Irrigation strategies alternative to continuous flooding to decrease water use and increase water productivity in Mediterranean rice-based agroecosystems

Authors: Arianna Facchi[1], Olfa Gharsallah[1], Marco Romani[2], Gerard Arbat[3], Sílvia Cufí[3]; Francesc Ramírez de Cartagena[3], Jaume Pinsach[3], Concepción Mira[4], Luciano Mateos[5]; Isabel P. de Lima[6]; Romeu Gerardo[6]; José M. Gonçalves[7]; Abdrabbo A. A. S. Aboukheira[8], Saad M. Metwaly Shebl[9]; Melih Enginsu[10]

Affiliation: *[1] Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy (DiSAA), Università degli Studi di Milano, Via Celoria 2, 20133 Milan, Italy; [2]Rice Research Centre, Ente Nazionale Risi, Strada per Ceretto 4, 27030 Castello d'Agogna (PV), Italy; [3] Department of Chemical and Agricultural Engineering and Technology, Universitat de Girona, Carrer de Maria Aurèlia Capmany, 61, 17003 Girona, Spain; [4] TEPRO Consultores Agrícolas SL, Avda. San Francisco Javier 24, 41018 Sevilla, Spain; [5] Instituto de Agricultura Sostenible, CSIC, Alameda del Obispo, 14004 Córdoba, Spain; [6] University of Coimbra, MARE – Marine and Environmental Sciences Centre / ARNET – Aquatic Research Network, Rua Luis Reis Santos, 3030-788 Coimbra, Portugal; [7] IPC - Instituto Politécnico de Coimbra, Escola Superior Agrária de Coimbra, 3045-601 Coimbra, Portugal; [8]National Water Research Cente, Delta Barrage, Kaluobiya, Egypt; [9]Agricultural Research Center, Dokki, Giza, Egypt; [10] Black Sea Agricultural Research Institute, PK.39 , Samsun - Turkey*

Abstract

In the Mediterranean basin, rice is cultivated over an area of 1,300,000 hectares. The most important rice-producing countries are Italy and Spain in Europe (72% of the EU production; 345,000 ha), and Egypt and Turkey among the extra-EU countries (almost totality of the production; 789,000 ha). Traditionally, in these areas, rice is cultivated under continuous flooding; thus, it requires much more irrigation than non-ponded crops. On the other hand, rice is strategic for food security in some countries and its consumption in the whole Mediterranean basin is steadily increasing.

The MEDWATERICE project (https://www.medwaterice.org/) includes 7 case studies (CSs) representative of different rice agroecosystems in 5 Mediterranean countries (Italy, Spain, Portugal, Egypt and Turkey). Innovative irrigation strategies alternative to the traditional wet-seeding and continuous flooding (WFL) were tested and tailored to local conditions in each CS, including: alternate wetting and drying (AWD), dry-seeding and delayed flooding (DFL), subsurface drip irrigation (SDI), surface drip irrigation (DRIP), reduction of water input (RWI), hybrid irrigation (HYBRID) and multi-nozzle sprinkler irrigation (SPRINKLER). In each CS, strategies were compared to WFL and field trials were carried out at least for two years during the period 2019-2021. A minimum dataset including agroclimatic data, soil physico-chemical properties, groundwater depth and salinity, irrigation water inflow and outflow, irrigation water salinity, grain yield and quality was collected and analyzed in all case studies.

Results suggest that AWD and DFL might be sound alternatives to WFL in Lomellina (IT), Baix Ter (SP), Lower Mondego and Lis Valleys (PT), and Bafra Valley (TR), leading to an increase in water productivity up to 30%. SPRINKLER and HYBRID irrigation tested in the Nile Delta (EG) resulted in an increase in water productivity of about 50% in both cases. Surface and subsurface drip irrigation systems have a great potential in reducing water use, while maintaining yield production as demonstrated in the Nile Delta (EG), Bafra Valley (TK), and Baix Ter (ES), where water productivity increased from 40 to 100% compared to WFL. Nevertheless, when adopting drip irrigation techniques, special attention must be paid to the irrigation system design and

management, by considering the site-specific soil hydraulic properties and agroclimatic conditions.

This communication describes the main aspects affecting rice production in each area participating in the MEDWATERICE project, and quantifies the water use and the quantity and quality of the rice production achieved with the traditional irrigation method (WFL) and the innovative irrigation solutions tested in each CS.

