictable microbial changes (not studied here). These aspects must be considered when looking for the use of raw pomace. Further studies on herbaceous crops are needed to define safe application rates, incorporation time, and strategies like pre-composting or mixing with other residues.

CONCLUSIONS

This study showed that the application of well-stabilized composted olive pomace significantly improves soil fertility, particularly in terms of pH, organic matter, P, K, Mg, cation exchange capacity, and base saturation. These improvements led to increased nutrient concentrations in plant tissues without negatively affecting biomass production, even at high application rates. In contrast, the application of raw olive pomace at rates above 50 t ha^{-1} resulted in negative effects, including reduced ryegrass biomass in the first cut and lower leaf N concentration. These effects can be attributed to N immobilization induced by the presence of high concentrations of organic substances, particularly phenolic compounds, which can interfere with soil microbial activity, leading to temporary inhibition of the nitrification process and/or residual phytotoxicity. It is important to note that the pomace used had been stored for six months, which may have partially mitigated these effects; thus, more severe impacts on herbaceous crops would be expected if applied immediately after olive oil extraction.

The response to these products was clearly influenced by the soil characteristics. The Podzol, with lower initial fertility, showed greater benefits from COP incorporation, while the naturally more fertile Luvisol exhibited more modest gains. Biomass production in the first cut was nearly twice as high in the more fertile soil, highlighting the critical role of soil properties in evaluating the effectiveness of organic amendments.

Therefore, the agricultural valorization of olive pomace emerges as a promising strategy for sustainable management of this agro-industrial residue, contributing simultaneously to soil fertility enhancement and reducing environmental impacts associated with residue accumulation. However, its application must be carefully planned, based on detailed soil characterization and tailored to the specific needs of the target crops. Selecting appropriate soils and respecting a safety interval between the application of fresh pomace and sowing herbaceous crops are essential to minimize potential adverse effects such as phytotoxicity or nutritional imbalances.

Thus, further studies are necessary to develop guidelines for best practices in the agricultural use of olive pomace from olive mills. Such guidelines should cover appropriate treatments, application techniques, and management strategies to ensure that the use of this residue within a circular economy framework delivers agronomic benefits without compromising agricultural ecosystem integrity.

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REFERENCES

Abid, N.; Aloui, F.; Dhouib, A. & Sayadi, S. (2010) - Olive mill wastewater sludge from evaporation ponds: Evolution of physico-chemical parameters during storage and composting process. *Environmental Technology*, vol 27, n. 2, p. 127-136. http://dx.doi.org/10.1080/09593332708618630

Alfano, G.; Lustrato, G. & Ranalli, G. (2011) - From the soil into the soil: a closed cycle of olive oil residues. *In:* Ferrer, A.S. (Ed) - *Compost III. Dynamic Soil Dynamic Plant*, vol. 5, sp. iss. 2, p. 51-57.

Ameziane, H.; Nounah, A.; Khamar, M. & Zouahri, A. (2020) - Composting olive pomace: evolution of organic matter and compost quality. *Agronomy Research*, vol. 18, n. 1, p. 5–17. https://doi.org/10.15159/AR.20.004

Benton-Jones, J.; Benton-Jones, J.Jr.; Wolf, B. & Mills, H.A. (1991) - *Plant analysis handbook*. Micro-Macro Publishing, 212 p.

Bouhia, Y.; Hafidi, M.; Ouhdouch, Y. & Lyamlouli, K. (2023) - Olive mill waste sludge: from permanent pollution to a highly beneficial organic biofertilizer: a critical review and future perspectives. *Ecotoxicology and Environmental Safety*, vol. 259, art. 114997. https://doi.org/10.1016/j.ecoenv.2023.114997

Brunetti, G.; Plaza, C. & Senesi, N. (2005) - Olive pomace amendment in Mediterranean conditions: effect on soil and humic acid properties and wheat (*Triticum turgidum* L.) yield. *Journal of Agricultural and Food Chemistry*, vol. 53, n. 17, p. 6730–6737. https://doi.org/10.1021/jf050152j

Bruzzone, J.; Conde, P.; Villamil, J.J.; Bianchi, D. & Zoppolo, R. (2017) - Estrategias de valorización del alperujo. *Revista INIA*, n. 51, p. 30–33.

