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RESEARCH ARTICLE

Alternate wetting and drying irrigation with field aged biochar may enhance water and rice productivity

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Abstract
Rice is traditionally cultivated worldwide under continuous flooding irrigation. However, in Mediterranean environments, there has recently been a decline in the area of rice cultivation in several producing regions where water supplies for this crop cannot always be guaranteed. Therefore, it is necessary to identify alternative crop management strategies that improve water-use efficiency in order to ensure the sustainability of rice production. It has been postulated that rice production under alternate wetting and drying (AWD) irrigation requires less water than flooding. However, the effects of the AWD system on rice yield components remain unclear, with different trends observed. It has been suggested that the soil properties are a crucial factor in this regard. In fact, drops in rice yields under AWD have been attributed to the low soil organic matter content. Consequently, the incorporation of organic amendments could offset this organic matter deficit, and the subsequent enhancement in rice productivity might also ensure its sustainability in areas where water availability is scarce. This study is the first to analyse how the soils properties, rice yields components, and water productivity were influenced by fresh and field aged biochar applied to rice soils under conventional flooding and AWD using two-threshold (mild and severe). The results showed that the transition from flood management to AWD management has had a significant impact on soil properties and rice yields, though this was dependent on the threshold. Consequently, yield losses occurred under severe AWD conditions in comparison to the flooded systems. Nevertheless, the use of holm oak biochar was found to enhance rice yields under AWD systems, particularly under severe conditions and following the field ageing process. Thus, the combined use of biochar and AWD may be a sustainable strategy to enhance water productivity, which is one of the main objectives in the rice crop.

Keywords AWD · Biochar-aging · Rice yield · Sustainable rice · Water management

1 Introduction

Rice (*Oryza sativa* L.) is threatened by the scarcity of water resources (Zhang et al. 2023) as permanent flooding irrigation system throughout the crop cycle uses large volumes of water. Indeed, Li et al. (2023a) indicated that rice production consumes approximately 40% of global freshwater resources, requiring up to 2500 L of water per kg yield. However, the water requirements of other typical cereals such as corn and wheat are estimated at 650–900 L per kg (Pimentel et al. 2007), showing the low water productivity in rice fields under flooding conditions. This situation is even less sustainable in areas with a Mediterranean climate, such as Italy and Spain which are the largest rice producers in the European Union (Rato-Nunes et al. 2023), where traditionally the rice crop contributes to their economic and social development (Oliver et al. 2019). For example, Straffelini

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and Tarolli (2023) indicated that, after years of extreme drought, around 60% of the rice yield in the Po Delta, one of the most important wetlands in Europe, has recently been compromised. Similarly, Stefano et al. (2014) indicated that the rice production under a permanent flooding system, in the Doñana wetlands (southern Spain), is quite vulnerable in view of the climate trends that imply a significant reduction in water availability in the region (Lavado et al. 2023). Hence, alternative irrigation management practices in rice cropping are urgently needed to improve its sustainability (Majumdar et al. 2023), especially in water-stressed regions (Rato-Nunes et al. 2023; Spanu et al. 2009). Against this backdrop, different irrigation systems such as sprinkler, subsurface drip, furrow-irrigated, and alternate wetting and drying (AWD) have been proposed as interesting alternatives to permanent flooding (e.g., Martín-Franco et al. 2023; Surendran et al. 2021). The most promising of these alternatives is AWD (Majumdar et al. 2023), mainly because it is not associated with changes in irrigation equipment, which allows its application without additional costs (Mallareddy et al. 2023), minimizing risks and boosting investment (Pavolová et al. 2021). Indeed, for an agricultural system to be considered sustainable, it must first be competitive and profitable. Thus, Majumdar et al. (2024) indicated that the application of the AWD practice promotes several aspects of the sustainable development goals (SDG) by the United Nations, such as food security, higher crop yields and sustainable agriculture (SDG-2, Zero Hunger), minimizing agricultural water consumption (SDG-6, Clean Water and Sanitation) and increasing the economic profit of agricultural products (SDG 12, Responsible Consumption and Production). However, a major problem in implementing the AWD system is concern over its effects on agronomic yields (Fertitta-Roberts et al. 2019). Indeed, in the scientific literature, the results on rice grain yields under AWD vary significantly across studies, with some indicating that the effects could be positive (e.g., Hoang et al. 2023), others that they could be negative (Carrijo et al. 2017; Zhang et al. 2023), and others finding them to be negligible (Loaiza et al. 2024; Martínez-Eixarch et al. 2021). This controversy could be caused by the complexity and extensive variability of AWD management, associated with three fundamental factors (Zhang et al. 2023). The first is related to the subjectivity in the use of the AWD system, such as the water potential level or the frequency and timing of the drying-wetting cycle (Fertitta-Roberts et al. 2019; Thakur et al. 2018). The second is related to the properties of the soils and their effects on AWD (e.g., Carrijo et al. 2017). And the third involves the agricultural practices in different regions, which reflect their specific characteristics and political, economic and climatic conditions (e.g., Martínez-Eixarch et al. 2021). However, whereas the impact of AWD on rice growing has been analyzed widely in Asia (Hoang et al. 2023; Li et al. 2024; Majumdar et al. 2023; Surendran et al. 2021), few studies have been conducted in other rice ecosystems in water-stressed regions (Lagomarsino et al. 2016; Oliver et al. 2019). Oliver et al. (2019) showed that the soil's properties (physical and chemical) were key factors in maintaining rice yields under AWD systems. Similarly, a meta-analysis conducted by Carrijo et al. (2017), based on 56 studies, found that rice yield losses were highest under severe AWD (when soils were dried to values of water potential above − 20 kPa) in soils with low soil organic carbon (< 1%).There is an urgent need to develop management strategies for rice production in combination with AWD irrigation system in order to achieve the sustainability of this substantial food security crop (Zhang et al. 2023).

Another promising strategy is the application of biochar (a quite stable substance very rich in carbon compounds and of high porosity), which has shown to increase a soil's organic carbon and pH, and improves its retention of nutrients and their uptake by plants (Maroušek and Trakal 2022; Materu et al. 2024). Biochar-amended soils show high levels of soil enzyme activities, which can greatly influence crop productivity (Wen et al. 2021). Furthermore, due to its important surface area, the use of biochar as organic amendment can improve paddy soil water retention capacity (Yang and Lu 2021). These beneficial impacts mean that the application of biochar improves soil quality and fertility, thereby enhancing crop productivity (Alburquerque et al. 2013; Li et al. 2023b), including that of rice (Liao et al. 2021). Nevertheless, the impact of biochar on rice yields under water-saving irrigation systems remains largely unexplored (Rato-Nunes et al. 2023), especially with AWD irrigation. Indeed, the few studies that have been carried out show great variability in their results, although all of them were conducted under a mild severity regime. Thus, whereas Sriphirom and Rossopa (2023), in Thailand, indicated that biochar did not cause significant changes in agronomic yields, regardless of the irrigation system used (flooding or AWD), Nam et al. (2024) found significant increases (up to 21%) after biochar application in rice fields in Vietnam. Similarly, Liu et al. (2024) showed in a study carried out in China that the effects of combining biochar with AWD are time-dependent, with decreases in its fresh effect (first year) and increases after the aging period (second and third years) in rice yields. Likewise, Haque et al. (2022) and Wen et al. (2021) indicated that biochar could outweigh the potential rice yield penalties under AWD, although both studies were carried out in pots experiments under controlled conditions. Therefore, in order to validate these results and to provide farmers with advice and recommendations, further studies need to carried out under other environments and in field conditions. Indeed, a review of the literature revealed no published studies evaluating the effects of combined use of biochar and AWD irrigation on rice production in semiarid regions.

The hypothesis of this study was that the combined use of AWD irrigation under high level of severity (− 70 kPa) and biochar (fresh and field aged) could represent an attractive strategy for ensuring the sustainability of rice production, promoting the rational use of water resources. To confirm this hypothesis, a 3-year field experiment was conducted to explore the effects of AWD irrigation systems with and without biochar application on physicochemical and biological soil properties, as well as on rice yield components and water productivity in a semiarid Mediterranean region (Fig. 1). Since one of the main sources of uncertainty about the impacts of AWD management on rice yields stems from the different types of AWD systems in terms of severity (threshold for reflooding) (Martínez-Eixarch et al. 2021), two categories for AWD (mild and severe) were implemented. Furthermore, since biochar properties can be altered by aging processes (López-Piñeiro et al. 2022), the effects of field-aged biochar were addressed 18 and 30 months after application, i.e., in the second and third year of the study, respectively.

2 Materials and methods

2.1 Site description

During the three rice growing seasons (from 2020 to 2022), field experiments were carried out in south-western Spain (38°92′N; 6°96′W), characterized climatically by hot conditions and low precipitation (mean annual air temperature of 16.6 °C and rainfall < 470 mm). Table 1 presents

Table 1 Mean maximum (TM) and minimum (Tm) temperature, total rainfall (R), and rice evapotranspiration (ETc), registered at the field location during the rice growing season (May–September) in 2020, 2021, and 2022.

Data	TM	Tm	R (mm)	ETc (mm)
2020				
May	28.4	13.2	33.6	94.0
June	29.5	12.8	0.200	141
July	36.8	17.1	5.17	216
August	33.8	15.3	0.200	218
September	34.0	13.6	0.000	84.9
2021				
May	26.4	11.3	0.200	93.3
June	29.2	13.2	42.8	149
July	32.5	14.6	0.000	198
August	34.1	15.7	0.200	236
September	30.1	16.2	30.9	69.7
2022				
May	29.1	12.0	0.400	145
June	31.0	14.7	1.60	161
July	37.7	17.1	0.000	227
August	34.8	16.4	0.790	248
September	29.3	13.9	0.200	38.2

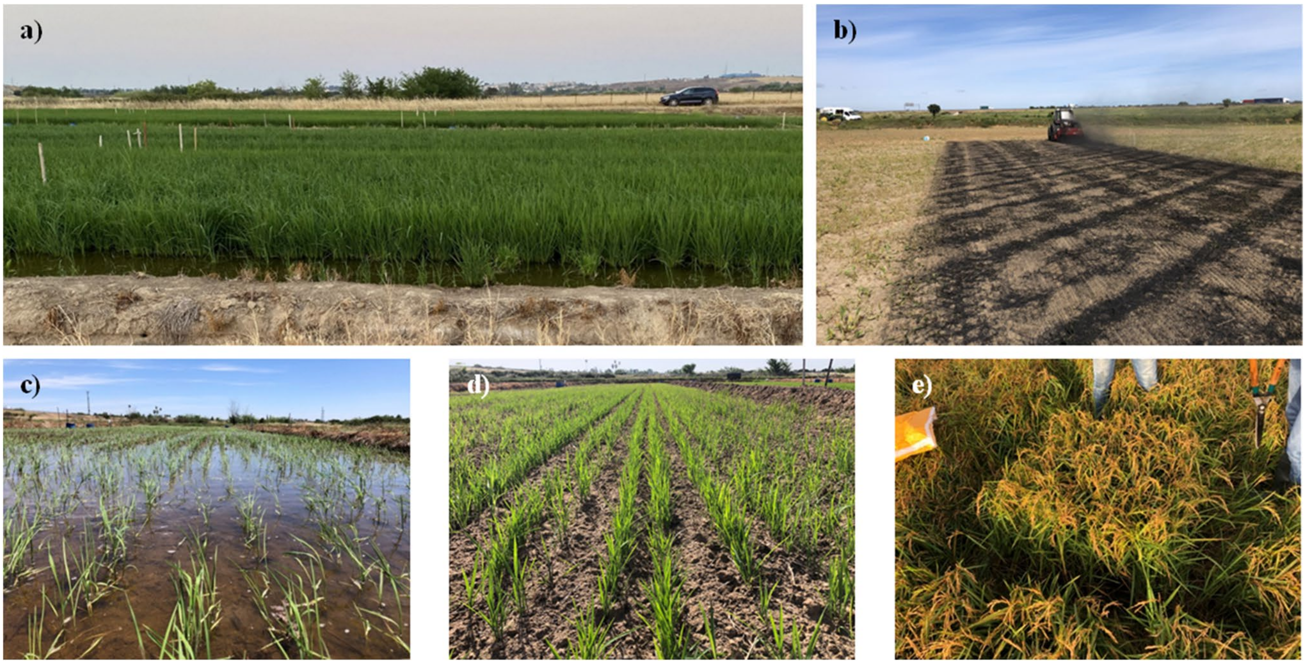

Fig. 1 **a** Photograph of rice field experiment. **b** Biochar application. Rice seedling growth under **c** flooding and **d** alternate wetting and drying irrigation during the early vegetative stage. **e** Rice harvest. Source: Photographs by the authors (Vicente L, Peña D, Fernández D, Albarrán A, Rato-Nunes JM, López-Piñeiro A).