Keywords: Water-saving irrigation; Water productivity; Mediterranean basin; Alternate Wetting and Drying (AWD), Dry-seeding and Delayed Flooding, Surface and subsurface drip irrigation, Hybrid irrigation; Multi-nozzle sprinkler irrigation

1. Introduction

Growing rice requires, in general, two to three times more water than other cereals (Kijne, 2006; Marcos *et al.*, 2018). The Mediterranean basin, where rice is cultivated over an area of 1,300,000 hectares, due to its high population and semi-arid climatic conditions, is among the most water-scarce regions, posing serious constraints on irrigation (Harmanny and Malek, 2019). Additionally, there is a strong competition for water use with other economic sectors, such as urban, industrial, environmental, recreational and touristic (Zikos and Hagedorn, 2016). Simultaneously, water scarcity in this region is being aggravated by the climate change, which is increasing temperatures and modifying the precipitation patterns (Iglesias and Garrote, 2015).

In the Mediterranean region, rice is traditionally grown under continuous flooding. Due to the threat of less water availability, alternative water management and irrigation systems, which may allow reducing water input to grow rice, are of great interest. Different research has been carried out worldwide to introduce strategies and technologies for reducing irrigation water at the field scale while maintaining yield. Nevertheless, most results show that rice yield declines as soon as the soil water content is below saturation (Bouman and Tuong, 2001). Different irrigation strategies alternative to the wet seeding and continuous flooding irrigation (WFL) have been tested to reduce water inputs in paddy fields (Tuong et al., 2005). Among them: Alternate Wetting and Drying (AWD), Dry-seeding and Delayed Flooding (DFL), different intensities and timings of Reduction of Water Input (RWI), Surface and subsurface drip irrigation (Drip and SDI), Hybrid irrigation (HYBRID) and Multi-nozzle sprinkler irrigation (SPRINKLER). Carrijo et al. (2017) analyzed available scientific literature focused on AWD and estimated that it led to a reduction in water use compared with WFL from 15% to 33%, depending on the severity of application of this technique. The same study revealed that the average water productivity (WP) was about 24% higher in AWD than in WFL. Nevertheless, information about the irrigation water needs and crop productivity using these innovative irrigation technologies is very scarce, and only a few studies were conducted in the Mediterranean region. Among these, Cesari de Maria et al. (2017), using DFL in western Po valley (Italy), observed an average reduction of 20% of the irrigation needs compared with WFL, while reduction in yield was only 3%.

The objective of this study is to describe the main characteristics of each CS involved in the MEDWATERICE project, quantify the water use, yield, and water productivity achieved with the traditional irrigation method (WFL), considered as the “reference” irrigation method for all CSs, and compare these results with those achieved with the tested innovative solutions in each CS.

2. Material and Methods

2.1. Description of the case study areas (CS) and experimental sites

Case studies (CSs) were implemented in pilot farms of the main rice producer countries around the Mediterranean basin (Italy, Spain, Portugal, Turkey and Egypt). For each irrigation solution, the experimental activities were conducted during at least two agricultural seasons in the period 2019-2021. Tested alternative irrigation methods and technologies adopted in each CS were tailored to local conditions using a participatory action research approach through the establishment of Stake-Holder Panels in each country, which included regional authorities, water managers, farmers' associations and consultants, and private companies of the rice production supply chain.

CS1, Italy: The main rice cultivated area in the country is located in the upper Po Valley, between the Piedmont and Lombardy regions, with about 120,000 ha, which contributes to about 92% of the total rice Italian production (Zampieri *et al.*, 2019). The experimental tests were carried out at the ENR Rice Research Centre's experimental farm located at Castello d'Agogna, Pavia, within the traditional rice production area.

During the period 2019-2020, the maximum and minimum temperatures within the cropping season were 4.2°C and 37.5°C, with an average precipitation of 287.5 mm and a potential evapotranspiration of 670.2 mm. Soil texture of the first soil layer was silty-loam and groundwater depth was about 200 cm at the beginning of the irrigation season and 15-20 cm in the center of the season (80 cm as an average). The different irrigation options were tested in six plots of about 20 m x 70 m each, with two replicates for each option.

CS2, Baix Ter, Spain: This area includes a surface devoted to rice of about 1,000 ha. Being a small surface within the total 105,000 ha of rice cultivated in Spain (Gómez de Barreda *et al.*, 2021), it is well-known by the quality label "Arròs de Pals" (Empordà Gastronòmic, 2022).

