Irrigation Science (2026) 44:52
https://doi.org/10.1007/s00271-026-01087-4

ORIGINAL PAPER

Status and perspectives for rice irrigation in the Mediterranean Basin

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Received: 29 October 2025 / Accepted: 29 January 2026

Abstract

Rice is cultivated on approximately 1,000,000 ha in the Mediterranean area, with production concentrated in Egypt, Italy, Türkiye, Spain, Grece and Portugal. In these areas, rice is traditionally established by wet seeding and cultivated under continuous flooding (WFL), which requires larger volumes of water compared to other irrigation practices. The aim of this study is to benchmark irrigation methods alternative to WFL across sites representative of the rice agro-ecosystems producing areas of 5 of the main rice-producing countries. For each site, WFL and one or more alternative methods, selected and adapted to site-specific conditions, were implemented and monitored for at least two years. The alternative methods included: alternate wetting and drying (AWD), dry seeding and delayed flooding (DFL), water input/output reduction (WIR), hybrid irrigation (HYBRID), sprinkler irrigation (SPRINKLER), surface drip irrigation (DRIP), and subsurface drip irrigation (SDI). The results suggest that AWD, DFL and WIR, which are easy-to-implement flooding techniques, increase water productivity (WP) and preserve yield production. Both SPRINKLER and HYBRID showed a higher increase in WP (by about 50%) while maintaining or even increasing yield production, but at the cost of changes in irrigation management and investments for equipment purchases (limited in the case of HYBRID and greater for SPRINKLER). DRIP and SDI increasing WP by more than 100% but, sometimes, yield was significantly reduced. Additionally, pressurized irrigation methods, and especially DRIP and SDI, showed the need for careful consideration of site conditions (during system design and management) to avoid yield losses.

Introduction

Rice is of strategic importance for food security in some countries (notably Egypt) and its consumption is steadily increasing throughout the Mediterranean basin where the rice is cultivated on an area of 1,000,000 ha (FAO 2023). The main rice producing countries are Egypt (EG), Italy (IT), Türkiye (TR) and Spain (SP). Italy and Spain (Europe) account for 80% of the European area devoted to rice (312,000 ha), while Egypt and Türkiye (extra-Europe)

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nearly cover the remaining Mediterranean rice area (604,000 ha). Among other rice producers of the Mediterranean area, Greece and Portugal are also relevant, both with about 30,000 ha.

Rice is a semi-aquatic crop traditionally grown in wetlands around rivers or in deltaic regions, creating a unique agro-ecosystem where the wet seeding and continuous flooding irrigation techniques have been widely used. In deltaic areas, a balance is established between the salty seawater and the fresh water distributed by the irrigation of the rice fields, which helps to remove some of the salt through the drainage channels. These artificial wetlands provide a valuable environment for wildlife (Propper et al. 2020, 2024; Chen et al. 2023). However, due to high population density and semi-arid climatic conditions, the Mediterranean is one of the most water-scarce regions, which is a serious constraint for irrigating rice paddies (Harmanny and Malek 2019). Rice grown under wet seeding and continuous flooding (WFL), which is the traditional irrigation method in practically all countries, requires from two to three times more water than other cereals (Kijne 2006; Marcos et al. 2018). Moreover, further pressure on water availability comes from competition for water with other economic sectors such as: urban, industrial, environmental, recreational and tourism (Zikos and Hagedorn 2017). These constraints are exacerbated by the effects of climate change, such as rising air temperatures and changes in rainfall patterns (Iglesias and Garrote 2015).

Water scarcity problems in recent years have led countries to develop regulations that limit or reduce the rice cultivation area. In Egypt, for instance, Ministerial Decree N^{o}. 305/2020 restricts the area in which rice can be grown and prohibits its cultivation outside these areas (USDA FAS 2021). In the Guadalquivir marshes, the main rice-growing area in Spain, water shortages reduced the area under rice by more than 50% in the 2021 and 2022 irrigation seasons (Irrigation Community Bajo Guadalquivir 2022). In 2023, unprecedented water shortages in Spain led to a significant reduction in irrigated agricultural area (Spanish Government 2023) and rice area was severely reduced in all geographical areas of the country. According to the National Rice Authority, Italy lost 26,000 ha of rice fields in 2022 and production fell by more than 30% compared to the previous year as a result of a historic drought in the Po Valley (Levantesi 2022).

To cope with water scarcity several irrigation strategies have been tested and adopted to reduce non-beneficial water use for rice cultivation in different geographical areas (Cesari de Maria et al. 2017; Monaco and Sali 2018; Mallareddy et al. 2023; Arouna et al. 2023; Yu et al. 2024). Among these techniques, the following are investigated in a number of studies: alternate wetting and drying (AWD), dry seeding and delayed flooding (DFL), different strategies to reduce irrigation inputs and outputs (WIR), hybrid irrigation (HYBRID), sprinkler irrigation (SPRINKLER) and surface and subsurface drip irrigation (DRIP and SDI).

AWD technique consists in alternating in the paddy flooded and non-flooded periods after reaching a specific rice growth stage. Depending on the length of the dry periods between two consecutive floodings, AWD can be classified as “safe” or “severe”. The degree of severity can affect the yield and the irrigation volume used (Bouman et al. 2007). Soil water status is monitored in the paddy field using tensiometers or by observing the perched water table in perforated water tubes inserted into the soil (Bouman et al. 2007). The latter is a practical approach to implement AWD, since the water tube can be self-built by farmers. In the literature, AWD-safe refers to a soil water potential ≥ -20 kPa or a perched water level which does not drop below 0.15 m from the soil surface. In case of a “safe” AWD, water savings of 23–24% without a significant yield loss have been observed in many experiments (Carrijo et al. 2017). An additional advantage of AWD is a 40–50% decrease in methane emissions when compared to WFL, which makes this irrigation alternative very interesting in terms of greenhouse gases (GHG) mitigation (Martínez-Eixarch et al. 2022), water saving (Chidthaisong et al. 2018) and reduction of arsenic content in the grain (Martínez-Eixarch et al. 2021). Nowadays, AWD has become a recommended practice in many irrigated rice areas suffering from water scarcity (Richards and Sander 2014). The technique is widespread throughout Southeast Asia, China, India and Japan, and has been successfully adapted to temperate areas such as California and Arkansas, USA (Carrijo et al. 2017).

Dry seeding and delayed flooding (DFL) consists in seeding rice under non-saturated soil conditions using a seed-drill sowing machine, and flooding the field when rice has developed 3–4 leaves (Pandey 2002). From that point onwards, the field is dried only once to conduct cultivation operations. Previous studies in Italy showed that DFL may reduce irrigation water inputs by 10–20% in the first part of the irrigation season, with an irrelevant yield reduction compared to WFL (Cesari de Maria et al. 2017). Nevertheless, its massive adoption could lead to a reduction in recharge to the shallow aquifer during the first part of the irrigation season. This would, in turn, increase the demand for irrigation in June, a critical period when other crops, such as corn, have high water requirements, thereby increasing the risk of water scarcity (Gilardi et al. 2023).

Water input/output reduction (WIR) included an ensemble of irrigation strategies that involve a reduction of the irrigation water volume used. They consist in reducing the field water level from the wet seeding till the dough grain stage and then cutting off the irrigation until harvest.

Previous studies showed that WIR can have a limited negative impact on grain yields (Surendran et al. 2021). Linquist (2020) indicates that there are opportunities to reduce water use with minimal or no yield reduction by preventing tailwater drainage, reducing percolation and seepage as much as possible, selecting short duration varieties and allowing water to percolate instead of draining at the end of the season. Perry et al. (2024) noted that mid-season drainage, as well as multiple drainage events during the season, can reduce methane emissions without affecting yield. However, the reduction of the irrigation water input must still ensure the leaching of salts from the soil while maintaining a soil water potential compatible with rice cultivation (Yang et al. 2007; Park et al. 2022); this is especially challenging in coastal areas where irrigation water has high electric conductivity (EC). In conclusion, since WIR includes a certain number of strategies for reducing water use, water savings and the absence of production losses depend on the technique selected and the specific context.

The hybrid irrigation system consists of a network pipes designed to distribute water evenly across the field through multiple outlets located within the field. This configuration enhances distribution uniformity, reduces deep percolation losses, thus improving application efficiency. The system has been implemented in commercial rice fields in the Nile Delta region-Egypt (Aboukheira 2021).

Surface drip (DRIP), subsurface drip (SDI) and sprinkler (SPRINKLER) irrigation systems can be used to irrigate rice in conditions different from soil saturation and continuous water ponding in the field. A wider designation of these techniques is “aerobic rice production” techniques, because rice is grown under aerobic rather than anaerobic soil conditions, allowing the reduction of irrigation requirements when compared to WFL, but making it more challenging to maintain a similar production (Bouman and Tuong 2001; Bouman et al. 2007).

Up to date, SPRINKLER has been tested for rice production in different countries, such as Pakistan (Kahlown et al. 2007), Italy (Spanu et al. 2009), USA (Vories et al. 2009), India (Senthil Kumar et al. 2018), Spain (Blanco-Alibés 2014; Moreno-Jiménez et al. 2014; Alvarenga et al. 2022) and Brazil (Pinto et al. 2020). These studies have shown a reduction in the irrigation water requirements compared to WFL. However, the effect on yield remains uncertain, with some studies showing reductions and others showing no change. Pinto et al. (2020) reported that when soil water tension was maintained above −10 kPa, sprinkler irrigation water use was reduced by 40% with minimal or no reduction in grain yield compared to WFL. The same threshold of -10 kPa was also found for other aerobic irrigation techniques (Bouman et al. 2007). On the other hand, Nie et al. (2012) and Girsang et al. (2019) pointed to a decrease in rice yield associated with successive rice crops under aerobic soil conditions. According to these authors, the reasons for the yield decline of successive monocropped rice under aerobic conditions could be explained by a combination of biotic and abiotic factors, such as soil structure, an increase in soil pH and nutrient deficiencies, among others. But they underline that further research is needed to better investigate the effect of aerobic rice cultivation on yield production in different environments.

Surface and subsurface drip irrigation (DRIP and SDI, respectively) are characterized by their ability to provide water, and possibly nutrients, directly to the plant’s root zone, minimizing water evaporation, deep water and nutrient percolation, as well as surface water and nutrient runoff. DRIP and SDI distribute water and nutrients across the field through a pipe network that includes manifolders, driplines and emitters, allowing low conveyance and distribution water losses. Depending on its design (emitter flowrate and spacing between driplines and emitters) and how it is managed (water volume for each irrigation event and frequency), DRIP and SDI may significantly reduce the amount of water and nutrients needed to cultivate rice. Compared to DRIP, SDI has the advantage that the driplines are buried and therefore does not interfere with the passage of agricultural machinery in the field. Conversely, soil working depth is limited by the installation of the system. SDI systems are becoming increasingly popular in agricultural regions suffering from water scarcity and have been successfully applied to various crops such as horticulture, orchards, cereals and fodder, but their use in rice is still very rare. In fact, its application to the irrigation of a semiaquatic crop with a very shallow root system such as rice is still a challenge, and the economic costs of the systems need to be assessed. Recently DRIP and SDI systems are receiving attention from researchers and government authorities, as they can be an effective option to strongly increase water productivity, diminish methane emissions and reduce arsenic contents in grains. However, the irrigation systems to be installed are rather expensive and often not economically sustainable considering rice prices on the market. Despite the interest generated, there are still few studies in the literature analysing the positive aspects and difficulties of rice production using drip irrigation methods (Sharda et al. 2017; Arouna et al. 2023).