Bryson, G.M. & Mills, H. (2014) - *Plant Analysis Handbook IV*. Micro-Macro Publishing, 609 p. ISBN 978-1-878148-03-2

Buono, D.D.; Said-Pullicino, D.; Proietti, P.; Nasini, L. & Gigliotti, G. (2011) - Utilization of olive husks as plant-growing substrates: phytotoxicity and plant biochemical responses. *Compost Science & Utilization*, vol. 19, n. 1, p. 52–60. https://doi.org/10.1080/1065657X.2011.10736976

Cabrera, A.; Cox, L.; Fernández-Hernández, A.; García-Ortiz Cívantos, C. & Cornejo, J. (2009) - Field appraisement of olive mill solid-waste application in olive crops: effect on herbicide retention. *Agriculture, Ecosystems & Environment*, vol. 132, n. 3-4, p. 260–266. https://doi.org/10.1016/j.agee.2009.04.006

Cayuela, M.L.; Sánchez-Monedero, M.A. & Roig, A. (2010) - Two-phase olive mill waste composting: enhancement of the composting rate and compost quality by grape stalks addition. *Biodegradation*, vol. 21, p. 465–473. https://doi.org/10.1007/s10532-009-9316-5

Černe, M.; Palčić, I.; Major, N.; Pasković, I.; Perković, J.; Užila, Z.; Lukić, M.; Romić, M.; Ferri, T.Z.; Ban, S.G.; Lapanje, A.; Hreščak, J.; Heath, D.J. & Ban, D. (2023) - Effect of olive-processing technology on the utilization of olive mill pomace as a soil amendment. *Journal of Environmental Quality*, vol. 52, n. 3, p. 610-629. https://doi.org/10.1002/jeq2.20464

Duarte, L.; Pacheco, C. & Dias, J.C.S. (1998) – *Métodos de análise de material vegetal*. Laboratório Químico Agrícola Rebelo da Silva, 108p.

Egnér, H.; Riehm, H. & Domingo, W.R. (1960) - Untersuchungen über die chemische bodenanalyse als grundlag für die beurteilung des nährstoffzustandes der böden. II: Chemische extraktionmethoden zur phosphor-und kalium-bestimmung. *Kungliga Lantbrukshögskolans Annaler*, vol. 26, p. 199–215.

FAO-GSP (2019) - *Soil organic carbon Walkley-Black method: Titration and colorimetric method (GLOSOLAN-SOP-02).* FAO-Global Soil Partnership, 25p.

Federici, E.; Massaccesi, L.; Pezzolla, D.; Fidati, L.; Montalbani, E., Proietti, P., Nasini, L.; Regni, L.; Scargetta, S. & Gigliotti, G. (2017) - Short-term modifications of soil microbial community structure and soluble organic matter chemical composition following amendment with different solid olive mill waste and their derived composts. *Applied Soil Ecology*, vol. 119, p. 234–241. https://doi.org/10.1016/j.apsoil.2017.06.014

Gigliotti, G.; Proietti, P.; Said-Pullicino, D.; Nasini, L.; Pezzolla, D.; Rosati, L. & Porceddu, P. R. (2012) – Co-composting of olive husks with high moisture contents: organic matter dynamics and compost quality. *International Biodeterioration & Biodegradation*, vol. 67, p. 8–14. https://doi.org/10.1016/j.ibiod.2011.11.009

Hernández, Z.; Figueiredo, D.; Royer, A. C.; Fonseca, F.; Almendros, G. & Figueiredo, T. (2022) – Qualidade da matéria orgânica e perda de fitotoxicidade em estágios progressivos da compostagem de bagaço de azeitona. *Revista de Ciências Agrárias*, vol. 45, n. 4, p. 262–266. https://doi.org/10.19084/rca.28423

Ilay, R.; Kavdir, Y. & Sümer, A. (2013) – The effect of olive oil solid waste application on soil properties and growth of sunflower (*Helianthus annuus* L.) and bean (*Phaseolus vulgaris* L.). *International Biodeterioration & Biodegradation*, vol. 85, p. 254–259. https://doi.org/10.1016/j.ibiod.2013.07.008

Inglezakis, V.J.; Moreno, J.L & Doula, M. (2012) – Olive oil waste management EU legislation: current situation and policy recommendations. *International Journal of Chemical and Environmental Engineering Systems*, vol. 3, n. 2, p. 65–77.

IUSS Working Group WRB (2022) – *World Reference Base for Soil Resources*. International soil classification system for naming soils and creating legends for soil maps, 4.ª ed., International Union of Soil Sciences (IUSS), Vienna, Austria.

Jiménez, N. S. (2015) – *Valorización del alperujo através del suelo. Evaluación como fertilizante*. Master Thesis. Lleida, Spain, Universitat de Lleida, 41 p.

