

ASSESSING DRY SEEDING AND DELAYED FLOODING IN RICE USING REMOTE SENSING IN THE LOWER MONDEGO VALLEY, PORTUGAL

ÉVALUATION DU SEMIS À SEC ET DE LA MISE EN EAU DIFFÉRÉE DU RIZ PAR TÉLÉDÉTECTION DANS LA BASSE VALLÉE DU MONDEGO, AU PORTUGAL

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ABSTRACT

Rice cultivation in the Lower Mondego Valley (LMV), Portugal, has traditionally relied on wet sowing with continuous flooding (WFL). Although improvements in land levelling have contributed to water savings, conventional rice production systems still face important challenges related to irrigation water use, energy consumption, production costs, and weed management. Dry seeding with delayed flooding (DFL) has emerged as a promising alternative management strategy with the potential to improve irrigation efficiency and reduce environmental impacts. An experimental study was conducted during the 2022–2025 rice growing seasons in farmers' fields located in the LMV to evaluate the agronomic and hydraulic performance of DFL under Mediterranean conditions. Conventional WFL plots were used as references. The study integrated field monitoring, meteorological observations, water balance calculations, and remote sensing (RS) techniques based on Sentinel-2 and Landsat imagery. Time series of the Normalized Difference Vegetation Index (NDVI), processed using the SPIDERwebGIS© platform (University of Castilla-La Mancha, Spain), were used to assess crop development under different irrigation systems. The results showed that DFL reduced irrigation water application and flooding periods compared with WFL management, while maintaining comparable seasonal crop development and similar grain yield. NDVI temporal profiles revealed slower vegetation development during the initial crop stages under DFL conditions due to delayed flooding, followed by rapid canopy recovery after flooding establishment. Maximum NDVI values during mid-season were similar under both irrigation systems, indicating comparable vegetation vigor. Overall, the integration of field measurements and remote sensing techniques provided valuable information for evaluating crop dynamics, irrigation performance, and water use under contrasting rice management systems. The results support the potential adoption of DFL as a more sustainable rice production strategy for Mediterranean rice-growing regions.

Keywords: Dry seeding; Remote sensing; rRice cultivation; Time series; Temporal profiles; Irrigation systems.

RÉSUMÉ

Dans la basse vallée du Mondego (LMV), au Portugal, la riziculture repose traditionnellement sur le semis en conditions humides avec submersion continue (WFL). Bien que l'amélioration du nivellement des terres ait contribué à économiser l'eau, les systèmes rizicoles conventionnels restent confrontés à d'importants défis liés à l'utilisation de l'eau d'irrigation, à la consommation d'énergie, aux coûts de production et à la gestion des adventices. Le semis à sec avec mise en eau différée (DFL) est apparu comme une stratégie de gestion alternative prometteuse, susceptible d'améliorer l'efficacité de

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l'irrigation et de réduire les impacts environnementaux. Une étude expérimentale a été menée pendant les campagnes rizicoles de 2022 à 2025 dans des parcelles d'agriculteurs situées dans la LMV, afin d'évaluer les performances agronomiques et hydrauliques du DFL en conditions méditerranéennes. Des parcelles conventionnelles conduites en WFL ont servi de référence. L'étude a combiné le suivi au champ, les observations météorologiques, les calculs de bilan hydrique et des techniques de télédétection (RS) fondées sur des images Sentinel-2 et Landsat. Des séries chronologiques de l'indice de végétation par différence normalisée (NDVI), traitées au moyen de la plateforme SPIDERwebGIS© (Université de Castille-La Manche, Espagne), ont permis d'évaluer le développement de la culture selon les différents systèmes d'irrigation. Les résultats ont montré que le DFL réduisait les apports d'eau d'irrigation et la durée de submersion par rapport à la conduite en WFL, tout en maintenant un développement saisonnier comparable de la culture et un rendement en grains similaire. Les profils temporels du NDVI ont révélé un développement plus lent de la végétation au cours des premiers stades de la culture sous DFL, en raison de la mise en eau différée, suivi d'une reprise rapide du couvert après l'établissement de la submersion. Les valeurs maximales du NDVI à la mi-saison étaient similaires dans les deux systèmes d'irrigation, indiquant une vigueur végétative comparable. Dans l'ensemble, l'intégration des mesures de terrain et des techniques de télédétection a fourni des informations précieuses pour évaluer la dynamique de la culture, les performances de l'irrigation et l'utilisation de l'eau dans des systèmes rizicoles contrastés. Les résultats confirment le potentiel d'adoption du DFL comme stratégie rizicole plus durable dans les régions méditerranéennes productrices de riz.