The objective of this work is to present the experimental activities conducted from 2019 to 2021 in rice-growing areas of the main Mediterranean rice-producing countries (Egypt, Italy, Türkiye, Spain, and Portugal), aimed at comparing water-saving irrigation techniques with the traditional water seeding and continuous flooding (WFL). The management of the research fields, including instrumentation and data analysis, were planned and conducted by different scientific teams within the MEDWATERICE PRIMA Project (Facchi 2022). To maximize the utility of the study for the local community, the water-saving techniques tested in each area (from one to three per area) were selected in collaboration with local stakeholder panels, which included key players of the rice production chain of each country. The panel considered the main challenges and potential constraints in each geographical location and selected solutions to be tested on pilot farms, always implemented in parallel with WFL (in one site changes to the WFL practice where made, see Sect. "Irrigation management of the trials"). For each irrigation strategy, the most appropriate techniques, technologies and rice varieties were chosen by the panels to minimize production losses as well as to fit local practices; consequently, often the same irrigation strategy shows differences among countries and sites.

Although it would have been possible to produce a paper for each geographical area covered by this study, all the experimental layouts and achieved results were instead summarized in a single paper. This approach allows readers to gain an overview of the state of the art of alternative rice irrigation techniques to WFL in the Mediterranean basin, and facilitates the transmission of the main lessons learned during the MEDWATERICE project.

Materials and methods

Main characteristics of the rice production areas

The field trials were carried out in five of the main rice producing countries in the Mediterranean basin (Fig. 1).

A brief description of the five rice production areas included in the study is given below.

Lomellina (Italy): It is located in the north of Italy, on the left bank of the river Po, in the region of Lombardy. Its rice area accounts for about 65,000 ha, which represents more than 25% of the Italy's total rice production. Historically, it had abundant surface water resources while, in recent years, it has experienced more frequent periods of water scarcity, especially in June and July. Competition with other water uses is increasing.

Baix Ter (Spain): It is located in NE Spain, at the river Ter. The rice area is about 1,000 ha, which accounts for about 1% of the Spanish rice production. Water availability is limited and strong competition with other sectors exists (especially civil and touristic uses).

Guadalquivir Marshes (Spain): It is located in SW Spain, between the Doñana Park (Biosphere Reserve) and the Guadalquivir River estuary. The rice area account for 40,000 ha, which is about 40% of the Spain's rice production. The availability of water for irrigation is limited, and the rice cropping area has been drastically reduced in recent years due to water scarcity. Salinity is also a potentially critical

Fig. 1 Location of the farms experimenting water-efficient irrigation strategies for rice during the period 2019–2021 in the Mediterranean basin (EG, IT, ES, TR, PT), as part of the MEDWATERICE project (https://www.medwaterice.org/)

problem, the severity of which depends on the rate of water release from upstream river reservoirs and ocean tides.

Lower Mondego and Lis valleys (Portugal): The two valleys are located in the central Portugal, at the Mondego and Lis rivers, respectively. The total area under rice is 6,000 ha, about 20% of the Portuguese rice production. Water availability is not currently a critical issue, but periods of water scarcity are increasing.

Nile Delta (Egypt): It accounts for about 600,000 ha of rice, almost all of Egypt's rice production. Rice cultivation in this region plays a key role in mitigating seawater intrusion from the Mediterranean Sea, helping to maintain soil quality and freshwater availability in the Delta. However, water scarcity has been increasing over the years, and competition for water with other crops is very high. The irrigated area affected by salinization in Egypt is about 30%–40% of the total cultivated area, making this a critical issue for rice production.

Bafra Valley (Türkiye): It is located in the Kizilirmark Delta, in the middle of the Black Sea coast. The rice area is about 13,000 ha, which represents 8% of Türkiye's total rice production. The availability of surface water is limited, and the excessive use of groundwater increases the risk of water scarcity and salinisation problems. Competition for water resources in the region is also increasing, and paddy production tends to consume excessive water and energy for water pumping.

Tested rice irrigation strategies

Irrigation strategies tested in each geographical area

For each specific irrigation strategy, the most appropriate technologies, rice varieties and agronomic practices were selected to minimize the impact on yield losses. The irrigation strategies tested in each geographical area are summarised in Table 1.

Experimental layouts

Table 2 lists in a structured fashion all the main characteristics of the experimental sites and their designs at each geographical location. It reports climate variables as air temperatures (Tmin and Tmax), cumulative rainfall and crop evapotranspiration during the experimental growing seasons under optimum soil water conditions (ETc; Allen et al. 1998). Field dimensions, soil texture, average depth to groundwater, rice variety and instrumentation installed in each area are also shown. Small experimental plots have replicates to ensure representativeness, while large production fields usually do not.

Table 1 Summary of irrigation strategies tested in different geographical areas

Irrigation strategy	Italy (Lomellina)	Spain (Baix Ter)	Spain (Lower Guadalquivir)	Portugal (Lower Mondego Valley)	Portugal (Lis Valley)	Egypt (Nile Delta)	Türkiye (Bafra Valley)
Wet-seeding and traditional flooding (WFL)	X	X	X	X	X	X	X*
Alternate Wetting and Drying (AWD)	X			X	X		X
Dry-seeding and Delayed Flooding (DFL)	X	X					
Reduction in irrigation input/output (WIR)			X				
Hybrid irrigation (HYBRID)						X	
Sprinkler irrigation (SPRINKLER)						X	
Surface Drip Irrigation (DRIP)					X	X	X
Subsurface Drip Irrigation (SDI)		X					

*At the Bafra Valley site some changes to WFL practices have been made

Data collected from each experimental site during the three years of experimental activities are archived in Dataverse (https://dataverse.unimi.it/), a FAIR (Findable, Accessible, Interoperable, and Reusable) and OpenAIRE-compliant repository provided by the University of Milan (UMIL). The Dataverse dedicated to the MEDWATERICE project, named MEDWATERICE Dataverse, is publicly accessible at https://dataverse.unimi.it/dataverse/MEDWATERICE. All datasets are openly available under a Creative Commons CC0 licence, ensuring unrestricted access and reuse.

Irrigation management of the trials

Water seeding and continuous flooding (WFL) is the reference irrigation strategy for the research project and has been adopted in all areas and years, apart from the Bafra Valley in Türkiye where changes to the WFL practice have been adopted. The reason is that, unlike in other countries, farmers in the Bafra Valley do not practise WFL. This would have made the reference meaningless for the local community.

Consequently, in Bafra Valley, WFL was modified into transplanted rice with continuous flooding in 2019, and dry seeding with immediate flushing (very similar to WFL) in 2020 and 2021. In both cases, the adopted practices are not too dissimilar to WFL; anyway, the anomaly is highlighted in the results discussion.

In Egypt, WFL is typically implemented in uneven plots, where furrows are established between rice rows and the surface water layer is generally thinner than in other locations. Despite these local variations, the practice involves wet seeding and continuous flooding, with water covering the entire field. Therefore, it can be considered functionally comparable to other WFL systems.

The alternative rice irrigation methods are presented hereafter, detailing the management decisions made to implement the solutions at each site.

Alternate wetting and drying (AWD) AWD was tested in Italy during years 2019 and 2020, and in Portugal and Türkiye in the period 2019–2021 (Fig. 2).

The AWD technique was applied in the same way at the Lomellina (Italy) and Portuguese sites.

Rice was water-sown and the first AWD cycle started at the beginning of tillering. A “safe AWD” was used, in order to avoid yield losses. In particular, a threshold of -0.10 m from the soil ground surface was set in the water tube before reflooding, which in Lomellina (where tensiometers were installed) corresponded to a soil matric potential of about −5 kPa at −0.05 m depth.

Each time the threshold was reached, the paddy was re-flooded to a water level of about 0.08–0.10 m above the soil surface. Particular attention was paid to panicle initiation, flowering and early ripening, as rice is highly sensitive to water stress during these stages. The final irrigation was applied at the dough growth stage of the grain.

In Türkiye, AWD was tested under three levels of severity, corresponding to three different thresholds in the water tube (−0.05 m, −0.10 m and −0.15 m); the three trials are named ADW5, ADW10 and ADW15, respectively. Rice was transplanted in 2019, while dry seeding and immediate flushing were carried out in 2020 and 2021. Irrigation management started at the beginning of early tillering in all cases. When the different water thresholds in each treatment were reached, paddies were re-flooded to an average water level of a maximum 0.10 m. Around the flowering stage, the water level was maintained between 0.08 and 0.10 m to reduce the risk of panicle sterility due to water deficit stress. At the end of the flowering stage, the AWD initial irrigation criteria were resumed until the dough stage.

Dry-seeding and delayed flooding (DFL) DFL was tested in Italy in 2019 and 2020, and in northern Spain in 2019, 2020 and 2021 (Fig. 3).

In Lomellina (Italy), the plots were dry sowed (Fig. 3a) at the end of April-beginning of May and maintained under aerobic conditions until tillering stage (3–4 leaves), around the beginning of June. Thus, approximately four weeks after sowing, the plots were flooded and water was managed as in the WFL strategy. Ponding water levels ranged from 0.06 to 0.10 m throughout the flooding period, which lasted until dough stage of the grain.

DFL in the Baix Ter (Spain) was implemented similarly to Lomellina, with some key differences. Once the fields were flooded (Fig. 3b), irrigation was managed to maintain the ponding water level and prevent runoff throughout the irrigation period to save water. Drainage valves were therefore kept closed throughout the season. After the initial flooding, water applications of 20–70 mm/day were made at intervals of 5 to 10 days, according to the irrigation consortium schedule. Water levels in the field ranged from 0.02 to 0.15 m during the flooding period, which ended at the early milky grain stage.

Irrigation input/output reduction (WIR) WIR was tested only in the Lower Guadalquivir rice area during the period 2019–2021 (Fig. 4). Flooding started at the same time as in WFL, but a water level of 0.05 m was maintained from the wet seeding till the grain dough stage. Another difference compared to WFL was that in WIR irrigation was cut off from the grain dough development stage until harvest,

Table 2 For each geographical area: irrigation strategies applied and characteristics of the experimental layouts

Lomellina (Italy)	
Location	Ente Nazionale Risi (ENR) – Rice Research Centre's experimental farm located at Castello d'Agogna (Pavia).
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	145 days, 4.2 °C, 37.5 °C, 18.3 MJ/m^2 day, 287 mm, 670 mm (2019–2021).
Irrigation strategies, field/plot dimension and replicates	WFL, DFL and AWD: plot dimensions: 20 m × 70 m; 2 replicates for each irrigation strategy.
Soil texture	Silty-loam in all the plots.
Groundwater depth	About 2 m before the irrigation season, 0.15–0.20 m in the middle of the season.
Rice variety	Centauro.
Instrumentation for the measurement of water balance terms	• Water inflow and outflow discharges: long throated flumes (self-made) completed with pressure transducers (Keller, Switzerland) installed in stilling wells. • Ponding water level: pressure transducers (Keller, Switzerland). • Soil water tension: tensiometers placed at −5 cm from the soil surface (Irrometer, USA). • Management of AWD strategy: periodic measurements of the water level below the ground surface in self-made water tubes (WTs). • Groundwater level: piezometers equipped with pressure transducers (Keller, Switzerland). All sensors were connected to dataloggers (Campbell scientific; USA).
Baix Ter (Spain)	
Location	Commercial fields in the municipalities of Pals and Torroella de Montgrí (Girona).
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	160 days, 5.7 °C, 35.5 °C, 20,0 MJ/m^2day, 128.0 mm, 508.2 mm (2019–2021).
Irrigation strategies, field/plot dimension and replicates	Gravity methods • WFL and DFL: 1 ha each, no replicates. Pressurized methods • SDI-1 and SDI-2: 0.5 ha and 0.75 ha, no replicates.
Soil texture	WFL: Silty-clay-loam, DFL: Loam, SDI 1: Silty-clay, SDI 2: Sandy-loam.
Groundwater depth	WFL and DFL: About 1 m before the irrigation season, from 0.35 to 0.96 m during the irrigation season. SDI 1: About 1 m before the irrigation, from 0.32 to 0.55 m during the cropping season. SDI 2: > 2 m.
Rice variety	Bahia
Instrumentation for the measurement of water balance terms	Gravity methods • Water inflow in WFL: volumetric meter CZ TJ125 (Contazara, Spain). • Water inflow in DFL: volumetric meter CZ Octave USDN150 (Contazara, Spain) • Water outflow: no drainage in the fields. • Water ponding level: radar sensor SITRANS LR100 (Siemens, Germany). • Soil water content: Drill & Drop multi-level probe (Sentek, Australia) with sensors at 0.05, 0.15, 0.25, 0.35, 0.45 and 0.55 m soil depths. • Groundwater level: piezometers (manual readings). Pressurized methods • Water inflow: volumetric meters: Woltman WP (Gaer, Spain) in SDI 1 and WST50SB (ARAD, Israel) in SDI 2. • Soil water content sensors 10HS (Meter Group, United States) at 0.10, 0.20 and 0.30 m soil depths. • Groundwater level: piezometers (manual readings).
Guadalquivir marshes (Spain)	
Location	Commercial fields in the municipality of Isla Mayor (Sevilla).