In the period 2019-2021, the maximum and minimum temperatures within the cropping season were 5.7°C and 35.5°C, with an average precipitation of 128.0 mm and a potential evapotranspiration of 508.2 mm. The soil texture of the first layer was loam to silty-clay-loam and average groundwater depth was 45.9 cm. The experimental tests were carried out in different fields of an area ranging from 0.4 to 1.1 ha. The soil texture at the first layer in the WFL field was silty-clay-loam, the DFL was loam and the two SDI fields were silty-clay and sandy-loam.

CS3, Guadalquivir Marshes, Spain: It is the main rice production area in Spain with 39,635 ha dedicated to rice in 2019, and the one with the highest average yield, around 8.6 t/ha (Gómez de Barreda *et al.*, 2021).

During the period 2019-2020, the maximum and minimum temperatures within the cropping season were 6.8°C and 37.8°C, with an average precipitation of 63 mm and a potential evapotranspiration of 733 mm. The soil texture at the upper layer was from clay to silty-clay and groundwater depth was about 60 cm. Furthermore, it is noticeable that the water quality level is low in terms of salinity, with an average electrical conductivity of 3.46 dS/m. The experimental fields had a mean area of 5.8 ha, except the drip irrigation experiment that had 0.4 ha.

CS4 and CS5, Lower Mondego and Lis Valley, Portugal: These areas are in the center of Portugal, near the Atlantic coast, with a total rice crop cultivation area of about 6,000 ha.

In the period 2019-2021 the maximum and minimum temperatures within the cropping season were 10.0°C and 36°C for Mondego Valley, and 4.8°C and 34.0°C for Lis Valley, with an average precipitation of 62.8 mm and a potential evapotranspiration of 565.0 mm. Soils are mainly alluvial, some of them poorly drained with waterlogging and salinization risks, especially in downstream areas. In Lis Valley the average groundwater depth was 64 cm and an electrical conductivity of 1.46 dS/m, no data are available for Mondego Valley. The irrigation water had good quality with an average electrical conductivity of 0.068 dS/m and 0.286 dS/m, for Mondego and Lis valley respectively. Soil textures vary from silty-clay to clay-loam. Experimental fields had an area ranging from 0.5 to 3.2 ha, except the drip-irrigated plot, which had an area of 240 m^2.

CS6, Delta Nile, Egypt: The Nile Delta covers an agricultural area of approximately 1.8 million ha, irrigated by a complex network of waterways. Rice growing area is about 500,000 ha with a national average yield of 10 t/ha.

During the period 2019-2021, the maximum and minimum temperatures within the cropping season were 20.3°C and 41.1°C, with an average potential evapotranspiration of 976.0 mm; there was no precipitation being recorded in this period. Groundwater is shallow, aquifers have an average salinity of 4.6 dS/m. The predominant soil texture is clayey, with poor drainage. In 2020 and 2021 agricultural seasons, the experimentation was conducted in three experimental sites. The data presented in this study are focusing on the field experiment located at the east Nile Delta. The tests were performed in 3 x 10 m^2 plots, with three replications of each treatment. All the data considered in the present study correspond to the Hybrid Rice-EH1 variety irrigated with freshwater (0.53-0.76 dS/m). The WFL treatment was practiced with raised-beds surrounded by small basins. Drip irrigation was designed with 4 l/h emitters spaced 0.3 m and driplines 0.5 m apart. Hybrid irrigation method consisted of a pressurized system delivering water to each experimental plot with a single outlet, 2" diameter, and a discharge of 6-9 m^3/h operating at 100 kPa. SPRINKLER irrigation used multi-nozzle impact sprinklers with 5 nozzles of 2.5-7 m^3/h at operating pressures of 200-500 kPa. The sprinklers were spaced 12 x 12 m apart, with an overlapping of 100%.

CS7, Bafra Valley, Turkey: It is a Delta plain located on the middle part of the Black Sea coast, with approximately 16,000 ha devoted to rice cultivation.

In the period 2019-2021, the maximum and minimum temperatures within the cropping season were 8.7°C and 33.0°C, with an average precipitation of 153.4 mm and a potential evapotranspiration of 481.6 mm. The soil texture at the first layer was silty-clay and average groundwater depth was about 114 cm. Also, it is noticeable the low water quality in terms of salinity, with an electrical conductivity of 1.63 dS/m. The field experiments were carried out in 5 x 5 m^2 plots, in a total of 36 plots, including 3 replications of each treatment x 6 irrigation treatments x 2 rice varieties.

