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RESEARCH ARTICLE

Using olive mill waste compost with sprinkler irrigation as a strategy to achieve sustainable rice cropping under Mediterranean conditions

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Abstract

Traditional rice (*Oryza sativa* L.) cropping systems under flooding irrigation combined with conventional tillage management are under increasing threat due to a loss of soil quality and a scarcity of water resources, especially in Mediterranean environments. Hence, the development of such management strategies as no-tillage, the application of organic amendments, and water-saving methods could be vital in enhancing the sustainability of rice crops. This work tests the combination of various management systems for growing rice under Mediterranean conditions. It assesses for the first time their influence on soil properties and rice yield components. A field experiment was carried out in southern Spain over 3 years (2015–2017) with six treatments: tillage and continuous flood irrigation either without or with application of two-phase olive mill waste compost; tillage and sprinkler irrigation either without or with application of mill waste compost; direct seeding (no tillage) and sprinkler irrigation either without or with application of mill waste compost. Applying mill waste compost in combination with sprinkler-rice systems improved significantly the soils' properties. Sprinkler-rice yield was similar to that of rice under tillage and flooding, but it used less irrigation water. In 2017, the greatest rice yield occurred under tillage and sprinkler irrigation with application of mill waste compost (8581 kg ha^{-1}), showing the importance of soil organic matter on yields. Additionnally, flooding increased significantly weed density because it lowered herbicide efficacy, making weed control a key issue for rice yields. Thus, the novelty of this communication is showing that the application of mill waste compost combined with sprinkler irrigation may be a sustainable alternative for rice crops under Mediterranean conditions, increasing the water efficiency and reducing weed pressure, while improving different soil properties.

Keywords Aerobic rice · Direct seeding · Flooding rice · Water productivity

1 Introduction

Rice (*Oryza sativa* L.) is an essential crop in regards to world food security. Spain is Europe's second largest rice producer, behind Italy, with annual turnover of more than €250 million, which underscores the social and economic importance of this crop (MAPA 2021). However, traditional rice cropping systems under flooding irrigation (anaerobic conditions) and conventional tillage cause major health and environmental problems. These include heavy-metal content in rice grain (Signes-Pastor et al. 2016), yield stagnation (Madhukar et al. 2020), greenhouse gas emissions (Jiang et al. 2019), degradation of soil quality (Mondal et al. 2020), and water pollution from pesticide use (Gusmaroli et al. 2019). Furthermore, the use of flood irrigation is under threat due to the shortage of water resources, especially in countries with a mediterranean climate. Therefore, there is a clear need to develop management strategies to enhance sustainability of the rice crop (Fig. 1) (Surendran et al. 2021). In this context, aerobic (non-flooding) rice together with direct seeding (no-tillage) has been proposed as an efficient management practice to reduce water consumption, which may reach 5000 L of water to produce one kilogram of rice under traditional flooded-field farming (IRRI 2019). Indeed, Mandal et al. (2013) reported that

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Fig. 1 (**a**) Aerial photograph of field experiment where amended soils (dark patches) are clearly differentiated from non-amended soils. Rice seedling growth under (**b**) flooding and tillage, (**c**) sprinkler and tillage, and (**d**) sprinkler and direct seeding during the early vegetative stage. Source: Photographs by the authors.

the potential saving of water input with aerobic rice was 42–60% compared with traditional flooded rice. However, the results concerning yields with the two systems (aerobic and anaerobic) have often been contradictory. Hence, whereas Patel et al. (2010) observed that the aerobic condition grain yield was about 30% less than the anaerobic case, other studies (Carrijo et al. 2019) found the yields of the two conditions to be quite similar. However, a study carried out under five different irrigation regimes by Froes de Borja Reis et al. (2018) showed the greatest grain yields to be for the aerobic rice with 9.1 Mg ha^{-1} versus 8.6 Mg ha^{-1} registered under continuous flooding, whereas the rest of the irrigation regimes (alternate wetting and drying with different cycles) gave an average 8.4 Mg ha^{-1}. Understanding the conditions that lead to yield reductions and adopting effective techniques are therefore vital to achieving sustainability of cultivating rice, a crucial food security crop (Nie et al. 2012). Sánchez-Llerena et al. (2016) reported that under short-term implementation of sprinkler irrigation combined with conservation agriculture management (no-tillage) the rice yields were lower than under conventional tillage and flooding (4.8 and 6.6 Mg ha^{-1}, respectively), but the greatest yield was obtained with long-term aerobic and no-tillage conditions (9.8 Mg ha^{-1}). Similar results concerning yield reductions had been found with no-tillage management regimes in the short-term with three different crops—rice, wheat, and maize (Song et al. 2019). These differences have been explained in terms of by the soil organic matter content, which is lower in a short-term than a long-term implementation (Xue et al. 2008). Hence, application of organic amendments might outweigh this deficit, as well as increasing the soils' water retention capacity and thereby contributing to greater water productivity and yields, especially in regions where water availability is limited (Haque et al. 2021). Determining the effects of organic amendments on rice productivity is complicated, however, due to the large number of variables involved such as weather conditions, soil type, rice variety, type of organic amendment, and dosage and time of application (Hazra et al. 2018).

In the Mediterranean countries, the olive oil extraction industry has a very significant socio-economic impact. Two-phase continuous extraction, which consumes less water than traditional pressing, is the commonest process used. A major problem with this new system is the waste that it generates as a semi-solid pomace (two-phase olive mill waste). In just the Mediterranean basin, this reaches amounts of more than 11 000 000 Mg annually (Gómez et al. 2019). It is therefore absolutely necessary to find a solution for its disposal. Two-phase olive mill waste is characterized by high organic matter content (greater than 85%), so its use as organic amendment represents a sustainable alternative that is in accordance with the Circular Economy Strategy of the European Union, one of whose main objectives is that wastes be reused (COM 2017). In this regard, several studies have shown the positive effects of two-phase olive mill waste on the properties and fertility of soils (López-Piñeiro et al. 2011; Lozano-García and Parras-Alcántara 2013). However, other studies (Pinho et al. 2017) have demonstrated that direct use of two-phase olive mill waste (raw or fresh) causes acidity in the soil and toxicity for the crops because of the presence of such substances as polyphenols. Furthermore, the high moisture content of two-phase olive mill waste hinders its use. Given its low technical and economic requirements, composting is therefore a very promising strategy for using this waste, and may well represent an eco-friendly solution for its disposal (Fernández-Hernández et al. 2014).

Despite the fact that the Mediterranean region is characterized by its water shortage, with rainfall not meeting the demand for crops (Mancha et al. 2021), and with soils that are very poor in organic matter content, we could not find published research about rice production under different management systems such as sprinkler irrigation and conservation agriculture practices in combination with application of organic amendments, Nevertheless, we hypothesised that the implementation of these practices could minimise the environmental risks associated with traditional rice crop systems, ensuring the sustainability of the crop and promoting the rational and efficient use of resources. To confirm this hypothesis, this study is the first to analyse the effects of different irrigation and tillage management systems (sprinkler versus flooding, and no-tillage versus conventional tillage) without and with composted two-phase olive mill waste (CW) application, on soil properties and the rice yield components under Mediterranean conditions. Since, the transformation of the soil's organic matter after a period of aging can play an important role in the properties of the soil, and may therefore influence crop productivity, direct and residual effects (first and third years after the CW application, respectively) were also evaluated.

2 Material and methods

2.1 Site description

The experimental field was in southern Spain (38°55'N; 6°57'W), with a mediterranean climate (rainfall < 480 mm, dry and hot summers). Data were taken during the three rice-growing seasons of 2015-2017. The temperature (maximum and minimum), rainfall, and rice evapotranspiration *(ETc)* data corresponding to the experimental period are shown in Fig. 2. The data of temperature, rainfall, and reference evapotranspiration (*ETo*-PM) were obtained from the irrigation advisory network of the Extremadura Regional Government (Redarex, 2021), and *ETc* was calculated as: $ETc = K_c\ ETo$ where K_c is the crop coefficient and *ETo* is the reference evapotranspiration. In accordance with Allen et al. (2006), the rice crop coefficients of the initial, intermediate, and final stages were taken as 1.05, 1.2, and 0.9, respectively. The soil of the experimental site is a Hydragic Anthrosol (FAO 2006) as a result of rice mono-cropping over a period of more than 10 years, under deep ploughing and flooding conditions. Its main properties were as follows: 50.3% sand, 28.9% silt, and 20.8% clay, with 12.6 g kg^{-1} total organic carbon (TOC), pH 4.42, and 1.28 g kg^{-1} total nitrogen (N).