Table 2 (continued)

Guadalquivir marshes (Spain)	
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	145 days for J.Sendra and 155 days for Puntal, 6.8°C, 37.8°C, 23.4 MJ/m^{2}day, 231.0 mm, 732.6 mm (2019–2021).
Irrigation strategies, field/plot dimension and replicates	WFL and WIR: 5 ha each, no replicates.
Soil texture	Silty-loam.
Groundwater depth	About 0.60 m during the irrigation season.
Rice variety	J. Sendra (in 2019 and 2020) and Puntal (in 2021)
Instrumentation for the measurement of water balance terms	• Water inflow and outflow: weir with pressure transducer HYDROS 21 (METER, USA). • Ponding water level: pressure transducer HYDROS 21 (METER group, USA). • Soil water tension: tensiometers (Irrometer, USA) installed at 0.05 and 0.15 m soil depths. • Groundwater level: piezometers equipped with pressure transducers (RBR, Canada).
Lower Mondego and Lis valleys (Portugal)	
Location	Lower Mondego: commercial fields in Quinta do Canal, municipality of Figueira da Foz. Lis: commercial fields in the municipality of Leiria.
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	145 days, 4.8 °C, 34.0 °C, 23,4 MJ/m^2 day, 63.0 mm, 565.0 mm (2019–2021).
Irrigation strategies, field/plot dimension and replicates	Gravity methods • Mondego Valley: WFL: 3.15 ha; AWD: 1.6 ha. • Lis Valley: WFL: 2.8 ha; AWD: 0.15 ha. Pressurized methods • Lis Valley: DRIP: 0.06 ha
Soil texture	Mondego Valley: Silty-loam. Lis Valley: Clay-loam.
Groundwater depth	0.65 m during the irrigation season in Mondego and 0.85 m in Lis Valley.
Rice variety	Ariete
Instrumentation for the measurement of water balance terms	Gravity methods • Water inflow: weir with pressure transducer Troll 100 (In-Situ, USA). • Water outflow: weir with pressure transducer Troll 100 (In-Situ, USA). • Ponding water level: pressure transducer Troll 100 (In-Situ, USA). • Management of AWD strategy: measures of water level below the ground surface in self-made water tubes (WTs). • Groundwater level: piezometers (manual readings). Pressurized methods • Volumetric flow-meter Hydroject (Hidroconta, Spain). • Soil water tension: tensiometers (Irrometer-SR, Riverside, USA). • Groundwater level: piezometers (manual readings).
Nile Delta (Egypt)	
Location	Two experimental sites, one to the north and one to the east of the Nile Delta.
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	135 days, 20.3°C, 41.1°C, 3950 MJ/ m^2 day, no rainfall, 976.0 mm (2019–2021).

Table 2 (continued)

Nile Delta (Egypt)	
Irrigation strategies, field/plot dimension and replicates	Gravity methods • North Nile Delta: WFL: 3 m x 10 m, 3 replicates. Pressurized methods • North Nile Delta: HYBRID: 3 m x 10 m, 3 replicates. • East Nile Delta: SPRINKLER: 3 m x 10 m, 3 replicates; DRIP: 3 m x 10 m, 3 replicates.
Soil texture	North Nile Delta: heavy clay; East Nile Delta: clay.
Groundwater depth	North Nile Delta: 0.9 m during the irrigation season. East Nile Delta: 1.2 m during the irrigation season.
Rice variety	Hybrid rice-EH1
Instrumentation for the measurement of water balance terms	Gravity methods • Water inflow: Parshall flume equipped with pressure transducers. • Water outflow: Parshall flume equipped with pressure transducers. • Groundwater level: piezometers (manual readings) Pressurized methods • Water inflow: volumetric flow-meter Ultra Oval Type S (Oval, Japan). • Soil water tension: tensiometers (Irrometer-SR, Riverside, USA) at 0.30, 0.60 and 0.90 m depth. • Groundwater level: piezometers (manual readings)
Bafra Valley (Türkiye)	
Field location	Rice field station of the Black Sea Agricultural Research Institute in Bafra Valley, Samsun province.
Length of the growing season, average Tmin and Tmax, average daily solar radiation, cumulative rainfall and ETc	135 days, 8.7°C, 33.0°C, 19.7 MJ/m2 day, 153.4 mm, 481.6 mm (2019–2021).
Irrigation strategies, field/plot dimension and replicates	Gravity methods • WFL (variations): 5 m × 5 m, 3 replicates. • AWD: 5 m × 5 m, 3 replicates. Pressurized methods • DRIP: 5 m × 5 m, 3 replicates.
Soil texture	Silty-clay.
Groundwater depth	1.40 m during the irrigation season.
Rice variety	Osmanscik-97.
Instrumentation for the measurement of water balance terms	Gravity methods • Water inflow: volumetric flow-meter (Klepsan Vana, Türkiye). • Water outflow: no drainage. • Water ponding level: manual daily measurements. • Soil water tension: tensiometers at 0.15 m depth (Irrometer, USA). • Management of AWD strategy: measured water level below the ground surface in self-made water tubes (WTs). • Groundwater level: piezometers (manual reading). Pressurized methods • Water inflow: volumetric flow-meter (Klepsan Vana, Türkiye). • Soil water tension: tensiometers at 0.15 m depth (Irrometer, USA). • Groundwater level: piezometers (manual readings).

Fig. 2 AWD plots in (a) Lomellina and (b) Bafra Valley

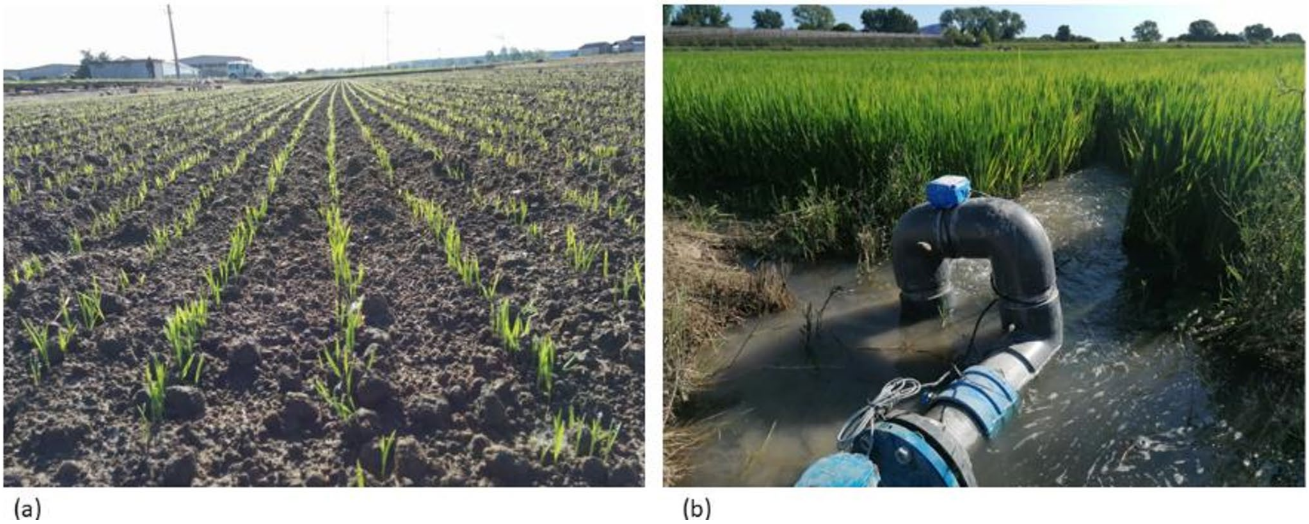

Fig. 3 DFL fields in **a** Lomellina and **b** Baix Ter

while in WFL the irrigation was maintained until a few days before harvesting. During the 2021 season, given the severe drought situation, that resulted in a 54% reduction of the normal water allocation for rice irrigation in the Guadalquivir area, both plots (WFL and WIR) were irrigated similarly, receiving the same amount of water at the rice paddy entry. The key difference, which contributed to lower water consumption, was that WIR had higher drainage than WFL, since the field was drained earlier. In the Guadalquivir marshes, salinity, exacerbated by water scarcity throughout the crop cycle, poses a significant challenge, especially in the vegetative and reproductive phases. However, during the ripening phase, salinity's impact is less pronounced, allowing for water use reduction without compromising yield or product quality.

Multi-outlet hybrid irrigation (HYBRID) This method was only tested in the Nile Delta during the period 2020–2021. Rather than supplying water through unlined ditches,

Fig. 4 WIR rice fields in Guadalquivir Marshes

Fig. 5 SPRINKLER irrigated fields in the Nile Delta

pressurised pipes were used to deliver water from outlets located at each experimental plot. A single 2” diameter outlet provided 6–9 m³/h at 100 kPa. The irrigation was applied when the average soil water tension at -0.30 m depth reached − 20 kPa, then the water volume required to replenish the soil water content from 0 to -0.60 m depth was applied.

Sprinkler irrigation (SPRINKLER) Sprinkler Irrigation was tested in Egypt in the agricultural seasons 2020 and 2021. Plots were irrigated by multi-nozzle impact sprinklers spaced 12 m × 12 m (Fig. 5), having nozzles providing 2.5–7 $m^3 h^{-1}$ each when operated at 250 kPa. The irrigation system was automatically commanded by solenoid valves connected to the platform U-Manange (NETAFIM, Israel). The average soil water tension at which irrigation was applied changed along the season: it was kept at -25 kPa at 0.20–0.30 m from sowing to tillering, at -15 kPa from tillering to the beginning of grain ripening, and at -45 kPa until the end of the irrigation period.

Surface drip irrigation (DRIP) Surface drip irrigation was tested in Lis Valley (Portugal), Nile Delta (Egypt) and Bafra Valley (Türkiye) (Fig. 6).

In the Lis Valley DRIP was tested during two irrigation seasons (2020 and 2021). Rice was drill seeded, the irrigation system configuration consisted in driplines spaced 0.60 m with 1 L h^{-1} emitters every 0.30 m. Crop row spacing was 0.20 m and 0.30 m in 2020 and 2021 seasons, respectively (Fig. 6a). Sprinkler irrigation was used during the first 10 days after sowing to promote germination, applying about 5 mm day^{-1} on a daily basis. Drip irrigation was scheduled to irrigate from 1 to 3 h per day, applying from 5 to 15 mm of water depending on soil water tension and plant visual appearance.

In the Nile Delta, DRIP was tested during two irrigation seasons (2020 and 2021) (Fig. 6b). Hybrid–EH1 variety was drill seeded. The system configuration consisted of driplines spaced 0.50 m with 4 L h^{-1} self-compensating emitters every 0.30 m. The irrigation was managed based on the average soil water tension measured at three different locations in the plot. The irrigation criterion was the same as that previously described for the sprinkler trials in the same location.