the data of temperature, rainfall, and rice evapotranspiration during the rice growing season (May-September) over the 3 years. The field had been under rice cultivation by conventional systems (permanent flooding irrigation and deep ploughing) during the previous 15 years. Once the rice was harvested, the field was left fallow until the following year. The soil of the experimental field was classified as Hydragic Anthrosol (IUSS Working Group WRB 2006), whose main properties (0–20-cm depth) before the start of the experiments were as follows: sandy loam texture (62% sand, 15% clay, and 23% silt), with 14.9 g kg^{-1} of organic matter, pH 5.51, 2.81 dS m^{-1} of electrical conductivity, and 0.755 g kg^{-1} of total nitrogen.

2.2 Experimental design and field management

In September 2019, after harvesting the rice, the field was divided into 180-m^2 (18 × 10 m) experimental plots and was subjected to the following six different rice-growing managements: permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached − 70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B). Watermark 200SS Sensors (Irrometer, Co., USA) were used to measure the soil matric potential. Each rice-growing management was carried out in triplicate so that the field trial had 18 plots in a completely randomized design. Only in the first year of the study (2020), in April, 1 month before sowing the rice, the biochar was manually applied at a dosage of 35 Mg ha^{-1} in the FB, AWD20B, and AWD70B treatments and later incorporated to the soil (0–20 cm) using a GRR-F200-16 disc harrow (Gascon, Spain). The biochar dosage was selected to achieve an optimal level of organic matter in the soil (3–4%), which, according to previous research, prevents rice yield loss under water-saving systems. In order for viable use of biochar as organic amendment, the following conditions must be met: easy to purchase and reasonably priced, as well as producible in large quantities. The biochar used in our study was provided by the company Carylevere (Zahinos, Spain) from holm oak prunings by pyrolysis (550 ºC for 48 hours). Its main properties were as follows: 79% total carbon, 4.9 g kg^{-1} total nitrogen, 4% total hydrogen, 12% ash, 9.78 pH, 2.89 dS m^{-1} electrical conductivity, and 76.6 m^2 g^{-1} specific surface area.

In the 3 years of the study, the rice was sown during the first 15 days of May (at a dosage of 160 kg ha^{-1}) of *O. sativa* variety Sirio purchased from Copsemar (Spain) which is a very important variety in the region of the study (De Barreda et al. 2021). All treatments were sown through a Sola Neumansem 799 (Sola, Spain). With respect to fertilization, each year a total of 115 kg N ha^{-1} was applied as inorganic fertilizer at different points in the rice growing season in the form of 40 kg N ha^{-1} (ammoniacal-N) as basal fertilizer and 75 kg ha^{-1} (ureic-N) as top dressing (Fertiberia, Spain). Different herbicides, of common use in the region, were applied by backpack sprayer (Matabi, Spain) for weed control. Thus, Pendimethalin (Finchimica, Italy) was used in pre-emergence as well as Imazamox (Basf, Spain) and a mixture of Bentazone (Basf, Spain) and MCPA (Nufarm, Spain) in post-emergence. Regarding water management, in F and FB treatments, water depth was maintained at 10 cm from the soil surface from 7 to 12 days after sowing until 10 to 15 days before rice harvest, which represents the traditional flooding irrigation procedure. Similarly, in AWD treatments, reflooding was instituted whenever the soil matric water potential reached − 20 kPa, moisture close to 80% field capacity (AWD20 and AWD20B) or − 70 kPa, moisture close to 65% field capacity (AWD70 and AWD70B) until before rice harvest. Nevertheless, according to Lampayan et al. (2015), during the flowering stage (about 14–20 days), all treatments were kept flooded to avoid water-stress at this sensitive stage. The amounts of water applied in the different treatments were quantified using Woltman Predator DN100 flowmeters (Hidroconta, Spain) and are shown in Fig. 2.

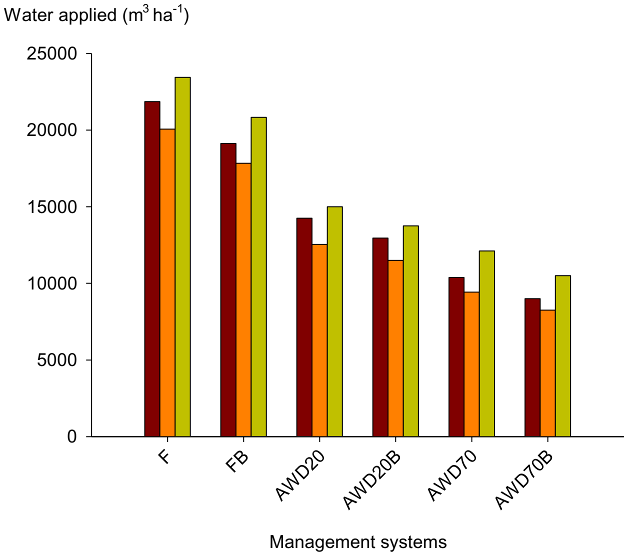

Fig. 2 The water applied in the rice-growing managements over the three years of the study (2020 brown bars; 2021 orange bars and 2022 green bars). Permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached − 70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B).

2.3 Soil measurements

Each year (2020, 2021, and 2022), in October, after the rice harvest, four to five subsamples of soil at 0–20 cm of depth were collected from each plot. These soil samples were air-dried at room temperature (20–25 °C), ground, and sieved at 2 mm. Then, total carbon (TC), electrical conductivity (EC), and pH were measured as described by López-Piñeiro et al. (2022). Labile organic carbon (LOC) was determined following the procedure of Culman et al. (2012). Furthermore, according to Zsolnay et al. (1999), for dissolved organic carbon, the specific ultraviolet absorbance at 254 nm ($SUVA_{254}$) and humification index (HIX) were also determined. Briefly, the absorbance values at 254 nm were determined using a Shimadzu UV1601 PC spectrophotometer (Shimadzu Corporation, Japan) and divided by concentration of dissolved organic carbon and expressed as $SUVA_{254}$. The HIX values were computed as the ratio of the area of the emission spectrum at 435–480 nm to the emission area at 300–345 nm at an excitation wavelength of 254 nm (using a Cary Eclipse Fluorescence Spectrophotometer from Varian, USA). With respect to soil biological properties, dehydrogenase (DH), urease (UR), phosphatase (PHO), and arylsulfatase (AR) activities were determined as described by López-Piñeiro et al. (2011).

2.4 Crop performance

Rice plant samples were collected at the maturity stage in two randomly selected quadrate areas of 1 m^2 for each plot (6 m^2 per treatment). Thus, this sampling area was used to determine the number of panicles per square meter (PM^2) by direct counting and grain yield (GY) after weighing all the filled grains per panicle collected. Furthermore, in order to calculate the harvest index (HI), biomass production was determined by weight of the aerial part of the rice plants. Then, 20 representative panicles for each plot were selected to analyze panicle length (LP) and ripening index (RI). A seed counter (Swantech-SC2; Sadkiewicz Instruments, Poland) was used to determine the 1000 grain weight (1000W). Finally, the water use efficiency (WUE) was determined, taken to be the ratio between the GY and amount of water applied.

2.5 Weed control

In order to assess the effects of different managements on weed control, weed samples were collected from each plot (30×30 cm^2) at harvesting time. Thus, in accordance with Mohammed et al. (2016), weed control efficiency (WCE) was determined using the following equation: WCE = ((DWC-DWT)/DWC) x 100, where DWC is the dry weight of weeds in a control area (without herbicide applications) and DWT is the dry weight of weeds in a herbicide-treated area.

2.6 Statistical analyses

SPSS (Version 22) was employed for statistical analyses. Analysis of variance (ANOVA) was used to test the statistical effects of the management, the year, and their interactions. The data were previously checked for normality and homogeneity of variances. The Duncan test was carried out for multiple comparisons. A Pearson correlation analysis was applied in order to find possible correlations between different parameters. Three levels of significance were considered: $p \leq 0.05$, 0.01, and 0.001.

3 Results and discussion

3.1 The soils' properties

3.1.1 Chemical properties of soils

The properties of the soils (at 0–20 cm of depth) are listed in Table 2. The different soil properties were significantly affected by rice-growing management regime (Table 2). These effects also differed during the study, as shown by significant management × year interaction (Table 2). With regard to total carbon (TC), the values observed in unamended managements were low (< 9.60 g kg^{-1}) through the 3 years of the study (Table 2), which is a common characteristic for agricultural soils under Mediterranean conditions (Alburquerque et al. 2013; López-Piñeiro et al. 2011), including rice soils (De Barreda et al. 2021; Rato-Nunes et al. 2023). In addition, the highest values of TC for the unamended managements were found under AWD70 during the 3 years of the study (Table 2), suggesting that soils' TC levels are influenced by the water management regimes in rice growing (Mi et al. 2019). This finding is consistent with Fan et al. (2012), who reported that non-flooded management increased TC compared with traditional flooding. This observation was probably because implementing the AWD systems could mitigate greenhouse gas emissions (especially CH_4) and accumulate TC (Li et al. 2024). Indeed, Oliver et al. (2019), also in European rice paddies, found that AWD did not enhance carbon loss. However, Xu et al. (2017) showed no significant differences in soil TC between continuous flooding and AWD managements in a sandy loam soil from paddy field of China, suggesting that future studies should address the effects of water management techniques on soil TC accumulation and stability in paddy soils. Despite the biochar only being applied in the first year (2020), it led to a significant increase in TC during the three years of the study (Table 2). Thus, compared with the respective

Table 2 Effect of different rice-growing managements on soil properties. *TC* total carbon, *LOC* labile organic carbon, *SUVA* specific UV absorbance, *HIX* humification index, *EC* electrical conductivity. Permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached − 70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B). ANOVA factors are management and year. Significant at $*p < 0.05$ and $***p < 0.001$. Different letters indicate significant differences ($p < 0.05$) between managements in the same year (lowercase letters) and between years within the same management (uppercase letters).