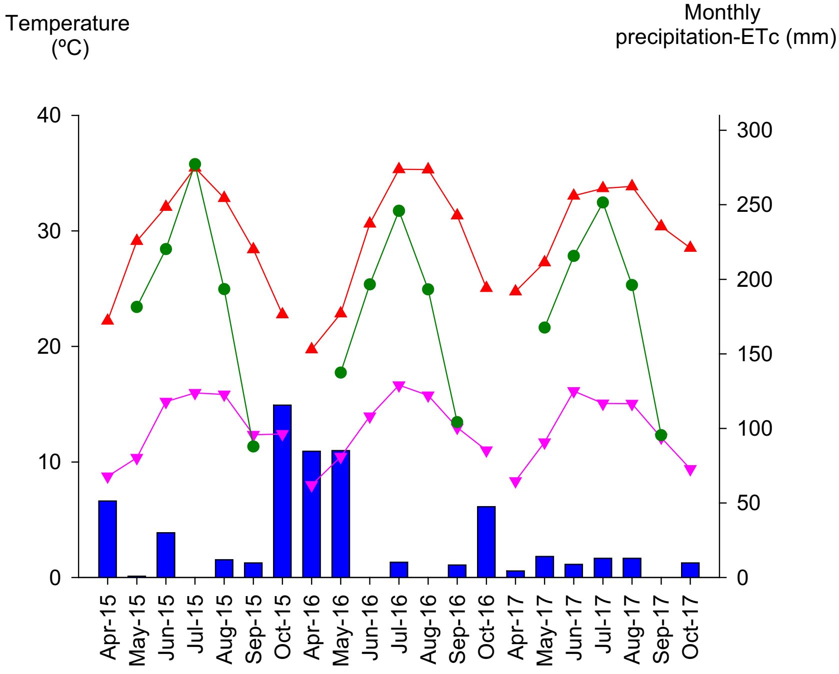
2.2 Experimental design and field management

In December 2014, after harvesting the rice, the field was divided into 180 m^2 (18 m×10 m) experimental plots and was subjected to the following six management regimes: rice-growing under conventional tillage and continuous flood irrigation without (TF) and with application of CW (TFCW); rice-growing through the conventional tillage and sprinkler irrigation without (TS) and with application of CW (TSCW); and rice-growing through the direct seeding (no-tillage) and sprinkler irrigation without (NTS) and with application of CW (NTSCW). Two-phase olive mill waste was composted (CW) in a trapezoidal pile with occasional turning, and water added regularly to maintain appropriate moisture. The CW obtained from a mixture of 90% two-phase olive mill waste and 10% olive leaves (as bulking agent) was applied only in the first year of the study (2015) at a dosage of 80 Mg ha^{-1} (dry weight), and incorporated (0-20 cm) using a rotary hoe. The relevant properties of the CW were the following: 382 g kg^{-1} TOC; 2.32 dS m^{-1} electrical conductivity (EC); pH 7.71; and 21.7 g kg^{-1} N. Each management regime was replicated thrice, so that the experimental field was divided into eighteen plots. Prior to sowing, in all treatments, base dressing was applied at a dosage of 550 kg ha^{-1} with 9-18-27 complex fertilizer, and then the tillage treatment plots (TF, TFCW, TS, and TSCW) were ploughed. In each year, the rice was sown in the first week of May at a dosage of 160 kg ha^{-1} seeds of *Oryza sativa* L. variety Gladio, because this is a genotype widely used in the study area. Sowing was with a Semeato TDNG 320 Disc Seeder for the sprinkler irrigated treatments (TS, TSCW, NTS, and NTSCW), and a broadcast seed drill for the flood irrigation treatments (TF and TFCW). For TS, TSCW, NTS, and NTSCW, an area cover sprinkler irrigation system was applied (of approximately 3 000 m^2) whose irrigation criterion was to apply the *ETc* values at a frequency of 6 days a week throughout the growing cycle, while the TF and TFCW treatments (approximately 1 500 m^2) were continuously flooded to a level height of 10 cm. Flow meters were used to monitor the water applied in the different treatments. The water applied in the sprinkler treatments was 10 803 m^3 ha^{-1}, 8 625 m^3 ha^{-1}, and 10 309 m^3 ha^{-1} for 2015, 2016, and 2017, respectively, and in the flooded treatments it was 16 125 m^3 ha^{-1}, 15 375 m^3 ha^{-1}, and 16 010 m^3 ha^{-1} for 2015, 2016, and 2017, respectively, amounts sufficient to cover the estimated crop needs (Table S1). Each year, two applications of urea as cover fertilizer were made at dosages of 200 kg ha^{-1} and 150 kg ha^{-1} in the tillering and initial panicle stages, respectively. Weed management was by pesticide application.

2.3 Soil measurements

In the three consecutive years, 2015–2017, four subsamples of soil (0–20 cm depth) were collected for each plot after harvest (October). The soils were sifted to < 2 mm, and their total organic carbon (TOC), water soluble organic carbon

Fig. 2 Mean rainfall (blue bars), mean maximum (red curve) and minimum (pink curve) temperatures, and rice evapotranspiration (ETc, green curve), registered at the field location during the rice growing period in 2015, 2016, and 2017.



(WSOC), fulvic acids (FA), humic acids (HA), humification index (HI), electrical conductivity (EC), pH, total nitrogen (N), available phosphorus (P), and aggregate stability (AS) were determined as described by Sánchez-Llerena et al. (2016). The soil penetration resistance was determined in situ with a hand penetrometer (using a 1 cm^2 conical tip). For the sprinkler irrigation treatments, during the crop cultivation season (May–October) the soil moisture content was measured once a week at 10, 20, 30, and 40 cm depths using a PR1 profile probe (Delta-T devices, England) with six probes per treatment. For the soils' biological properties, different enzymatic activities—dehydrogenase (DH), β-glucosidase (GL), urease (UR), and phosphatase (PHO)—were determined as described by López-Piñeiro et al. (2011).

2.4 Crop performance

The germination index (GI) was calculated as the ratio of sprouting seeds to total seeds sown. Agronomic parameters were determined by sampling all the rice plants in a 2 m^2 area for each plot. The production parameters were adjusted to a standard moisture content of 0.14 g H_2O g^{-1} fresh weight. The number of panicles per square metre (PANM2), total number of grains per panicle (GPAN), ripening index (RI), grain yield (Y), harvest index, and water productivity (WP) were measured as described by Sánchez-Llerena et al. (2016).

2.5 Weed density and bioassays

In order to assess the effect of the different management regimes on weed infestation, weed density was measured in all management systems for the first and third years of the study. To this end, in triplicate, 50 g of soil of each treatment was put into pots. The soils of the treatments TS, TSCW, NTS, NTSCW were incubated at 80% field capacity, and those of TF and TFCW with a 1:1.25 soil-to-water ratio. For incubation, the pots were placed in a growth chamber at 25°C with 12 hours of daylight. After 14 days, the number of weeds was counted for each treatment (weed density). The weeds were then removed by hand, and 10 uniformly pre-germinated seeds of *E. crus-galli* were placed in each pot since this is one of the main weeds causing important rice yield losses (Khanh et al. 2008). After 10 days, bispyribac-sodium, a herbicide extensively used to control a wide range of rice weeds, was applied to one set of pots at a dosage of 50 g active ingredient ha^{-1}, leaving another set without herbicide to be used as controls. After 14 days of herbicide application, the weights of *E. crus-galli* were measured in order to assess the effects of different treatments on weed control efficiency (WCE) calculated as WCE = (DWC - DWT) / DWC, where DWC is the dry weight of weeds in the control pots and DWT is the dry weight of weeds in the treated pots (Mohammed et al. 2016).

2.6 Statistical analyses

Statistical analyses were performed using the SPSS (22.0) software package. The data were checked for homogeneity of variance and error normality, and subjected to a one-way ANOVA. The Duncan test was applied for multiple comparisons. Pearson's correlation coefficient was employed to find possible correlations between soil properties and the rice agronomic and productivity parameters. Statistically significant differences at the 0.05, 0.01, and 0.001 levels of probability will be indicated by *, **, and ***, respectively.

