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Agricultural use of compost under different irrigation strategies in a hedgerow olive grove under Mediterranean conditions – a comparison with traditional systems

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Abstract. Soil and water-efficient management are key factors in ensuring the olive sector's sustainable production practices. The use of compost based on olive waste (alperujo) as fertilizer could enhance ecosystem services while the need to transition to a zero-waste approach based on a circular economy is achieved. The present work includes a comparative study of the effect of alperujo compost (AC) vs. inorganic fertilization under different management systems: a traditional adult olive grove under rainfed conditions and a young hedgerow olive system, in which a factorial test of tree irrigation regimes (full, deficit and no irrigation) is implemented as well. At the hedgerow plots, the addition of AC and soil sampling time greatly impacted soil chemical parameters and, to a lesser extent, enzymatic activities, whereas irrigation regimes did not exert a marked influence. In the traditional rainfed system, the addition of AC proved to be an efficient tool for carbon sequestration. The first soil sampling revealed a clear stoichiometric relationship between soil organic matter (SOM) and the nitrogen, phosphorus and potassium (NPK) contents in both systems, whereas the correlations were weak and scarce in the second sampling at the hedgerow plots. This fact was related to the decay of the compost effect. Compost in combination with irrigation tended to trigger a certain priming effect on the native SOM with time since the carbon stocks were reduced between 6 % and 38 % from one sampling to the other in the hedgerow system, depending on the irrigation intensity. However, the deficit irrigation caused a less intense reduction of the SOM and essential nutrients representing the best alternative to maximizing the agronomic effects of the compost under a water-saving strategy. Recurrent application of compost would be necessary to maintain soil quality, especially with high tree densities. The combined management of AC and the deficit irrigation proved to be an efficient tool toward a zero-waste circular economy and a water conservation strategy.

1 Introduction

Olive growing is a pivotal piece in Mediterranean countries as an economic engine and a source of employment due to its production under adverse conditions, adaptability and natural abundance (Kostelenos and Kiritsakis, 2017). Spain, one of the leading producers, accounts for 2.62×10^6 ha, which represents 20 % of the world's olive area (FAO, 2021). Over the last decades, olive cultivation has experienced a fast and large-scale intensification process in areas characterized by medium to poor soil fertility and water scarcity (Kavvadias and Koubouris, 2019). Typically, the traditional olive-growing systems characterized by low tree density (< 250 trees ha^{-1}) under a rainfed strategy are moving rapidly to intensive and high-density irrigated systems (> 300–1200 trees ha^{-1}) guided by profit-maximizing objectives and cost reduction (Camposeo et al., 2022). However, these strong changes in olive grove structures (e.g., higher densities and hedgerow formation) are leading to a great deal of pressure on these ecosystems, where the control of irrigation and soil resources has become essential to ensuring its sustainability and production (García-Garví et al., 2022; Morgado et al., 2022). The main environmental impacts of the expansion of higher-density or hedgerow olive groves include biodiversity and local genotype loss, increased consumption of soil and water resources and more intensive agrochemical use (phytosanitary treatments and fertilizers), and hence their transformation should be gradually optimized (Guerrero-Casado et al., 2021). In this sense, there are studies such as Pellegrini et al. (2016) or Camposeo et al. (2022) that show how the different olive agronomic cropping systems could heavily affect the carbon and water footprints.

New sustainable strategies are needed to adapt efficient water use and fertilization according to the phenological tree state and its nutritional needs (Cano-Lamadrid et al., 2015). In fact, there is evidence that suggests that this tree phenology could be altered by a differential development related to the use of organic amendment as fertilizers (Mekki et al., 2019). Consequently, the new European strategies (such as the European Union's Green Deal) foster and fund sustainable management practices based on increasing soil organic carbon inputs and optimizing water resources to maintain long-term productivity and preserve agroecosystem services (Hernández et al., 2015). In this sense, the use of byproducts from olive oil production (e.g., solid byproducts of the two-phase centrifugation method for olive oil extraction called in Spanish "alperujo") is gaining more attention, as it constitutes an interesting and sustainable option as a source of nutrients and carbon (Calvano and Tamborrino, 2022; de Sosa et al., 2022). Alperujo, which is one of the major waste products of the oil industry, is of particular interest due to its high water percentage, high salt concentration and organic matter (Ghilardi et al., 2022). Its agricultural use allows an effective valorization of a widespread agricultural waste into a value-added product with nutritional benefits for the soil, reducing in turn the need for inorganic fertilizers. Studies have shown that amendments based on alperujo can influence soil enzymatic activity that controls the patterns of organic matter decomposition (Panettieri et al., 2022), increase soil fertility through the slow release of nutrients (Alburquerque et al., 2011), control weed proliferation (Camposeo and Vivaldi, 2011; Russo et al., 2015), improve soil water-soluble carbon (Madejón et al., 2016) and modify soil chemical properties (Podgornik et al., 2022) or the oil quality (Proietti et al., 2015). In this sense, irrigation management has been proposed as a central piece to maximize the effect of organic amendments and as a tool to palliate the effect of climate change (Kavvadias and Koubouris, 2019; Mairech et al., 2021; Michalopoulos et al., 2020). However, little attention has been paid to how the agronomic effects of the compost or organic amendments can evolve under different irrigation regimes, essential with high tree densities. Hirich et al. (2014) showed how the combined effect of deficit irrigation (in contrast to full irrigation) and the organic amendment was able to maximize yield and biomass production, while Baghbani-Arani et al. (2020) observed better water use efficiency and an increase in sunflower productivity when an organic amendment was applied regardless of the irrigation regime. Kavvadias and Koubouris (2019) also showed that most of the soil properties were favored by irrigation. However, this combined effect of the organic amendment and irrigation has a number of limitations that need to be considered. Thus, research in this field has showed some disagreement on the negative (and positive) effects of the compost due to the variability in experimental conditions (e.g., the dose used, phenological stage of the crop, climatic conditions or spreading methods) (Regni et al., 2016). Moreover, there are some major drawbacks of irrigation such as poor irrigation water quality, water overuse, exacerbation of soil erosion and leaching of soil nutrients (Khaliq and Kaleem Abbasi, 2015; Morgado et al., 2022; Sousa et al., 2019). Consequently, studies that clarify the relationships between nutrition and water application are of great interest for maximizing resources under a climate change scenario.