In the Bafra Valley (Türkiye), DRIP was tested during two agricultural seasons (2019 and 2020) (Fig. 6c). The technique followed a water transplanting in the first year and a dry seeding in the second year. Before designing the system, infiltration tests were carried out on the plots. The system was characterized by driplines spaced 0.40 m, with emitters having a discharge of 2.5 L h^{-1} spaced 0.40 m along the line, to allow a complete and uniform saturation of the soil surface. Two different irrigation criteria were applied, based on the application of 1.75 and 2 times the reference evaporation measured with a "Class A" pan evaporimeter (DRIP1 and DRIP2). For both treatments, the soil was kept saturated for the first 3 weeks after transplanting or sowing to promote better seedling establishment. Drip irrigation was then scheduled every two days and applied until 2 weeks before harvest.

Sub-surface drip irrigation (SDI) SDI was tested in two different soil conditions in Baix Ter (Spain). The first experimental field was located on a sandy-loam soil (SaL) outside the traditional Baix Ter rice cropped area (Fig. 7a and b); the trial was carried out for three years (2019–2021). In addition, in years 2020–2021 the trial was extended to a silty-clay soil (SiC) within the traditional Baix Ter rice area. In the SaL field, drip lines were installed at a depth of 0.15 cm, with a spacing of 0.66 m and emitters of 1 L h^{-1} every 0.30 m along the line. In the SiC field, the configuration was the same as in the previous case, except for the 0.75 m

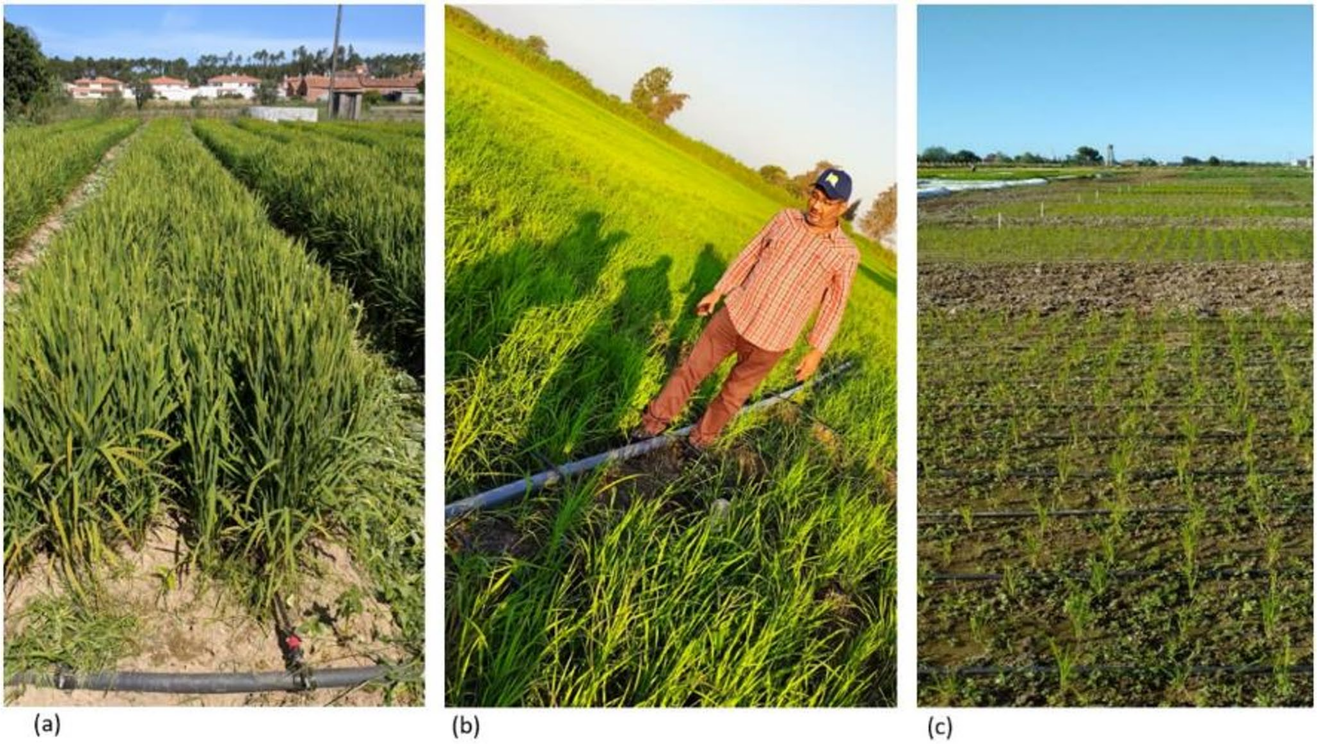

Fig. 6 DRIP irrigation rice plots/fields in **a** Lis Valley, **b** Nile Delta, and **c** Bafra Valley

Fig. 7 SDI irrigation rice plots on a sandy-loam soil in the Baix Ter, **a** first irrigation event, **b** crop development

drip line spacing. In 2019, the irrigation criterion was based on supplying every day the potential crop evapotranspiration (ETc) water amount. Since 2020, the general irrigation criterion was based on keeping the soil between −10 and 0 kPa at a depth of 0 to 15 cm throughout the whole irrigation period.

Water balance equation

The water balance was calculated for each experimental plot or field. The time step is seasonal, and the cropping season was considered from rice sowing to the harvest date in case of dry seeded rice, and from the pre-seeding flooding to harvest for water seeded rice. A field control volume ranging from the top of the ponding water level to 0.30 m soil depth (i.e., bottom of the rice root system), was considered. The following equation was used to calculate the water balance:

$$I + P \pm \Delta\theta \pm \Delta l = ET_c \pm SP \tag{1}$$

where: I is irrigation water ($m^3\ ha^{-1}$), P is precipitation ($m^3\ ha^{-1}$), $\Delta\theta$ is soil water content variation ($m^3\ ha^{-1}$), Δl is ponding water level variation ($m^3\ ha^{-1}$), ETc is crop evapotranspiration under optimal soil water condition computed as Penman-Monteith modified by FAO (Allen et al. 1998) ($m^3\ ha^{-1}$), and SP ($m^3\ ha^{-1}$) includes two main processes: deep percolation (DP), namely the net vertical flux at the bottom of the root zone volume (directed downward in flooding conditions), and the net lateral seepage S through the bunds (Bouman et al. 2007; Facchi et al. 2018). However, the deep percolation flux is usually much greater than the lateral seepage through the bunds, especially in large fields (Facchi et al. 2018); therefore, in this paper, DP ~ SP was considered in the water balance computations. The SP term was calculated as the closure of the water balance Eq. (1).

In some of the areas (Baix Ter, Lower Mondego and Lis Valleys, Nile Delta and Bafra Valley) irrigation was managed in such a way that there was no irrigation outflow from the irrigated fields. In the Lomellina and Guadalquivir marshes, where the irrigation runoff is reused to irrigate downstream paddy fields, irrigation (I) was calculated as (Q_{in}-Q_{out}) / A, where Q_{in} is the irrigation inflow, Q_{out} is the irrigation outflow and A is the irrigated area.

Irrigation performance indices and data treatment

Water productivity (WP, in kg m^{-3}), relative water supply (RWS, dimensionless) and deep percolation fraction (DPF, expressed in %) were chosen as indices to evaluate the irrigation performances throughout the rice growing season. They have been calculated as set out below.

$$WP = \frac{Yield}{I + P} \tag{2}$$

$$RWS = \frac{I + P}{ETc} \tag{3}$$

$$DPF = \frac{DP}{I} \cdot 100 \tag{4}$$

where: ETc is the actual crop evapotranspiration under optimal soil water conditions ($m^3\ ha^{-1}$); I is irrigation ($m^3\ ha^{-1}$); P is precipitation ($m^3\ ha^{-1}$); DP is the deep percolation ($m^3\ ha^{-1}$). Rice yield has been standardised to 14% moisture content (kg ha^{-1}) to allow comparisons. When considering only irrigation in the calculation, WP is replaced by WP_{Irr}.

Irrigation volume, rainfall, crop evapotranspiration under optimal soil water conditions, grain yield and irrigation performance indices were reported for each irrigation strategy in all geographical locations. Mean values and percent coefficient of variation (CV%) were calculated considering the years of experimentation (two or three) within the period 2019–2021. The values of these variables for each irrigation strategy were compared with those obtained for WFL in each area, as comparing water fluxes and index values obtained using the same irrigation strategy in different geographical contexts can be misleading due to the strong dependence of the variables from on site-specific conditions such as climate, soil characteristics and agronomic practices.

Statistical analysis

To identify statistically significant differences between WFL and the alternative irrigation strategies, statistical tests were applied to each observed variable (irrigation, percolation, ET, yield, WP, RWS, DPF) at each site.

The main tests applied are the parametric two-sample t-test, which is powerful but relies on distributional assumptions that may not fully hold in this context, and the non-parametric Wilcoxon rank-sum test. While parametric tests can suggest statistical significance in this study's data analysis, only non-parametric tests can determine the significance level with certainty.

When experimental years and the number of observations coincided between WFL and the alternative method, the paired *t*-test and the non-parametric sign-rank test were adopted, as they offer greater power but need data pairing.

Results and discussion

Seven different water-saving irrigation options were tested and compared with the traditional irrigation strategy in seven rice-growing areas across the Mediterranean basin, resulting in 13 experimental trials (Table 1). The results in terms of irrigation water volumes, rainfall, crop evapotranspiration under optimal soil water conditions, grain yield, WP, RWS and DPF obtained for the alternative irrigation strategies (AWD, DFL, WIR, HYBRID, SPRINKLER, DRIP, and SDI) are reported and compared with those obtained when implementing water seeding and continuous flooding (WFL) at each site. The results obtained with each technique are, moreover, discussed in the light of the previous studies published in the literature.

Given the very limited number of observations, most of the applied statistical tests did not reach the 5% significance level (Tables 1 and 2 - *supplementary material*). This is not unexpected, as irrigation management is only one of several factors influencing the observed variables (e.g. inter-annual variability due to weather conditions can easily overshadow the differences among methods). Consequently, only rarely do statistically significant differences appear, and only in those cases they are explicitly highlighted in the text. Higher statistical significance can be reached with larger datasets, especially when the observed differences are stable across years (e.g., irrigation in WFL consistently exceeding that in AWD) and are corroborated by findings in the literature. For this reason, comparisons with published results are carefully discussed throughout the text.

Water seeding and continuous flooding (WFL)

In Table 3 are summarized, for the WFL water management and for each geographical location, the main soil water balance terms, rice variety, grain yield, and the indices WP, RWS, and DPF.

The results presented in Table 3 show large differences in terms of soil water balance terms between the different locations.

Four sites show an average irrigation amount around 13,500 m^3 ha^{-1} (Baix Ter, Lower Mondego, Lis Valley and Nile Delta), two are around 23,000 (Guadalquivir Marshes, Lomellina), while Bafra Valley reaches the extreme value of about 39,000 m^3 ha^{-1}. Few published studies have directly measured irrigation water applied to rice using flow meters or gauges, and a substantial yearly variation in the volume of water applied has been reported. Previous studies conducted in Lomellina found that the applied net irrigation volume, excluding water lost through lateral seepage, ranged from 15,200 to 30,200 m^3 per hectare (Cesari de Maria et al. 2017). This range is consistent with the values observed across the different geographical areas examined in this study. With the exception of the Nile Delta, the Lower Mondego and the Lis Valley, DPF values are higher than 60%, indicating that most of the applied water is lost through vertical deep percolation. These DPF values are in line with those previously reported by Hatiye et al. (2017) and Xu et al. (2017), who found a DPF ranging from 50 to 90%. However, these values can decrease to around 20% in clayey soils with a very shallow groundwater table, as upward capillary flow can also contribute to the crop water supply (Xu et al. 2019). Indeed, the variability in the amount of irrigation is mainly due to the wide range of SP values, which span from approximately 5,000 m^3/ha in the Nile Delta to 25,000 m^3/ha in the Lomellina region, and even up to 35,000 m^3/ha in the Bafra Valley, despite the silty clay soil.