3 Results and discussion

3.1 Physicochemical properties of the soil

Table 1 lists the values of the soil's properties for the years 2015, 2016, and 2017 at 0–20 cm depth. All the selected properties were significantly influenced by the management systems, and these effects varied during the 3 years of study as shown by the significant year × treatment interaction (Table 1). In the first year of study (2015), the values of TOC for unamended soils were very similar to each other (10.2–10.9 g kg^{-1} for NTS and TF, respectively), and low, as is usual in Mediterranean agricultural soils. However, after 3 years of management system implementation, the TOC values in NTS were greater by 15% over TS (Table 1). Similar results were found by López et al. (2012) who reported that 20% more of TOC was stored under a no-tillage management regime than under conventional tillage, this in Mediterranean soils dedicated to cereal crops. These results reflect the great importance of organic matter content in relation to many soil properties and processes, such as degradation and fertility. Indeed, it is the main indicator of soil quality (Diacono and Montemurro 2010). In addition, the application of CW significantly increased the TOC content, although the magnitudes of the direct and residual effects differed. Thus, in 2015 the treatments that received CW showed increases in TOC by factors of 1.9 in TF, 1.5 in TS, and 2.0 in NTS, whereas in 2017 these increases were by factors of 1.4, 1.4, and 1.3, respectively (Table 1), due to the mineralization process during the 3 years of CW application. It is also important to

Table 1 Effects of different management systems on soil physicochemical properties (0–20 cm depth). TOC total organic carbon; WSOC water soluble organic carbon, FA fulvic acid; HA humic acid; HI Humification Index, EC electrical conductivity; N total nitrogen; P available phosphorus. Conventional tillage and continuous flood irrigation without (TF) and with application of composted two-phase olive mill waste (TFCW); conventional tillage and sprinkler irrigation without (TS) and with application of composted two-phase olive mill waste (TSCW); direct seeding (no-tillage) and sprinkler irrigation without (NTS) and with application of composted two-phase olive mill waste (NTSCW). ANOVA factors are Y: Year; T: Treatment; Y×T: Interaction Year × Treatment. F-values indicate the significance levels * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and NS: not significant. Different letters indicate differences ($p < 0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

		TOC (g kg^{-1})	WSOC (mg kg^{-1})	FA (g kg^{-1})	HA (g kg^{-1})	HI	EC (dS m^{-1})	pH	AS (%)	N (g kg^{-1})	P (mg kg^{-1})
2015											
TF		10.9aA	72.7aA	0.848aB	1.49abB	13.7cC	3.60bB	4.93aA	58.2abB	0.770aA	29.2aB
TFCW		20.3cAB	490eC	1.02bB	1.60bB	7.89aB	4.46cB	6.06dB	57.9abA	1.61bA	32.9bA
TS		10.7aA	137bA	0.965bA	1.34aB	12.5cB	3.74bB	5.64bB	52.8aA	0.805aA	34.8cA
TSCW		15.7bA	497eB	1.29dC	2.02cB	12.9cB	4.19cB	5.99dA	62.3bB	1.53bA	35.7cA
NTS		10.2aA	210cA	1.10cC	1.62bC	15.9dB	2.14aA	5.77cA	53.2aA	0.725aA	35.5bcB
NTSCW		21.3dC	448dA	1.29dB	2.35dB	11.0bB	3.69bB	6.58eB	64.3bA	1.82bA	38.3dB
2016											
TF		13.4bB	113aB	0.773aA	0.659aA	4.91aA	3.07cA	5.27aB	50.2aA	1.47aB	28.9aB
TFCW		22.0dB	401bcB	0.784abA	1.25bA	5.70aA	4.56eB	5.76cA	58.3abA	2.31dB	31.4aA
TS		11.3aA	335bB	0.920bcA	1.17bA	10.3cdA	2.21aA	5.41bA	53.1aA	1.59bB	40.9cC
TSCW		17.4cB	519cB	0.761aA	1.59cA	9.14bcA	2.40abA	6.56fC	57.6abA	2.15cB	43.4cB
NTS		9.99aA	309bB	0.809abcA	1.14bA	11.4dA	2.49bA	5.86dB	52.1aA	1.52aB	37.0bC
NTSCW		16.5cA	533cA	0.929cA	1.35bA	8.16bA	3.63dAB	6.42eA	66.6bA	2.37dA	40.8cB
2017											
TF		13.9bB	220aC	1.03bC	1.48aB	10.7bB	3.37aAB	5.65aC	52.3aA	1.85bC	26.6aA
TFCW		19.1eA	325bA	1.19cdC	1.88bC	9.84aC	3.29aA	5.80bA	63.2bcB	2.48dC	35.8cB
TS		13.1aB	337bcB	1.48eB	1.55aC	11.9cB	4.62dC	5.61aB	55.7abA	1.67aB	36.9cB
TSCW		18.2dB	395cA	1.13cB	2.40cC	13.2dB	3.73bcB	6.35dB	64.1bcB	2.24cB	36.8cA
NTS		15.1cB	316bC	0.946aB	1.44aA	9.53aA	3.96cB	6.08cC	62.2bcB	1.81bC	30.1bA
NTSCW		19.1eB	498dA	1.24dB	2.24cB	11.7cC	3.44abA	6.61eB	66.4cA	2.38dA	34.6cA
Y	*F*-values	29.4***	7.27**	188***	181***	186***	78.7***	74.9***	10.1**	179***	42.5***
T	*F*-values	276***	63.6***	29.4***	76.8***	45.6***	51.3***	853***	18.8***	68.6***	52.1***
Y×T	*F*-values	24.3***	8.00***	19.9***	8.85***	27.2***	60.2***	61.6***	9.18***	1.74 NS	3.67**

highlight the effect of the irrigation system on TOC levels. Thus, while in 2015 there were no significance differences in TOC between the TS and TF treatments, in 2016 and 2017 the TF treatment presented higher values than the TS treatment. Furthermore, the higher values of TOC observed in TFCW than in TSCW throughout the study period also demonstrate the influence of the irrigation system, probably due to the fact that the organic matter mineralization depends on the air-water ratio (Grzyb et al. 2020). In particular, the anaerobic conditions under flooding treatments could lead to a slower rate of organic matter mineralization than the aerobic conditions under sprinkler treatments.

The WSOC content varied from the values of 72.7 to 533 mg kg^{-1} for TF in 2015 and NTSCW in 2016, respectively (Table 1). The results showed that the WSOC under anaerobic irrigation was lower than under aerobic irrigation during the 3 years of study. Thus, in 2015 WSOC in TF was less by factors of 1.88 and 2.88 compared with TS and NTS, respectively, and in 2017 by factors of 1.53 and 1.44 also respectively. Similar results were reported by Yang et al. (2020) who observed that the application of water-saving irrigation methods increased the WSOC of paddy soils. These increases could be due to soil conditions under aerobic irrigation treatments which possibly benefit microbial activity and the decomposition of soil organic matter to produce substantial WSOC. Furthermore, regardless of the management system, the CW application increased the WSOC content, having both a direct and a residual effect (Table 1). However, similar to the unamended treatments, the values of WSOC under anaerobic irrigation (TFCW) were significantly lower than under aerobic irrigation (TS and NTS), further confirming the important role of the irrigation system on WSOC.

In the first year of the implementation of the management systems there were significant differences in FA content between unamended treatments, with the greatest value in the NTS treatment (1.10 g kg^{-1}) relative to TS and TF (0.965 g kg^{-1} and 0.848 g kg^{-1}, respectively). In 2017 however, the greatest value was in the TS treatment with 1.48 g kg^{-1}, indicating faster degradation of organic matter under tillage and aerobic irrigation conditions. With regard to HA, for unamended systems, in 2015 the NTS showed the greatest value (1.62 g kg^{-1}), as was the case with FA, showing the importance of no-tillage techniques for the quality of organic matter. After 3 years, however, there were no significant differences between these treatments, their mean value being 1.49 g kg^{-1}. The application of CW as organic amendment significantly increased the FA and HA contents. Thus, in the direct year, the values of FA increased by factors of 1.2, 1.3, and 1.2 in TFCW, TSCW and NTSCW, respectively, relative to unamended treatments. In the case of HA, these increases were by factors of 1.5 and 1.5 in TSCW and NTSCW, respectively (Table 1). Also, in the residual year, the FA and HA contents were greater in amended than unamended systems except in the TSCW treatment for FA, but these increases were always lower in FA than HA. Similar results were found by López-Piñeiro et al. (2011) for agricultural soils amended with olive mill wastes. They observed that increases in HA content were greater than FA, probably due to the greater degradability of FA and/or the transformation the latter to more complex substances including HA. In the first year, the application of CW reduced the humification index (HI) of the soils due mainly to the increases of TOC content in amended treatments (Table 1). However, in the residual year, the TSCW and NTSCW had values of HI significantly greater than TS and NTS, respectively, whereas in TFCW the HI was still below that of TF, indicating that the irrigation methods may influence the quality of organic matter. Indeed, 3 years after the management system implementations, the HI was significantly greater in TS than in TF (Table 1). Furthermore, under aerobic conditions, significant differences between NTS and TS treatments were observed, with greater HI values in TS (Table 1). This result is consistent with other published work (Loke et al. 2018) in which no-tillage management led to a greater carbon content attributable to the accumulation of plant residue, and therefore a lower HI.