The present work was aimed at (i) evaluating the effect of alperujo compost (AC) on soil physicochemical properties and enzyme activities under two different management systems (hedgerow/traditional olive groves) after repeated AC applications and (ii) verifying the feasibility and sustainability of the AC as fertilizers under high tree densities and different irrigation regimes. We hypothesize that the supply of stabilized organic matter could alleviate the negative effects of water stress while improving water efficiency and soil fertility. To that end, we evaluated changes in some key soil physical, chemical and biochemical parameters as indicators of soil quality.

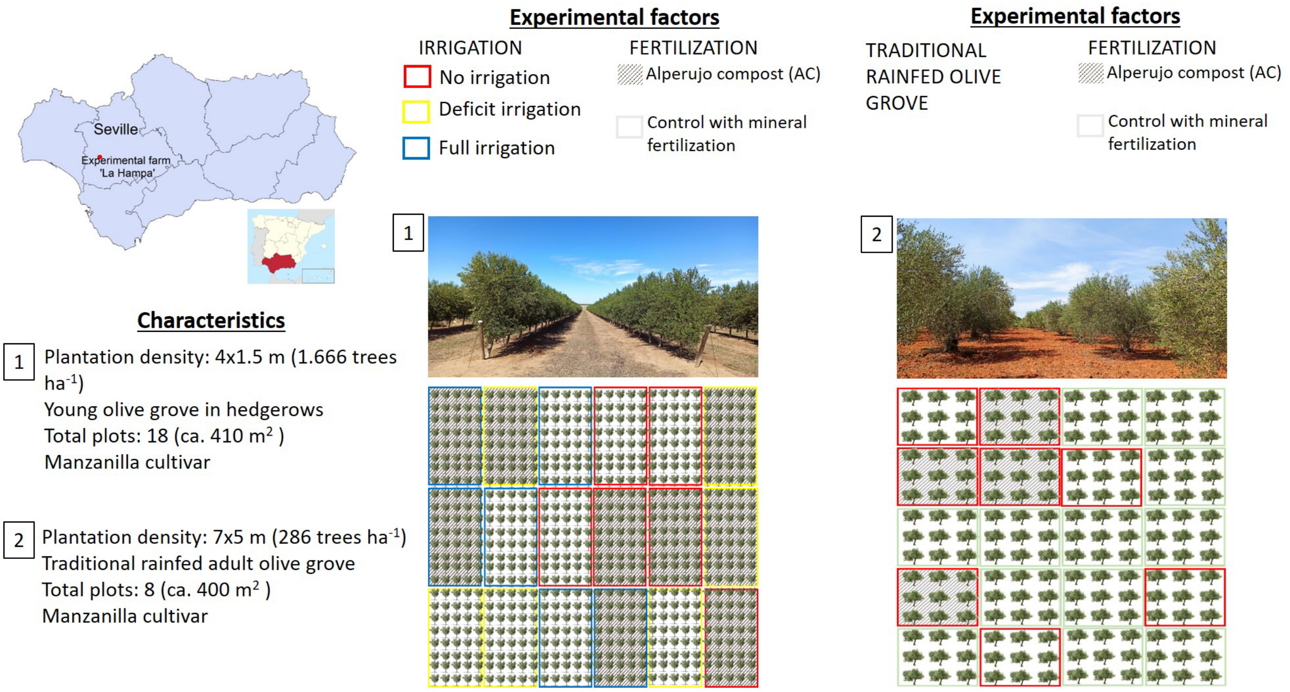


Figure 1. Experimental plots in two olive grove areas with different management strategies at the experimental farm La Hampa located in Coria del Río, Seville (Spain).

2 Methods

2.1 Experimental area and experimental design

A study was carried out at the agriculture experimental farm La Hampa of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC) (37°17′01.8″ N, 6°03′57.4″ W). The soil was a calcic Cambisol (IUSS Working Group WRB, 2015) characterized by a sandy clay loam texture, low fertility and low organic matter content (pH: 7.5; TOC: $8\,g\,kg^{-1}$; N: $0.8\,g\,kg^{-1}$; Olsen-P: $10\,mg\,kg^{-1}$; Available-K: $200\,mg\,kg^{-1}$). The climate is typically Mediterranean, with 3–5 months of summer droughts and moderately wet, cool winters. A summary of the meteorological data of the experimental area can be found in Fig. S1 in the Supplement.

The experiment was conducted between December 2020 and June 2022 in two olive grove areas with different managing strategies. The first experimental site comprises an area of 0.7 ha of a young olive grove of cv. Manzanilla, planted in a pattern of 4 m × 1.5 m as a hedgerow system established in 2018. The area was divided into 18 plots (ca. $410\,m^2$ consisting of five lines of trees, 1.666 trees ha^{-1}) and had a completely randomized design with irrigation and fertilization as the main experimental factors as explained in Fig. 1. The second study site was set in an area of 1.2 ha of an adult rainfed olive grove of cv. Manzanilla, planted in a pattern of 7 m × 5 m under traditional management established in 1997. The study site was divided into 20 plots (ca. $400\,m^2$, 285 trees ha^{-1}), of which 8 were selected to carry out the present experiment (Fig. 1).

2.1.1 Fertilization

Fertilization treatments included control plots with mineral fertilization and plots treated with AC (60 % alperujo and 40 % pruning wastes and legumes). A detailed description of the main parameters of the AC can be found in Table 1.