In the particular case of CS7 (Bafra Valley), the WFL traditional technique refers to transplanted rice with continuous flooding in 2019 and dry seeding plus immediate flooding with about 2-3 mm of water level till emergence and then continuous flooding (about 8-10 mm) in 2020 and 2021; in this study, both cases have been included as WFL (**Table 2**).

2.2. Tested alternative irrigation strategies

Innovative irrigation strategies tested in the pilot farms were compared with wet seeding and continuous flooding (WFL), which is considered as the 'reference' irrigation method in all CSs.

The tested alternative irrigation strategies and methods were (**Table 1**): dry seeding and delayed flooding (DFL), alternate wetting and drying (AWD), reduction in water inflow/outflow (RWI1: 26% during the whole crop cycle, RWI2: reduction from 100 days after sowing, RWI3: 30% reduction with longer drying periods), hybrid irrigation (HYBRID), multi-nozzle sprinkler irrigation (SPRINKLER), surface and sub-surface drip irrigation (DRIP and SDI). For each irrigation solution, innovative technologies and the most appropriate rice varieties and agronomic practices were implemented to minimize impacts of irrigation water reduction on yield quantity and quality.

Table 1: Summary of irrigation strategies tested in the project experimental areas

Innovative irrigation strategy	**Italy (Lomellina) CS1**	**Spain (Baix Ter) CS2**	**Spain (Guadalquivir marches) CS3**	**Portugal (Lower Mondego Valley) CS4**	**Portugal (Lis Valley) CS5**	**Egypt (Nile Delta) CS6**	**Turkey (Bafra Valley) CS7**
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 of Water Input (RW1, RWI2+RWI3)			X				
Subsurface Drip Irrigation (SDI)		X					
Surface Drip Irrigation (DRIP)			X		X	X	X
Hybrid irrigation (HYBRID)						X	
Multi-noozle sprinkler irrigation (SPRINKLER)						X	

RWI1 – 26% reduction in water inflow/outflow during whole crop cycle, RWI2- reduction of water inflow 100 days after sowing, RWI3 - longer drying periods and inflow/outflow reduction (30%).

2.3. Data collection and statistical analysis

Average yield, irrigation water, crop evapotranspiration (ETc), percolation and Water Productivity (WP), Relative Water Supply (RWS), and contents of cadmium and arsenic accumulated in the husked grain are reported for WFL, considering all available years. For the other irrigation treatments, and considering the limited space of this communication, only the increase or decrease of each of these parameters compared with WFL for each CS is provided in the following sections.

Statistical analyses were carried out using SPSS Statistics software v.28 (IBM, New York, USA). Tukey's pairwise comparison test was used for assessing if averages were significantly different with a probability of 0.05 or less.

3. Results and discussion

3.1. Wet seeding and continuous flooding (WFL)

Results showed in **Table 2** indicate great differences in the irrigation water use, percolation, and grain yield among the different CSs. Therefore, the comparisons of innovative irrigation systems with WFL were made for each CS.

Table 2: Water balance components, WP and RWS indicators, grain yield, total arsenic and cadmium grain contents for WFL in the different case studies (average ± standard deviation over the years of experimentation).

CS	Rice varieties	Irrigation water (m³/ha)	ETc (m³/ha)	Percolation (m³/ha)	Grain yield (t/ha)	WP $_{I+R}$ (kg/m³)	RWS (m³/m³)	Grain Cd (mg/kg)	Grain As (mg/kg)
CS1	Centauro	24,750 ±1,004 b	6,640 ±141 bc	20,505 ±1,648 a	10.6 ±0.88 a	0.39 ±0.06 c	4.1 ±0.2 b	0.006 ±0.001	0.240 ±0.059
CS2	Bahia/Onice/Mare	13,055 ±583 d	5,529 ±707 c	10,058 ±1276 b	6.5 ±141 c	0.46 ±0.05 bc	2.6 ±0.2 c	0.081 ±0.103	0.128 ±0.152
CS3	J. Sendra/Puntal	23,346 ±5,474 bc	8,835 ±1321 a	1,507 ±25 d	8.9 ±0.4 ab	0.35 ±0.03 cd	2.9 ±0.1 ab	0.020 ±0.000	0.271 ±0.070
CS4	Ariete	14,168 ±2,420 cd	6,805 ±223bc	NA	9.2 ±0.5 ab	0.61 ±0.08 b	2.2 ±0.3 c	0.012 ±0.007	NA
CS5	Ariete	14,586 ±1,749 cd	6,618 ±430 bc	7,203 ±1,858 bc	6.6 ±0.8 c	0.43 ±0.05 c	2.4 ±0.3 c	0.010 ±0.000	0.313 ±0.140
CS6	Hybrid-EH1	12,395 ±2,176 d	8,199 ±1 ab	4,635 ±664 cd	10.2 ±0.8 a	0.83 ±0.09 a	1.5 ±0.3 c	0.239 ±0.232	0.259 ±0.045
CS7	Osmancik/Rekor	38,937 ±4,435 a	5,283 ±408 c	NA	7.9 ±0.7bc	0.19 ±0.0d	7.7 ±1.0 a	0.038 ±0.008	0.023 ±0.005