Mots clés : Semis à sec; Télédétection; Riziculture; Séries chronologiques; Systèmes d'irrigation.

INTRODUCTION

Rice cultivation plays an important socio-economic, environmental, and cultural role in several Mediterranean regions, including Portugal, where rice is mainly cultivated in lowland valleys and coastal wetland areas. Traditional rice production systems are commonly based on wet sowing with continuous flooding (WFL), a management practice adopted for centuries due to its agronomic, environmental, and microclimatic benefits.

Despite its importance for crop establishment and weed control, continuous flooding is associated with high irrigation water requirements, elevated pumping energy consumption, nutrient losses through drainage and percolation, and increasing pressure on water resources. Under Mediterranean conditions, future climate variability and growing competition for water may further increase the need for more efficient irrigation management strategies in rice production systems.

Dry seeding with delayed flooding (DFL) has emerged as a promising alternative crop establishment method and is increasingly considered a climate-smart management strategy for rice production (Bouman et al., 2007; Ahmed et al., 2025). In DFL systems, rice is sown under non-flooded soil conditions, while permanent flooding is postponed until crop establishment and early vegetative development. Compared with conventional WFL practices, DFL may reduce irrigation water use, surface drainage losses, labor requirements, and pumping energy consumption. However, delayed flooding may also affect crop establishment and early vegetation development, particularly during the initial crop stages.

Recent advances in in situ monitoring systems and remote sensing (RS) technologies have improved the capacity to monitor crop development, irrigation performance, and water use dynamics under field conditions. Satellite-derived vegetation indices have demonstrated strong potential for monitoring crop temporal dynamics and evaluating the effects of irrigation management practices on crop performance and productivity (Calera et al., 2017; Ferreira et al., 2023; Wei et al., 2022). The integration of field measurements and RS techniques may therefore support the development of more efficient and sustainable irrigation strategies for rice production systems.

In this context, an experimental field study was conducted in the Lower Mondego Valley (LMV), Portugal, during the 2022–2025 crop seasons to evaluate the agronomic and hydraulic performance of DFL under Mediterranean conditions. The study integrated field monitoring, water balance analysis, and satellite-derived NDVI time series to assess the effects of delayed flooding on crop development, irrigation water use, and productivity in comparison with conventional WFL management.

MATERIALS AND METHODS

The experimental study was conducted between 2022 and 2025 in the Lower Mondego Valley (LMV), located in the central coastal region of Portugal. The irrigation district comprises approximately 12,000 ha, including about 6,000 ha of rice paddies. The region has a Mediterranean climate (C_{sb}/C_{sa} , Köppen classification), with annual precipitation ranging from 800 to 900 mm, mild summers with limited rainfall, and rainy winters (IPMA, 2022) (Figure 1). The soils are predominantly alluvial, with high agricultural suitability, although poorly drained conditions, waterlogging, and salinization risks occur in downstream areas where rice is cultivated.