Application of AC

In December 2020, AC, the compost based on solid waste from two-phase olive oil extraction (alperujo), was applied at a rate of $17\,t\,ha^{-1}$ with a fertilizer spreader in the lanes in between the tree rows in the traditional plots. The product was supplied by an olive oil cooperative after a composting process for more than 12 months. The same product with the same dose was applied in the hedgerow plots in July 2021 to test the short-lasting effect of the organic amendment under high densities. Additionally, trees of all treatments were supplemented with three foliar applications of KNO_3 at a rate of $12.5\,kg\,ha^{-1}$ each time and one application of B ($2\,L\,ha^{-1}$) before fruit set.

In March 2022, AC was applied at the same rate of $17\,t\,ha^{-1}$ as described before at both sites (hedgerow/traditional).

Table 1. Characterization of the alperujo compost (AC) used in this study. Data are mean values ($n = 3$) ± standard error of the mean (SEM).

Parameter	Average value	Parameter	Average value
Humidity (%)	21.6 ± 0.33	SO_3 (%)	2.14 ± 0.06
pH	9.19 ± 0.01	Fe ($g\,kg^{-1}$)	5.42 ± 0.94
EC ($mS\,cm^{-1}$)	5.88 ± 0.24	Mn ($mg\,kg^{-1}$)	332 ± 34.9
OM (%)	58.4 ± 1.34	Cu ($mg\,kg^{-1}$)	69.5 ± 7.83
N (%)	2.50 ± 0.26	Zn ($mg\,kg^{-1}$)	301 ± 21.3
NH_4^+-N	56.8 ± 2.69	B ($mg\,kg^{-1}$)	52.9 ± 0.92
NO_3^--N	26.1 ± 0.78	As ($mg\,kg^{-1}$)	< 0.10 ± 0.000
P_2O_5 (%)	2.52 ± 0.21	Cd ($mg\,kg^{-1}$)	0.09 ± 0.03
K_2O (%)	3.38 ± 0.07	Co ($mg\,kg^{-1}$)	1.70 ± 0.11
CaO (%)	9.40 ± 1.04	Cr ($mg\,kg^{-1}$)	38.6 ± 2.65
MgO (%)	2.34 ± 0.01	Ni ($mg\,kg^{-1}$)	19.0 ± 1.06
Na (%)	0.93 ± 0.003	Pb ($mg\,kg^{-1}$)	5.47 ± 0.64

Table 2. Nutrient concentrations ($kg\,ha^{-1}$) calculated depending on the crop demands. The irrigation dose was adapted to deliver the same nutrient concentration adjusting the amount of water for the full and deficit treatments.

$kg\,ha^{-1}$	Apr	May	Jun	Jul	Aug	Sep	Oct
N	11	24	24	24	11	11	5
P	2.5	5	5	5	5	5	2.5
K	5	13	13	27	27	27	13

Mineral fertilization

- In March 2022, Nitrofoska perfect (15–5–20) was supplied at rates of 1.7 kg per tree at the traditional site and 63 g per tree at the hedgerow site to meet plant needs.
- The hedgerow site was completed with fertirrigation at a variable rate (Table 2) for the treatments of full and deficit irrigation in the 2022 season.

As in 2021, trees of all treatments were supplemented with three foliar applications of KNO_3 at a rate of 12.5 $kg\,ha^{-1}$ each time and one application of B (2 $L\,ha^{-1}$) before fruit set.

Phytosanitary treatments consisted of the application of Cu as a fungicide and two applications of dimethoate as an insecticide.

2.1.2 Irrigation regimens

Three irrigation treatments were selected for the hedgerow plots: (1) full irrigation, (2) deficit irrigation and (3) no irrigation. Irrigation was scheduled weekly in each plot according to the trees' water status. The trees' water status was characterized by stem water potential (Ψ) and leaf conductance following the same procedure as Corell et al. (2020). The water potential was measured at midday in one leaf per tree using the pressure chamber technique (Scholander et al., 1965). The leaves near the main trunk were covered in aluminum foil at least 2 h before measurements were taken every 7–10 d. Leaf conductance was measured at midday in the same trees in which the water potential was measured with a dynamic diffusion porometer (DC-1, Decagon, UK). Data of the stem water potential and the leaf conductance of the area of study can be found in detail in Sánchez-Piñero et al. (2023).

Irrigation was carried out during the night by drip, using one lateral pipe per row of trees and three emitters per plant, delivering 2 $L\,h^{-1}$ each. All the measurements were made on the central tree of each plot.

1. Full irrigation (F): the irrigation schedule is programmed to supply 100 % of the crop evapotranspiration (ETc). The ETc was estimated by means of a soil water balance approach following the FAO methodology (Doorenbos and Pruitt, 1977) in which ETc is calculated as a product of three terms: ETc = ETo × Kc × Kr, where ETo is the reference evapotranspiration obtained from the nearest agricultural weather station, Kc is a crop coefficient set to 0.6 for our case and Kr is the reduction coefficient based on the soil surface covered by the plantation crown set to 1 for our particular case (Steduto et al., 2012). This water dose was increased to 125 % ETc if the water potential measurements were more negative than those estimated by the baseline established in Corell et al. (2016). The same irrigation treatment combined with the compost addition is defined as FC.

2. Deficit irrigation (D): conditions of low or moderate stress are maintained during several phenological stages. The water dose was 1 $mm\,d^{-1}$ along the irrigation season. This applied water was changed accordingly to the water status and phenological stages of the trees. During all the seasons, except for the pit-

hardening period from mid-June to the end of August, water potential was compared with the Corell et al. (2016) baseline. Applied water was increased (by 1, 2 and 3 mm) when measured values were more negative than expected (10 %, 20 % and 30 % more negative). During the pit hardening, the threshold value decreased until −2 MPa according to Girón et al. (2015). The same irrigation treatment combined with the compost addition is defined as DC.

3. No irrigation (NI): no irrigation was applied even under conditions of severe water stress. The same irrigation treatment combined with the compost addition is defined as NIC.