WP$_{I+R}$: Water productivity considering irrigation plus precipitation, RWS: Relative water supply defined as Irrigation plus rain / ETc. Different letters mean that there were significant differences ($p<0.05$) in the average values of each parameter for each CS.

Depending on the CS, WFL irrigation inputs ranged from 12,395 to 38,937 m³/ha; ETc ranged from 5,283 to 8,835 m³/ha; percolation ranged from 1,507 to 20,505 m³/ha; grain yield ranged from 6.5 to 10.6 t/ha; WP$_{I+R}$ ranged from 0.83 to 0.19 kg/m³ and RWS ranged from 1.5 to 4.7 m³/m³.

As can be observed, most of the values in Table 2, except for the Cd and As contents, resulted to be significantly different among CSs. Therefore, in the following, the effects of the tested irrigation solutions were assessed considering the WFL results achieved in each CS.

3.2. Alternate Wetting and Drying (AWD)

When adopting AWD irrigation and comparing results with WFL, it can be observed that: no yield reductions were found in Lomellina and Mondego Valley, while 9% and 12% yield reductions were obtained in Lis and Bafra Valleys, respectively. In addition, water saving was around 20% in Lomellina, 2% in Mondego Valley, 10% in Lis Valley and 26% in Bafra Valley. Percolation was reduced by 24% in Lomellina, and 29% in Lis Valley. On the other hand, Water Productivity (WP$_{I+R}$) was increased by 23% in Lomellina and 19% in Bafra Valley, while it was similar to WFL in Mondego and Lis Valleys. Finally, Relative Water Supply (RWS) was reduced by 17% in Lomellina, 11% in Lis Valley and 23% in Bafra Valley while it was similar to WFL in Mondego Valley.

According to these results, AWD can be considered a promising irrigation technique for rice cultivation in the Mediterranean basin, as it allowed to achieve a reduction in water consumption which barely penalized the yield.

3.3. Dry Seeding and Delayed Flooding (DFL)

In comparison with WFL, yield with DFL increased by 13% in Baix Ter and reduced by 5% in Lomellina. The yield improvement in the Baix Ter can be probably explained by the more homogeneous distribution of the seeds, as seed-drill was used. This fact facilitated a good establishment of the plants before the tillering stage, and consequently an efficient competition of rice with the weeds. The amount of irrigation water was reduced by 14% in Lomellina, but it was increased by 6% in the Baix Ter. Percolation was reduced by 15% in Lomellina and was maintained in the Baix Ter. This can be explained by the greater amount of irrigation in DFL compared with WFL in the Baix Ter, probably because the DFL field was sandier that the WFL field. Water Productivity (WP_{I+R}) increased in both CSs, by 8% in Lomellina and 6% in the Baix Ter. Relative Water Supply (RWS) was reduced by 9% in Lomellina and 2% in the Baix Ter.

According to the obtained results, DFL can be considered a promising irrigation technique which can be considered as an alternative solution to the WFL; the results have been positive in both case studies as the application of DFL increased water productivity. However, a massive adoption of the DFL technique could slow down the rising of the groundwater level of about one month in rice areas thus reducing the water reuse; how acceptable this may be is to be assessed from case to case.