In the first year of the study, the EC values were unaffected by water management as reflected in the similar values for TS and TF (3.74 and 3.60 dS m^{-1}, respectively), whereas the lowest values corresponded to the NTS treatment (Table 1). However, after 3 years, the greatest values corresponded to TS treatment (4.62 dS m^{-1}) and the lowest to TF (3.37 dS m^{-1}). Moreover, it is important to note that under a no-tillage system (NTS) the EC values increased by a factor of 1.85 over the 3 years (Table 1). Similar results were found by Sánchez-Llerena et al. (2016) who observed the greatest values of EC in no-tillage systems because of the TOC accumulation under these management regimes. The application of CW showed differences in EC between the direct and residual effects (Table 1). Thus, in the direct year the application of CW significantly increased the EC values regardless of the management system, whereas in the residual year EC had decreased compared to the unamended treatments, especially under aerobic conditions (Table 1). These results could be very interesting since rice is the most salt-sensitive cereal with a threshold value of 3 dS m^{-1} (Grieve et al. 2012), with important yield losses and a decrease in profits of up to €300 per hectare for this crop (Genua-Olmedo et al. 2016).

The management system significantly influenced the soil pH (Table 1). Throughout the study period, the lowest values of pH corresponded to anaerobic treatments (TF and TFCW) and the highest to no-tillage treatments (NTS and NTSCW). Similar results had been found in previous studies (Luján-Soto et al. 2021), although pH increases have been widely reported in no-tillage system soils (Du et al. 2014). In both direct and residual years, the application of CW increases the soil pH regardless of the management system (Table 1). This is because of the high pH of the CW, which in turn could improve availability of nutrients to the rice crop (Das et al. 2020). Indeed, the total nitrogen (N) and available phosphorous (P) were significantly ($p < 0.001$) correlated with the soil pH ($r = 0.597$ and $r = 0.501$, respectively). Hence, in coherence with previous studies (e.g. Romanyà et al. 2019), the application of CW caused significant increases in the values of essential plant nutrients such as N and P in both the direct and the residual years (Table 1). Therefore, the recycling of CW as organic amendment could be a sustainable alternative for improving soil fertility and promoting a circular economy, together with a viable approach to maximizing crop yield sustainably (Marks et al. 2021). In addition, the implementation of a sprinkler irrigation system, regardless of the tillage management, led to significant increases in P (Table 1). Similar results were found by Kirk (2004) who observed that under prolonged flooding conditions concentrations of P decrease due mainly to its immobilization by Fe oxyhydroxides.

In the unamended treatments during the first 2 years of the study, there were no significant differences for aggregate stability (AS). However, in the third year, under a conservation management system (NTS) the values of AS increased by factor of 1.19 relative to TF (Table 1). This effect of mid-term no-tillage on AS is coherent with results of previous studies (Six and Paustian 2014) probably because of greater TOC content under no-tillage relative to conventional tillage, hence the observed significant correlation between AS and TOC ($r = 0.481$, $p < 0.001$). Indeed, the application of CW caused an increase in AS of about 14% relative to unamended soils over the three study years (Table 1). Also, the quality of the organic matter was an important factor for AS due to its significant correlations with HA ($r = 0.506$; $p < 0.001$) and FA ($r = 0.316$, $p < 0.05$). These results demonstrate that both the quantity and the quality of organic matter are important factors in soil stabilization.

The soil penetration resistance for each management system during the 3 years of study is shown in Fig. 3. Regarding unamended treatments, in the first and second year of study, the aerobic irrigation system, regardless of tillage management (NTS and TS treatments), showed a greater penetration resistance than the anaerobic treatment (TF) in the upper soil layers. Thus, in NTS and TS treatments, the maximum values of penetration resistance were reached at 15–20 cm of depth, whereas in the TF treatment the greatest compaction was observed at 30–35 cm. However, 3 years after implementation of the management systems, the no-tillage practice (NTS) led to a further degree of compaction of the soil surface compared with tillage treatments (TS and TF). Furthermore, important differences were observed between the two tillage treatments (TS and TF), with increases in soil penetration resistance under the anaerobic irrigation method (Fig. 3). It is also notable that the greatest compaction of deeper soil layers was found for TF in all the years of the study, suggesting that the traditional rice cropping system generates a plough pan. The application of CW influenced soil penetration resistance, especially in the direct year. In particular, in 2015, the soil compaction in upper soil layers (0–20 cm of depth) was reduced in NTSCW (10%), TSCW (28%), and TFCW (20%) relative to NTS, TS, and TF, respectively. In the residual year, the reductions were in NTSCW (6%) and TSCW (14%) relative to NTS and TS, respectively, without any difference between TFCW and TF. This result is quite relevant in terms of soil fertility since a reduced degree of compaction could ensure adequate root development and consequently improve the plants' nutrient intake. Moreover, a greater stability of soil aggregates related decreased compaction could lead to a greater content of water available for plants (Pranagal and Woźniak 2021).

In the first year, a significant increase in soil moisture content was observed in amended treatments throughout the growth cycle (Fig. 4). Thus, after direct applications of CW, the water soil content at 0–20 cm depth increased by factors of 1.32 in TS and 1.54 in NTS, whereas there were no important differences between the TS and NTS treatments. In the third year, however, soil moisture content at 0–10 cm of depth was greater in NTS than in TS by a factor of 1.27, suggesting that in the medium term the implementation of a no-tillage system instead of conventional tillage could increase the soil moisture content under aerobic irrigation regimes. Similar results have been reported by Mondal et al. (2019) who found that the use of conservation agriculture practices increased soil moisture content by 14% relative to a conventional tillage system of rice and wheat cropping. Similarly, Jin et al. (2020) observed that putting back rice straw increases soil moisture content due to less direct sunlight evaporation and surface run-off and improved water infiltration, as well as obviating the pollution caused by straw burning. Three years after application of CW, the TSCW and NTSCW treatments showed greater soil moisture content than unamended treatments (Fig. 4B). However, the direct effect of CW application on soil moisture content was greater than the residual effect, probably due to an organic amendment mineralization process. Indeed, the soil moisture content was significantly and positively correlated with TOC ($p < 0.001$, $r = 0.737$), indicating that organic matter improves the moisture holding capacity of soils.

3.2 Enzyme activities

Table 2 presents the values of the enzymatic activities for the years 2015, 2016, and 2017 at 0–10 cm depth. All the selected enzymatic activities were significantly influenced by the management systems, and these effects differed during the 3 years of study as shown by the significant year × treatment interaction (Table 2). In the first year of the study, the unamended treatments showed no significant differences for dehydrogenase activity (DH), considered to be a good indicator of a soil's total microbial activity. In the third year however, NTS