Kabata-Pendias, A. (2010) – *Trace elements in soils and plants*, 4.ª ed., Boca Raton, USA, CRC Press. https://doi.org/10.1201/b10158

Kavdır, Y.; Cetin, S. C.; Killi, D.; Ilay, R. & Kavdır, I. (2008) – Potential use of olive oil solid waste in agriculture. *In: Proceedings of the International Meeting on Soil Fertility Land Management and Agroclimatology*. Turkey, p. 1027–1032.

Khdair, A.I.; Khdair, S.I. & Abu-Rumman, G.A. (2019) – Dataset on some soil properties improvement by the addition of olive pomace. *Data in Brief*, vol. 24, art. 103878. https://doi.org/10.1016/j.dib.2019.103878

Khdair, A. & Abu-Rumman, G. (2020) – Sustainable environmental management and valorization options for olive mill byproducts in the Middle East and North Africa (MENA) region. *Processes*, vol. 8, n. 6, art. 671. https://doi.org/10.3390/pr8060671

Killi, D. & Kavdir, Y. (2013) – Effects of olive solid waste and olive solid waste compost application on soil properties and growth of *Solanum lycopersicum*. *International Biodeterioration & Biodegradation,* vol. 82, p. 157–165. https://doi.org/10.1016/j.ibiod.2013.03.004

Koutsos, T. M.; Chatzistathis, T. & Balampekou, E. I. (2018) – A new framework proposal, towards a common EU agricultural policy, with the best sustainable practices for the re-use of olive mill wastewater. *Science of the Total Environment*, vol. 622–623, p. 942–953. https://doi.org/10.1016/j.scitotenv.2017.12.073

Lal, R. (1997) – Degradation and resilience of soils. *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 352, n. 1356, p. 997–1010. https://doi.org/10.1098/rstb.1997.0078

López-Piñeiro, A.; Murillo, S.; Barreto, C.; Muñoz, A.; Rato, J.M.; Albarrán, A. & García, A. (2007) – Changes in organic matter and residual effect of amendment with two-phase olive-mill waste on degraded agricultural soils. *Science of the Total Environment*, vol. 378, n. 1–2, p. 84–89. https://doi.org/10.1016/j.scitotenv.2007.01.018

López-Piñeiro, A.; Albarrán, A.; Rato Nunes, J.M. & Barreto, C. (2008) – Short and medium-term effects of two-phase olive mill waste application on olive grove production and soil properties under semiarid Mediterranean conditions. *Bioresource Technology*, vol. 99, n. 17, p. 7982–7987. https://doi.org/10.1016/j.biortech.2008.03.051

López-Piñeiro, A.; Cabrera, D.; Peña, D.; Albarrán, A. & Rato Nunes, J.M. (2009) – Phosphorus adsorption and fractionation in a two-phase olive mill waste amended soil. *Soil Science Society of America Journal*, vol. 73, n. 5, p. 1539–1544. https://doi.org/10.2136/sssaj2009.0035

López-Piñeiro, A.; Albarrán, A.; Rato Nunes, J.M.; Peña, D. & Cabrera, D. (2011) – Cumulative and residual effects of two-phase olive mill waste on olive grove production and soil properties. *Soil Science Society of America Journal*, vol. 75, n. 3, p. 1061–1069. https://doi.org/10.2136/sssaj2010.0230

López-Piñeiro, A.; Albarrán, A.; Rato Nunes, J.M.; Peña, D. & Cabrera, D. (2021) – Long-term impacts of de-oiled two-phase olive mill waste on soil chemical properties, enzyme activities and productivity in an olive grove. *Soil and Tillage Research*, vol. 114, n. 2, p. 175–182. https://doi.org/10.1016/j.still.2011.05.002

Mengel, K. & Kirkby, E. A. (2001) – *Principles of plant nutrition*. Bern, Switzerland, International Potash Institute.

Motsara, M.R. & Roy, R.N. (2008) – *Guide to laboratory establishment for plant nutrient analysis*. Rome, FAO, 204 p.

Ouzounidou, G.; Zervakis, G. & Gaitis, F. (2010) – Raw and microbiologically detoxified olive mill waste and their impact on plant growth. *Terrestrial and Aquatic Environmental Toxicology,* vol. 4, sp.iss.1, p. 21–38.