A detailed description of the amount of water provided monthly according to the irrigation treatment can be found in Table S1 in the Supplement.

A traditional rainfed regime without supplemental irrigation was implemented at the traditional plots.

2.2 Soil sampling, chemical analysis and enzyme activity analysis

Three soil cores (0–10 cm) per plot were taken from the tree rows at approximately 15 cm from the tree trunk and drippers and were merged together to obtain a composite sample per plot in November 2021 (after the first compost application) and April 2022 (after the second compost application) at both experimental sites. After sieving at 2 mm, soil samples were split into two subsamples: the first one was stored at 4 °C prior to enzymatic analysis in the laboratory, and the second one was air for chemical analysis.

Sample dry weights were used to calculate soil water content (SWC) by the gravimetric method. Soil pH and electrical conductivity (EC) were measured in the water extract (1 : 5, m/v) after shaking for 1 h using a pH meter (CRISON micro pH 2002). Soil organic matter (SOM) was calculated by dichromate oxidation and titration with ferrous ammonium sulfate (Walkley and Black, 1934). Water-soluble carbon (WSC) content was determined using a TOC-VE Shimadzu analyzer after extraction with water using a sample-to-extractant ratio of 1 : 10. Total Kjeldahl-N (TN) was determined by the method described by Hesse and Hesse (1971). Nitrate (NO_3^--N) was extracted in water (1 : 5 w/v) and quantified in the aqueous extracts by a continuous-flow auto-analyzer Luebbe GmbH AA3 dual channel (Norderstedt, Germany). Ammonium (NH_4^+-N) was extracted in KCl 2 M (1 : 5 w/v) and determined using the same flow auto-analyzer. Available-P was determined after extraction with sodium bicarbonate at pH 8.5 (Olsen et al., 1954), while available-K was determined after extraction with ammonium acetate at pH 7.5 (Dewis and Freitas, 1970). Dehydrogenase activity (DHA) was determined according to Trevors (1984) after soil incubation with p-iodonitrotetrazolium chloride (INT) and measurement of the p-iodo-nitrotetrazidin formazan (INTF) absorbance at 490 nm. Glucosidase activity (β-Glu) was measured as indicated by Eivazi and Tabatabai (1988) after soil incubation with p-nitrophenyl-β-D-glucopyranoside and measurement of the p-nitrophenol absorbance at 400 nm. Urease activity was determined according the method proposed by Kandeler and Gerber (1988) and modified by Kandeler et al. (1999).

A chronogram of the compost addition, soil sampling and irrigation months performed during the experiment is displayed in Fig. S1.

2.3 Statistical analysis

A multi-way ANOVA followed by Tukey's post hoc test was performed for the hedgerow plots to test the effect of compost addition, irrigation and sampling time on soil physicochemical parameters and enzymatic activities, and a two-way ANOVA with compost addition and sampling time as the main factors was performed in the traditional plots. For all statistical tests, $p < 0.05$ was selected as the significance cutoff value. Statistical analysis was performed with SPSS v25 for Windows (IBM Corp., Armonk, NY). Heatmaps of Pearson's correlation coefficients were created with Origin Pro v2022 software.

3 Results

3.1 Main drivers controlling soil physical and chemical parameters in a hedgerow grove with irrigation

Compost addition and sampling time exerted the greatest influenced on soil chemical parameters and to a lesser extent irrigation (Tables 3 and S2). The first compost addition increased SWC by 33 % for the DC and 6 % for the FC treatment compared with their respective controls, whereas no changes were detected for the NIC treatment and its control. The second compost addition improved SWC by 13 % and 26 % for NIC and DC compared with their controls, respectively.

Compost addition increased SOM on average by 28 % regardless of the irrigation treatment at the first sampling time, whereas an overall increment of 12 % after the compost addition and irrespective of the irrigation dose was detected during the second sampling (Tables 3 and S2). The amount of WSC was influenced by the combination of the three factors (i.e., compost, sampling time and irrigation) showing an increase of 34 % for the NIC and DC treatments and 54 % for the FC during the first sampling, while the percent improvements over their control were 34 %, 58 % and 18 % for NIC, DC and FC, respectively, for the second sampling. Compost had a significant positive effect on TN, P and K concentration ($p < 0.01$). Thus, TN increased on average by 23 %, P by 46 % and K by 41 % with the addition of compost and irrespective of sampling time and irrigation regime.

Table 3. Results of ANOVA (F and p value) showing the main significance factors (i.e., compost addition, irrigation, sampling time or interactions) controlling changes in soil physical and chemical properties at the hedgerow plots. SWC: soil water content, EC: electrical conductivity, SOM: soil organic matter, WSC: water-soluble carbon, Avail-K: available K.

ANOVA results	SWC		pH		EC		SOM		WSC		TN		NO_3^--N		NH_4^+-N		Olsen-P		Avail-K	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Compost addition	7.58	*	ns		ns		22.2	***	53.0	***	12.6	**	ns		ns		18.7	***	28.2	***
Irrigation	15.6	***	ns		8.28	*	ns		7.17	**	ns		ns		ns		ns		ns	
Sampling time	17.1	***	49.0	***	25.2	***	14.9	***	58.6	***	ns		13.0	***	54.2	***	ns		ns	
Compost × irrigation × sampling time	ns		ns		ns		ns		3.77	*	ns		ns		ns		ns		ns	
Compost × sampling time	ns		ns		ns		6.10	*	7.17	*	ns		ns		5.33	*	ns		ns	
Irrigation × sampling time	ns		5.70	**	ns		ns		ns		ns		ns		ns		ns		ns	
Compost × irrigation	ns		ns		3.92	*	ns		ns		ns		ns		ns		ns		ns	

Significance level: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Values of pH were highly sensitive to seasonal changes and, to a lesser degree, to the irrigation management, but no clear trend regarding the latter was observed during the second sampling time. Values of EC increased with the addition of compost and under a higher irrigation dose (DC, F and FC) (Table S2). This effect tended to disappear over time (Tables 3 and S2).