3.4. Reduction of Water Input (RWI1, RWI2 and RWI3)

Compared with WFL, reduction irrigation treatments RWI1, RWI2 and RWI3, applied in CS3 reduced yield by 6%, 7% and 8%, with a corresponding irrigation reduction of 14%, 31% and 7%, respectively. Percolation was barely affected in the different irrigation treatments. Water Productivity (WP_{I+R}) was increased, especially in RWI2, achieving a 30% gain compared with WFL, while RWI1 and RWI3 produced small increases of WP, 16% and 5%, respectively. Relative Water Supply (RWS) was reduced by 32%, 28% and 16% for RWI1, RWI2 and RWI3, respectively.

Among the RWI treatments, the best results were obtained with the strategy RWI2 (reduction of water inflow 100 days after sowing), as it reduced the irrigation volume more than the other treatments and showed a very small effect on yield.

3.5. Subsurface drip irrigation (SDI) and surface drip irrigation (DRIP)

SDI irrigation: SDI was tested in two different fields in CS2, one with sandy-loam texture (SDI_SaL) and deep groundwater and another one with silty-clay texture and shallow groundwater (SDI_SiC). The results have been quite different for the two fields. When adopting SDI, and comparing results with WFL, it can be observed that: yield was reduced by 45% and 4.5% in SDI-SaL and SDI-SiC, respectively. The yield obtained with SDI in the silty-clay soil was quite similar to the one obtained with WFL. The amount of irrigation water was reduced by 30% and 42% in SDI-SaL and SDI-SiC, respectively. Percolation was reduced by 40% and 66% with SDI-SaL and SDI-SiC, respectively. Water Productivity (WP_{I+R}) was reduced by 29% in SDI-SaL and increased by 58% in SDI-SiC. Relative water supply (RWS) was reduced by 22% and 39% in SDI-SaL and SDI-SiC, respectively.

The positive results obtained in SDI-SiC demonstrated that irrigation water volume can be reduced by 40% without affecting yield and reducing deep percolation about 60-70%. The poor results in SDI-SaL were probably due to an inefficient design: different dripline spacings were tested (66 cm and 75 cm) but they might be excessive for this coarse soil.

DRIP irrigation: Compared with WFL, yield was reduced by 64% in Guadalquivir marshes, 38% in Lis Valley and 5% in Bafra Valley. Instead, it increased by 10% in Nile Delta. The amount of irrigation water was maintained in Guadalquivir marshes and reduced by 35%, 38% and 75% in Lis Valley, the Nile Delta and Bafra Valley, respectively. Percolation was reduced by 32% and 90% in Lis Valley and the Nile Delta (percolation was not available for Guadalquivir marshes and Bafra Valley). In addition, Water Productivity (WP_{I+R}) was reduced by 66% and 6% in Guadalquivir marshes and Lis Valley; on the contrary, it was increased by 78% and 268% in Nile Delta and Bafra Valley, respectively. Relative Water Supply (RWS) was increased by 4% Guadalquivir Marshes and reduced by 26%, 32% and 73% in Lis Valley, the Nile Delta and Bafra Valley, respectively.

In summary, contradictory results were found for DRIP irrigation in different contexts: while in yield increased by 10% in the Nile Delta and it was maintained in Bafra Valley, in Lis Valley and Guadalquivir marshes it was dramatically reduced by 38% and 64%, respectively.

It must be highlighted that SDI and DRIP are very innovative irrigation techniques for rice cultivation. These tests pioneered the application of these technologies in rice irrigation. Difficulties in selecting the appropriate design of the irrigation system adapted to agro-climatic conditions and soil type (depth of driplines, emitter and dripline spacings and emitters flowrate), irrigation management criteria to be adopted for drip-irrigated rice, lack of experience in weed control when rice grows under aerobic conditions, were a challenge in many of the CSs. Nevertheless, the experience gained in the framework of this project and the positive results in some of the design and management options show that drip is a very promising technique which can be adopted in water scarce areas and for extending the rice production out of the traditional paddy areas.

3.6. Hybrid irrigation (HYBRID)

The results obtained in CS6 with HYBRID irrigation compared with WFL revealed that rice yield was increased by 23%, irrigation water was reduced by 18%, percolation was reduced, Water Productivity (WP_{I+R}) was increased by 49% and, Relative Water Supply (RWS) was reduced by 18%.

According to the reported results, hybrid irrigation can be considered as a valid alternative irrigation solution to WFL, as it increased yield and reduced irrigation water and percolation. Water Productivity with Hybrid irrigation achieved 1.24 kg/m^3, being among the highest found in the project.