Paredes, C.; Bernal, M. P.; Cegarra, J. & Roig, A. (2002) – Biodegradation of olive mill wastewater sludge by its co-composting with agricultural wastes. *Bioresource Technology*, vol. 85, n. 1, p. 1–8. https://doi.org/10.1016/S0960-8524(02)00078-0

Peña, D.; Albarrán, A.; López-Piñeiro, A.; Rato-Nunes, J.M.; Sánchez-Llerena, J. & Becerra, D. (2013) – Impact of oiled and de-oiled olive mill waste amendments on the sorption, leaching and persistence of S-metolachlor in a calcareous clay soil. *Journal of Environmental Science and Health, Part B*, vol. 48, n. 9, p. 767–775. https://doi.org/10.1080/03601234.2013.780884

Perez, J.D. & Gallardo-Lara, F. (1987) - Effects of the application of wastewater from olive processing on soil nitrogen transformation. *Communications in Soil Science and Plant Analysis*, vol. 18, n. 9, p. 1031-1039. https://doi.org/10.1080/00103628709367879

Pinho, I. A. O. (2016) – *Phytotoxicity assessments of olive mill solid wastes: influence of phenolic compounds*. Master's Thesis, Universidade de Coimbra, Coimbra, Portugal. 85 p.

Pinho, I. A.; Lopes, D.V.; Martins, R.C. & Quina, M.J. (2017) – Phytotoxicity assessment of olive mill solid wastes and the influence of phenolic compounds. *Chemosphere*, vol. 185, p. 258–267. https://doi.org/10.1016/j.chemosphere.2017.07.002

Regni, L.; Nasini, L.; Ilarioni, L.; Brunori, A.; Massaccesi, L.; Agnelli, A., & Proietti, P. (2017a) – Long-term amendment with fresh and composted solid olive mill waste on olive grove affects carbon sequestration by prunings, fruits, and soil. *Frontiers in Plant Science*, vol. 7, art. 2042. https://doi.org/10.3389/fpls.2016.02042

Regni, L.; Gigliotti, G.; Nasini, L.; Agrafioti, E.; Galanakis, C. M. & Proietti, P. (2017b) – Chapter 5: reuse of olive mill waste as soil amendment. *In:* Galanakis, C.M. (Ed.) - *Olive mill waste: Recent advances for sustainable management*. Academic Press. p. 97–117. https://doi.org/10.1016/B978-0-12-805314-0.00005-4

Regni, L.; Pezzolla, D.; Gigliotti, G. & Proietti, P. (2020) – The sustainable reuse of compost from a new type of olive mill pomace in replacing peat for potted olive tree. *Agronomy Research*, vol. 18, sp. iss. 2, p. 1444-1454. https://doi.org/10.15159/ar.20.129

Rengel, Z.; Cakmak, I. & White, P. J. (Eds.) (2023) – Marschner's mineral nutrition of plants. 4th ed. Academic Press, 817 p. https://doi.org/10.1016/C2019-0-00491-8

Sempiterno, C. & Fernandes, R. (2006) – Efeito da aplicação ao solo de água-ruça, bagaço de azeitona e um composto sobre as características produtivas da cevada (*Hordeum vulgare*, cv. 'Sereia'). *Revista Melhoramento*, vol. 41, p. 311–316.

Sempiterno, C. (2007) – *Contribuição para o estudo da aplicação de subprodutos da indústria de extração de azeite em solos agrícolas – Efeito sobre alguns parâmetros químicos indicadores do estado de fertilidade do solo, o estado de nutrição e produtividade de algumas culturas*. Doctoral thesis. Lisbon, Universidade Técnica de Lisboa. 226 p.

Sempiterno, C. & Fernandes, R. (2010) – Efeito da aplicação ao solo de água-ruça, bagaço de azeitona e um composto sobre os teores de azoto total e mineral e de carbono orgânico. *Revista de Ciências Agrárias*, vol. 33, n. 1, p. 79–87. https://doi.org/10.19084/rca.15765

Sempiterno, C.; Fernandes, R.; Dias, A.; Pinheiro, A.; Falcão, J. & Albardeiro, A. (2022) – GO TECOLIVE – Efeitos de um composto orgânico na fertilidade do solo e no desenvolvimento de uma planta teste. *Revista de Ciências Agrárias*, vol. 45, n. 4, p. 370–374. https://doi.org/10.19084/rca.28492

Toscano, P. & Montemurro, F. (2012) – Olive mill by-products management. *In:* Muzzalupo, I. (Ed.) - *Olive germplasm – The olive cultivation, table olive and olive oil industry in Italy*. InTech. https://doi.org/10.5772/52039

Zucconi, F.; Pera, A.; Forte, M. & de Bertoldi, M. (1981) - Evaluating toxicity of inmature compost. *BioCycle,* vol. 22, p. 54 -57.