	TC (g kg^{-1})	LOC (mg kg^{-1})	$SUVA_{254}$ (L mg^{-1} m^{-1})	HIX	EC (dS m^{-1})	pH
2020						
F	7.10aA	265aA	0.910aA	2.85aA	2.61dA	5.70aA
FB	20.0cB	313bA	1.17bB	3.72abA	2.14cA	6.43cB
AWD20	7.60aA	302abB	1.19bA	4.19bA	1.88bB	6.20bA
AWD20B	19.8cB	377cB	1.35cB	5.53cA	1.53aC	6.95dB
AWD70	9.00bA	363cA	1.19bB	3.74abA	1.88bB	6.20bA
AWD70B	21.9dA	379cB	1.45dC	5.74cA	2.67dB	7.30eB
2021						
F	7.50aA	248aA	1.01aA	3.91aA	2.43eA	5.75aA
FB	17.5bA	289bA	1.01aB	4.52abA	2.29eA	5.84aA
AWD20	7.40aA	237aA	1.08abA	5.16bcAB	1.20cA	6.07bA
AWD20B	17.7bA	291bA	1.15bcA	5.94cdA	0.88aA	6.82dB
AWD70	9.30bA	287bA	1.18bcB	5.80cdB	1.12bA	6.35cA
AWD70B	22.9cA	301bA	1.22cB	6.06dA	1.89dA	7.12eAB
2022						
F	9.10bB	405bB	0.909bA	5.44abB	3.20dB	5.94abB
FB	16.9dA	398bB	0.826aA	4.11aA	2.33cA	5.75aA
AWD20	8.60aB	373aC	1.09cA	5.86bB	1.09aA	6.25bA
AWD20B	19.4eB	486cC	1.04cA	5.79bA	1.14aB	6.53cA
AWD70	9.60cB	469cB	1.06cA	5.99bB	1.34bA	6.11bA
AWD70B	24.8fB	557dC	1.11cA	7.09cB	2.16cA	6.94dA
Management	***	***	***	***	***	***
Year	***	***	***	***	***	***
Management x year	***	***	***	*	***	***

unamended managements, the biochar increased the values of TC by factors of 2.82, 2.61, and 2.43 in FB, AWD20, and AWD70B for 2020; by factors of 2.33, 2.39, and 2.46 in FB, AWD20, and AWD70B for 2021; and by factors of 1.86, 2.26, and 2.58 in FB, AWD20, and AWD70B for 2022 (Table 2). These results were consistent with the conclusions from previous research (Haque et al. 2022; Sriphirom et al. 2020) which indicated that the combination of AWD with biochar application in rice growing could enhance the soil's carbon pool. These findings are very important as TC plays an essential role in soil productivity because it is strongly linked to the soil's physicochemical and biological properties, being an essential parameter of agroecosystem sustainability (Mi et al. 2019).

The labile organic carbon (LOC) showed a similar trend to TC, with greater values in AWD70 compared with F and AWD20 during the years of the study (Table 2). This is consistent with findings by Yang et al. (2020) who, in a pot study, also reported increases in LOC fractions under AWD irrigation in a China rice soil, but with a much higher organic matter (21.71 g kg^{-1}) and pH (7.4). Chen et al. (2023) also reported higher values of LOC under AWD than under flooding, which was attributed to stimulating the growth of microorganisms that decompose plant residues under AWD management. Furthermore, the biochar increased the LOC content, regardless of the water management, although not always significantly (Table 2). Similar to our study, other researchers have shown that the application of different biochars can increase LOC in rice soils (Chen et al. 2023; Pei et al. 2017). This result could not be attributed to biochar, which is of a highly recalcitrant chemical nature and has a very low labile fraction content (López-Piñeiro et al. 2022). Thus, the increases in LOC under biochar amendment, regardless of water management regime (Table 2), could be attributable to the entrapment of dissolved organic carbon, a prevalent form of LOC in rice fields (Kögel-Knabner et al. 2010), in the pores of the biochar (Pei et al. 2017).

For unamended managements, the values of $SUVA_{254}$ ranged from 0.909 to 1.19 L mg^{-1} m^{-1} (Table 2), which are of the same order of magnitude as those found by Li et al. (2019) who indicated 1.10 ± 0.54 as the mean value of $SUVA_{254}$ for different paddy soils from China. Thus, during the study, the values of $SUVA_{254}$, which indicate the presence of aromatic substances of dissolved organic carbon, were significantly increased (by factors of 1.07–1.31) in the water-saving managements (AWD20 and AWD70) relative to permanent flooding (F) (Table 2), which reflected that the water management in rice growing exercised a significant influence on SUVA$_{254}$. However, Linam et al. (2023) found that flooding of paddy soils produced more aromatic dissolved organic matter compared to AWD and non-flooded water management, albeit in a pot study. The effect of biochar on SUVA$_{254}$ was time-dependent due to its aging process. Indeed, in 2020, the biochar amended managements showed significant increases in SUVA$_{254}$ values relative to the unamended managements, whereas in 2022, after its field aging, decreases were observed, although not always significant (Table 2). These results agree with Yue et al. (2023) who indicated that values of SUVA$_{254}$ declined with aged biochar. Nevertheless, the effects of biochar aging on the characterization of dissolved organic matter are unclear (Yue et al. 2023) and even less pronounced than the effects of water management (Linam et al. 2023). In accordance with Chen et al. (2020), due to the low solubility of aromatic hydrocarbons in water, the increase of LOC values, which were significant ($p < 0.001$) throughout the study regardless of management regimes (Table 2), also contributed to the decrease in aromaticity. Furthermore, Linam et al. (2023) indicated that water management had a greater effect on SUVA$_{254}$ than biochar (from rice husk), but this requires further investigation. In all the years of the study, the values of the humification index (HIX) were higher in AWD managements, regardless of the severity (AWD20 or AWD70), than in F (Table 2), albeit these not always significantly. Therefore, these results were very similar to those found for SUVA$_{254}$. Indeed, a significant and positive correlation was observed between SUVA$_{254}$ and HIX values ($r = 0.336$, $p < 0.05$) (Fig. 3), confirming the positive relationship between both properties. This finding had been reported in previous studies, which indicated that high values of SUVA$_{254}$ could indicate high values of HIX, and thus more resistant aromatic substances such as humic acids, which have a low biodegradability (Nguyen and Choi 2015). Furthermore, in general and regardless of water management system, the biochar increased the HIX values (Table 2). Similar results were described by Huang et al. (2023), who indicated that biochar application led to increases in HIX of a silt loam soil, enhancing the soil its humification, especially with biochar produced at medium pyrolysis temperatures (500 °C), which is very close to the temperature for our biochar, although in a laboratory incubation experiment (at 75 % field water holding capacity) for 200 days. Also, it is important to emphasize that the effects of biochar were time-dependent. Thus, after 30 months of the biochar's field aging, the HIX values in FB and AWD20B did not show significant differences with respect to F and AWD, respectively, whereas under AWD70B, it increased by a factor of 1.18 with respect to AWD70 (Table 3). An increasing trend of humification under severe AWD in combination with biochar application (AWB70B, Table 2) is probably related to soil microbiology, which plays an essential role in humification processes (Huang et al. 2023).

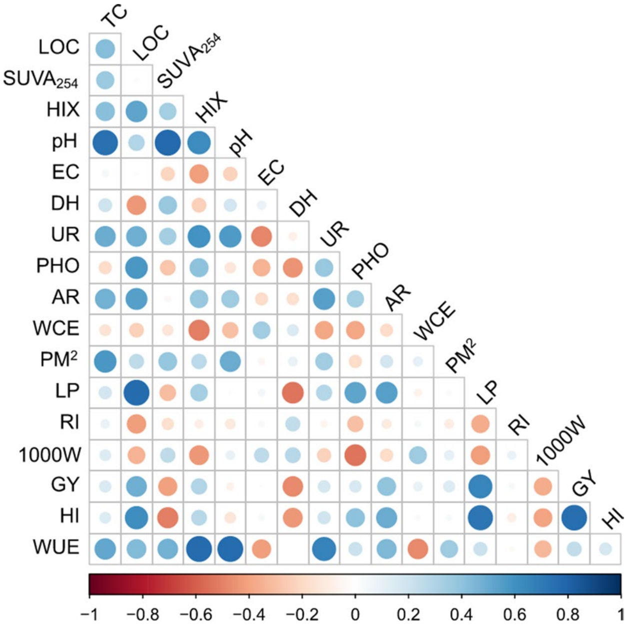

Fig. 3 Pearson correlation matrix among different variables. The blue color corresponds to (+) positive interaction, and red color corresponds to (-) negative interaction, and white corresponds to neutral interaction between variables. TC, total carbon; LOC, labile organic carbon; SUVA, specific UV absorbance; HIX, humification index; EC, electrical conductivity. DH, dehydrogenase activity; UR, urease activity; PHO, phosphatase activity; AR, arylsulfatase activity; WCE, weed control efficiency; PM^2, panicles per square meter; LP, panicle length; RI, ripening index; 1000W, 1000 grain weight; GY, grain yield; HI, harvest index; WUE, water use efficiency.

The trends found for soil pH values were consistent during the study (Table 2). For unamended managements, the implementation of AWD systems, regardless of the severity, caused increases in soil pH compared with F by factors that ranged from 1.03 to 1.10 (Table 2). Similar findings were observed by Zhao et al. (2023) who observed significant increases in soil pH (about 2%) under AWD with respect to permanent flooding. However, Haque et al. (2022) showed that flooding increased the soil pH over AWD (5.90 and 5.78, respectively). These opposing trends in pH values could be due to different experimental conditions, such as the type of climate and/or soil environments (Zhao et al. 2023). In general, the biochar significantly increased the soil pH with respect to unamended management, reaching values of neutral soil pH (6.5–7.5), especially under both of the AWD managements (Table 2). Its effects were different in the three years as determined by the significant management × year interaction ($p < 0.001$; Table 2). Thus, whereas in the first year of the study (fresh effect), the biochar caused large pH increases in all managements, after 3 years of its

Table 3 Effect of different rice-growing managements on rice yield components. *PM*^{2} panicles per square meter, *LP* panicle length, *GY* grain yield, *WUE* water use efficiency. Permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached −70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B). ANOVA factors are management and year. Significant at *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and NS (not significant). Different letters indicate significant differences ($p < 0.05$) between managements in the same year (lower case letters) and between years within the same management (upper case letters).

	PM^2	LP (cm)	GY (kg ha^{-1})	WUE (g L^{-1})
2020				
F	692aA	18.5aA	9067aA	0.420aA
FB	819bcA	19.0aA	8447aA	0.440aA
AWD20	803bcA	18.7aB	8304aA	0.583bA
AWD20B	850cA	18.8aA	8504aA	0.657bA
AWD70	737abA	18.4aA	7100aA	0.683bA
AWD70B	871cA	18.2aA	8191aA	0.910cA
2021				
F	720aA	17.5aA	9580cA	0.480aB
FB	781aA	17.3aA	9148cAB	0.513aA
AWD20	796aA	17.7aA	8224bA	0.657bAB
AWD20B	769aA	17.8aA	9374cA	0.813cB
AWD70	738aA	18.0aA	7227aA	0.770cA
AWD70B	797aA	18.6aA	8474bA	1.03dAB
2022				
F	710aA	21.1abB	10744abcB	0.457aB
FB	817abA	21.4abB	10016abB	0.480aA
AWD20	778abA	20.9abC	11672bcB	0.780bB
AWD20B	805abA	21.6bB	12226cB	0.890cB
AWD70	692aA	20.5aB	8916aA	0.737bA
AWD70B	877bA	21.8bB	11146bcB	1.06dB
Management	**	*	**	***
Year	NS	***	***	***
Management x year	NS	NS	NS	*

application (aging effect), this was only observed under AWD70B. According to Nyambo et al. (2023), this could be attributed to the increase of carboxyl and hydroxyl in the biochar surface after the aging process, which would tend to reduce the pH values. Furthermore, the decline in pH values could also be related to the amounts of water applied in each management. In this sense, the large volume of water used under flooding irrigation could have led to an effect of elution of alkali compounds.