Regarding ETc, the average value for each site ranged from about 5,300 to 8,200 m^3 ha^{-1} per season, being minimal in the Bafra Valley and maximal in the Nile Delta. Nile Delta also has the minimum rainfall (0 m^3 ha^{-1}), while Lomellina shows the higher amount (2,710 m^3 ha^{-1}). The relative water supply (RWS, which indicates the relationship between irrigation plus rainfall and ETc), ranged from 1.5 in the Nile Delta (i.e. water supply is 1.5 times ETc+rainfall), to 7.7 in the Bafra Valley. This shows that there is a wide range of situations between sites.

Grain yield ranges from around 10 t ha^{-1} in the Lomellina and Nile Delta regions to around 6.5 t ha^{-1} in the Baix Ter

Table 3 Rice varieties, soil water balance terms, grain yield and water productivity (WP), relative water supply (RWS), deep percolation fraction (DPF) indices for the wet seeding and continuous flooding (WFL) practice at each geographical location

Geographical area	Rice varieties	Irrig water (m^3 ha^{-1})	Rainfall (m^3/ha)	ETc (m^3 ha^{-1})	SP (m^3 ha^{-1})	Grain yield (t ha^{-1})	WP (kg m^{-3})	RWS (m^3 m^{-3})	DPF (%)
Lomellina (Italy)	Centauro	24,750 (4.1%)	2710 (44.9%)	6,640 (2.1%)	20,505 (8.0%)	10.58 (8.0%)	0.39 (10.3%)	4.1 (4.9%)	82.8 (4.0%)
Baix Ter (Spain)	Bahia	13,055 (4.5%)	1132 (24.6%)	5,529 (12.8%)	10,658 (4.7%)	6.50 (6.0%)	0.46 (8.7%)	2.6 (7.7%)	73.3 (18.3%)
Guadalquivir Marshes (Spain)	J. Sendra/ Puntal	23,346 (23.4%)	593 (61.2%)	7,527 (5.8%)	16,412 (35.2%)	8.92 (5.0%)	0.38 (18.4%)	3.2 (9.4%)	68.9 (14.1%)
Lower Mondego Valley (Portugal)	Ariete	14,028 (12.3%)	1299 (42.8%)	6,664 (3.1%)	5,258 (27.2%)	9.19 (6.0%)	0.61 (8.2%)	2.3 (13.0%)	37.4 (25.4%)
Lis Valley (Portugal)	Ariete	14,586 (12.0%)	986 (22.5%)	6,618 (6.5%)	7,203 (25.8%)	6.61 (12.2%)	0.43 (9.3%)	2.4 (12.5%)	49.1 (16.9%)
Nile Delta (Egipt)	Hybrid EH1	12,395 (17.5%)	0 (0.0%)	8,199 (0.0%)	4,634 (14.3%)	10.21 (8.5%)	0.83 (8.4%)	1.5 (20%)	34.3 (2.6%)
Bafra Valley* (Türkiye)	Osmancik 97	38,937 (11.4%)	1739 (84.4%)	5,283 (7.7%)	35,393 (1.1%)	7.89 (8.6%)	0.19 (0%)	7.7 (13.0%)	91.0 (3.4%)

The results of the experiment are given as means and coefficients of variation (in brackets) over the 2 or 3 years of the experiment

SP: Seepage and Percolation

* Modified WFL (see Sect. "Irrigation management of the trials")

and Lis Valley regions. Using the complete dataset of yields and the corresponding ETc estimates from the WFL experiments, a significant correlation was found between yield and ETc ($r=0.57$, $p<0.01$). This reflects the direct relationship between climatic conditions and crop evapotranspiration across the different geographical areas (Table 2). Extending the analysis to include all alternative irrigation managements in the entire project dataset increased the strength of the correlation between ETc and yield ($r=0.67$) and made it highly significant ($p<0.001$). As expected, yield production is correlated with evapotranspiration, which can be considered a proxy for climatic conditions.

In general, the length of the growing period is not directly related to yield potential. For instance, traditional varieties such as Bahía have a relatively long growth cycle of around 160 days (Table 2) but have only moderate yield potential. Conversely, other cultivars such as the EH1 hybrid, combine a shorter growth cycle of around 135 days with high yield potential, particularly in environments characterized by high solar radiation and elevated temperatures, such as in the Nile Delta.

The water potential (WP) ranged from 0.38 to 0.81 kPa, with the lowest value recorded in the Bafra Valley and the highest in the Nile Delta. The higher WP in the Nile Delta may be attributed to the combination of elevated temperatures, solar radiation and ETc, and the low soil permeability of this site. These WP values fall within the ranges reported by Bouman et al. (2007) and Debnath et al. (2025) for Asia, as well as those previously observed in the Lomellina region by Cesari de Maria et al. (2017). These figures suggest that the water savings that could be achieved by using alternative irrigation strategies can vary significantly from one location to another.

Alternate wetting and drying (AWD)

AWD was tested in Italy (Lomellina), Portugal (Mondego and Lis Valleys) and Türkiye (Bafra Valley). Means and CV% of the main soil water balance terms, grain yield and irrigation performance indices are shown in Table 4. In the case of the Bafra Valley, the table reports the values obtained separately with the three tested threshold for reflooding (i.e. water levels inside the water tubes equal to -5 cm, -10 cm and −15 cm from the ground surface), as well as their mean values.

The relative change in the value of each variable, as derived from the dataset when switching from WFL to AWD, is shown in Fig. 8 for each site. It can be observed that water savings ranged from 6% in Mondego Valley to 32% in Bafra Valley, when using water tube thresholds of −0.15 m. These findings, particularly those from Lomellina and Bafra Valley, are in agreement with Carrijo et al. (2017),

Table 4 Soil water balance terms, grain yield and water productivity (WP), relative water supply (RWS), deep percolation fraction (DPF) indices for alternative wetting and drying (AWD), dry seeding and delayed flooding (DFL), irrigation Input/Output reduction (WIR), hybrid irrigation, drip and subsurface drip irrigation (SDI) in the different geographic areas

Irrig. system	Geographical area	Irrig water (m^3 ha^{-1})	ETc (m^3 ha-^{1})	SP (m^3 ha-^{1})	Grain yield (t ha^{-1})	WP (kg m^{-3})	RWS (m^3m^{-3})	DPF (%)
AWD	Lomellina	19,705 (11.8%)	6,560 (0.6%)	15,685 (8.5%)	10.75 (8.6%)	0.48 (4.8%)	3.4 (5.9%)	79.8 (3.2%)
AWD	Lower Mondego Valley	13,117 (8.3%)	6,617 (5.0%)	5,141 (25.9%)	9.25 (*)	0.61 (*)	2.2 (0.0%)	39.7 (34.0%)
AWD	Lis Valley	13,061 (14.8%)	6,648 (1.8%)	5,089 (0.7%)	5.98 (7.5%)	0.43 (4.6%)	2.1 (14.3%)	39.6 (14.9%)
AWD (-0.05)	Bafra Valley	31,525 (19.9%)	5,053 (2.5%)	27,232 (20.4%)	7.35 (10.6%)	0.23 (4.3%)	6.4 (18.7%)	86.3 (0.5%)
AWD (-0.10)		28,975 (19.5%)	5,053 (2.5%)	24,682 (20.0%)	6.75 (15.7%)	0.23 (0.0%)	5.9 (18.6%)	85.1 (0.5%)
AWD (-0.15)		26,430 (11.5%)	5,287 (7.8%)	22,940 (12.7%)	6.65 (17.6%)	0.23 (4.3%)	5.3 (11.3%)	86.8 (6.1%)
Average (-0.05, -0.10 and − 0.15)		28,613 (15.7%)	5,153 (5.4%)	24,664 (16.1%)	6.88 (13.4%)	0.23 (4.3%)	5.8 (15.5%)	86.2 (3.6%)
DFL	Lomellina	21,285 (2.0%)	6,435 (1.9%)	17,440 (5.7%)	10.04 (13.5%)	0.42 (14.3%)	3.8 (5.3%)	81.9 (3.8%)
	Baix Ter	13,884 (10.7%)	6,021 (7.1%)	10,220 (35.4%)	7.34 (15.3%)	0.49 (14.3%)	2.5 (0.16%)	68.5 (17.4%)
WIR	Guadalquivir Marshes	19,470 (23.6%)	7,679 (4.7%)	12,367 (37.6%)	8.55 (6.7%)	0.45 (31.1%)	2.6 (24.2%)	62.0 (17.6%)
HYBRID	Nile Delta	10,126 (6.0%)	8,200 (0.0%)	1,274 (24.2%)	12.56 (2.7%)	1.24 (2.4%)	1.2 (8.3%)	12.7 (29.9%)
DRIP	Lis Valley	9,403 (30.6%)	5,934 (9.9%)	4,871 (9.9%)	4.06 (5.7%)	0.40 (15.0%)	1.7 (17.6%)	51.1 (9.0%)
	Nile Delta	7,632 (4.9%)	7,380 (0.0%)	441 (23.3%)	11.29 (2.7%)	1.48 (5.4%)	1.0 (10%)	5.8 (60.3%)
DRIP_1.75	Bafra Valley	9,080 (14.2%)	5,053 (2.5%)	4,787 (11.8%)	7.40 (13.4%)	0.75 (9.3%)	1.9 (5.3%)	52.8 (2.5%)
DRIP_2	Bafra Valley	10,380 (14.2%)	5,053 (2.5%)	6,087 (12.3%)	7.55 (14.0%)	0.68 (8.8%)	2.2 (9.1%)	58.7 (1.9%)
SDI_SiC	Baix Ter	7,530 (1.8%)	5,458 (21.5%)	3,360 (7.6%)	6.24 (8.5%)	0.73 (4.11%)	1.6 (0.0%)	44.6 (5.8%)
SDI_SaL		9,083 (21.2%)	5,335 (17.2%)	5,969 (25.6%)	3.52 (43.2%)	0.33 (21.2%)	2.0 (20.0%)	55.1 (15.2%)

Results of the experimentation are reported as means and percentage coefficient of variation (in brackets) over the 2 or 3 experimental years