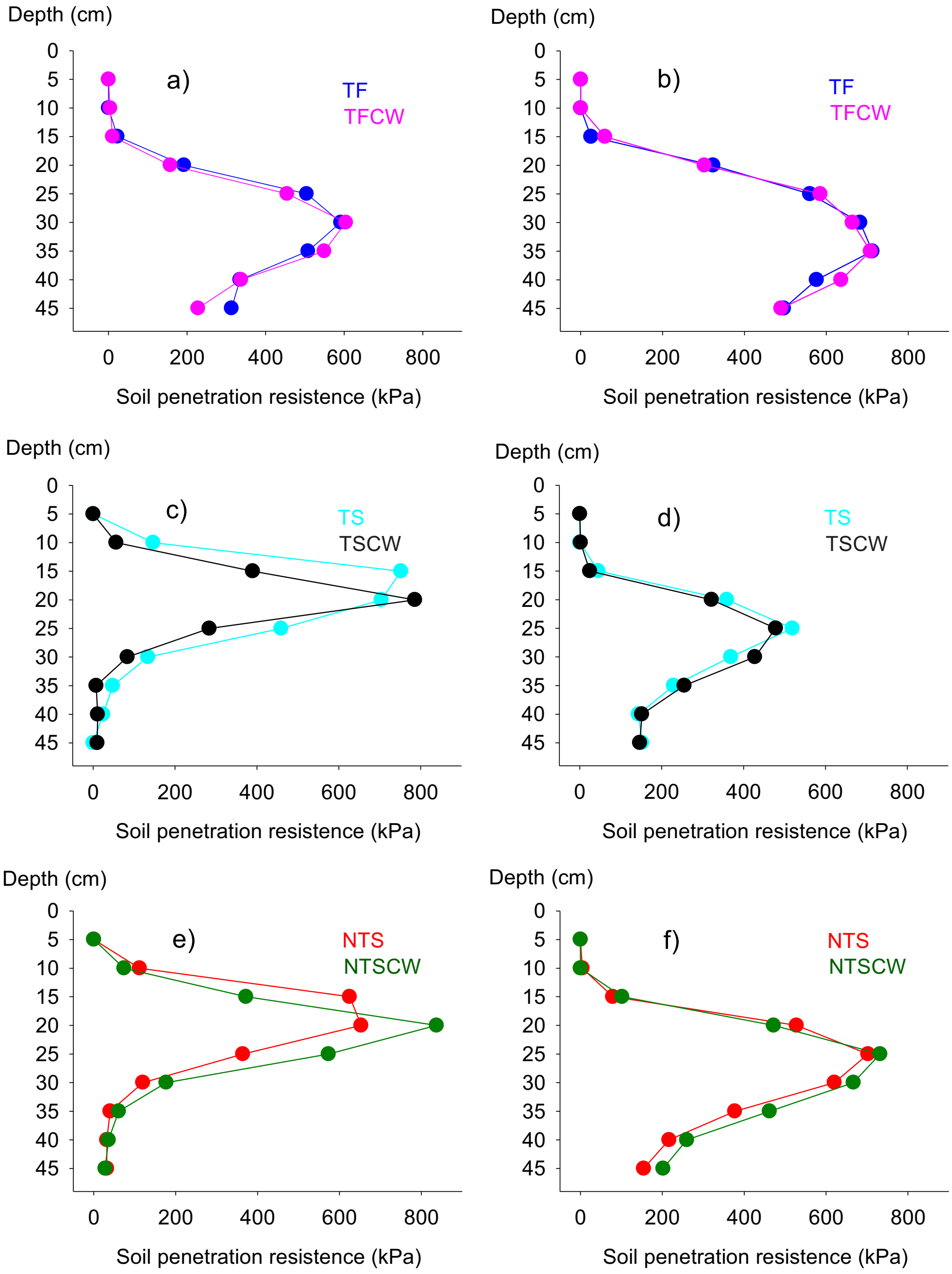
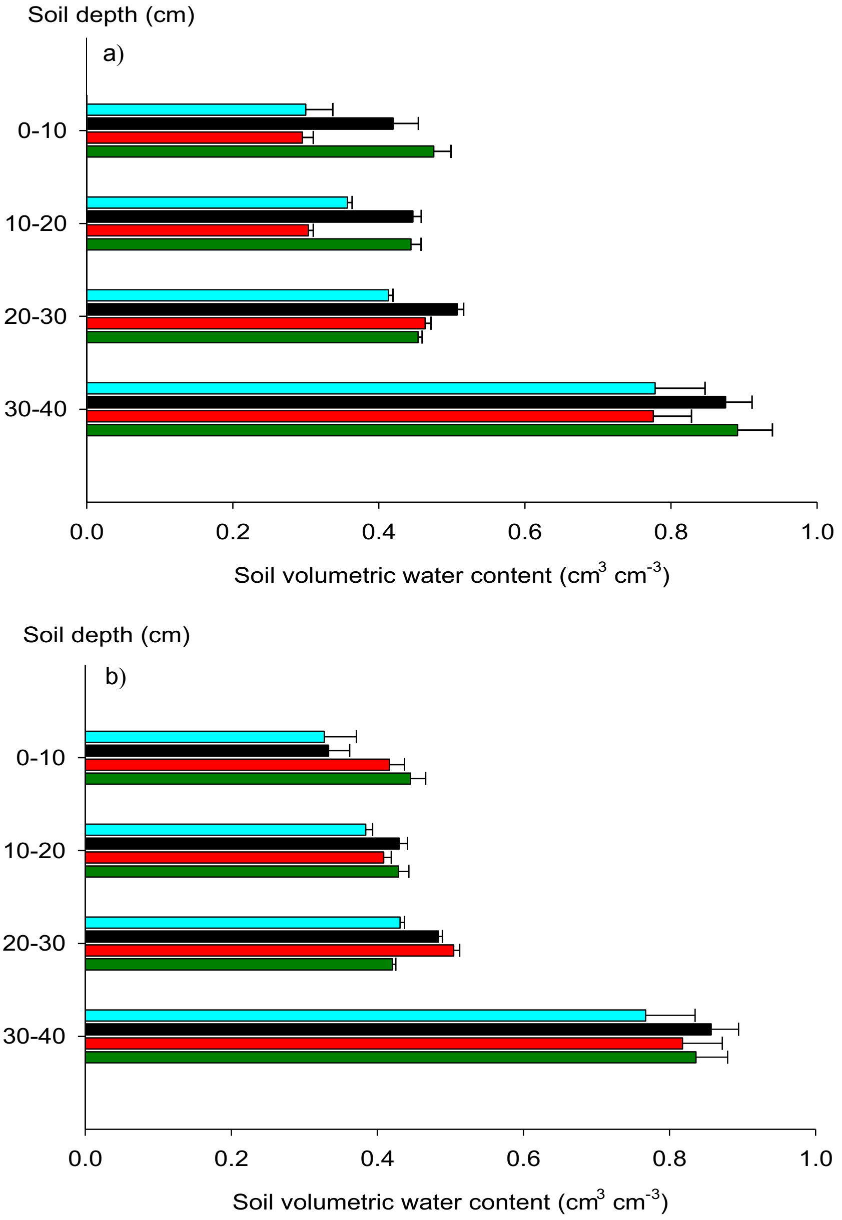


Fig. 3 Direct (left-hand side, **a**, **c**, **e**) and residual (right-hand side, **b**, **d**, **f**) effects of different management systems on soil penetration resistance. The measurements were made in October (mean, n = 30). TF: tillage and flooding irrigation; TFCW: tillage and flooding irrigation with application of composted two-phase olive mill waste; TS: tillage and sprinkler irrigation; TSCW: tillage and sprinkler irrigation with application of composted two-phase olive mill waste; NTS: no-tillage and sprinkler irrigation; NTSCW: no-tillage and sprinkler irrigation with application of composted two-phase olive mill waste.

increased the values of DH by a factor of 2.14 relative to TS, with there being no significance differences between NTS and TF. Therefore, under an aerobic irrigation system, no-tillage practices enhanced the soil's microbial activity, coherent with previous findings about this technique as a suitable management strategy for soil quality in mediterranean conditions (Zuazo et al. 2020). In addition, the CW application improved the DH of the soils regardless of the management system. Thus, in the direct year the DH values were greater than in the corresponding unamended treatments by factors of 2.53, 1.27, and 1.90 in TFCW, TSCW, and NTSCW, respectively, and in the residual year by factors of 1.17, 2.48, and 1.52 in TFCW, TSCW, and NTSCW, respectively (Table 2). These results could be due to the observed increases in quantity and quality of the soil organic matter. Indeed, DH showed a positive and significant ($p < 0.01$) correlation with TOC ($r = 0.477$) and AH ($r = 0.451$). Over the course of the study, the greatest values of DH were always found in NTSCW (Table 2). Apart from the TOC and AH, this result can be explained by the increases of pH registered under no-tillage treatments and aerobic irrigation, as reflected in the positive and significant correlation between pH and DH ($r = 0.544$, $p < 0.01$), confirming that soil pH is a further key factor in soil microbial activity (Chen et al. 2018).

Fig. 4 Direct (**a**) and residual (**b**) effects of different management systems on mean soil volumetric water content during the rice growing cycle. Error bars represent one standard error of the mean (n = 6). TS: tillage and sprinkler irrigation (cyan bars); TSCW: tillage and sprinkler irrigation with application of composted two-phase olive mill waste (black bars); NTS: no-tillage and sprinkler irrigation (red bars); NTSCW: no-tillage and sprinkler irrigation with application of composted two-phase olive mill waste (green bars).