Over the 3 years of study, the values of electrical conductivity (EC) were higher in F than in AWD20 and AWD70 managements (Table 2). Thus, the values of EC for F management ranged from 2.43 to 3.20 dS m^{-1} and for AWD managements (AWD20 and AWD70) from 1.09 to 1.88 dS m^{-1}·(Table 2). These results are consistent with those observed by Li et al. (2018), who also indicated that the values of EC decreased in AWD regime reference to flooding, probably due to better nutrient uptake by the rice roots. Therefore, the implementation of AWD, regardless of the threshold of severity, led to positive effects on the soil's EC, which is very interesting since rice is one of the most salt-sensitive cereals (Genua-Olmedo et al. 2016). The application of biochar showed differences between the managements in its effects on EC (Table 2). Thus, whereas under FB and AWD20B the values of EC were lower than under F and AWD20, respectively (Table 2), an opposite effect was found under AWD70B whose values were significantly higher than those of AWD70 throughout the study (Table 2). These results could be attributable to a greater loss of salts and ions by leaching under flooding and AWD20 than under AWD70 (De la Rosa et al. 2018).

3.1.2 Biological properties of the soils

The values of different soil enzymatic activities (at 0–10 cm of depth) are shown in Fig. 4. In general, none of these activities analyzed were negatively affected either by the implementation of AWD managements systems or by the biochar application (Fig. 4). Indeed, dehydrogenase (DH), which is considered a suitable indicator of microbial activity as well as soil quality, was unaffected by the different water managements, with an average value of 0.903 µg INTF g^{-1} h^{-1} over the study for unamended managements (Fig. 4a). However, Haque et al. (2022) observed decreases in DH values under AWD relative to flooding, which indicates that DH is inversely proportional to the amount of oxygen in the soil (Brzezińska et al. 1998). Nevertheless, the experimental conditions differed between the two studies—whereas Haque et al. (2022) carried out a pots study under greenhouse conditions, our study was carried out at farm field scale over 3 years. Considering the unamended managements, the effects of biochar on DH were time-dependent, with increases in DH values for the first and second years of study, but no important changes being found in the third year (after 30 months of aging processes) (Fig. 4a). Similarly, the increased DH in paddy soils with biochar (produced from wheat straw or rice husk) application had been observed in previous studies (Chen et al. 2013; Yang et al. 2023), suggesting an important role of biochar in paddy soils' biochemical processes. However, these studies did not address the combination of biochar with AWD.

The urease activity (UR) was clearly affected by water irrigation management during the 3 years of study (Fig. 4b). Thus, compared with F, UR increased on average by a factor of 1.60 in AWD20 and AWD70. Similarly, Majumder et al. (2022), in different rice agroecosystems, observed that UR exhibited a significantly higher response

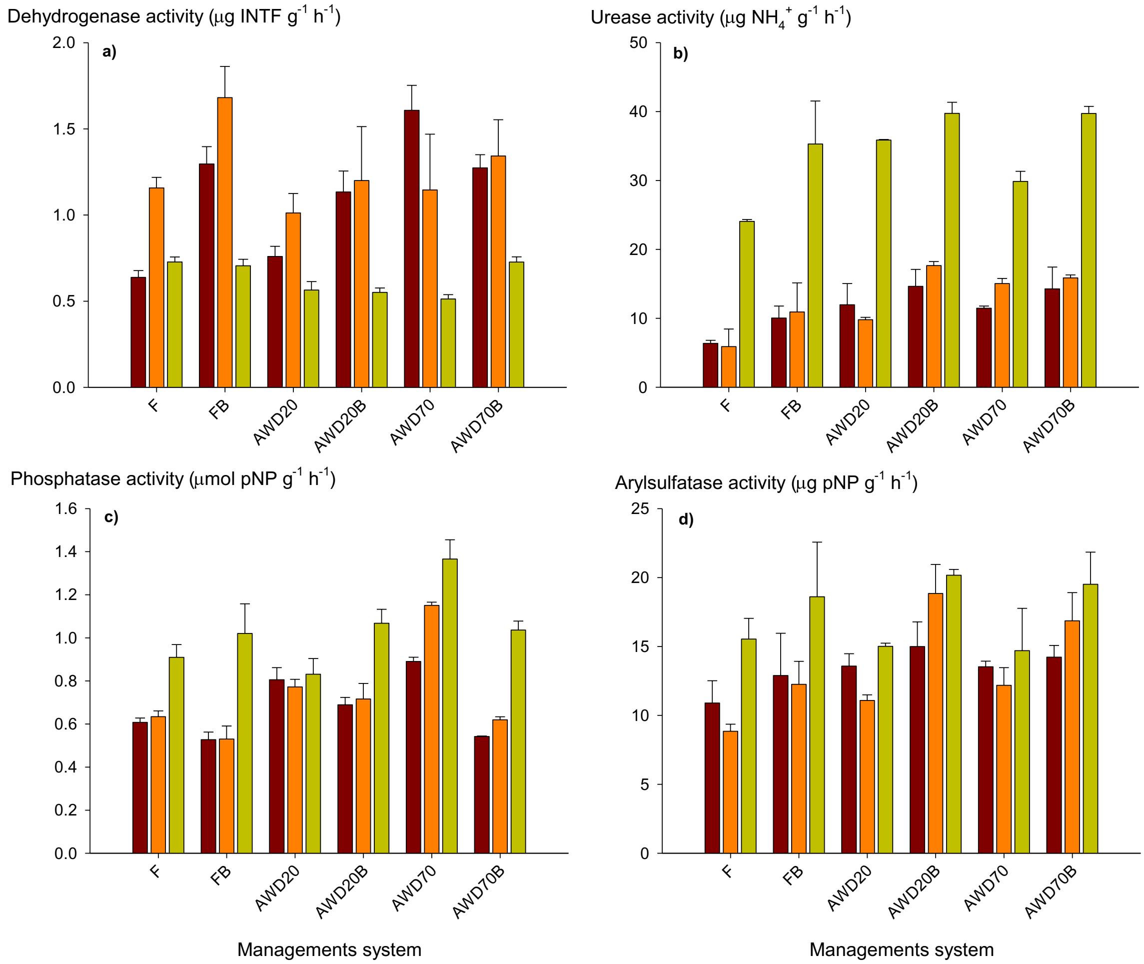

Fig. 4 Effect of different rice-growing managements on soil enzymatic activities (2020 brown bars; 2021 orange bars and 2022 green bars). **a** Dehydrogenase activity, **b** urease activity, **c** phosphatase activity, and **d** arylsulfatase activity. Error bars represent one standard error of the mean ($n = 3$). Permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached − 70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B).

under aerobic than anaerobic conditions (14–16% greater). Furthermore, regardless of management, the application of biochar increased the values of UR with respect to unamended managements. Thus, the values of UR increased by average factors of 1.55, 1.25, and 1.24 in FB, AWD20B, and AWD70B with respect to F, AWD20, and AWD70, respectively. Similar effects of biochar on UR were described by Khan et al. (2024), who indicated that biochar application at 30 Mg ha^{-1} (very close to our dosage) increased the UR activity by up to 52% with respect to unamended treatments. These results are quite relevant since increases in UR, an enzyme involved in the behavior of nitrogen fertilizers, would improve the bioavailability of this important nutrient. The increases in UR could be attributed to the improvement in soil properties with biochar addition. Indeed, in our study, UR was significantly and positively correlated with TC (r = 0.494, $p < 0.01$), LOC (r = 0.481, $p < 0.01$), and HIX (r = 0.591, p < 0.01) (Fig. 3), suggesting the importance of organic matter for UR.

Similarly to UR, the phosphatase activity (PHO) was affected by the water irrigation system (Fig. 4c). Thus, during all the years, the highest values of PHO were observed in AWD70, whose values increased on average by factors of 1.58 and 1.41 with respect to F and AWD20, respectively. These results are consistent with previous reports indicating that PHO values declined significantly under waterlogging conditions (Deng et al. 2021; Majumder et al. 2022). Therefore, the implementation of water saving managements such as AWD in rice soils, especially under severe conditions, could improve the availability of essential nutrients, such as phosphorus, whose forms available for cultivation are very limited (mainly calcium-based phosphates; Stávková and Maroušek 2021). These results are consistent with those of

Peña et al. (2022) who, also in rice fields under Mediterranean conditions, indicated that sprinkler irrigation enhanced the PHO activity. The effects of biochar on PHO activity were dependent on the different water management systems (Fig. 4c). Thus, whereas under FB and AWD20B, the values of PHO did not differ with respect to F and AWD20, respectively, under AWD70B, the values of PHO declined with respect to AWD70 by a factor of 1.55. Similar results were described by Pei et al. (2017), who indicated that there was no clear trend of maize biochar impacts on the PHO activity in rice fields, although only fresh effects were tested under flooding irrigation conditions. Nevertheless, according to Maroušek and Trakal (2022), it is recommended that biochar be modified to improve the efficiency of phosphorus, as inorganic forms are mainly represented by anions (PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^{-}$) and are therefore repelled by the negatively charged of biochar surface. Furthermore, the decrease of PHO under AWD70B could be associated to EC, due to significant and negative correlation between PHO and EC ($r = -0.341$, $p < 0.05$) (Fig. 3), which is in line with the findings observed by Mukhopadhyay et al. (2023).

Another important soil enzymatic activity is that of arylsulfatase (AR), which plays a key role in dynamic sulfur compounds. Coherent with the findings of Majumder et al. (2022) and Nadimi-Goki et al. (2018), we found increases in AR values under AWD20 and AWD70 with respect to F management (Fig. 4d). In agreement with previous studies, this could be associated with changes in soil properties (Majumder et al. 2022; Sánchez-Llerena et al. 2016). Thus, AR was significantly and positively correlated with TC ($r = 0.476$, $p < 0.01$), LOC ($r = 0.540$, $p < 0.01$), HIX ($r = 0.377$, $p < 0.01$), and pH ($r = 0.359$, $p < 0.01$) (Fig. 3). In this sense, regardless of water managements, the biochar addition caused increases in AR, with both fresh and aged effects (Fig. 4d). Hence, the AR activity increased during the study by factors of 1.24, 1.36, and 1.24 in FB, AWD20B, and AWD70B relative to F, AWD20, and AWD70, respectively, due to biochar potential to improve soil properties (Haque et al. 2022).