*Yield was available only in 2020. SP: Seepage and Percolation

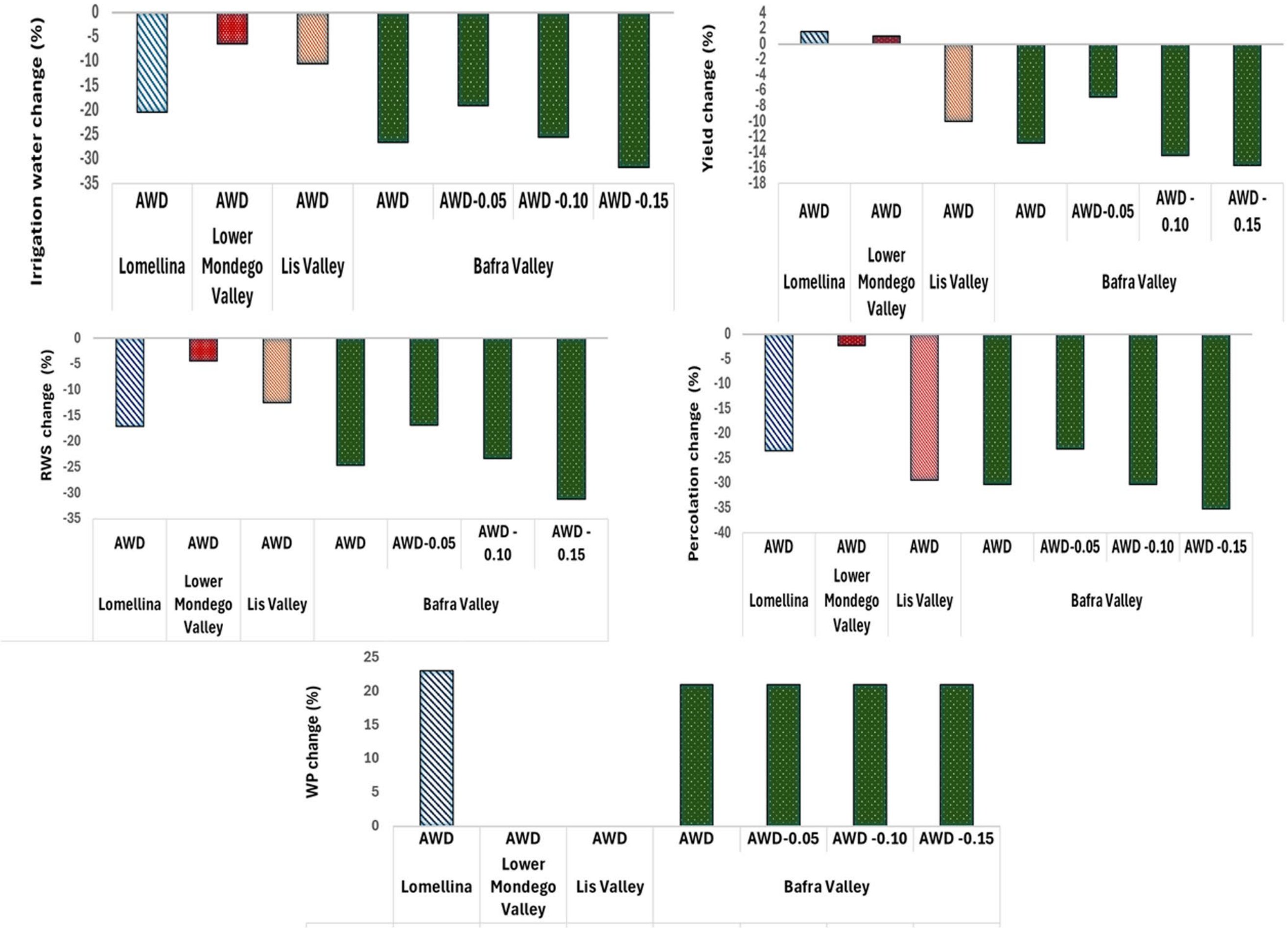

Fig. 8 Changes in average irrigation water volume used, yield, relative water supply (RWS), deep percolation, and water productivity observed when comparing AWD to WFL in the different geographical locations, expressed as a percentage (%)

whose meta-analysis reported that under "safe AWD," average water savings were around 23% compared to WFL. In cases of "severe AWD," water savings could increase up to 33%. Moreover, for Bafra Valley the AWD sample (taking the records of all the three variants – 7 values) is large enough to assess a statistical significance in the reduction of the irrigation requirements with the Wilcoxon rank-sum test (5% significance) and the two-sample t-test (1% significance).

Yield was not reduced when compared to WFL in Lomellina, but even slightly increased; it was practically the same in Mondego; on the contrary, yield reductions of 10% were observed in Lis Valley and from 7% to 16% (as a consequence of the different treatments) in Bafra Valley. The results obtained in Lomellina and Mondego are in line with previous studies (Monaco et al. 2021; Vuciterna et al. 2024), which reported that no significant yield reductions under "safe AWD" (as defined by Bouman et al. 2007; and described in Sect. "Alternate wetting and drying (AWD)") unless the soil water potential falls below −20 kPa.

WP increased about 20% in the Lomellina and Bafra Valley, with the highest WP increase when using the −0.15 m threshold. Similar results were reported by Carrijo et al. (2017), who found an average WP increase of 26% when using safe AWD instead of WFL. On the contrary, WP in the Mondego and Lis Valleys remained similar to those obtained under WFL.

RWS decreased by 4% in Mondego Valley and 31% in Bafra Valley, corresponding to percolation loss reductions of 4% and 35%, respectively. The reduction in the Bafra Valley was statistically significant according to the Wilcoxon rank-sum test ($p<0.05$) and the two-sample t-test ($p<0.01$).

Dry seeding and delayed flooding (DFL)

Dry-seeded rice followed by a delayed flooding (DFL) was tested in Lomellina (Italy) and Baix Ter (Spain). Means and CV% of the main variables and indices are shown in Table 4.

Figure 9 compares the results of DFL with those of WFL. It can be observed that the irrigation volume was reduced by 14% in Lomellina, but increased by 6% in Baix Ter; however, the need for a higher irrigation input in Baix Ter could be explained by the higher sand content in the soil of the DFL field compared to that of the WFL field. Previous studies have shown that DFL might reduce irrigation inputs up to 40%, even though with a yield decrease from 23 to 41% (Singh et al. 2002). However, no or insignificant production losses were also found in some studies. An irrigation input reduction of 15% with no yield loss was observed in central China (Liu et al. 2015), while an irrigation reduction of 20% resulting in a 3% yield loss was reported for the western Po Valley (Cesari de Maria et al. 2017); similar reductions in irrigation have been reported at the farm scale in the Baix Ter area (Cufí et al. 2025). The yield losses can be explained by the fact that the dry seeding and subsequent aerobic growing of rice until the tillage stage may introduce some potential yield-reducing factors like micronutrient deficiency (iron), and nematode-induced root damage (Singh et al. 2002).

In the present study grain yield under DFL decreased by 5% in Lomellina but increased by 13% in Baix Ter (Fig. 9). Yield improvement in Baix Ter can be explained by an improved seed distribution achieved by using a seed-drill, enhancing plants establishment before the tillering stage, and, consequently, reducing weeds competition. Another advantage compared to WFL is that DFL allows the application of pre-emergence herbicides, which are very effective for weed control (Shekhawat et al. 2020).

Regarding irrigation efficiency indices, WP was higher in DFL than in WFL at both locations, showing increases of 6% to 8%. Conversely, relative water supply (RWS) decreased by 2% to 9%, and percolation losses were reduced by 10% to 15%.

It should be noted that the widespread adoption of DFL - or any irrigation technique based on dry seeding - may have hydrological implications. In particular, it could influence groundwater level at the beginning of the irrigation season, potentially reducing the contribution of groundwater to the water discharge in rivers and in unlined irrigation networks

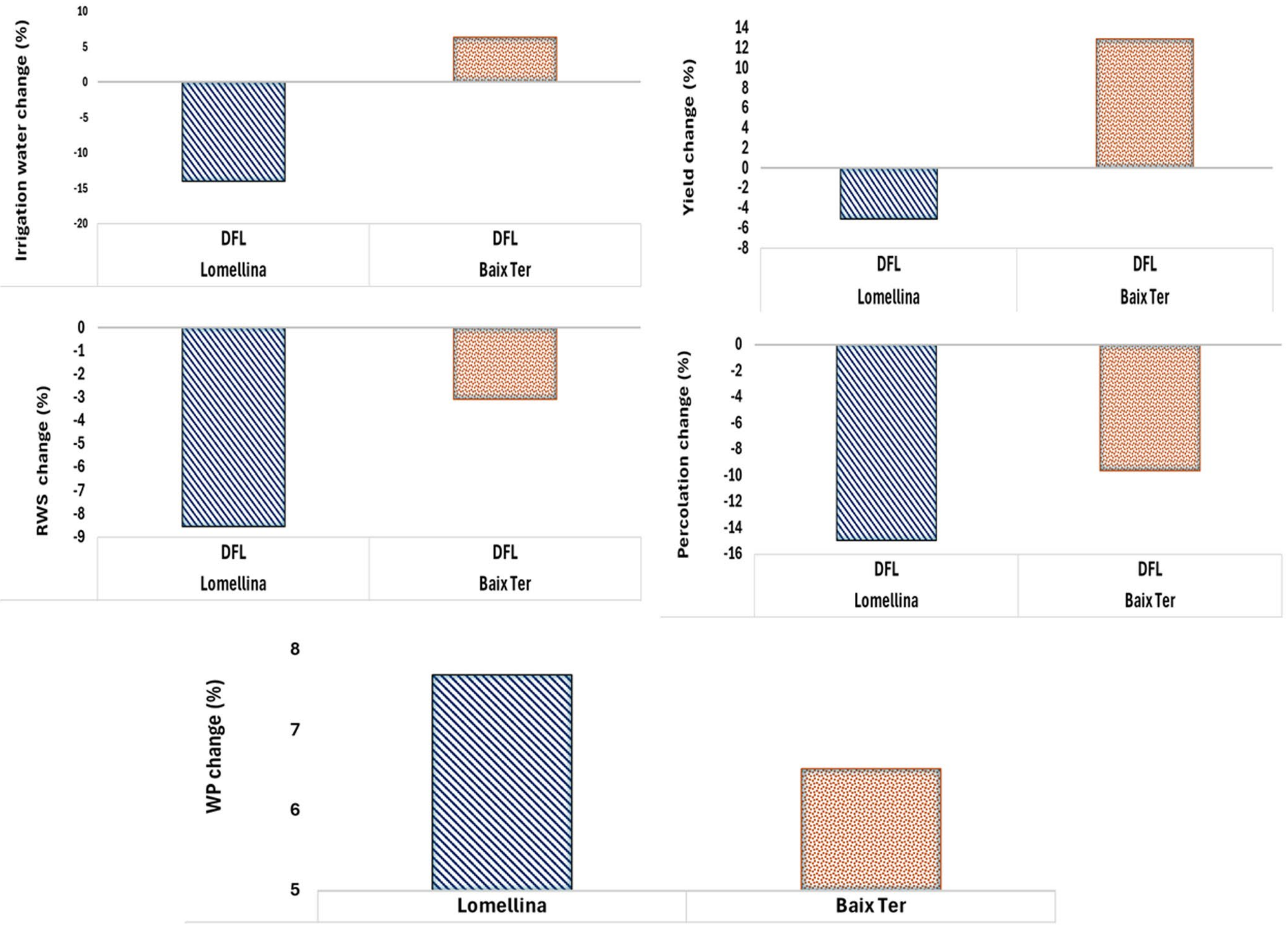

Fig. 9 Changes in irrigation water used, yield, relative water supply (RWS), deep percolation and water productivity (WP) observed when comparing DFL to WFL in the two different geographical locations, expressed as a percentage (%)

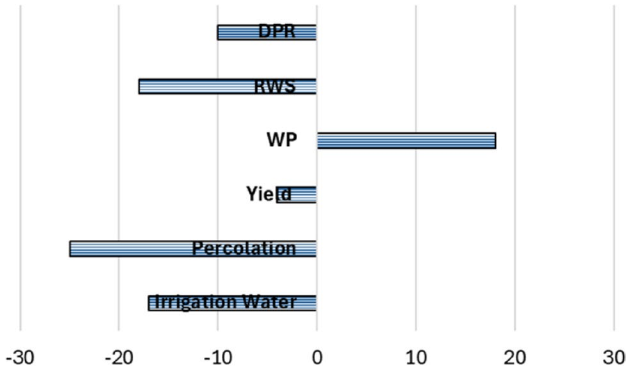

Fig. 10 Changes in irrigation water used, percolation, yield, water productivity (WP), relative water supply (RWS), and deep percolation fraction (DPF) observed when comparing WIR to WFL in the Lower Guadalquivir, expressed as a percentage (%)

of rice-growing areas characterized by shallow aquifers (Gilardi et al. 2023).

Irrigation input/output reduction (WIR)

Means and CV% for the main variables and indices in the case of WIR in the Guadalquivir Marshes are compared to WFL in Table 4.

Comparing the results of WIR with those of WFL, Fig. 10 shows that irrigation and percolation were reduced by 17% and 25%, respectively, as WIR was implemented by lowering the ponded water level to 0.05 m and draining the field at the grain dough stage. Those changes in irrigation and percolation, together with the change in DPR%, are significative for the paired t-test at the 5% significance level.

The WIR method resulted in only a slight 4% reduction in grain yield, while WP increased by 18%.