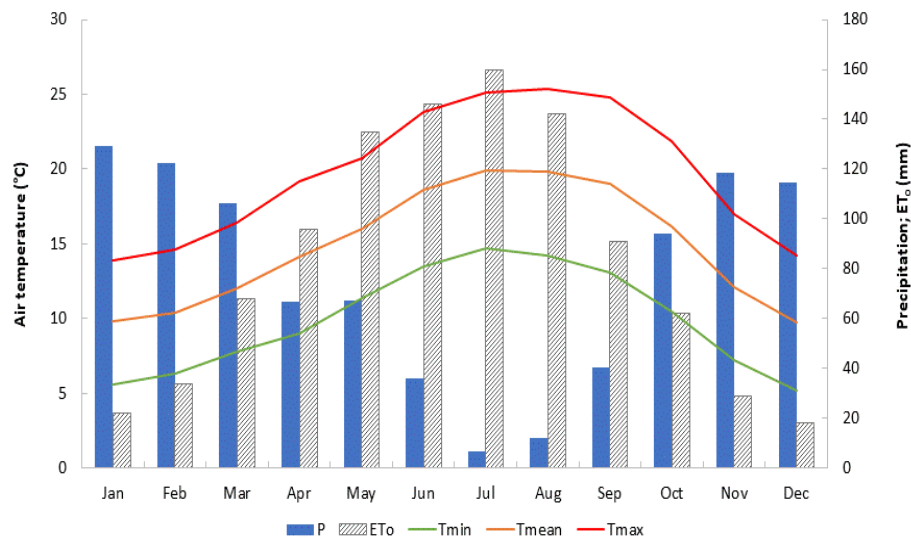


Figure 1. Average monthly precipitation (P, mm), reference evapotranspiration (ET_0 , mm), and minimum (T_{min}), mean (T_{med}), and maximum (T_{max}) air temperature (°C) in the Lower Mondego study area for the 1981–2021 period (source: IPMA, 2022).

The location and main soil characteristics of the experimental rice fields are presented in Figure 2 and Table 1, respectively. Soil preparation practices were similar for both treatments and included ploughing, harrowing, and land levelling under dry soil conditions. Irrigation water was supplied from adjacent ditches through manually operated pumping systems.

Table 1. Location, area, altitude and soil characteristics of experimental rice fields.

Parameter	Field 1		Field 2	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm
Area (ha)	2.85		3.07	
Coordinates	40°10'35.6"N 8°41'20.0"W		40°10'36.9"N 8°41'34.0"W	
Elevation (m a.s.l.)	3		3	
Groundwater depth (cm bss)	50–90		50–90	

Parameter	Field 1		Field 2	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm
Sand (%)	75.9	79.8	68.1	43.9
Silt (%)	13.7	11.4	14.7	26.0
Clay (%)	10.4	8.9	17.2	30.1
Texture class	Sandy loam	Loamy sand	Sandy loam	Clay loam
pH (H ₂ O)	7.29	7.53	7.35	7.49
SOC (%)	1.10	1.00	1.09	2.18
Bulk density (g cm ⁻³)	1.30	1.27	1.28	1.25

Note: BSS — Below Soil Surface; ASL. — Above Sea Level; SOC — Soil Organic Carbon.



Figure 2. Location of the experimental rice fields (Field 1 and Field 2) in the LMV, Portugal (source: Google Earth, 2026).

A single Italian rice cultivar, Ariete (japonica type), was used in all experimental fields. Ariete is classified as a semi-early cultivar, with a growth cycle ranging from approximately 139 to 150 days. The main crop development stages and irrigation management practices adopted under WFL and DFL conditions are summarized in Table 2. Dry seeding field operations under DFL management are illustrated in Figure 3. The experimental design, irrigation management practices, and main crop calendar dates adopted during the study period are summarized in Tables 3 and 4.

Table 2. Main crop development stages and irrigation practices under WFL and DFL management in the LMV.

Crop stage / irrigation practice	WFL (DAS)	DFL (DAS)
Soil flooding	0 to 2	~35
Sowing	0 (wet sowing)	0 (dry sowing)
Start of tillering	30–35	38–45
Panicle differentiation	55–65	55–65
Flowering	85–95	85–95
Last irrigation event	~105	104–108
Harvest	~140	~140



Figure 3. Dry seeding operations adopted under delayed flooding (DFL) management in the experimental rice fields of the LMV, Portugal.

Table 3. Experimental design and irrigation management practices adopted between 2022 and 2025.

Crop season	Field 1	Field 2
2022	WFL	WFL
2023	DFL	WFL
2024	DFL	DFL
2025	DFL	DFL

WFL — wet sowing with continuous flooding; DFL — dry seeding with delayed flooding.

Table 4. Main dates of rice crop experiments.

Crop season	Field	Management practice	Sowing	First flooding	Harvesting	Season length (days)
2022	1 and 2	WFL	22 May	21 May	30 Sep	132
2023	2	WFL	15 May	14 May	2 Oct	140
2023	1	DFL	15 May	16 Jun	2 Oct	140
2024	1 and 2	DFL	23 May	19 Jun	10 Oct	140
2025	1 and 2	DFL	6 Jun	8 Jul	27 Oct	144

In situ monitoring

The in situ methodology followed the experimental approach previously applied in the LMV by Gonçalves et al. (2022). A hydraulic monitoring system was implemented to continuously measure floodwater level (FWL), inflow and outflow discharges, together with meteorological observations and daily water balance calculations for estimating deep percolation following standard crop evapotranspiration approaches (Allen et al., 1998). Crop yield was determined at harvest through biomass sampling in representative 0.5 m² unit areas, with approximately five sampling locations per hectare. Biomass samples were processed under laboratory conditions to determine grain dry matter at 14% moisture content and straw biomass.