3.2 Agronomic parameters

The rice yield components are listed in Table 3. Except for the ripening index (RI), these were significantly affected by the rice-growing management. Nevertheless, in general, these effects were not different during the course of the study, as shown by the not significant management × year interaction (Table 3). With respect to the number of panicles per square meter (PM^2), the values ranged from 692 to 803 PM^2 for unamended managements (Table 3), values close to those observed by Rato-Nunes et al. (2023) for the same variety of rice (Sirio) and also under Mediterranean conditions, although in a 2-year study evaluating the effect of switching to sprinkler irrigation instead of alternate wetting and drying irrigation as in the present study. Generally, the water managements did not cause significant differences in PM^2 (Table 3), indicating that AWD managements, regardless of the threshold of severity, have no negative impacts on panicle density. This finding is consistent with the studies of Jiang et al. (2023) and Sriphirom et al. (2019) which found that the density of panicles was unaffected by AWD relative to flooding irrigation in several Asian countries. Under Mediterranean conditions, Martínez-Eixarch et al. (2021) indicated that in silty clay loam soils from the Ebre delta (Southern Catalonia, NE Spain) with a pH of 8.3, the effects of AWD on panicle density might largely depend on rice variety, ranging from unaffected to a 21% decrease, but in a 2-year study and without exceeding the AWD threshold (− 50 kPa). The biochar additions led to increased PM^2 over the study but without significant differences under FB and AWD20B relative to F and AWD20, respectively (Table 3). Nevertheless, under AWD70 (severe AWD conditions), biochar significantly increased the values of PM^2 by factors of 1.18 and 1.27 for the fresh (2020) and aged (2022) effects, respectively. Probably, this result could be attributed to biochar enabling a greater capacity for resilience to the stress induced by severe AWD (AWD70) due to its beneficial effects on soil properties. Indeed, PM^2 was significantly and positively correlated with TC ($r = 0.573$, $p < 0.01$), pH ($r = 0.497$, $p < 0.01$) $SUVA_{254}$ ($r = 0.390$, $p < 0.01$), and UR ($r = 0.346$, $p < 0.05$) (Fig. 3). Similar findings were reported by Ghorbani et al. (2023) who observed that the application of rice husk biochar in the clay soil of Iran caused a significant increase in panicle density, especially under strong moisture stress conditions.

With regard to values of panicle length (LP), the implementation of AWD management, regardless of the level of severity (AWD20 or AWD70), did not lead to significant differences compared with F management during the 3 years of study (Table 3). Thus, the mean values of LP for unamended management were 18.5, 17.7, and 20.8 cm in the first, second, and third years of the study, respectively, which is in agreement with Grimm et al. (2013), who carried out morphological traits of rice plants, including Sirio, in northern Italy. However, Mboyerwa et al. (2021) indicated that LP was significantly affected by water management, finding that AWD led to greater values of LP than did continuous flooding, although this was a greenhouse pots experiment. Generally, the biochar addition (both the fresh and the aged effects) caused an increase in values of LP relative to unamended managements, although it was only significant in AWD70B for the third year, whose value of LP was 21.8 cm (Table 3). Likewise, Singh et al. (2018) reported positive effects of biochar application on LP in rice growing under a no-waterlogged condition, which could be attributed to improved soil nutrient availability. In our study, significant and positive correlations of LP values were found with LOC (r = 0.767, $p < 0.01$), HIX (r = 0.339, $p < 0.05$), PHO (r = 0.529, $p < 0.01$), and AR (r = 0.542, $p < 0.01$) (Fig. 3), indicating their influence on this rice yield component. However, Liu et al. (2022) found that biochar application did not cause significant changes in LP of different rice cultivation, although under flooding irrigation and in a soil with a higher TC content than that observed in the present study.

During the 3 years of the study, there were no significant differences for ripening index (RI) in the unamended managements, whose values ranged from 76% to 85% (Table S1). Similar values of RI were indicated by Rato-Nunes et al. (2023) who determined the effects of sprinkler irrigation in combination with biochar application on rice yield components, also for the Sirio cultivar in a Mediterranean environment. Furthermore, also in a Mediterranean growing area, Martínez-Eixarch et al. (2021) observed that AWD management could produce slight RI increases relative to flooding irrigation, although in their study, the AWD thresholds were kept in the range of 0 to − 16 kPa before flowering. Regardless of irrigation system, the biochar application did not lead to significant changes in RI values (Table S1), which agrees with Rato-Nunes et al. (2023), who investigated the effects of sprinkler irrigation in combination with biochar application on rice yield components. Nevertheless, it is important to highlight that in the 3rd year of study (aging effects), the RI values were higher in biochar amended managements than unamended managements, regardless of the irrigation system. Similarly, Peña et al. (2022) observed that the application of compost such as organic amendment in the water-saving irrigation system (sprinkler) increased the values of RI, suggesting that soil organic matter is a key factor in spikelet fertility (filled grain number per rice panicle).

The values of 1000W were significantly affected by the management implemented (Table S1). Thus, for the unamended managements, regardless of the year of the study, the highest value of 1000W was found under F management, with values of 23.8, 22.8, and 22.1 g for 2020, 2021, and 2022, respectively (Table S1). These values were in line with those found by Martínez-Eixarch et al. (2021) who reported 22.6 and 24.6 g of 1000W for Puntal rice cultivars, which is also a long-grain type similar to Sirio, under permanent flooding in a Mediterranean growing area. Nevertheless, there were generally no significant differences in 1000W values between F and AWD managements, regardless of the severity level (AWD20 or AWD70). This is consistent with Kakehashi et al. (2021), who, in a 4-year field experiment in Kenya's highlands, also reported no significant differences between flooding and AWD for the 1000W of Basmati, another variety of long-grain rice. The biochar application caused an increase in 1000W during the study relative to unamended management, except in FB and AWD70B for 2020, although not always significant. This could be due to the positive effects of biochar application on soil properties (Liu et al. 2016). Indeed, 1000W was significantly ($p < 0.05$) correlated with DH (r = 0.277) (Fig. 3), which indicates the relationship between yield components and soil microbial activity.

The implementation of different irrigation regimes had significant effects on grain yield (GY), whose values generally exceeded the average GY value for the study area (7 342 kg ha^{-1}). Thus, for unamended managements, significant differences in GY were found in the second and third years of the study, whereas there were no significant differences in the first year (Table 3). Nevertheless, the values of GY showed a similar trend over the first 2 years of the study, indicating a decline in GY under AWD relative to F management. Indeed, AWD20 and AWD70 managements reduced GY by factors on average of 1.13 and 1.30, respectively (years 2020 and 2021), reflecting that the use of a high level of severity in AWD (AWD70) could significantly decrease rice yields. Indeed, this regime showed the lowest values of GY over the 3 years of the study (Table 3). However, in the 3rd year, the highest value of GY was found under AWD20 (11,672 kg ha^{-1}, Table 3), showing that the implementation of AWD with a moderate level of severity (AWD20) is more effective in promoting rice productivity than AWD70. This is consistent with the findings of Zhang et al. (2023) who, in a global meta-analysis, showed that the optimal implementation of AWD in rice growing was when the soil matric potential was maintained at pressures above − 15 kPa. These authors indicated that when AWD was implemented with more severe water-saving approaches (< − 40 kPa) GY values decreased by 18%, which is in line with our findings in which the GY values decreased by up to 25%. Likewise, Carrijo et al. (2017) indicated that the implementation of severe AWD (with values of the soil matric potential beyond − 20 kPa) led to GY losses of 23% relative to flooding conditions, whereas under mild AWD (with values of the soil matric potential ≥ − 20 kPa), GY values were not significantly reduced. Nevertheless, several authors have pointed out that although the soil matric potential increased above 100 kPa at some points in the rice growing cycle, this did not affect yield (Kukal et al. 2005; Loaiza et al. 2024). Therefore, future research is needed to identify appropriate AWD management to achieve correct use of water resources without negatively affecting grain yield.

The effects of biochar on GY depended on the irrigation system implemented. Thus, under flooding irrigation (F management), the effects of biochar (FB management) on GY were not significant, whether in its fresh or its residual effects (Table 3). However, under AWD irrigation the biochar improved GY values during the study, regardless of the level of severity implemented (Table 3). Thus, the GY were greater by factors of 1.02, 1.14, and 1.05 in AWD20B than in AWD20 in 2020, 2021, and 2022, respectively, and by 1.15, 1.17, and 1.25 in AWD70B than in AWD70 in 2020, 2021, and 2022, respectively, which indicates the positive effect of biochar on rice yield under AWD irrigation, especially with a high level of severity, being consistent over three cycles of rice growing when fresh and aging effects were evaluated. In this sense, there have been recent reports recommending the implementation of AWD irrigation in combination with other measures (such as biochar application) in order to improve rice yields (Bo et al. 2022; Zhang et al. 2023). These results establish that the combined use of biochar and AWD can achieve high rice productivity, thereby minimizing the food supply crisis in the market, especially in semiarid areas, and promoting SDG 2 to address the issue of zero hunger (Majumdar et al. 2024). Furthermore, Carrijo et al. (2017) observed lower GY under severe AWD in low organic carbon soils relative to high organic carbon soils, indicating that AWD irrigation performed better in soils with organic carbon content of more than 1%. In our study, positive and significant correlations between GY and LOC ($r = 0.483$, $p < 0.01$) (Fig. 3) were found, showing the importance of these properties on soil fertility. According to Chen et al. (2023), this type of carbon is a key factor in regulating the nutrient supply for crops. Furthermore, the GY values were positively and significantly ($p < 0.01$) correlated with LP ($r = 0.656$) (Fig. 3) and plant height ($r = 0.549$; data not shown), indicating the importance of the crop's growth on its productivity level. However, Liu et al. (2022) found that the effect of biochar on GY varied significantly between rice genotypes, suggesting that further research is needed to optimize the benefits of agroecology by combining selected genotypes with biochar.

The harvest index (HI) values observed ranged from 0.452% to 0.639% for AWD70 (2021) and FB (2022), respectively (Table S1), which are considered normal rice crop values (Bueno and Lafarge 2009). Thus, for unamended management, whereas in the first year of study (2020), there were no significant differences between the managements, in the second and third years (2021 and 2022), the values of HI were significantly lower in AWD70 than in F (Table S1). This result was consistent with those of Araus et al. (2002) who indicated that HI could be affected by water availability, which is often reduced by drought, causing stress in the rice crop (Dwivedi et al. 2023). Nevertheless, in the years 2021 and 2022, the biochar produced significant increases in HI under AWD70, reaching values similar to those of the other managements (Table S1), which reflects that the use of resources was improved (Yang and Zhang 2023). Furthermore, the effects of biochar on HI were also demonstrated by significant and positive correlations between HI and LOC ($r = 0.615$, $p < 0.01$), AR ($r = 0.498$, $p < 0.01$) and LP ($r = 0.725$, $p < 0.01$) (Fig. 3).