For the unamended treatments, the values of the β-glucosidase (GL), enzyme, which plays an important role in processes of organic matter degradation, did not differ significantly (Table 2). Similar results have been reported by Sánchez-Llerena et al. (2016) who observed that significant differences in GL were not found until after long-term implementation of irrigation and tillage systems. The CW application increased the values of GL in both the direct and residual years, although the magnitudes differed between treatments (Table 2). In particular, the GL values were greater by factors of 6.3, 5.2, and 4.7 in TFCW, TSCW, and NTSCW, respectively, than in their corresponding unamended treatments (TF, TS, and NTS) in the direct year, and by factors of 3.5, 9.6, and 19.2 in TFCW, TSCW, and NTSCW, respectively, than in their corresponding unamended treatments in the residual year (Table 2). The increases in the GL values were greater in the residual than in the direct years under aerobic irrigation. These results agree with those reported by López-Piñeiro et al. (2011) who observed in Mediterranean olive grove soils amended with olive mill waste a similar GL trend, indicating that the soil has gained the capacity to utilize the carbohydrate material added with the amendments (Piotrowska et al. 2006). Furthermore, these results suggest that TOC may not be the only factor determining GL activity in soils. On the contrary, they show that the labile fraction of the soil organic matter (WSOC) was the most important factor in GL activity, probably due to the fact this fraction constitutes the most readily available source of energy for soil microorganisms (López-Piñeiro et al. 2013). Indeed, GL was positively and significantly ($p < 0.01$) correlated with WSOC ($r = 0.730$).

Table 2 Effects of different management systems on soil enzyme activities (0–10 cm depth). DH dehydrogenase activity; GL β-glucosidase activity; UR urease activity; PHO phosphatase activity. Conventional tillage and continuous flood irrigation without (TF) and with application of composted two-phase olive mill waste (TFCW); conventional tillage and sprinkler irrigation without (TS) and with application of composted two-phase olive mill waste (TSCW); direct seeding (no-tillage) and sprinkler irrigation without (NTS) and with application of composted two-phase olive mill waste (NTSCW). ANOVA factors are Y: Year; T: Treatment; Y×T: Interaction Year × Treatment. *F*-values indicate the significance levels * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and NS: not significant. Different letters indicate differences ($p < 0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

		DH (μg INTF g^{-1} h^{-1})	GL (μmol pNP g^{-1} h^{-1})	UR (μg NH_4^+ g^{-1} h^{-1})	PHO (μmol pNP g^{-1} h^{-1})
2015					
TF		0.560aA	0.123aA	4.62aA	0.633aA
TFCW		1.42bcB	0.780bB	14.1bA	0.957bA
TS		1.06abB	0.233aB	17.8bA	1.23cA
TSCW		1.35bcA	1.20bA	26.1bA	1.30cdA
NTS		0.993ab	0.210aA	17.7bA	1.45dA
NTSCW		1.89cB	0.980bA	45.2cA	1.28cdAB
2016					
TF		0.487aA	0.110aA	10.5abA	1.34aB
TFCW		0.810abA	0.390abA	24.4cA	1.67bB
TS		0.510aA	0.117aA	8.00aA	1.56bB
TSCW		0.877abA	1.12bA	20.6bcA	1.57bA
NTS		0.663abA	0.156aA	19.9bcA	1.59bA
NTSCW		1.13cA	2.32cA	28.5cA	1.67bB
2017					
TF		0.820bB	0.077aA	5.95aA	1.19abB
TFCW		0.963bA	0.267abA	26.8bA	0.947aA
TS		0.333aA	0.093aA	9.23aA	1.40bB
TSCW		0.827bA	0.890bcA	25.9bA	1.41bA
NTS		0.713bA	0.077aA	13.9aA	1.41bA
NTSCW		1.09bA	1.48cA	27.7bA	1.20abA
Y	*F*-values	28.6***	2.90 *	1.35 NS	35.8***
T	*F*-values	5.98**	14.3***	16.4***	16.4***
Y×T	*F*-values	2.84*	3.61**	4.21**	3.48**

Soil urease (UR) activity plays an important role in the nitrogen cycle, with the enzyme's importance also being due to the widespread use of urea as fertilizer. In particular, for unamended soils the lowest values of UR were found in the TF treatment, regardless of the year of study (Table 2). These results indicate that the type of irrigation method is a crucial factor for UR, with aerobic irrigation being an effective management strategy to possibly improve nitrogen fertilizer uptake and utilization, as previously suggested by Zhang et al. (2018) for rice crops. For the direct and residual years (2015 and 2017, respectively), the values of UR in the amended treatments were significantly greater than those without CW regardless of the irrigation and tillage practices. Similar trends have been reported by El-Bassi et al. (2021) who observed that UR activity can be increased by the addition of organic materials, probably due to organic amendments protecting the increase of soil microorganisms. Indeed, UR was significantly ($p < 0.01$) and positively correlated with TOC and HA ($r = 0.579$ and $r = 0.550$, respectively), indicating that the type of organic matter is another important factor affecting UR activity (Mulvaney and Bremmer 1981).

In the unamended treatments, soil phosphatase (PHO) activity, which has an important role to play in the mineralization of organic P, significantly ($p < 0.05$) increased under aerobic irrigation, regardless of the tillage system (Table 2). Therefore, this increase in PHO could suggest that the implementation of aerobic irrigation system can stimulate bacterial growth and enzyme activities. In general, regardless of the management system, CW application did not lead to significant changes in PHO (Table 2). Similar observations have been reported by Sarfraz et al. (2020) who also found that in amended soils an increase in available P could produce a feedback inhibition of PHO activity.

3.3 Agronomic parameters

Table 3 presents the effects of the different management systems on rice yield components and grain yield. All the selected parameters were significantly influenced by the management system and year of study (Table 3). However, for the most part, these effects did not differ during the 3 years of study as shown by the non-significant year × treatment interaction (Table 3).

In general, the values of the germination index (GI), which represents the percentage of germinated seeds, were below the potential germination capacity (80%) certificated for the seeds

Table 3 Effect of different management systems on rice yield components and grain yield. GI Germination index; PANM2 number of panicles per square meter; GPAN grains per panicle; RI ripening index; Y Yield; WP water productivity. Conventional tillage and continuous flood irrigation without (TF) and with application of composted two-phase olive mill waste (TFCW); conventional tillage and sprinkler irrigation without (TS) and with application of composted two-phase olive mill waste (TSCW); direct seeding (no-tillage) and sprinkler irrigation without (NTS) and with application of composted two-phase olive mill waste (NTSCW). ANOVA factors are Y: Year; T: Treatment; Y×T: Interaction Year × Treatment. F-values indicate the significance levels * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and NS: not significant. Different letters indicate differences ($p < 0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

		GI (%)	PANM2	GPAN	RI (%)	Y (kg ha^{-1})	Harvest Index	WP (g L^{-1})
2015								
TF		49.8abA	789abB	92.8aA	84.2bA	11006bcC	0.548aAB	0.683aC
TFCW		54.7bA	780aB	99.3aA	88.9bA	11267cC	0.519aAB	0.700aC
TS		56.5cB	978bB	86.2aA	69.3aAB	9699abC	0.483aA	0.913bC
TSCW		44.4aA	880abA	83.7aA	70.1aA	8776aB	0.506aA	0.813bA
NTS		52.3bB	825abA	84.4aA	73.2aAB	8785aB	0.581aB	0.810bA
NTSCW		48.6abA	736aA	83.1aA	72.4aB	8855aC	0.553aB	0.820bB
2016								
TF		53.0bAB	514aA	108cA	88.8cA	6259aA	0.531bA	0.407abA
TFCW		50.0abA	561abA	93.2bcA	88.8cA	5180aA	0.480abA	0.337aA
TS		38.7aA	570abA	79.8abA	58.8aA	5427aA	0.488abA	0.627bcA
TSCW		47.5abA	757dA	64.7aA	68.6abA	5506aA	0.396aA	0.637bcA
NTS		38.9aA	662cA	108cA	71.3abA	6046aA	0.423abA	0.697cA
NTSCW		37.6aA	628bcA	112cA	76.5bcA	4938aA	0.386aA	0.567abcA
2017								
TF		54.8abB	772bB	93.2aA	86.1bA	8470bcB	0.611bB	0.530bB
TFCW		48.3aA	559aA	93.5aA	84.8bA	7800abcB	0.578abB	0.483aB
TS		65.0bcB	859bB	91.7aA	76.1aB	7698abcB	0.537aA	0.743bcB
TSCW		65.9bcB	915bA	79.6aA	85.1bB	8581cB	0.547aA	0.837cA
NTS		64.2bcC	772bA	92.8aA	80.4abB	7308abAB	0.549abB	0.710bA
NTSCW		77.8cB	752bA	88.8aA	77.8abB	6782aB	0.543abB	0.657bA
Y	*F*-values	38.2 ***	16.4 ***	0.947 NS	6.17 **	92.7 ***	22.3 ***	32.9 ***
T	*F*-values	3.83 *	17.0 ***	5.54 **	10.6 ***	3.32 *	6.00 **	11.8 ***
Y×T	*F*-values	5.96 ***	2.27 *	1.76 NS	2.38*	1.76 NS	1.22 NS	1.13 NS