Remote sensing monitoring

Satellite imagery from Sentinel-2A/2B (Copernicus Programme) acquired during the 2022–2025 rice growing seasons was used to monitor crop development under WFL and DFL management. Sentinel-2 imagery provides a revisit frequency of approximately 5 days and spatial resolutions of 10–20 m, while Landsat imagery provides revisit intervals of 16 days with 30 m spatial resolution for visible and near-infrared bands.

The SPIDERwebGIS© platform (University of Castilla-La Mancha, Spain) was used to analyze satellite imagery. Orthorectified Bottom-Of-Atmosphere (BOA) reflectance imagery was considered, using atmospherically corrected datasets provided by the platform. Time series of the Normalized Difference Vegetation Index (NDVI) were analysed to characterize crop temporal dynamics and vegetation development during the crop season.

Five representative sampling points were selected within each experimental field, and average NDVI values were calculated for each acquisition date. For dates without available imagery, NDVI values were linearly interpolated between adjacent satellite acquisitions to obtain continuous temporal profiles during the crop season.

RESULTS AND DISCUSSION

The 2023 crop season provided the main side-by-side comparison between WFL and DFL management systems, since both irrigation strategies were simultaneously implemented under comparable field conditions. Therefore, the detailed analysis of floodwater dynamics and NDVI temporal evolution focused primarily on the 2023 experimental season.

Soil flooding dynamics and crop establishment

The monitored floodwater dynamics clearly reflected the differences between WFL and DFL management practices (Figure 4). Under WFL conditions, soil flooding was established immediately before or during sowing and maintained throughout most of the crop cycle, resulting in longer periods with saturated soil conditions. In contrast, under DFL management, permanent flooding was established approximately 35 days after sowing, increasing the duration of dry soil conditions during crop establishment.

The number of days with wet soil conditions was consistently lower under DFL management compared with WFL (Table 5). Under WFL conditions, wet soil periods ranged from 98 to 112 days, whereas under DFL conditions they decreased to values between 73 and 86 days during the 2023–2025 crop seasons. Consequently, DFL fields presented longer dry soil periods during the initial crop development stages.

Despite delayed flooding, crop establishment under DFL remained stable and agronomically viable throughout the experimental period.

After the establishment of permanent flooding, crop development accelerated rapidly, indicating that delayed flooding did not substantially compromise canopy establishment under the studied conditions.

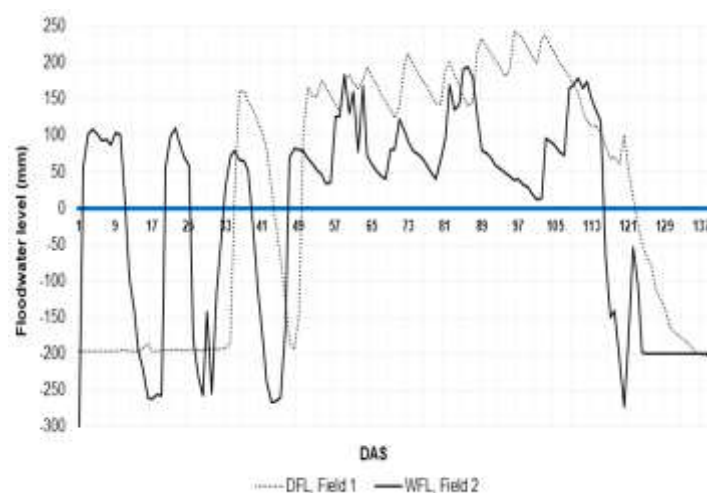


Figure 4. Floodwater level above and below the soil surface (mm) under WFL and DFL irrigation management, during the 2023 rice season. DAS: days after sowing.