Mallareddy et al. (2023), called "saturated soil irrigation technique", the one based on maintaining water depth of less than 0.05 m. The same authors, reporting the results of several studies using this technique, showed that irrigation can be reduced by 30 to 60% with minimal or no yield reduction compared to WFL. In a meta-analysis, Yu et al. (2024) reported a 10–20% reduction in irrigation water compared to WFL when lower water ponding levels were applied to rice fields.

Hybrid irrigation (HYBRID)

HYBRID irrigation was tested in the Nile Delta. Means and CV% of the main water balance components, yield, and indices are shown in Table 4. When applying HYBRID irrigation, water savings compared to WFL were found to be 18% (Fig. 11, significative at 5% to the two sample t-test), while yield increased by 23% (significative at 1% to t-test and rank-sum tests). The obtained results are in agreement with Vories et al. (2005), who showed that HYBRID irrigation required 24% less irrigation input than WFL, leading to a 36% increase in WP_{Irr} compared to WFL. Additionally, the same authors reported an unexpected 3% increase in grain yield when this irrigation strategy was applied. They hypothesized that a shallower water depth could reduce the negative effects of cold water and improve nitrogen uptake efficiency.

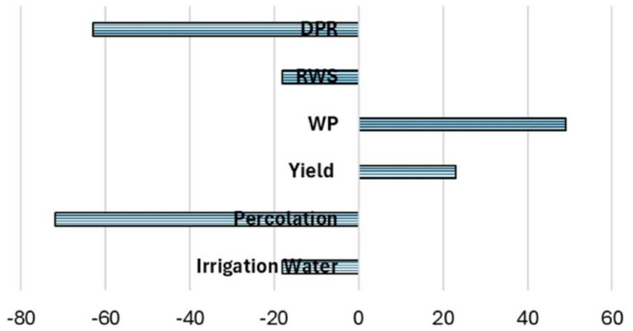

Fig. 11 Changes in irrigation water used, percolation, yield, water productivity (WP), relative water supply (RWS), and deep percolation ratio (DPF) observed when comparing HYBRID to the WFL in the Nile Delta, expressed as a percentage (%)

In the present study, HYBRID irrigation shows a 49% increase in WP compared with WFL, mainly because percolation was substantially reduced through the use of plastic pipes to distribute the water into the plot. It should be noted that this irrigation solution had the highest WP value of all the irrigation solutions tested, reaching 1.24 kg m^{-3} (Table 4). The remarkable improvement in efficiency indices may be attributed to a more uniform water distribution within the plots, which reduced both, the irrigation volume required and the percolation flux.

Sprinkler irrigation (SPRINKLE)

Sprinkler irrigation was tested in the Nile Delta. Means and CV% of the main soil water balance terms, grain yield, WP, RWS and DPF are shown in Table 4.

Comparing the results obtained by testing SPRINKLER strategy with those obtained by testing WFL (Fig. 12), it emerged that the volume of irrigation water was reduced by 25%, while the yield increased by 10%, therefore RWS decreased by 23%, while WP increased by 46% (significant at 1% to the two samples t-test). In particular, WP reached 1.21 kg m^{-3}, which is one of the highest values obtained among all the different irrigation methods (Table 4).

While several studies agree that sprinkler irrigation can significantly reduce water use (Kahlown et al. 2007; Spanu et al. 2009; Vories et al. 2013; Blanco-Alibés 2014; Senthil Kumar et al. 2018; Pinto et al. 2020), there is still no general consensus on its effect on rice yield. In particular,

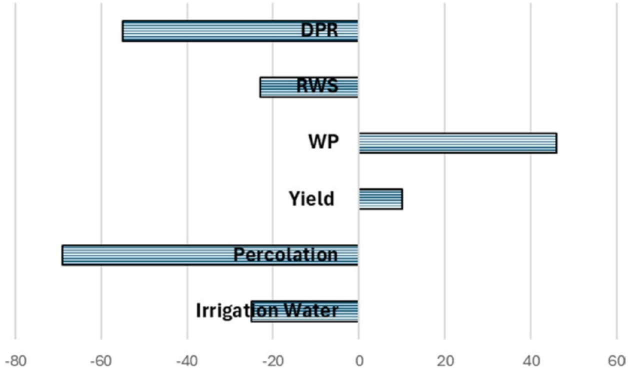

Fig. 12 Changes in irrigation water used, percolation, yield, water productivity (WP), relative water supply (RWS), and deep percolation fraction (DPF) observed when comparing SPRINKLER to WFL, expressed as a percentage (%)

Vories et al. (2013) reported comparable yields using center pivot sprinkler irrigation and WFL in Missouri and Arkansas, with WP_{Irr} improving from 55% to 122%. Similarly, Kahlown et al. (2007) reported that WFL and sprinkler irrigation achieved similar yields, resulting in a 90% increase in WP. The same authors found out that increasing the irrigation input from 100 to 150% of ETc resulted in only a 3% increase in grain yield with sprinkler irrigation compared to WFL. Senthil Kumar et al. (2018) reported a reduction in grain yield of about 25% with sprinkler irrigation compared to WFL, suggesting that the application of sprinkler irrigation during flowering may lead to pollen shedding.

Surface drip irrigation (DRIP)

DRIP was tested in Lis Valley, Nile Delta and Bafra Valley. Means and CV% of the main water balance terms, yield and irrigation performance indices are shown in *the* Table 4 and compared to WFL in Fig. 13. In Bafra Valley, two different treatments were implemented (DRIP-1.75 and DRIP-2.0), referred to the calculation of the irrigation requirement (1.75 times ETc and 2.0 times ETc).

Figure 13 shows that the amount of irrigation used under DRIP was reduced by approximately 35% compared to WFL treatment in the Lis Valley and Nile Delta. This reduction was significant at the 5% level according to the t-test. Furthermore, the reduction was approximately 75% for the Drip_1.75 and Drip_2 treatments in Bafra Valley, which was significant at the 1% level according to the t-test. Grain yield decreased by 39% in the Lis Valley (significant at the 5% level according to the t-test), and by around 5% under the DRIP_1.75 and DRIP_2 treatments in the Bafra Valley. Whereas an 11% increase was observed in The Nile Delta. Grain yield in the Lis Valley was notably low, and the reason is mainly due to the difficulties experienced in managing weeds. Indeed, no herbicides are authorised for use on non-flooded rice in this region, so weeds in the experimental plots had to be removed by hand. Meanwhile, the presence of weeds increased due to the aerobic conditions. Moreover, agronomic practices had to be adjusted to accommodate this irrigation management, which is unconventional in the region. Conversely, the results from the other case studies demonstrate that rice production under drip irrigation is technically feasible.

These findings are consistent with previous studies. In particular, using surface DRIP irrigation for rice, He et al. (2013) found that irrigation water was reduced from 68% to 73%, but also grain yield decreased from 30% to 50%; therefore, WP_{Irr} increased from 41% to 108%. Sasmita et al. (2022) found that DRIP irrigation reduced by 50% the irrigation water applied and by 6% the grain yield. Arbat et al. (2018) reported that irrigation water was reduced by 45%, yield by 14% and, consequently, WP increased by 60% when benchmarking DRIP irrigation to WFL. Sharda et al. (2017) found that drip irrigation led to higher grain yields compared to WFL, resulting in a yield increase of approximately 7%, while saving over 40% of water.

Regarding the efficiency indices, WP decreased by 6% in the Lis Valley, while it increased by 83% in the Nile Delta ($<1\%$ t-test) and by 295% and 258% in Bafra Valley (both $<1\%$ t-test) for DRIP_1.75 and DRIP_2 (Fig. 13). RWS was reduced by approximately 25% in both the Lis Valley and the Nile Delta and by around 75% under the DRIP_1.75 and DRIP_2 treatments in the Bafra Valley. Percolation was reduced by 32% in Lis Valley, by 90% in Nile Delta (significant at 5% level, t-test), and by approximately 85% in DRIP_1.75 and DRIP_2 treatments in Bafra Valley, respectively (both significant at the $<1\%$ level, t-test).

As can be seen, the results of DRIP were different in the three tested areas. The large differences in yield and irrigation performance indices can be attributed to several factors. In the Lis Valley, the lack of previous experience with drip irrigation in rice played an important role. In addition, suboptimal agronomic management under aerobic conditions - partly due to legal restrictions on pesticides that can be used in aerobic conditions - further affected performance. The challenges of designing and managing these systems effectively under different site-specific conditions also contributed to these differences.

Subsurface drip irrigation (SDI)

The SDI was tested in two different fields in the Baix Ter area (Spain), one with a sandy-loam soil texture (SDI-SaL) and deep groundwater and, the second one having a silty-clay soil texture and shallow groundwater (SDI-SiC). The results obtained were rather different depending on the field (Table 4).

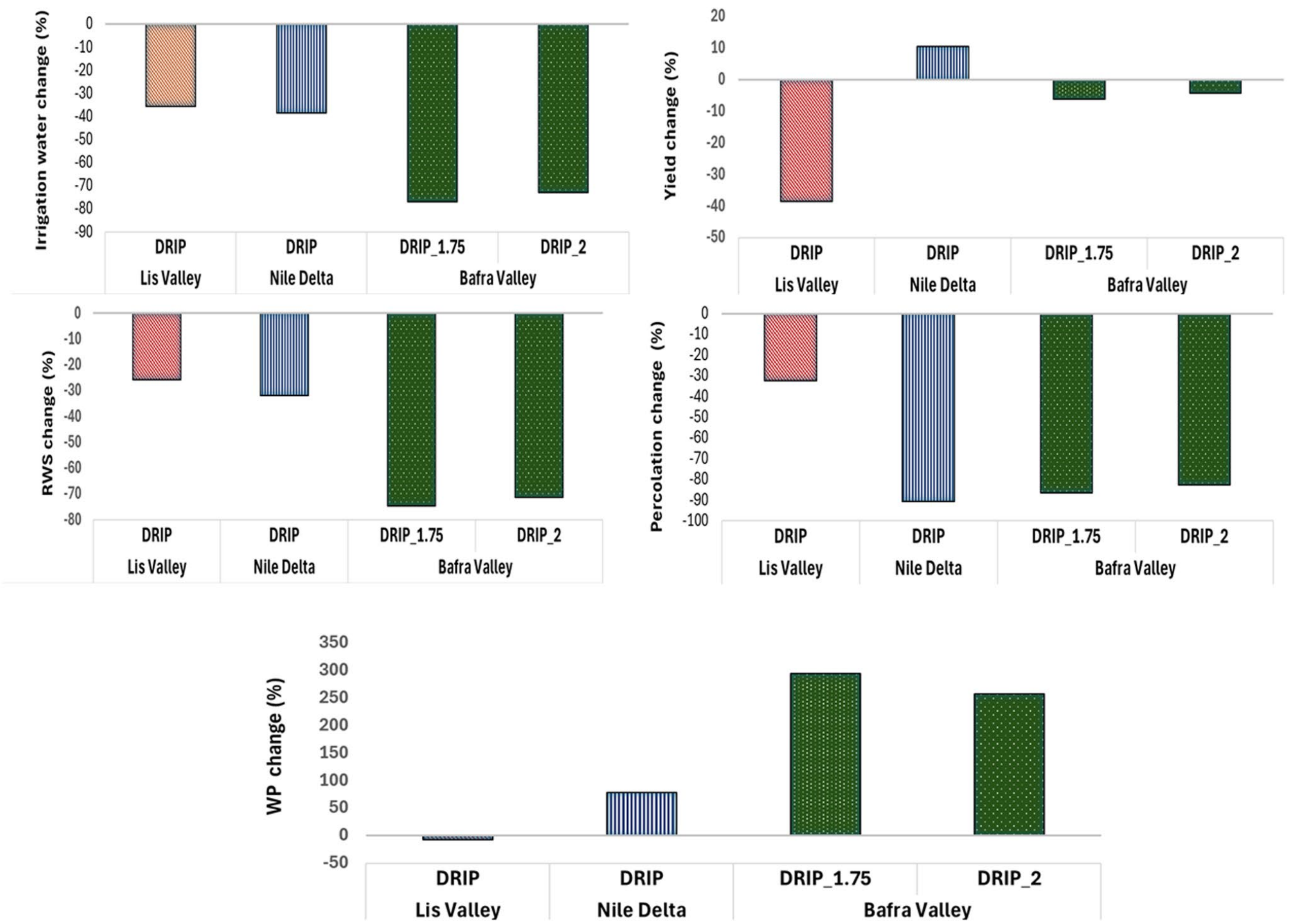

Fig. 13 Changes in irrigation water used, yield, relative water supply (RWS), percolation and water productivity (WP) observed when comparing DRIP to WFL in the different geographical locations, expressed as a percentage (%)

When applying SDI and comparing the results with WFL (Fig. 14), it was found that: (i) the amount of irrigation water was reduced by approximately one third in SDI-SaL and SDI-SiC (for both < 1% t-test, and 5% rank-sum when pooling the two SDI samples); (ii) yield was drastically reduced in the sandy-loam soil compared to WFL, while it remained quite similar to WFL in the silty-clay field; (iii) percolation was reduced by 40% and 66% in SDI-SaL and SDI-SiC, respectively (for both < 1% t-test, 5% rank-sum is obtained with the pooled sample); (iv) percolation was reduced by more than 50% in both SDI-SaL and SDI-SiC; (v) WP decreased by 28% in SDI-SaL (< 1% t-test), while it increased by 59% in SDI-SiC; (vi) RWS was reduced by 23% and 40% in SDI-SaL (5% t-test) and SDI-SiC (1% t-test), respectively (5% rank-sum is obtained with the pooled sample).