Table 4. Results of ANOVA (F and p value) showing the main significance factors (i.e., compost addition, sampling time or interaction) controlling changes in soil physical and chemical properties at the traditional plots.

ANOVA results	SWC		pH		EC		SOM		WSC		Kjeldahl-N		NO_3^--N		NH_4^+-N		Olsen-P		Avail-K	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Compost addition	ns		12.1	*	8.14	*	9.01	*	ns		ns		ns		5.43	*	ns		ns	
Sampling time	ns		ns		ns		10.0	*	ns		363	**	ns		7.21	*	5.61	*	ns	
Compost × sampling time	ns		ns		ns		ns		ns		4.85	*	ns		ns		ns		ns	

No significant changes were detected with respect to NO_3^--N and NH_4^+-N contents, but some trends were identified. During the first sampling, the compost addition increased by 26 % and 54 % NO_3^--N contents in NIC and DC treatments, whereas the FC treatment caused a decrease of 74 % in NO_3^--N content in comparison with its control. The content of NH_4^+-N increased on average with AC addition irrespective of the irrigation regime. Both inorganic forms were greatly reduced in the second sampling for all treatments.

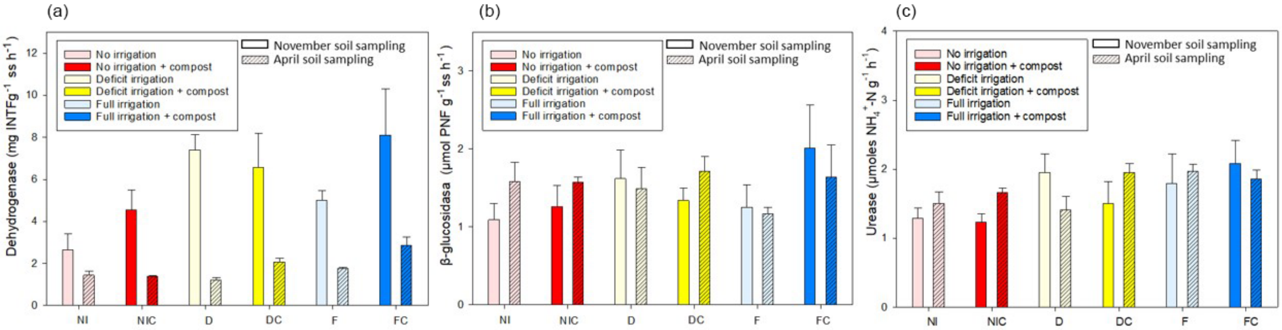
3.2 The main drivers controlling soil physical and chemical parameters with a traditional management with no irrigation

As in the hedgerow plots, the addition of compost significantly impacted some of the main soil chemical parameters, but to a lesser extent. The SWC differed by 20 % between the plots with AC addition and their control irrespective of the sampling time, although this difference was not significant.

Values of soil pH increased by 0.6–0.8 units on average with the addition of AC, and the same trend was also observed for the EC that increased by 28 % after compost addition regardless of the sampling time (Tables 4 and S3). The percentage of SOM only differed by 1 % between the control plots and the plots treated at the first sampling time (11 months after compost addition). However, after the second compost addition, SOM increased by 23 % in the AC-amended plots compared with the control. The content of TN improved by 8 % with the addition of compost, whereas this amount rose up to 20 % in the second sampling. Different accumulation patterns of NH_4^+-N were seen during the two samplings. Thus, the addition of compost caused an increase of 16 % in the organic amended plots, whereas the control plots showed 2.5 times greater NH_4^+-N concentrations than those with compost (Tables 4 and S3).

3.3 Soil enzyme activity in a hedgerow grove with irrigation

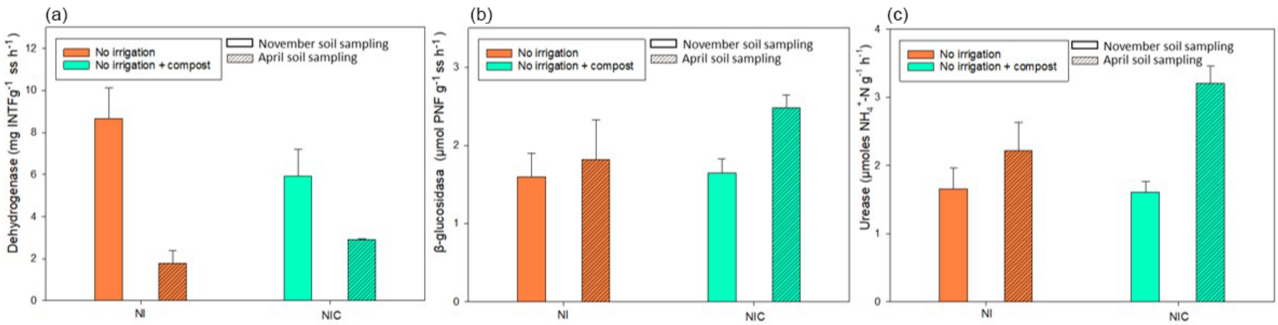
Strong seasonal patterns were found with respect to the DHA, showing a decrease in the activity of 67 % on average irrespective of the treatment from the first sampling to the second (Fig. 2, $p < 0.05$). Compost addition did not seem to have a great effect on this activity, but some trends were detected. During the first sampling, both the NIC and the FC showed an increase in the DHA of approximately 40 % on average, whereas the DC experienced a decrease of 11 % compared with its control. However, for the second sampling, the NIC treatment did not show any difference with NI treatment, while the compost addition enhanced by 40 % on average the DHA in the DC and FC treatments. Irrigation impacted significantly the DHA, but only the NI and F treatments were different ($p < 0.05$). On average, in both years, DHA increased by ca. 42 % from the NI regime to the F treatment irrespective of the compost addition.