3.7. Sprinkler irrigation (SPRINKLER)

Sprinkler irrigation in CS6 increased rice grains yield by 10% compared to WFL. The amount of irrigation water was reduced by 25%, percolation was reduced, Water Productivity (WP_{I+R}) was increased by 46%, Relative Water Supply (RWS) was reduced by 23%.

According to the reported results, sprinkler irrigation can be a sound irrigation alternative to WFL as it increased yield, reduced irrigation water needs and percolation. Water Productivity achieved 1.21 kg/m^3, being among the highest observed in the project.

3.8. Grain quality: Arsenic and Cadmium contents for all irrigation treatments

Experimental results showed that in the case of AWD, DRIP and SDI Arsenic in rice grain tended to decrease while Cadmium tended to increase compared to WFL in most of the CSs, but these differences were not statistically significant at $p<0.05$. No clear patterns were observed for the other irrigation solutions.

In particular, AWD Cadmium rice content increased by 0.01 mg/kg in Lomellina, decreased by 0.01 mg/kg in Mondego Valley and remained nearly the same as in WFL in Mondego Valley and Bafra Valley. As expected, due to the soil aerobic conditions characterizing AWD, Arsenic in the rice grain decreased by 0.02 mg/kg in Lomellina and by 0.01 mg/kg in Bafra Valley; however, it was 0.03 mg/kg higher than WFL in Lis Valley.

In the case of SDI (Baix Ter), Cadmium rice content was lower compared to WFL of 0.071 mg/kg in SDI-SaL and 0.061 mg/kg in SDI-SiC. Arsenic content in the rice grain increased in SDI-SaL by 0.017 mg/kg and decreased by 0.015 mg/kg in SDI-SiC with respect to WFL. It must be considered that irrigation water for SDI-SaL was pumped from a well in which Arsenic content was higher than in the water used to irrigate the SDI-SiC and WFL fields, provided by an open channel.

When considering DRIP irrigation, Cadmium rice content was nearly the same as in WFL in the Guadalquivir marshes, it increased by 0.018 mg/kg and 0.008 mg/kg in the Delta Nile and Bafra Valley, and reduced by 0.018 mg/kg in Lis Valley. Arsenic content in the rice grain was lower than WFL by 0.191 mg/kg in Guadalquivir marshes, 0.213 mg/kg in Lis Valley, 0.003 mg/kg in Bafra Valley, while it was 0.052 mg/kg higher than WFL in the Nile Delta.

4. Conclusions

Yield quantity, irrigation water use, percolation and corresponding Water Productivity and Relative Water Supply using the conventional irrigation system for rice (WFL – wet seeding and continuous flooding) were found to be significantly different for the experimental sites (CSs) around the Mediterranean basin considered in the MEDWATERICE project. The agroclimatic and soil characteristics, the groundwater table depth, the irrigation and agronomic practices adopted, the presence of salinity problems in some rice areas are probably responsible of what observed. Therefore, the comparisons shown in this paper among WFL and tested innovative solutions were carried out within the same CS.

AWD irrigation technique is found to be a sound alternative to WFL to reduce irrigation inputs (CS1, CS4, CS5 and CS7). Even though, slight reductions of yield compared to continuous flooding irrigation might happen, especially when this technique is adopted considering more severe soil water content thresholds. Water Productivity increases when compared to WFL and DFL.

DFL can be seen as an interesting alternative to WFL, which can facilitate many agronomic practices to the farmer. Literature reports an irrelevant decrease in yield and a slight reduction in irrigation water input adopting DFL. In MEDWATERICE we observed: i) the same yield with a slight reduction of irrigation water input (CS1), and ii) a slight increase in irrigation water needs, yield and Water Productivity (CS2).

Reduction of water input irrigation strategies RWI1, RWI2 and RWI3 may be interesting alternatives when the available water for irrigation is limited. The best results in the experimentation were achieved with the strategy RWI2 (reduction of water input after the day 100 after seeding), which was characterized by a reduction of about 30% of the total irrigation input compared to WFL during the last development stages of the rice cropping cycle. This irrigation practice showed to have no negative impacts on yield, neither on rice quality. The main concern may be water quality in terms of salinity, which may affect yield when water input is reduced. If water quality is not an issue, reduction of water input after the day 100 after seeding can considered as a sound water saving alternative to WFL.