These results show that SDI works well with low-permeability soils. Its poor performance on the SDI-SaL test plot was probably due to the pressurised system being inadequately designed, particularly the drip line spacing of 0.66 m, which may have been too wide for coarse-textured soils. Previous studies have emphasised the importance of appropriate spacing and system design for the specific soil types. For instance, Arbat et al. (2020) found that optimal spacing and management practices in SDI can substantially reduce water usage and increase yields. This demonstrates that successful implementation hinges on understanding the soil characteristics and adapting the irrigation system accordingly.

Conclusions

In this study, carried out in five Mediterranean rice-producing countries, water-saving irrigation techniques were tested on pilot farms and compared with the traditional WFL. The results highlight the effectiveness of such alternatives in conserving water resources in different geographical contexts.

With regard to the specific results of the pilot farms, it can be noted that although general trends emerge when comparing the same irrigation strategy with WFL, the absolute values of these results are highly dependent on the specificities

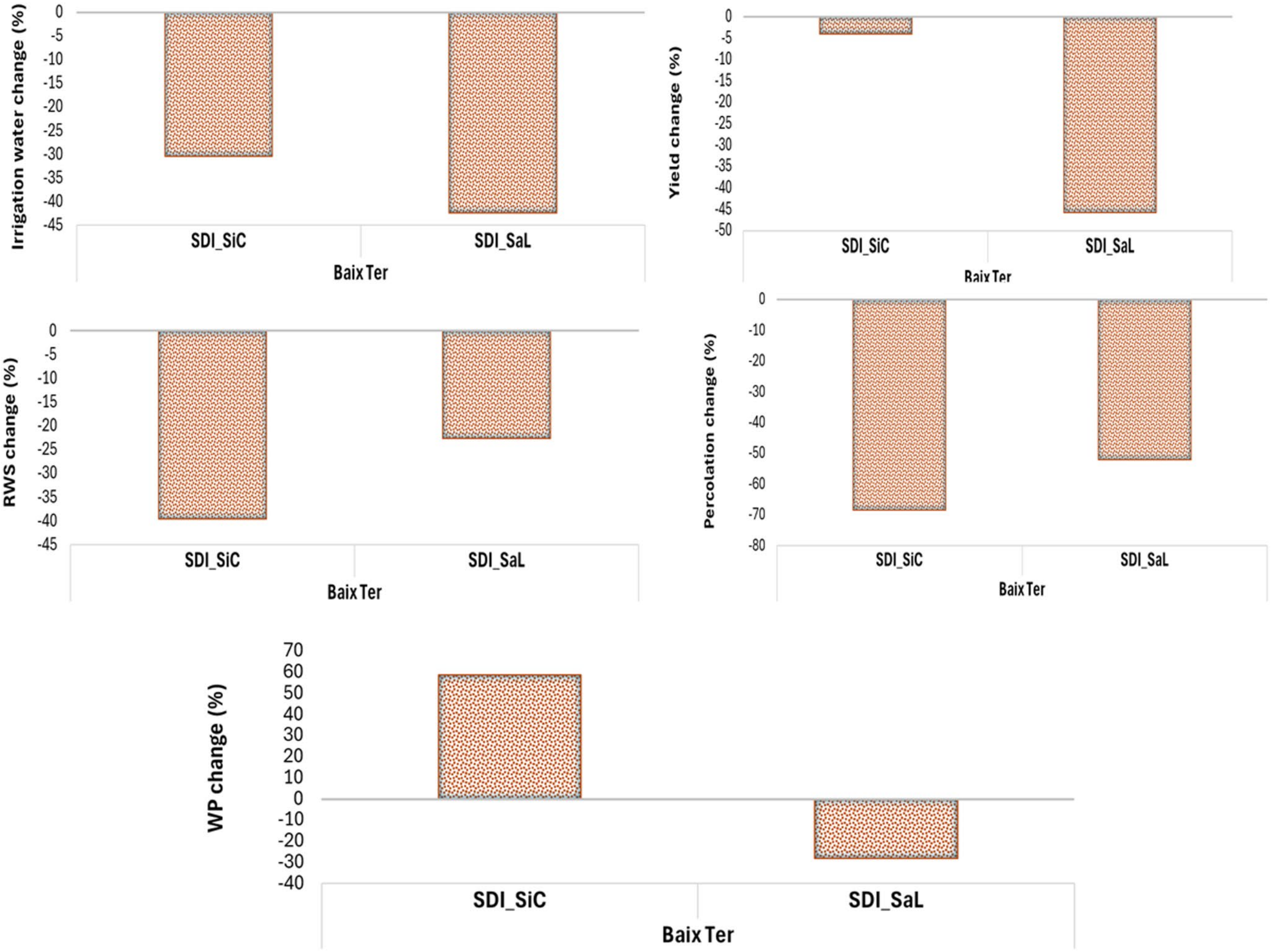

Fig. 14 Changes in irrigation water used, yield, relative water supply (RWS), percolation and water productivity (WP) observed when comparing SDI to WFL in Baix Ter and expressed as a percentage (%); in particular, results for silty-clay (SiC) and sandy loam (SaL) soils are reported

of each geographical area. This variation is undoubtedly due to site-specific environmental conditions, rice varieties, irrigation system design and management, and local agronomic practices. Main findings are listed below.

(i) Alternate Wetting and Drying (AWD) can be considered a good alternative to WFL when irrigation water is limited and soil salinity is not an issue, although slight yield losses may occur. For this irrigation strategy, the WP index has been shown to outperform WFL and DFL irrigation techniques.

(ii) DFL is a technique based on continuous flooding, alternative to WFL. It has the same yield potential as WFL, requires less irrigation and provides agronomic advantages, such as ensuring the correct establishment of plants and reducing lodging, particularly on sandy soils.

(iii) Reducing water input/output (WIR) could be a good alternative to WFL in areas where irrigation water is limited, particularly those with heavy soils. It has been shown to improve the WP index with limited impact on yield. However, if salt leaching is insufficient to maintain soil water salinity compatible with rice tolerance, water salinity could affect yields.

(iv) HYBRID and SPRINKLER irrigation techniques proved to be suitable alternatives to WFL as both showed increased yields, reduced deep percolation and reduced irrigation water requirements compared to WFL. However, as these techniques and technologies have only been tested in Egypt, their testing needs to be extended to other geographical contexts to better assess their potential and limitations before general conclusions can be drawn.

DRIP and SDI performed differently in the different geographical areas considered in this study. In most cases, acceptable yield reductions occurred, and WP was significantly increased when irrigation systems were properly designed and managed taking into account site-specific conditions.

The findings of this study were obtained from experimental plots and commercial fields. However, it is essential to consider the potential impact of any significant change in irrigation techniques on the entire water resources system, including surface water, groundwater and soil salinisation. This is particularly critical in areas with shallow aquifers and/or marine intrusion, where irrigation management has a strong influence on groundwater levels, surface–groundwater interactions and overall water quality. Furthermore, the large-scale conversion of WFL to water-saving techniques requires the active involvement of irrigation authorities, who may need to adapt collective irrigation infrastructure and services. For example, it may be necessary to increase the flexibility of irrigation delivery to overcome the rigidity of fixed irrigation schedules or to convert open-channel gravity systems into pressurised networks. If irrigation strategies are changed on farms without planning them at the scale of the irrigation scheme with water irrigation managers, the use of the collective irrigation network no longer remains guaranteed. In fact, if farmers' needs are not met, farmers may dig wells to supply water to support the water saving techniques implemented on their farms. This would make monitoring irrigation use and protecting water resources much more difficult, if not impossible.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00271-026-01087-4.

Acknowledgements To the memory of Dr. Luciano Mateos, who did not only contribute to develop MEDWATERICE project, but also supported all partners with his knowledge and, above all, his friendship. We also wish to acknowledge NETAFIM for their valuable contribution of materials and technical support.

Author contributions Gerard Arbat (GA), Olfa Gharsallah (OG), Sílvia Cufí (SC); Francesc Ramírez de Cartagena (FR), Jaume Pinsach (JP), Marco Romani (MR), Concepción Mira (CM), Isabel P. de Lima (IL); Romeu Gerardo (RG); José M. Gonçalves (JG); Manuel Nunes (MN), Abdrabbo A. A. S. Aboukheira (AA), Saad M. Metwaly Shebl (SM); Melih Enginsu (ME), Rasim Ünan (RU), Michele Rienzner (MRI), Arianna Facchi (AF) Conceptualization: A.F., O.G. and G.A.; Methodology in Lomellina, M.R, M.R.I. and O.G.; Statistical treatments: M.R.I Methodology and experimentation in Baix Ter, S.C., F.R., G.A.; Methodology and experimentation in Guadalquivir Marshes, C.M.; Methodology and experimentation in Mondego Valley, I.L.,R.G.; Methodology and experimentation in Lis Valley, J.G. and M.N.; Methodology and experimentation in Nile Delta, A.A. and S.M.; Methodology and experimentation in Bafra Valley, M.E. and R.U. and Wrote the main manuscript text G.A., O.G; review and editing, A.F., J.P, F.R., M.R.I.; Project administration, A.F., O.G, J.P.; Funding acquisition, A.F., J.P.,F.R. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. The present work was conducted in the context of MEDWATERICE project "Towards a sustainable water use in Mediterranean rice-based agro-ecosystems", selected by the Partnership for Research and Innovation in the Mediterranean Area (PRIMA), under Section 2–2018; Topic: 1.1.3: Irrigation technologies and practices. The contribution of the MEDWATERICE partners was funded by their respective national funding agencies (MUR for Italy, STDF for Egypt, AEI and CDTI for Spain, ISERD for Israel, FCT for Portugal, TUBITAK for Türkiye).

Data availability Data collected from each experimental site during the three years of experimental activities are archived in Dataverse (https://dataverse.unimi.it/), a FAIR (Findable, Accessible, Interoperable, and Reusable) and OpenAIRE-compliant repository provided by the University of Milan (UMIL). The Dataverse dedicated to the MEDWATERICE project, named MEDWATERICE Dataverse, is publicly accessible at https://dataverse.unimi.it/dataverse/MEDWATERICE. All datasets are openly available under a Creative Commons CC0 licence, ensuring unrestricted access and reuse.

Declarations

Conflict of interest The authors declare no competing interests.

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