ANOVA results	Dehydrogenase F	Dehydrogenase p	β-glucosidase F	β-glucosidase p	Urease F	Urease p
Compost addition	ns		ns		ns	
Irrigation	4.42	*	ns		ns	
Sampling time	96.5	**	ns		ns	

(* $p < 0.05$, ** $p < 0.001$)

Figure 2. Mean values of dehydrogenase **(a)**, β-glucosidase **(b)** and urease **(c)** activities measured for control soils and amended with alperujo compost under different irrigation regimes at the hedgerow plots showing the seasonal changes from November (no shaded bars) to April (shaded bars). Error bars represent standard deviations. No interaction between the ANOVA factors (compost addition, irrigation regime and sampling time) was found.



ANOVA results	Dehydrogenase F	Dehydrogenase p	β-glucosidase F	β-glucosidase p	Urease F	Urease p
Compost addition	ns		ns		ns	
Sampling time	35.0	**	5.22	*	14.4	*
Compost*Sampling time	8.45	*	ns		ns	

(* $p < 0.05$, ** $p < 0.001$)

Figure 3. Mean values of dehydrogenase **(a)**, β-glucosidase **(b)** and urease **(c)** activities measured for control soil and amended with alperujo compost under a rainfed regime at the traditional plots showing the seasonal changes from November (no shaded bars) to April (shaded bars). Error bars represent standard deviations.

The β-Glu and the urease activity did not show any significant difference with respect to the parameters considered (i.e., compost, irrigation regime and sampling time) (Fig. 2, $p > 0.05$). As opposed to the DHA, there seemed to be an increase in both activities at the second sampling time, except for the D and FC treatments.

3.4 Soil enzyme activity under traditional management and no irrigation

In general, the enzyme's activity showed similar patterns to the hedgerow plots, with the DHA displaying a decreasing trend in the second soil sampling (Fig. 3, $p < 0.05$), whereas the β-Glu and the urease activity tended to increase irrespective of the compost addition (Fig. 3). In the first sampling (11 months after the compost addition), the compost addition did not cause higher enzymatic activities with respect to the control. However, during the second sampling, increases of 38 %, 26 % and 31 % in DHA, β-Glu and urease, respectively, were detected with the addition of compost, although this was not significant (Fig. 3, $p > 0.05$).

3.5 Soil physicochemical correlations and seasonal patterns

Different patterns of correlations among the variables measured were found at the hedgerow and traditional plots according to the sampling time (Figs. 4 and 5). The first sam-

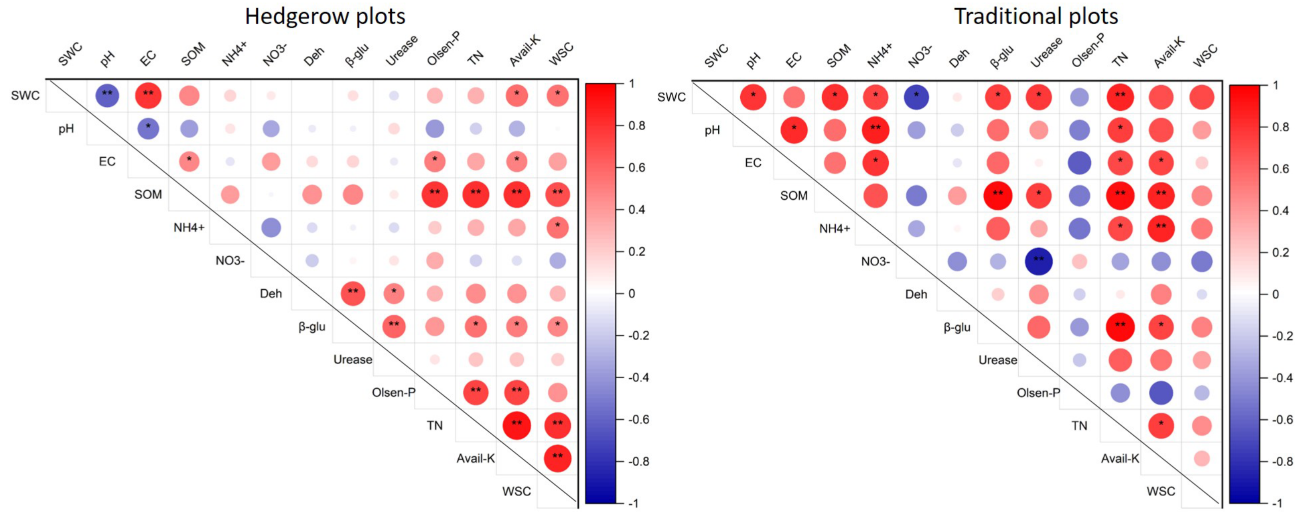


Figure 4. Pearson's correlation coefficients of soil chemical parameters for the first sampling time (November) at the hedgerow and traditional plots. The circle's color in the correlogram corresponds to the correlation coefficient, wherein a positive correlation (red end of the scale) is closer to 1 and a negative correlation (blue end the of scale) is closer to −1. The size of the circles corresponds to the significance level (* $p < 0.05$, ** $p < 0.01$). Nonsignificant correlations are not shown. SWC: soil water content, EC: electrical conductivity, SOM: soil organic matter, NH_4^+: ammonium, NO_3^-: nitrate, Deh: dehydrogenase, β-Glu: β-glucosidase, TN: total nitrogen, Avail-K: available potassium, WSC: water-soluble carbon.