Hybrid irrigation and sprinkler irrigation showed to be interesting alternatives to WFL as they increased yield, reduced deep percolation and irrigation water (by 18% and 25%, respectively) compared to WFL in the Nile Delta.

Surface and subsurface drip irrigation systems (DRIP and SDI) showed that if the irrigation system is properly designed and managed (CS2, CS6 and CS7), acceptable yield reduction can be achieved with a high water saving (up to 50% and more), leading to an important increase in WP. However, further research needs to be carried out to have best insight on: i) the choice of the most favorable rice varieties which could better adapt to aerobic conditions; ii) the proper design of the irrigation system to take into account site-specific soil conditions (e.g., flowrate, lateral and emitter spacing); and iii) the setup of an irrigation scheduling taking into consideration local agroclimatic conditions, soil hydraulic properties, crop physiology, and irrigation water quality.

Acknowledgments: The project MEDWATERICE 'Towards a sustainable water use in Mediterranean rice-based agro-ecosystems' (PRIMA-Section2-2018) was selected in the context of the PRIMA Programme (https://prima-med.org). The authors wish to tank PRIMA-IS for the possibility given, and the National Funding Agencies of the participating countries for the research funds received.

References

Bouman, B.A.M. and Tuong, T.P. (2001) 'Field water management to save water and increase its productivity in irrigated lowland rice', *Agricultural Water Management*, 49(1), pp. 11–30. Available at: https://doi.org/10.1016/S0378-3774(00)00128-1.

Carrijo, D.R., Lundy, M.E. and Linquist, B.A. (2017) 'Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis', *Field Crops Research*, 203, pp. 173–180. Available at: https://doi.org/10.1016/j.fcr.2016.12.002.

Cesari de Maria, S. *et al.* (2017) 'The role of water management and environmental factors on field irrigation requirements and water productivity of rice', *Irrigation Science*, 35(1), pp. 11–26. Available at: https://doi.org/10.1007/s00271-016-0519-3.

Empordà Gastronòmic (2022) *Pals impulsa una campanya de promoció de l'arròs per tal que tot el procés de producció es quedi a la localitat*, *Revista del Baix Empordà*. Available at: https://revistabaixemporda.cat/pals-impulsa-una-campanya-de-promocio-de-larros-per-tal-que-tot-el-proces-de-produccio-es-quedi-a-la-localitat/ (Accessed: 21 July 2022).

Gómez de Barreda, D. *et al.* (2021) 'An Overview of Rice Cultivation in Spain and the Management of Herbicide-Resistant Weeds', *Agronomy*, 11(6), p. 1095. Available at: https://doi.org/10.3390/agronomy11061095.

Harmanny, K.S. and Malek, Ž. (2019) 'Adaptations in irrigated agriculture in the Mediterranean region: an overview and spatial analysis of implemented strategies', *Regional Environmental Change*, 19(5), pp. 1401–1416. Available at: https://doi.org/10.1007/s10113-019-01494-8.

Iglesias, A. and Garrote, L. (2015) 'Adaptation strategies for agricultural water management under climate change in Europe', *Agricultural Water Management*, 155(C), pp. 113–124.

Kijne, J.W. (2006) 'Abiotic stress and water scarcity: Identifying and resolving conflicts from plant level to global level', *Field Crops Research*, 97(1), pp. 3–18. Available at: https://doi.org/10.1016/j.fcr.2005.08.011.

Marcos, M. *et al.* (2018) 'Spatio-temporal salinity dynamics and yield response of rice in water-seeded rice fields', *Agricultural Water Management*, 195, pp. 37–46. Available at: https://doi.org/10.1016/j.agwat.2017.09.016.

Tuong, P., Bouman, B.A.M. and Mortimer, M. (2005) 'More Rice, Less Water—Integrated Approaches for Increasing Water Productivity in Irrigated Rice-Based Systems in Asia', *Plant Production Science*, 8(3), pp. 231–241. Available at: https://doi.org/10.1626/pps.8.231.

Zampieri, M. *et al.* (2019) 'Adaptation and sustainability of water management for rice agriculture in temperate regions: The Italian case-study', *Land Degradation & Development*, 30. Available at: https://doi.org/10.1002/ldr.3402.

Zikos, D. and Hagedorn, K. (2016) 'Competition for Water Resources From the European Perspective', in *Competition for Water Resources: Experiences and Management Approaches in the US and Europe*, pp. 19–35. Available at: https://doi.org/10.1016/B978-0-12-803237-4.00002-1.