Water use and crop development based on remote sensing and field measurements

The combined analysis of field water balance components and satellite-derived NDVI profiles highlighted clear differences between WFL and DFL irrigation management systems during the experimental period.

Under DFL conditions, irrigation water application was consistently lower than under WFL management (Table 5). During the 2023 crop season, total irrigation depth under DFL reached 1041 mm, whereas the WFL field required 1378 mm. Similar trends were observed during the 2024 and 2025 seasons, confirming the potential of delayed flooding practices to reduce irrigation requirements under the conditions of the LMV. Similar reductions in irrigation water use and improvements in water productivity have been also reported by Sudhir-Yadav et al. (2011), Monaco and Guido (2018) and Gunacti et al. (2019).

Table 5. Water use parameters and productivity on the experimental fields per crop season.

Year		2022		2023		2024		2025	
Field		1	2	1	2	1	2	1	2
Management practice		WFL	WFL	DFL	WFL	DFL	DFL	DFL	DFL
Water use parameters	Irr (mm)	1443	1355.5	1041	1378	957.3	922.4	945.7	929.3
	ETc (mm)	611.9	607.4	562	593	561	557.8	530.5	538.8
	P (mm)	78.2	78.2	158.4	164.4	112.2	112.2	210.6	203.3
	DP (mm)	400.8	343.6	392.5	506.5	295.4	338.1	526.5	446.8
	SD (mm)	542.9	571.5	245	407.1	187.7	117.1	73.8	100.5
Crop Productivity	Y (t/ha)	7.5	9.0	6.6	7.0	7.0	7.2	7.3	7.4
	WP (kg/m ³)	0.49	0.63	0.52	0.50	0.54	0.70	0.63	0.65
Number of days	Wet soil	112	98	82	100	86	80	73	74
	Dry soil	21	35	58	40	58	64	71	70

The reduction in irrigation water applied under DFL was mainly associated with shorter flooding periods, lower surface drainage volumes, and reduced periods with saturated soil conditions. In 2023, the number of wet soil days decreased from 100 days under WFL to 82 days under DFL management, while dry soil periods increased from 40 to 58 days.

Temporal NDVI profiles derived from Sentinel-2 imagery reflected these differences in irrigation management (Figure 5). Under DFL conditions, lower NDVI values were observed during the early crop stages due to delayed flooding and slower initial canopy development associated with non-saturated soil conditions after sowing. In contrast, WFL management promoted earlier vegetation development due to flooding established at the beginning of the crop cycle.

However, despite the presence of standing water during the early WFL stage, strongly negative NDVI values were not consistently observed in 2023. Similar flooded conditions associated with negative NDVI values were previously reported by Ferreira et al. (2023), although this behaviour was not consistent across all years. In the present study, the slightly positive NDVI values observed during the initial flooded period likely reflect the limited sensitivity of NDVI to shallow and spatially heterogeneous flooded surfaces under Sentinel-2 spatial resolution. Mixed spectral contributions from standing water, exposed wet soil, and early crop emergence may have reduced the expected open-water spectral response during the first days after sowing. These findings highlight the importance of integrating complementary water-sensitive indices, such as NDWI, in future studies to improve the characterization of early flooding dynamics in rice systems.

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Following the establishment of permanent flooding in the DFL field at approximately 33 days after sowing (DAS), NDVI values increased rapidly, indicating accelerated crop development and rapid canopy recovery during the vegetative growth stage. Peak NDVI remained close to 0.90 under both irrigation systems during the mid-season period, demonstrating comparable vegetation vigor and canopy development despite the different irrigation strategies. The relationship between NDVI temporal dynamics and rice crop performance has also been reported in previous remote sensing studies focused on rice productivity assessment (Guan et al., 2019).