used. However, according to International Rice Research Institute (IRRI), 50% is considered to be a common value for sowing under field conditions, and is very close to the mean value observed in the present study. In the unamended treatments, the aerobic irrigation system favoured the germination of seeds, regardless of the tillage management and year of the study except for 2016 (Table 3). Specifically, in 2016, the values of GI for aerobic irrigation treatments were the lowest of all the study. This could be attributable to the abundant rainfall during the time of sowing in that year (Fig. 2), since there is evidence that, when the rice seed is buried, an increase in soil moisture leads to decreased germination. Thus, whereas in the first half of May 2016 the cumulative rainfall was 81.6 mm, in the same period for 2015 and 2017 it was 0.800 and 13.7 mm, respectively. This might be related to the observed decreases in values of GI under the aerobic amended treatments (TSCW and NTSCW) compared with the unamended treatments (TS and NTS) for the direct effect (2015) due to increasing the soil moisture content by the organic amendment application.

For the unamended soils, significant differences ($p < 0.05$) between treatments in the number of panicles for square metre (PANM2) were only found in 2016, the year in which the GI values were lowest (Table 3). The results were not conclusive with regard to the impact of CW application on PANM2. Whereas the direct effects caused decreases in PANM2 especially under aerobic irrigation regardless of the tillage system, in the residual effects there were no significant differences observed between aerobic irrigation treatments. Furthermore, after the 3 years of the study, the lowest values were observed for the TFCW treatment (Table 3). This could be due to the high level of weeds found under this management. In addition, PANM2 was positively and significantly ($p < 0.01$) correlated with FA, HA, and HI ($r = 0.377$, $r = 0.401$, and $r = 0.597$, respectively), suggesting that the humic substances are important factors affecting PANM2. With respect to the values of the total number of grains per panicle (GPAN), the mean values for all treatments were 88.3 and 89.9 for the direct and residual years, without any significant differences between treatments regardless of the irrigation and tillage systems used (Table 3). Similar results were reported by Sánchez-Llerena et al. (2016) for the same rice variety (Gladio). They observed significant differences in GPAN only under no-tillage and sprinkler irrigation in the long-term effects (7 years), although their work did not assess the effect of organic amendment.

For unamended treatments, the flooded irrigation system caused a significant ($p < 0.05$) increase in the ripening index (RI) compared with sprinkler irrigation during the first two years, regardless of the tillage system (Table 3). These results suggest that rice-growing may be exposed to water stress processes under aerobic systems (Wei et al. 2011). This, however, could be a temporary situation since, in the third year of the study, the values of RI for the TF and NTS treatments (86.1% and 80.4%, respectively) showed no significant differences, whereas the lowest value corresponded to the TS treatment (76.1%). These results could be understood as due to the lower soil moisture content under tillage compared with no-tillage conditions (Fig. 4). Indeed, there was a positive significant ($p < 0.05$) correlation between RI and soil moisture content ($r = 0.497$). In general, the application of CW increased the RI, indicating that TOC could be a quite important property affecting RI. Indeed, RI was significantly ($p < 0.01$) and positively correlated with TOC ($r = 0.433$), suggesting that greater organic matter content of the soils could help offset any possible water stress.

During the first year of study, no significant differences in yield (Y) were observed for the unamended treatments, regardless of the irrigation and tillage systems used (Table 3). Thus, values of Y for the unamended soil ranged from 8 785 to 11 006 kg ha^{-1} in NTS and TF, respectively, exceeding the average value (7 550 kg ha^{-1}) for the area of the River Guadiana basin in that year (MAPA 2020). For all treatments, in 2016 there was a significant decrease in Y compared with 2015 (Table 3). According to MAPA (2020), the average Y for the study area in 2016 was 6 751 kg ha^{-1}, less than that in 2015 (by 10.6%). This pattern suggests that in 2016 there were factors outside the scope of the present study with a great influence on Y. In addition to the aforementioned high rainfall during May 2016 that may have influenced seed germination, the temperatures between 20 August and 8 September 2016, coinciding with the grain filling stages, were higher than usual. In particular, in this period, the mean maximum temperatures were 30.4°C, 36.5°C, and 32.4°C for 2015, 2016, and 2017, respectively, and differences of even above 10°C were recorded on specific days. Indeed, different studies have indicated that high temperatures are a crucial factor determining Y (Lyman et al. 2013). Furthermore, other workers have shown that temperatures in excess of 35°C could affect the pollination of rice, giving rise to high levels of spikelet sterility (Kim et al. 1996). In the third year of the present study, the values of Y for unamended treatments ranged from 7 308 kg ha^{-1} in NTS to 8 470 kg ha^{-1} in TF, without the differences between the treatments being statistically significant (Table 3). Similar values were reported by MAPA in 2017 for the study area, with an average Y of 7 315 kg ha^{-1}. It is important to note that in 2017 a 23% decrease in Y was observed for the TF treatment relative to 2015, showing that flooding irrigation could lead to a fall in rice yield after prolonged use. This result can be attributed to the observed significant increase in weed density. Thus, while in the first year no significant differences in weed density were observed for unamended treatments, in the third year the weed density was significantly greater under flooding than under sprinkler irrigation, regardless of the tillage conditions (Fig. 5). Furthermore, under flooded irrigation the weed density increased significantly over the 3 years of the study, seriously compromising the sustainability of rice growing under this management regime. Indeed, a negative and significant correlation ($p < 0.05$; $r = -0.884$) was observed between grain yield and weed density with flooding conditions. Similar results were reported by Tian et al. (2020), who indicated that rice yields are highly sensitive to weed competition, with 50% and 95% yield losses due to high levels of weed infestation of *Cyperus difformis* and *Echinochloa crus-galli*, respectively.

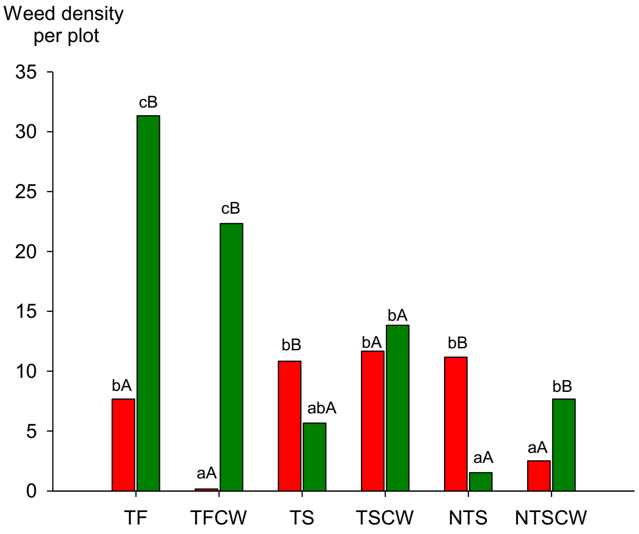


Fig. 5 Direct (2015; red bars) and residual (2017; green bars) effects of different management systems on weed density (expressed here as a number of weeds per plot). Bars with different letters indicate significant differences ($p < 0.05$) between management systems in the same year (lower case letters) and between years within the same management system (upper case letters). TF: tillage and flooding irrigation; TFCW: tillage and flooding irrigation with application of composted two-phase olive mill waste; TS: tillage and sprinkler irrigation; TSCW: tillage and sprinkler irrigation with application of composted two-phase olive mill waste; NTS: no-tillage and sprinkler irrigation; NTSCW: no-tillage and sprinkler irrigation with application of composted two-phase olive mill waste.