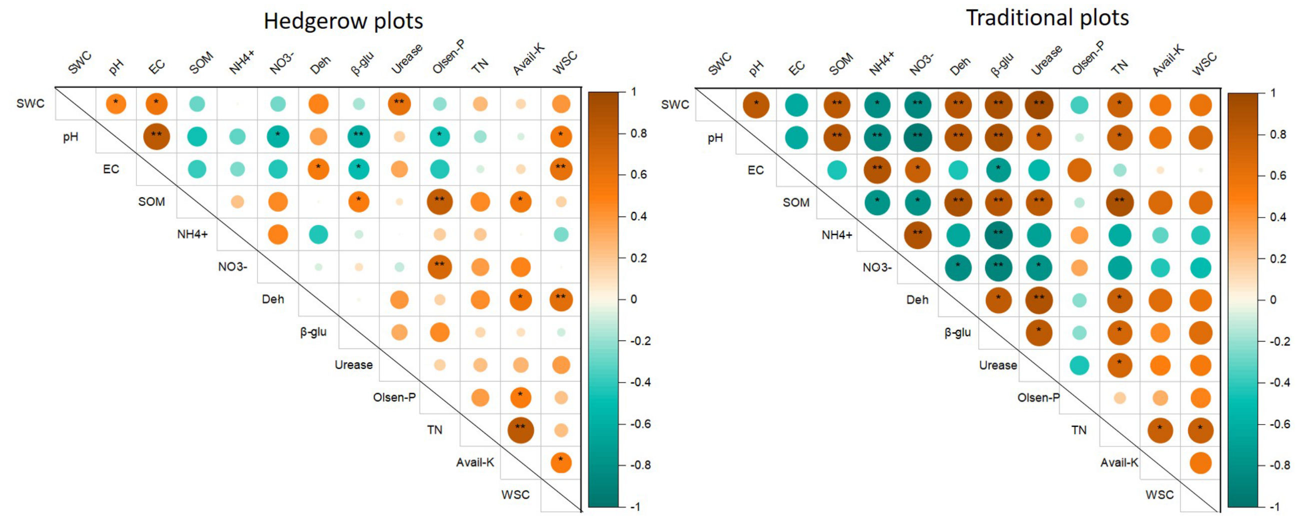


Figure 5. Pearson's correlation coefficients of soil chemical parameters for the second sampling time (April) at the hedgerow and traditional plots. The circle's color in the correlogram corresponds to the correlation coefficient, wherein a positive correlation (white end of the scale) is closer to 1 and a negative correlation (brown end of the scale) is closer to −1. The size of the circles corresponds to the significance level (* $p < 0.05$, ** $p < 0.01$). Nonsignificant correlations are not shown.

pling time showed the greatest number of correlations at the hedgerow plots, displaying a clear stoichiometric relationship between SOM and the nitrogen, phosphorus and potassium (NPK) content ($p < 0.01$). This was also true for the traditional plots, although the SOM content was also highly correlated with the β-Glu and the urease activity (Fig. 4). Additionally, SWC seemed to exert a great influence on some key chemical parameters (e.g., pH, SOM, inorganic N, TN and enzyme activity) at the traditional plots (with no supplementary irrigation).

On the other hand, the second sampling time revealed stronger correlations at the traditional plots. Thus, the SWC and SOM were highly correlated with most of the variables, and the inorganic N was correlated negatively with all enzymatic activities. However, at the hedgerow plots, the correlations exhibited among the variables were weak and scarce (Fig. 5).

Regarding the seasonal patterns, different rates of soil carbon mineralization between the sampling times were observed, and this was dependent on the compost addition and irrigation as well. The percentage of reduction of SOM between the first and second sampling times was 6 % for both the NI and NIC treatments and 4 %, 25 %, 13 % and 39 % for the D, DC, F and FC treatments, respectively.

4 Discussion

4.1 Compost and irrigation as drivers of soil properties and enzymatic activities

Intensification of olive groves demands new management strategies to avoid over-fertilization and environmental pollution. Contrasting results are often presented, depending on some factors such as the amount of irrigation, tillage practices, nature of the organic amendment and timing of fertilization (Kavvadias et al., 2018a, b; Zipori et al., 2020). In this sense, numerous studies point to irrigation among all these agronomic factors as the pivotal piece driving soil carbon dynamics (Fraga et al., 2020; Pascazio et al., 2018; Sofo et al., 2014). In our case, it is somewhat surprising, considering the scarcity of rainfall, that the compost addition had the most striking effect on soil physicochemical properties, and the irrigation effect was very limited to some soil properties. Likewise, Kavvadias et al. (2018b) could not find a significant effect of irrigation management on soil properties, with the exception of some soil cation concentrations (e.g., Mg). However, in their case, they attributed this lack of effect to the fact that their study was based on an area with high precipitation (> 950 mm). Olmedilla et al. (2004) also concluded that irrigation could take up to 1 year to have a response to vegetative growth and olive grove yield. With our conditions, a much more decisive effect of the irrigation practices would be expected in soil properties. A plausible explanation could be that the seasonal fluctuation of the sampling times masked the irrigation effect, a decision that was made to test the lasting effect of the compost.

On the other hand, Kavvadias et al. (2018a) found in other study a substantial decrease in soil carbon content in irrigated plots after the addition of the organic amendment compared with the non-irrigated sites. Here, by contrast, at first, the addition of compost remarkably improved SOM contents in the full irrigated plots when compared with the non-irrigated ones, but this effect only remained during the first sampling. In the second sampling (just 1 month after the second compost application), the trend was reversed, and we found the lowest SOM content in the full irrigated parcels. Our results suggest that the compost was steadily mineralized at higher moisture contents, and once there was a source of carbon available, this was rapidly consumed or leached into deeper soil layers, being practically exhausted in the second sampling.

As mentioned in previous studies, a strong relationship between the compost addition and the increase in the availability of N, P, K and SOM content was observed here. Koubouris et al. (2017) reported a marked improvement in SOM (+30 %) following 2 years of organic amendments, and Regni et al. (2016) also reported a positive effect on carbon sequestration after the addition of a mixture of fresh olive pomace deriving from a mixture of a three-phase oil extraction and shredded olive tree pruning residues. Likewise, Fernández-Hernández et al. (2014) detected an improvement in most of the soil characteristics, including an increase in SOM content.