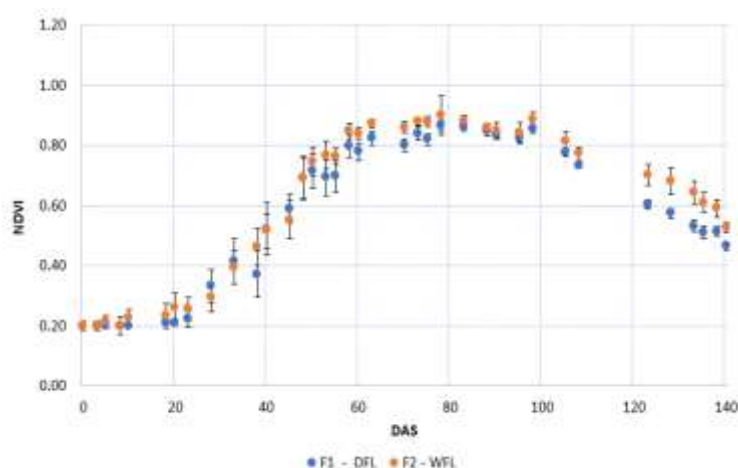


Figure 5. Temporal evolution of NDVI under dry seeding with delayed flooding (DFL, Field 1) and wet sowing with continuous flooding (WFL, Field 2) during the 2023 crop season. Points represent mean NDVI values derived from Sentinel-2 imagery, and error bars indicate standard deviation among sampling points within each field. DAS: days after sowing.

After flowering and during crop maturation, NDVI values progressively decreased under both systems, reflecting crop senescence and the reduction of green biomass. Although both irrigation systems showed comparable seasonal NDVI trajectories, differences became more evident during the late maturation stage, with WFL maintaining slightly higher NDVI values than DFL. This behavior may indicate a somewhat earlier senescence process under DFL conditions, potentially associated with reduced soil water availability during the final stages of crop development. Nevertheless, the overall seasonal dynamics suggest that DFL management maintained crop development patterns broadly comparable to those observed under WFL conditions.

In 2022, when both experimental fields were managed under WFL conditions, NDVI temporal profiles showed very similar seasonal patterns. Similarly, during 2024 and 2025, when both fields were managed under DFL conditions, NDVI temporal evolution remained comparable between plots. These observations reinforce the interpretation that the differences observed during the 2023 season were mainly associated with contrasting irrigation management practices rather than intrinsic field variability. The relatively low standard deviation values associated with NDVI averages throughout most of the crop cycle further support the consistency of the temporal patterns observed between sampling points within each field.

The NDVI temporal evolution was also consistent with the observed crop productivity results. Despite lower irrigation water application under DFL management, only small differences in grain yield were observed between treatments. During the 2023 crop season, grain yield reached 6.6 t ha⁻¹ under DFL and 7.0 t ha⁻¹ under WFL conditions. In addition, water productivity values under DFL were comparable or slightly higher than those observed under WFL conditions, suggesting improved irrigation efficiency under delayed flooding management.

These results suggest that delayed flooding can substantially reduce irrigation water use during the initial crop stages without significantly compromising seasonal canopy development and final grain yield under Mediterranean conditions.

Overall, the integration of field measurements and remote sensing techniques proved useful for evaluating crop development, irrigation performance, and water use dynamics under contrasting rice management systems.

CONCLUSIONS

Dry seeding with delayed flooding proved to be a technically viable alternative to conventional wet sowing with continuous flooding under the conditions of the LMV.

DFL management reduced irrigation water application and shortened flooding periods, while maintaining comparable crop development and only small differences in grain yield relative to WFL conditions. NDVI temporal profiles derived from Sentinel-2 imagery successfully captured the differences in crop establishment and vegetation dynamics between irrigation systems, particularly during the initial growth stages.

Despite slower early development under DFL conditions, NDVI values rapidly increased after flooding establishment and reached seasonal maximum values similar to those observed under WFL management. Water productivity values under DFL were comparable or slightly higher than those obtained under WFL conditions, indicating improved irrigation efficiency.

The integration of field measurements and remote sensing techniques proved effective for evaluating crop development, water use, and irrigation performance under contrasting rice management practices. The results support the potential adoption of DFL as a more sustainable rice production strategy in Mediterranean rice-growing regions.

The complete multi-year dataset collected between 2022 and 2025 will support further analyses relating vegetation indices, crop coefficients, evapotranspiration, and irrigation performance under contrasting rice establishment methods. Future research should also explore the suitability of alternative vegetation indices and advanced remote sensing processing approaches for flooded rice systems, where NDVI performance may be influenced by the presence of surface water during part of the crop cycle.

Acknowledgments: Project PROMEDRICE - Effective farming practices to protect water resources in Mediterranean rice-based agroecosystems - 10.54499/PRIMA/0007/2022, www.promedrice.org. This project is part of the PRIMA Programme supported by the European Union.

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