The values of water use efficiency (WUE) were significantly affected by the management implemented (Table 3). Thus, regardless of the year of the study, the transition from flooding to AWD increased WUE, especially under AWD70, where these increments correspond to a factor of 1.61 relative to F over the study, indicating that AWD70 allowed for more efficient use of the applied water. However, a global meta-analysis carried out by Gao et al. (2024) indicated that a severe AWD threshold did not cause any significant effect on WUE, it being crucial to avoid excessive water saving measures that compromise rice yields. Furthermore, in the case of AWD20, the values of WUE were also higher than F, although generally lower than AWD70 (Table 3). Therefore, considering the scarcity of water resources in the Mediterranean area, the implementation of AWD irrigation instead of flooding could be an interesting strategy to reduce the water consumption in rice growing, as well as enhancing its efficacy, which really helps to reduce the problem of water scarcity and contribute to the achievement of SDG-6 for clean water and sanitation (Majumdar et al. 2024). Furthermore, the biochar addition increased the WUE values for both the fresh and the aged effects (Table 3). Nevertheless, significant differences were only observed under the two AWD managements (AWD20 and AWD70). Thus, WUE values were factors of 1.13, 1.24, and 1.14 higher in AWD20B than AWD20 in 2020 (fresh effect), 2021, and 2022 (aging effects), respectively, and 1.33, 1.34, and 1.44 higher in AWD70B than AWD70 in 2020 (fresh effect), 2021, and 2022 (aging effects), respectively. In line with our findings, Zhang et al. (2023) concluded that the combined use of AWD with soil friendly agricultural practices, such as biochar, caused significant improvement in WUE (by up to 65%). Indeed, the WUE values correlated positively with TC ($r = 0.517$; $p < 0.01$), HIX ($r = 0.770$; $p < 0.01$), pH ($r = 0.767$; $p < 0.01$), and UR ($r = 0.660$; $p < 0.01$) (Fig. 3), which indicates that the rice managements used to enhance the soil's properties could also be interesting to improve water efficiency under Mediterranean conditions.

Future research perspectives on a highly relevant and topical issue such as water use efficiency could include the use of soil temperature and moisture sensors. These results can be used to build information bases that, if properly integrated into decision support systems, will contribute significantly to improving the efficiency of rice production systems in semi-arid environments. According to Kliestik et al. (2023), although in a work more focused on industrial activity, the same concept is reinforced by stating that the analysis of data from sensors and other sources within the IoT (Internet of Things) ecosystem will allow the presentation of predictive models, especially through the implementation of artificial intelligence technology, which, in the case of irrigated agriculture in the Mediterranean region, will certainly be of enormous added value for the sustainable development of agricultural systems. As stated by Dvorský et al. (2023), referring generally to small and medium-sized enterprises, the perception by the surrounding community, policy makers, and the general public of the continuous search for sustainability by the main actors in the agricultural sector is fundamental and can contribute decisively to the different vision of agriculture that is so necessary in our times.

3.3 Weed control

Figure 5 shows the effects of different management systems on weed control efficiency (WCE). With regard to unamended managements, whereas in the first year of the study, the values were similar between the managements, with their mean value being 86%, in the 3rd year, the herbicide efficacy values under F were up to 1.75 times higher than those found under AWD70, suggesting that weed management needs to be taken into account after the transition to severe AWD. However, when AWD was implemented under moderate water-saving approaches (≥ − 20 kPa) no significant differences were observed relative to F (Fig. 5), which is consistent with previous research (Dossou-Yovo and Saito 2021) who indicated that, in a 2-year study on a rice farm with multi-location trials from West Africa, weed biomass was lower under safe AWD (re-flooded whenever soil water potential reaches − 25 kPa at 15 cm below the soil surface) than continuous flooding. Furthermore, it is important to note that, in the 3rd year of the study, the herbicide efficacy values were 1.10 and 1.17 times higher in ADW20B and AWD70B than in AWD20 and AWD70, respectively. The aged-biochar processes are driven by oxidation, which results in an increase of oxygen groups (-COOH and -OH) in the biochar surface, thereby improving its sorption capacity (Maroušek and Trakal 2022) and reducing herbicide leaching (López-Piñeiro et al. 2022). Thus, we suggest that the combined use of biochar and AWD irrigation enhances weed control efficacy. These results agree with López-Piñeiro et al. (2022) who indicated that a herbicide's effectiveness increased with aged biochar amendment under sprinkler irrigation, although in laboratory bioassays. A positive and significant correlation was observed between WCE and 1000W ($r = 0.354$, $p < 0.01$) (Fig. 3), suggesting that increased weed control is of paramount importance to improve the quality of the rice grain.

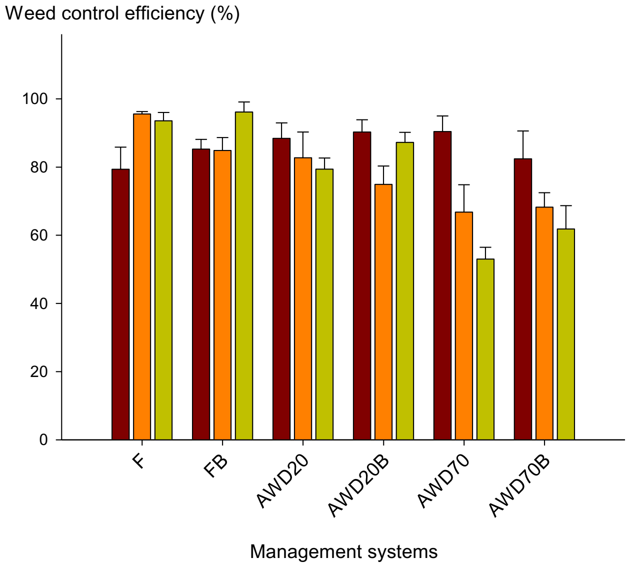

Fig. 5 Effect of different rice-growing managements on weed control efficiency (2020 brown bars; 2021 orange bars and 2022 green bars). Error bars represent one standard error of the mean (n = 3). Permanent flood irrigation without (F) and with application of biochar (FB); reflooding whenever the soil matric potential reached − 20 kPa (at 15–20-cm depth) without (AWD20) and with application of biochar (AWD20B), and reflooding whenever the soil matric potential reached − 70 kPa (at 15–20-cm depth) without (AWD70) and with the application of biochar (AWD70B).

4 Conclusions

The present field experiment was the first to explore the effects of two different severities of AWD irrigation systems with and without biochar application on soil properties, as well as on rice yield components and water productivity, under Mediterranean conditions. The use of biochar in combination with different severities of alternate wetting and drying irrigation (AWD) led to significant improvements in soil properties, which could potentially influence rice cultivation, information until now unclear, especially under Mediterranean conditions. With regard to the agronomic parameters, over the 3 years of the study (short-term), when the soil dried beyond − 20 kPa, yield losses could be observed, indicating the importance of the threshold to AWD application, as expected. In addition, the combined use of biochar (particularly under the influence of aging) and AWD managements (regardless of the threshold of severity) increased grain yield values even above those observed with the flooding system. This confirms our hypothesis that the use of biochar with AWD, in particular the aging effect of biochar, allows a significant increase in water productivity, which is an essential indicator for areas with water scarcity, thus fulfilling one of the main sustainable development goals elaborated by the United Nations. Therefore, the transition from flooding to AWD systems (mild and/or severe) in combination with biochar application could be considered a sustainable alternative, at least under Mediterranean conditions. Nevertheless, further research is needed to test the effects of AWD irrigation systems combined with biochar application on rice agroecosystem services under different cultivars and at different time scales (middle- and long-term effects). In addition, cost-benefit analyses are required to ascertain the economic viability of these alternative management systems.

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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.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Alburquerque JA, Salazar P, Barrón V, Torrent J, Del Campillo MDC, Gallardo A, Villar R (2013) Enhanced wheat yield by biochar addition under different mineral fertilization levels. Agron Sustain Dev 33(3): 475–484. https://doi.org/10.1007/s13593-012-0128-3

Araus JL, Slafer GA, Reynolds MP, Royo C (2002) Plant breeding and drought in c3 cereals: what should we breed for? Ann Bot-London 89(7):925–940. https://doi.org/10.1093/aob/mcf049

Bo Y, Jägermeyr J, Yin Z, Jiang Y, Xu J, Liang H, Zhou F (2022) Global benefits of non-continuous flooding to reduce greenhouse gases and irrigation water use without rice yield penalti. Global Change Biol 28(11):3636–3650. https://doi.org/10.1111/gcb.16132

Brzezińska M, Stępniewska Z, Stępniewski W (1998) Soil oxygen status and dehydrogenase activity. Soil Biol Biochem 30(13):1783–1790. https://doi.org/10.1016/S0038-0717(98)00043-1

Bueno CS, Lafarge T (2009) Higher crop performance of rice hybrids than of elite inbreds in the tropics: 1. Hybrids accumulate more biomass during each phenological phase. Field Crop Res 112(2–3):229–237. https://doi.org/10.1016/j.fcr.2009.03.006

Carrijo DR, Lundy ME, Linquist BA (2017) Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crop Res 203:173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Chen J, Liu X, Zheng J, Zhang B, Lu H, Chi Z, Pan G, Li L, Zheng J, Zhang X, Wang J, Yu X (2013) Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from Southwest China. Appl Soil Ecol 71:33–44. https://doi.org/10.1016/j.apsoil.2013.05.003

Chen Q, Jia R, Li L, Qu D (2020) Effects of high concentrations of sulfate on dissolved organic matter in paddy soils revealed by excitation-emission matrix analyzing. Chemosphere 249:126207. https://doi.org/10.1016/j.chemosphere.2020.126207

Chen L, Sun S, Zhou Y, Zhang B, Peng Y, Zhuo Y, Ai W, Gao C, Wu B, Liu D, Sun C (2023) Straw and straw biochar differently affect fractions of soil organic carbon and microorganisms in farmland soil under different water regimes. Environ Technol Innov 32:103412. https://doi.org/10.1016/j.eti.2023.103412

Culman SW, Snapp SS, Freeman MA, Schipanski ME, Beniston J, Lal R, Drinkwater LE, Franzluebbers AJ, Glover JD, Stuart Grandy A, Lee J, Six J, Maul JE, Mirksy SB, Spargo JT, Wander MM (2012) Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Sci Soc Am J 76(2):494–504. https://doi.org/10.2136/sssaj2011.0286

De Barreda DG, Pardo G, Osca JM, Catala-Forner M, Consola S, Garnica I, López-Martínez N, Palmerín JA, Osuna MD (2021) An overview of rice cultivation in spain and the management of herbicide-resistant weeds. Agronomy-Basel 11(6):1095. https://doi.org/10.3390/agronomy11061095

De la Rosa JM, Rosado M, Paneque M, Miller AZ, Knicker H (2018) Effects of aging under field conditions on biochar structure and composition: implications for biochar stability in soils. Sci Total Environ 613–614:969–976. https://doi.org/10.1016/j.scitotenv.2017.09.124

Deng Y, Qiao S, Wang W, Zhang W, Gu J, Liu L, Zhang H, Wang Z, Yang J (2021) Tolerance to low phosphorus was enhanced by an alternate wetting and drying regime in rice. Food Energy Secur 10(3):e294. https://doi.org/10.1002/fes3.294

Dossou-Yovo ER, Saito K (2021) Impact of management practices on weed infestation, water productivity, rice yield and grain quality in irrigated systems in Côte d'Ivoire. Field Crop Res 270:108209. https://doi.org/10.1016/j.fcr.2021.108209

Dvorský J, Bednarz J, Blajer-Gołębiewska A (2023) The impact of corporate reputation and social media engagement on the sustainability of SMEs: perceptions of top managers and the owners. Equilibrium 18(3):779–811. https://doi.org/10.24136/eq.2023.025

Dwivedi SK, Kumar S, Natividad MA, Quintana MR, Chinnusamy V, Henry A (2023) Disentangling the roles of plant water status and stem carbohydrate remobilization on rice harvest index under drought. Rice 16(1):14. https://doi.org/10.1186/s12284-023-00631-6