Although the compost addition had a clear impact on the SOM and TN, this was not translated into a greater enzymatic response. The DH and β-Glu enzymes, which are highly related to the oxidation and hydrolysis of SOM, can be considered proxies of the intensity of microbial metabolism and an index of soil quality related to the agronomic management (Baležentienė, 2012; Moreno et al., 2009). Numerous studies reported a rise in their activity after the addition of an exogenous source of organic carbon (Federici et al., 2017; Magdich et al., 2020; Panettieri et al., 2022). However, their potential to mineralize organic compounds is often associated with a complex balance between the autochthonous and allochthonous microbial communities that weigh the metabolic investment of the different decomposition pathways of the exogenous and native sources of carbon and that are also limited with nutrient and substrate constraints (Lehmann et al., 2020; Panettieri et al., 2022). This balance can be altered in turn by the climatic conditions, irrigation management as in our case or tillage operations. It is well known that irrigation can exert a strong influence on microbial growth and composition and biogeochemical cycles through the control of soil moisture (Bastida et al., 2017; Michalopoulos et al., 2020; Placella et al., 2012), but for us this was mainly reflected in the DHA, while the other enzymes were less responsive to this factor.

4.2 Seasonal influence on soil physicochemical properties and enzymatic activities

Understanding the agronomic performance of organic amendments under different irrigation regimes and systems over time is essential for predicting future needs and the evolution of the amendments. Here, an overall decay of the compost effect was detected in most of the soil physicochemical properties over time independently of the irrigation regime or system. In a previous study, de Sosa et al. (2021) showed the same seasonal patterns in soil chemical properties following 2 years of compost application under traditional management, but at higher densities where irrigation is essential, the synergetic effect of both factors over time should be considered. Little information is available on the combined effects of irrigation regimes and organic amendments and even less if more traditional management is considered. Our results revealed that our source of carbon in combination with water tended to trigger a certain priming effect on the native SOM with time since the carbon stocks were reduced between 6 % and 38 % in the hedgerow plots from the first sampling to the second, as other studies also reported (Kavvadias et al., 2018b). In this sense, it is interesting to note that the deficit irrigation caused a less intense reduction of the SOM and essential nutrients (i.e., N, P, K) than the full irrigation treatment, so it could represent the best alternative to maximize the agronomic effects of the compost under a water-saving strategy. Another aspect to consider is that carbon stocks did increase over time in the traditional intensive plots with compost amendment, so it is clear that tree density played a key role in controlling soil carbon storage and that the amount of compost provided at high densities was not enough to meet the crop needs and to promote carbon sequestration. Rui et al. (2016) concluded that the formation of new biomass increasing soil carbon could be limited by insufficient inorganic nutrients in systems with low inputs, and Ferrara et al. (2015) also observed limited changes in SOM related to a late response of soil quality indicators that could be the case in our experiment as well.

Our results showed that limitations in soil fertility would make necessary a recursive application of compost to maintain productivity, since this type of compost resulted in being highly biodegradable with time, which has been identified before (Panettieri et al., 2022). However, considering the time factor in the agronomic effect of the compost, it was clear that the deficit irrigation treatment managed more efficient compost use by slowing the nutrient loss over time or favoring nutrient storage. For instance, it is interesting to note that there was an enrichment of P and K contents over time with non-irrigated and deficit treatments, whereas the full irrigation treatment enhanced P mobility, as has been described before (Ibrahimi and Gaddas, 2015; Ojekanmi et al., 2011; Proietti et al., 2015). Given the fundamental role that both macronutrients play in olive tree nutrition and drought tolerance, their evolution should be monitored after successive applications of AC (Christopoulou et al., 2021; Fernández-Escobar, 2019).

The study of the evolution of the compost over time reflected different strategies of SOM decomposition within the hedgerow and the intensive plots. During the first sampling, SOM was highly correlated with NPK content in both management systems, which suggested that both processes were coupled after a few months of compost application. However, during the second sampling, right after the second compost addition, where the soil nutrient status was greatly reduced under hedgerow management, the correlations among all variables became weak and were difficult to establish. By contrast, under traditional management, a steady carbon assimilation rate mediated by the SWC, the pH and the enzymatic activities continued its course.

No major fluctuations of the enzyme activities were detected over time apart from the DHA, which was clearly affected by a seasonal pattern. Panettieri et al. (2022) identified either greater or no differences in DHA in plots treated with AC according to the sampling time, and β-Glu activity also remained unaltered after the organic amendment. Likewise, Peña et al. (2022) identified a seasonal response of the DH, β-Glu and urease activities after the compost addition, whereas Ciadamidaro et al. (2016) only observed a response of DHA depending on the sampling area and no response for β-Glu activity.

5 Conclusions

Agricultural techniques need to be optimized to manage the best compost use and an efficient irrigation management with low environmental impacts. The application of alperujo compost improved the soil organic matter content in both cultivation systems. However, the traditional management proved to have a better nutrient balance over time without any supplemental irrigation. On the other hand, it was clear that, when the conversion from traditional to more intensive systems needs to be done, the combined effect of the compost and the irrigation regime has to be taken into account. Our results showed that the deficit irrigation regime helped to maximize the agronomic effects of the compost and the nutrient supply, promoting in turn a water-saving strategy. The full irrigation regime caused a priming effect of the native soil organic matter besides consuming an amount of water that will surely not be available in a climate change scenario. Moreover, the repeated application of compost managed a high availability of N, P and K in the soil, an effect that tended to disappear under a full irrigation regime.

The sustainability of hedgerow olive groves depends largely on guaranteeing soil fertility in tandem with good water availability at the most critical stages of the crop, and in this sense, the AC in combination with the deficit irrigation regime proved to be an efficient tool toward a zero-waste strategy within a circular economy framework and for reducing the vulnerability of water resources caused by climate change.

Data availability. Original data are available upon request. The dataset used for this study is made available under the CSIC data repository https://doi.org/10.20350/digitalCSIC/15331 (de Sosa et al., 2023).

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