Probably, the high level of weed infestation under anaerobic relative to aerobic irrigation conditions, regardless of the tillage system, might be explained by differences between the two irrigation systems in the bispyribac-sodium herbicide's effectiveness at controlling *E. crus-galli*. Thus, the results obtained over the 3 years with regard to the use of bispyribac-sodium, a herbicide widely used to control a broad range of rice weeds, gave an average value of herbicide effectiveness under sprinkler irrigation of 70%, whereas under flooding conditions it was only 40%, showing that water management could be a important factor in weed control (Fig. 6). The main reason for these results could be the different effects of water and tillage management systems on herbicide behaviour. Thus, a study conducted on the same soils (Gómez et al. 2019) found that bispyribac-sodium dissipation was influenced significantly ($p < 0.001$) by the type of treatment, with the shortest persistence corresponding to flooding conditions, which could mean a decrease in the herbicide's activity. In flooded rice cropping, Zhang et al. (2021) found that irrigation water was a major factor affecting the spread of weed seeds. Therefore, the irrigation filter in sprinkler systems could well block seed dispersal, thus contributing to reducing the seed bank.

In the first year of the study, the CW application did not lead to significant changes in Y relative to the unamended soils, although there were significant differences between amended treatments (Table 3). Thus, the TFCW treatment gave the greatest Y (11 268 kg ha^{-1}), although this management system can increase water requirements by up to 50% in comparison with aerobic irrigation treatments. After 3 years of CW application however, the greatest value of Y (8 581 kg ha^{-1}, Table 3) corresponded to TSCW, with increases of 26.5% and 10.0% relative to NTSCW and TFCW, respectively. This result could be attributable to greater soil compaction under no-tillage regimes. Indeed, a negative and significant ($p < 0.05$) correlation was found between Y and soil penetration resistance ($r = -0.391$). Similar results were described by Mondal et al. (2019) who observed that a high degree of soil compaction led to decreases in rice yields due to poor root development. Furthermore, in 2017 the TSCW and TF treatments gave similar values of Y (8 581 kg ha^{-1} and 8 470 kg ha^{-1}, respectively), indicating the strong influence of the quality and quantity of soil organic matter on rice yields, especially under aerobic irrigation. Indeed, Y was correlated significantly and positively with HA ($r = 0.326$, $p < 0.05$), FA ($r = 0.319$, $p < 0.05$), and HI ($r = 0.441$, $p < 0.01$). Another important factor affecting rice yields could be weed control. Thus, while in NTSCW and TFCW treatments, the values of Y were significantly ($p < 0.05$) and negatively correlated with weed density ($r = -0.881$ and $r = -0.845$, respectively), under TSCW (a treatment whose herbicide efficacy was 71.2%, Fig. 6) no significant correlation was observed, showing that efficient weed control is essential in order to ensure the yields and economic viability of rice-growing.

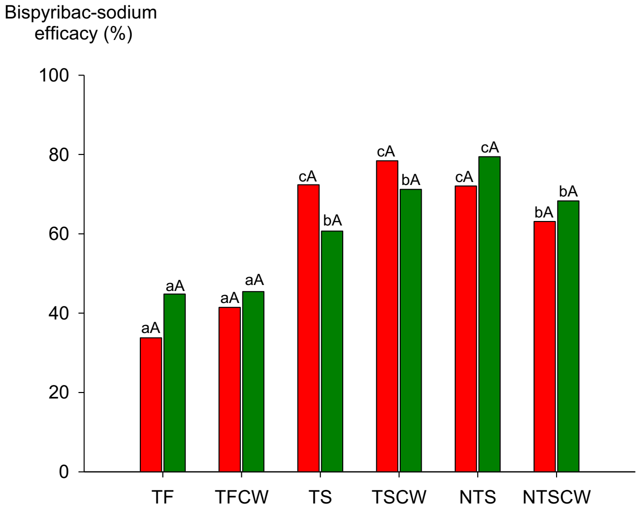


Fig. 6 Direct (2015; red bars) and residual (2017; green bars) effects of different management systems on bispyribac-sodium efficacy. Bars with different letters indicate significant differences ($p < 0.05$) between management systems in the same year (lower case letters) and between years within the same management system (upper case letters). TF: tillage and flooding irrigation; TFCW: tillage and flooding irrigation with application of composted two-phase olive mill waste; TS: tillage and sprinkler irrigation; TSCW: tillage and sprinkler irrigation with application of composted two-phase olive mill waste; NTS: no-tillage and sprinkler irrigation; NTSCW: no-tillage and sprinkler irrigation with application of composted two-phase olive mill waste.

The values of harvest index ranged from 0.386 to 0.611 (Table 3). Similar values were reported by Sánchez-Llerena et al. (2016), and can therefore be considered normal for rice-growing (Bueno and Lafarge 2009). Kumar et al. (2021) found that harvest index depends strongly on the environmental conditions, with the lowest values of harvest index being observed for 2016 in all treatments, regardless of the soil management and irrigation system, because of the impact of the environmental conditions on rice yields for that year. The highest harvest index value (0.611) for the entire experiment was found for TF, a value close to that of 0.670 beyond which there is a strong risk of lodging.

The management system significantly affected the values of water productivity (WP) over the 3 years, and the effects were similar from year to year as indicated by the non-significant year × treatment interaction ($p > 0.05$). Thus, with respect to the unamended soils, the lowest value of WP in the 3 years of the study was found under the TF treatments (Table 3). In 2017, after 3 years of implementation of aerobic irrigation, the WP values were significantly lower in TF than in TS and NTS (29.2% and 25.6% less, respectively). Therefore, our results indicate that implementation of aerobic irrigation systems in rice-growing, regardless of tillage management, allows high productivity per unit of water use, a critical issue in Mediterranean regions. Similar results have been described by Froes de Borja Reis et al. (2018) who found values of 0.800 g L^{-1} and 0.400 g L^{-1} for WP under aerobic and anaerobic irrigation, respectively, proof that flooding is an inefficient irrigation system. Likewise, our findings are in line with other studies also carried out under mediterranean conditions that show significant increases in WP after implementation of aerobic rice, such as drip irrigation (Bozkurt Çolak, 2021) or alternate wetting and drying systems (Martínez-Eixarch et al., 2021), since the implementation of these systems does not compromise the rice yield.

The application of CW did not lead to significant differences relative to unamended soils, regardless of the year of study (Table 3). Nonetheless, the correlation study showed that WP was significantly ($p < 0.01$) and positively correlated with HA (r = 0.434), FA (r = 0.412), and HI (r = 0.669). Indeed, after 3 years of CW application, the values of WP under aerobic treatments, regardless of tillage system (TSCW and NTSCW), were significantly greater than under the anaerobic treatment (TFCW). These results suggest therefore that the implementation of management systems that promote increases in the humic fractions of soil organic matter could be a useful strategy for improving WP in rice-growing, at least under mediterranean conditions. Furthermore, WP was positively and significantly ($p < 0.05$) correlated with AD (r = 0.401), suggesting that the management systems used to enhance the soil's microbial activity could also be useful for achieving greater efficiency and optimizing water use in rice-growing (Ansari et al. 2021).

4 Conclusions

The use of CW as organic amendment in combination with diverse irrigation methods and tillage managements may cause important differences in soil properties which can affect rice-growing, information that has been lacking until now. Thus, the implementation of direct seeding under sprinkler irrigation significantly increases the organic matter and pH, although it also raised the soil's penetration resistance relative to tillage treatments. In addition, the CW application improved such soil properties as organic matter quantity and quality, pH, enzymatic activities, and water retention, with both direct and residual effects. With respect to the development of the crop, the implementation of sprinkler irrigation led to a lower rice yield, although the differences were only significant in the first year and with no-tillage. Over time, there was reduced yield in the treatment under flooding as a consequence of weed infestation. After 3 years of study, the implementation of sprinkler irrigation with CW application and conventional tillage management gave the greatest grain yield, with the key factors for this result being soil compaction and quality of organic matter and weed control. In addition, regardless of the tillage management, the use of sprinkler irrigation from the beginning of the study led to high productivity per unit of water use, which is one of the primary goals in the Mediterranean region which is characterized by a paucity of water resources. Thus, this study is the first to show that the combination of sprinkler irrigation with CW application could be a viable technique in order to ensure the sustainability of rice cropping under Mediterranean conditions. Nevertheless, further research is needed to understand the long-term effects of these management systems on soil properties, and thus on rice productivity, since adopting effective strategies is crucial to achieving the sustainability of rice, one the most important crops for global food security.

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Data availability The authors confirm that the data supporting the findings of the current study are available within the article. Further supplementary data is available from the corresponding author upon reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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