Fan MS, Lu SH, Jiang RF, Six J, Zhang FS (2012) Long-term non-flooded mulching cultivation influences rice productivity and soil organic carbón. Soil Use Manage 28(4):544–550. https://doi.org/10.1111/j.1475-2743.2012.00432.x

Fertitta-Roberts C, Oikawa PY, Darrel Jenerette G (2019) Evaluating the GHG mitigation-potential of alternate wetting and drying in rice through life cycle assessment. Sci Total Environ 653:1343–1353. https://doi.org/10.1016/j.scitotenv.2018.10.327

Gao R, Zhuo L, Duan Y, Yan C, Yue Z, Zhao Z, Wu P (2024) Effects of alternate wetting and drying irrigation on yield, water-saving, and emission reduction in rice fields: a global meta-analysis. Agr Forest Meteorol 353:110075. https://doi.org/10.1016/j.agrformet.2024.110075

Genua-Olmedo A, Alcaraz C, Caiola N, Ibáñez C (2016) Sea level rise impacts on rice production: The Ebro Delta as an example. Sci Total Environ 571:1200–1210. https://doi.org/10.1016/j.scitotenv.2016.07.136

Ghorbani M, Neugschwandtner RW, Konvalina P, Asadi H, Kopecký M, Amirahmadi E (2023) Comparative effects of biochar and compost applications on water holding capacity and crop yield of rice under evaporation stress: a two-years field study. Paddy Water Environ 21(1):47–58. https://doi.org/10.1007/s10333-022-00912-8

Grimm A, Fogliatto S, Nick P, Ferrero A, Vidotto F (2013) Microsatellite markers reveal multiple origins for Italian weedy ric. Ecol Evol 3(14):4786–4798. https://doi.org/10.1002/ece3.848

Haque ANA, Uddin MK, Sulaiman MF, Amin AM, Hossain M, Solaiman ZM, Mosharrof M (2022) Rice growth performance, nutrient use efficiency and changes in soil properties influenced by biochar under alternate wetting and drying irrigation. Sustainability-Basel 14(13):7977. https://doi.org/10.3390/su14137977

Hoang TN, Minamikawa K, Tokida T, Wagai R, Tran TXP, Tran THD, Tran DH (2023) Higher rice grain yield and lower methane emission achieved by alternate wetting and drying in central Vietnam. Eur J Agron 151:126992. https://doi.org/10.1016/j.eja.2023.126992

Huang S, Zhu X, Fang J, Zhang X, Zhang H, Zhang Z, Wu X, Zhu X (2023) Pyrolysis temperature dependent effects of biochar on shifting fluorescence spectrum characteristics of soil dissolved organic matter under warming. Sci Total Environ 892:164656. https://doi.org/10.1016/j.scitotenv.2023.164656

IUSS Working Group WRB (2006) World reference base for soil resources 2006. World Soil Resources Reports 103, Rome

Jiang S, Du B, Wu Q, Zhang H, Zhu J (2023) Increasing pit-planting density of rice varieties with different panicle types to improves sink characteristics and rice yield under alternate wetting and drying irrigation. Food Energy Secur 12(1):e335. https://doi.org/10.1002/fes3.335

Kakehashi T, Kikuta M, Menge DM, Gichuhi EW, Samejima H, Makihara D (2021) Alternate Wetting and Drying (AWD) Mitigates the decline in grain filling of Basmati 370 due to low temperature in tropical highlands. Agronomy-Basel 11(11):2345. https://doi.org/10.3390/AGRONOMY1111234

Khan Z, Zhang K, Khan MN, Zhu K, Hu L (2024) Effects of biochar persistence on soil physiochemical properties, enzymatic activities, nutrient utilization, and crop yield in a three-year rice-rapeseed crop rotation. Eur J Agron 154:127096. https://doi.org/10.1016/j.eja.2024.127096

Kliestik T, Nica E, Durana P, Popescu GH (2023) Artificial intelligence-based predictive maintenance, time-sensitive networking, and big data-driven algorithmic decision-making in the economics of Industrial Internet of Things. Oecon Copernic 14(4):1097–1138. https://doi.org/10.24136/oc.2023.033

Kögel-Knabner I, Amelung W, Cao Z, Fiedler S, Frenzel P, Jahn R, Kalbitz K, Kölbl A, Schloter M (2010) Biogeochemistry of paddy soils. Geoderma 157(1–2):1–14. https://doi.org/10.1016/j.geoderma.2010.03.009

Kukal SS, Hira GS, Sidhu AS (2005) Soil matric potential-based irrigation scheduling to rice (Oryza sativa). Irrigation Sci 23(4):153–159. https://doi.org/10.1007/s00271-005-0103-8

Lagomarsino A, Agnelli AE, Linquist B, Adviento-Borbe MA, Agnelli A, Gavina G, Ravaglia S, Ferrara RM (2016) Alternate wetting and drying of rice reduced CH_4 emissions but triggered N_2O peaks in a clayey soil of central Italy. Pedosphere 26:533–548. https://doi.org/10.1016/S1002-0160(15)60063-7

Lampayan RM, Samoy-Pascual KC, Sibayan EB, Ella VB, Jayag OP, Cabangon RJ, Bouman BAM (2015) Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in Central Luzon, Philippines. Paddy Water Environ 13(3):215–227. https://doi.org/10.1007/s10333-014-0423-5

Lavado N, Prieto MH, Mancha LA, Moreno D, Valdés ME, Uriarte D (2023) Combined effect of crop forcing and reduced irrigation as techniques to delay the ripening and improve the quality of cv. Tempranillo (Vitis vinifera L.) berries in semi-arid climate conditions. Agr Water Manage 288:108469. https://doi.org/10.1016/j.agwat.2023.108469

Li Z, Li Z, Letuma P, Zhao H, Zhang Z, Lin W, Chen H, Lin W (2018) A positive response of rice rhizosphere to alternate moderate wetting and drying irrigation at grain filling stage. Agr Water Manage 207:26–36. https://doi.org/10.1016/j.agwat.2018.05.022

Li S, Li M, Wang G, Sun X, Xi B, Hu Z (2019) Compositional and chemical characteristics of dissolved organic matter in various types of cropped and natural Chinese soils. Chem Biol Technol Agric 6(1):20. https://doi.org/10.1186/s40538-019-0158-z

Li S, Zhuang Y, Liu H, Wang Z, Zhang F, Lv M, Zhai L, Fan X, Niu S, Chen J, Xu C, Wang N, Ruan S, Shen W, Mi M, Wu S, Du Y, Zhang L (2023a) Enhancing rice production sustainability and resilience via reactivating small water bodies for irrigation and drainage. Nat Commun 14(1):3794. https://doi.org/10.1038/s41467-023-39454-w

Li Z, Wang B, Liu Z, Zhang P, Yang B, Jia Z (2023b) Ridge–furrow planting with film mulching and biochar addition can enhance the spring maize yield and water and nitrogen use efficiency by promoting root growth. Field Crop Res 303:109139. https://doi.org/10.1016/j.fcr.2023.109139

Li J, Li Y, Wan Y, Wang B, Cai W, Qin X, Zhou Z, Wang X, Yuan J, Deng Q (2024) Annual greenhouse gas emissions from a rice paddy with different water-nitrogen management strategies in Central China. Soil till Res 235:105906. https://doi.org/10.1016/j.still.2023.105906

Liao P, Sun Y, Zhu X, Wang H, Wang Y, Chen J, Zhang J, Zeng Y, Zeng Y, Huang S (2021) Identifying agronomic practices with higher yield and lower global warming potential in rice paddies: a global meta-analysis. Agr Ecosyst Environ 322:107663. https://doi.org/10.1016/j.agee.2021.107663

Linam F, Limmer MA, Ebling AM, Seyfferth AL (2023) Rice husk and husk biochar soil amendments store soil carbon while water management controls dissolved organic matter chemistry in well-weathered soil. J Environ Manage 339:117936. https://doi.org/10.1016/j.jenvman.2023.117936

Liu Y, Lu H, Yang S, Wang Y (2016) Impacts of biochar addition on rice yield and soil properties in a cold waterlogged paddy for two crop seasons. Field Crop Res 191:161–167. https://doi.org/10.1016/j.fcr.2016.03.003

Liu M, Ke X, Liu X, Fan X, Xu Y, Li L, Solaiman ZM, Pan G (2022) The effects of biochar soil amendment on rice growth may vary greatly with rice genotypes. Sci Total Environ 810:152223. https://doi.org/10.1016/j.scitotenv.2021.152223

Liu C, Chen T, Zhang F, Han H, Yi B, Chi D (2024) Soil carbon sequestration increment and carbon-negative emissions in alternate wetting and drying paddy ecosystems through biochar incorporation. Agr Water Manage 300:108908. https://doi.org/10.1016/j.agwat.2024.108908

Loaiza S, Verchot L, Valencia D, Guzmán P, Amezquita N, Garcés G, Puentes O, Trujillo C, Chirinda N, Pittelkow CM (2024) Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production. Agr Ecosyst Environ 360:108787. https://doi.org/10.1016/j.agee.2023.108787

López-Piñeiro A, Albarrán A, Rato Nunes JM, Peña D, Cabrera D (2011) Long-term impacts of de-oiled two-phase olive mill waste on soil chemical properties, enzyme activities and productivity in an olive grove. Soil till Res 114(2):175–182. https://doi.org/10.1016/j.still.2011.05.002

López-Piñeiro A, Sánchez-Terrón J, Martín-Franco C, Peña D, Vicente LA, Gómez S, Fernández-Rodríguez D, Albarrán Á (2022) Impacts of fresh and aged holm-oak biochar on clomazone behaviour in rice cropping soils after transition to sprinkler irrigation. Geoderma 413:115768. https://doi.org/10.1016/j.geoderma.2022.115768

Majumdar A, Dubey PK, Giri B, Moulick D, Srivastava AK, Roychowdhury T, Bose S, Jaiswal MK (2023) Combined effects of dry-wet irrigation, redox changes and microbial diversity on soil nutrient bioavailability in the rice field. Soil till Res 232:105752. https://doi.org/10.1016/j.still.2023.105752

Majumdar A, Upadhyay MK, Giri B, Yadav P, Moulick D, Sarkar S, Thakur BK, Sahu K, Srivastava AK, Buck M, Tibbett M, Jaiswal MK, Roychowdhury T (2024) Sustainable water management in rice cultivation reduces arsenic contamination, increases productivity, microbial molecular response, and profitability. J Hazard Mater 466:133610. https://doi.org/10.1016/j.jhazmat.2024.133610

Majumder S, Powell MA, Biswas PK, Banik P (2022) The impact of Arsenic induced stress on soil enzyme activity in different rice agroecosystems. Environ Technol Innov 26:102282. https://doi.org/10.1016/j.eti.2022.102282

Mallareddy M, Thirumalaikumar R, Balasubramanian P, Naseeruddin R, Nithya N, Mariadoss A, Eazhilkrishna N, Choudhary AK, Deiveegan M, Subramanian E, Padmaja B, Vijayakumar S (2023) Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. Water-Sui 15(10):1802. https://doi.org/10.3390/w15101802

Maroušek J, Trakal L (2022) Techno-economic analysis reveals the untapped potential of wood biochar. Chemosphere 291:133000. https://doi.org/10.1016/j.chemosphere.2021.133000

Martínez-Eixarch M, Alcaraz C, Guàrdia M, Català-Forner M, Bertomeu A, Monaco S, Cochrane N, Oliver V, Teh YA, Courtois B, Price AH (2021) Multiple environmental benefits of alternate wetting and drying irrigation system with limited yield impact on European rice cultivation: the Ebre Delta case. Agr Water Manage 258:107164. https://doi.org/10.1016/j.agwat.2021.107164

Martín-Franco C, Sánchez JT, Alvarenga P, Peña D, Fernández-Rodríguez D, Vicente LA, Albarrán Á, López-Piñeiro A (2023) Effects of fresh and field-aged holm-oak biochar on As, Cd and Pb bioaccumulation in different rice growing environments. Sci Total Environ 887:164012. https://doi.org/10.1016/j.scitotenv.2023.164012

Materu ST, Chen T, Liu C, Chi D, Jun M (2024) Effect of acid-modified biochar coupled with alternate wetting and drying on P leaching, soil P retention and plant P uptake in paddy fields. J Environ Manage 350:119603. https://doi.org/10.1016/j.jenvman.2023.119603

Mboyerwa PA, Kibret K, Mtakwa PW, Aschalew A (2021) Evaluation of growth, yield, and water productivity of paddy rice with water-saving irrigation and optimization of nitrogen fertilization. Agronomy-Basel 11(8):1629. https://doi.org/10.3390/agronomy11081629

Mi W, Sun Y, Zhao C, Wu L (2019) Soil organic carbon and its labile fractions in paddy soil as influenced by water regimes and straw management. Agr Water Manage 224:105752. https://doi.org/10.1016/j.agwat.2019.105752

Mohammed U, Aimrun W, Amin MSM, Khalina A, Zubairu UB (2016) Influence of soil cover on moisture content and weed suppression under system of rice intensification (SRI). Paddy Water Environ 14(1):159–167. https://doi.org/10.1007/s10333-015-0487-x

Mukhopadhyay R, Fagodiya RK, Narjary B, Barman A, Prajapat K, Kumar S, Bundela DS, Sharma PC (2023) Restoring soil quality and carbon sequestration potential of waterlogged saline land using subsurface drainage technology to achieve land degradation neutrality in India. Sci Total Environ 885:163959. https://doi.org/10.1016/j.scitotenv.2023.163959

Nadimi-Goki M, Bini C, Wahsha M, Kato Y, Fornasier F (2018) Enzyme dynamics in contaminated paddy soils under different cropping patterns (NE Italy). J Soil Sediment 18(6):2157–2171. https://doi.org/10.1007/s11368-017-1830-1

Nam TS, Van Thao H, Chiem NH (2024) Reducing greenhouse gas emissions from rice cultivation applied with melaleuca and rice husk biochar in the Vietnamese Mekong Delta. Soil Sci Plant Nutr 70(3):150–159. https://doi.org/10.1080/00380768.2024.2324823

Nguyen HVM, Choi JH (2015) Changes in the dissolved organic matter leaching from soil under severe temperature and N-deposition. Environ Monit Assess 187(6):323, 1–15. https://doi.org/10.1007/s10661-015-4549-8

Nyambo P, Motsi H, Chiduza C, Malobane M (2023) Biochar ageing improves soil properties, growth and yield of red radish (Raphanus sativus) in a Haplic Cambisol. PLoS ONE 18:e0288709. https://doi.org/10.1371/journal.pone.0288709

Oliver V, Cochrane N, Magnusson J, Brachi E, Monaco S, Volante A, Courtois B, Vale G, Price A, Teh YA (2019) Effects of water management and cultivar on carbon dynamics, plant productivity and biomass allocation in European rice systems. Sci Total Environ 685:1139–1151. https://doi.org/10.1016/j.scitotenv.2019.06.110

Pavolová H, Bakalár T, Kyšeľa K, Klimek M, Hajduová Z, Zawada M (2021) The analysis of investment into industries based on portfolio managers. Acta Montan Slovaca 26(1):161–170. https://doi.org/10.46544/AMS.v26i1.14

Pei J, Zhuang S, Cui J, Li J, Li B, Wu J, Fang C (2017) Biochar decreased the temperature sensitivity of soil carbon decomposition in a paddy field. Agr Ecosyst Environ 249:156–164. https://doi.org/10.1016/j.agee.2017.08.029

Peña D, Fernández D, Albarrán A, Gómez S, Martín C, Sánchez-Terrón J, Vicente L, López-Piñeiro A (2022) Using olive mill waste compost with sprinkler irrigation as a strategy to achieve sustainable rice cropping under Mediterranean conditions. Agron Sustain Dev 42(3):36. https://doi.org/10.1007/s13593-022-00769-5

Pimentel D, Berger B, Filiberto D, Newton M, Wolfe B, Karabinakis E, Clark S, Poon E, Abbett E, Nandagopal S (2007) Water resources: agricultural and environmental issues. In: Food, Energy, and Society, 3rd edn, Routledge, pp 183–200. ISBN 9780429142857. https://doi.org/10.1201/9781420046687

Rato-Nunes JM, Martín-Franco C, Peña D, Terrón-Sánchez J, Vicente LA, Fernández-Rodríguez D, Albarrán Á, López-Piñeiro A (2023) Combined use of biochar and sprinkler irrigation may enhance rice productivity in water-stressed regions. Ann Agric Sci 68(1):48–59. https://doi.org/10.1016/j.aoas.2023.05.002

Sánchez-Llerena J, López-Piñeiro A, Albarrán Á, Peña D, Becerra D, Rato-Nunes JM (2016) Short and long-term effects of different irrigation and tillage systems on soil properties and rice productivity under Mediterranean conditions. Eur J Agron 77:101–110. https://doi.org/10.1016/j.eja.2016.04.005

Singh C, Tiwari S, Gupta VK, Singh JS (2018) The effect of rice husk biochar on soil nutrient status, microbial biomass and paddy productivity of nutrient poor agriculture soils. CATENA 171:485–493. https://doi.org/10.1016/j.catena.2018.07.042

Spanu A, Murtas A, Ballone F (2009) Swater use and crop coefficients in sprinkler irrigated rice. Ital J Agron 4(2):47–58. https://doi.org/10.4081/ija.2009.2.47

Sriphirom P, Rossopa B (2023) Assessment of greenhouse gas mitigation from rice cultivation using alternate wetting and drying and rice straw biochar in Thailand. Agr Water Manage 290:108586. https://doi.org/10.1016/j.agwat.2023.108586

Sriphirom P, Chidthaisong A, Towprayoon S (2019) Effect of alternate wetting and drying water management on rice cultivation with low emissions and low water used during wet and dry season. J Clean Prod 223:980–988. https://doi.org/10.1016/j.jclepro.2019.03.212

Sriphirom P, Chidthaisong A, Yagi K, Tripetchkul S, Towprayoon S (2020) Evaluation of biochar applications combined with alternate wetting and drying (AWD) water management in rice field as a methane mitigation option for farmers' adoption. Soil Sci Plant Nutr 66(1):235–246. https://doi.org/10.1080/00380768.2019.1706431

Stávková J, Maroušek J (2021) Novel sorbent shows promising financial results on P recovery from sludge water. Chemosphere 276:130097. https://doi.org/10.1016/j.chemosphere.2021.130097

Stefano LD, Hernández-Mora N, Iglesias A, Sánchez B (2014) Water for rice farming and biodiversity: Exploring choices for adaptation to climate change in doñana, southern spain. In: Adaptation to climate change through water resources management: capacity, equity and sustainability. Routledge, pp 158–179. ISBN 9780815395324. https://doi.org/10.4324/9780203085875-20

Straffelini E, Tarolli P (2023) Climate change-induced aridity is affecting agriculture in Northeast Italy. Agr Syst 208:103647. https://doi.org/10.1016/j.agsy.2023.103647

Surendran U, Raja P, Jayakumar M, Subramoniam SR (2021) Use of efficient water saving techniques for production of rice in India under climate change scenario: a critical review. J Clean Prod 309:127272. https://doi.org/10.1016/j.jclepro.2021.127272

Thakur AK, Mandal KG, Mohanty RK, Ambast SK (2018) Rice root growth, photosynthesis, yield and water productivity improvements through modifying cultivation practices and water management. Agr Water Manage 206:67–77. https://doi.org/10.1016/j.agwat.2018.04.027

Wen E, Yang X, Chen H, Shaheen SM, Sarkar B, Xu S, Song H, Liang Y, Rinklebe J, Hou D, Li Y, Wu F, Pohořelý M, Wong JWC, Wang H (2021) Iron-modified biochar and water management regime-induced changes in plant growth, enzyme activities, and phytoavailability of arsenic, cadmium and lead in a paddy soil. J Hazard Mater 407:124344. https://doi.org/10.1016/j.jhazmat.2020.124344

Xu Y, Zhan M, Cao C, Ge J, Ye R, Tian S, Cai M (2017) Effects of irrigation management during the rice growing season on soil organic carbon pools. Plant Soil 421:337–351. https://doi.org/10.1007/s11104-017-3467-7

Yang CD, Lu SG (2021) Effects of five different biochars on aggregation, water retention and mechanical properties of paddy soil: a field experiment of three-season crops. Soil till Res 205:104798. https://doi.org/10.1016/j.still.2020.104798

Yang J, Zhang J (2023) Simultaneously improving grain yield and water and nutrient use efficiencies by enhancing the harvest index in rice. Crop Environ 2(3):157–164. https://doi.org/10.1016/j.crope.2023.07.001

Yang S, Chen X, Jiang Z, Ding J, Sun X, Xu J (2020) Effects of biochar application on soil organic carbon composition and enzyme activity in paddy soil under water-saving irrigation. Int J Env Res Pub He 17:333. https://doi.org/10.3390/ijerph17010333

Yang X, Wen E, Ge C, El-Naggar A, Yu H, Wang S, Kwon EE, Song H, Shaheen SM, Wang H, Rinklebe J (2023) Iron-modified phosphorus- and silicon-based biochars exhibited various influences on arsenic, cadmium, and lead accumulation in rice and enzyme activities in a paddy soil. J Hazard Mater 443:130203. https://doi.org/10.1016/j.jhazmat.2022.130203

Yue Y, Xu L, Li G, Gao X, Ma H (2023) Characterization of dissolved organic matter released from aged biochar: a comparative study of two feedstocks and multiple aging approaches. Molecules 28(11):4558. https://doi.org/10.3390/molecules28114558

Zhang Y, Wang W, Li S, Zhu K, Hua X, Harrison MT, Liu K, Yang J, Liu L, Chen Y (2023) Integrated management approaches enabling sustainable rice production under alternate wetting and drying irrigation. Agr Water Manage 281:108265. https://doi.org/10.1016/j.agwat.2023.108265

Zhao Q, Chen T, Wang S, Sha Y, Zhang F, Sun Y, Chi D (2023) Effects of five-year field aged zeolite on grain yield and reactive gaseous N losses in alternate wetting and drying paddy system. Sci Total Environ 904:166279. https://doi.org/10.1016/j.scitotenv.2023.166279

Zsolnay A, Baigar E, Jimenez M, Steinweg B, Saccomandi F (1999) Differentiating with fluorescence spectroscopy the sources of dissolved organic matter in soils subjected to drying. Chemosphere 38(1):45–50. https://doi.org/10.1016/S0045-6535(98)00166-0