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ORIGINAL PAPER

Synergistic impact of agro-ecological water and nutrient management practices on rice yield and water use efficiency in inland valleys

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Abstract

This study evaluates the effects of irrigation and agro-ecological nutrient management practices on rice yield and water use efficiency (WUE) over two cropping seasons (2022 and 2023) in southwestern Benin. Field experiments were conducted at two contrasted sites, Matekpo (in-season) and Sewahoue (off season), using a split-split-plot design with three replications. Treatments included four irrigation regimes Continuous Flooding (CF), Soil Saturation (SS), moderate Alternate Wetting and Drying (– 15 kPa, AWD15), and severe (-30 kPa, AWD30) and eight nutrient treatments: Control (C), recommended Mineral (M), Mineral Micro-dosing (MM), Compost (CO), Rice Straw (RS), Biochar plus Compost (BCO), Rice Straw plus Compost (RSCO), and Mucuna biomass (BM). Daily water dynamics were monitored throughout the production cycle, and grain yield was measured at maturity. Linear models in R 4.4.2 were used for data analysis.

Results showed that AWD15 significantly reduced water inputs by 30–70% while maintaining comparable yields to CF, especially when combined with organic amendments (compost and biochar). In-season rice yield (3.3 t/ha) was slightly higher than off-season (3.1 t/ha), with greater WUE observed during the in-season (1.16 kg/m³ vs. 0.87 kg/m³). Mineral fertilizers performed best under CF, whereas organic amendments were more effective under AWD. The highest WUE was recorded under AWD30 and AWD15, particularly when integrated with organic nutrient sources. These findings highlight the potential of AWD, combined with agro-ecological nutrient management strategies, to improve rice productivity and water efficiency in lowland systems, supporting sustainable intensification under variable climatic conditions.

Keywords Water use efficiency · Alternate wetting and drying · Organic amendments · Rice yield · Sustainable agriculture

Introduction

Rice is one of the most important staple foods worldwide, playing a vital role in ensuring food security across many regions, including West Africa (Kinhou 2019). As a strategic crop, rice plays a central role in the effort of policymakers to address persistent food insecurity (Bignebat et al. 2024). In recent years, rice production in Africa has expanded significantly, with a 40% increase in cultivated area over the past decade (Yuan et al. 2024). However, this expansion has not translated into a matching increase in production, and the continent still relies on imports to meet approximately 40% of its rice consumption (Yuan et al. 2024).

Rice is also represents one of the most water-demanding crops, traditionally cultivated under continuous flooding conditions (Datta et al. 2017; Qiu et al. 2023). This cultivation method explains the predominance of rice in wetland environments such as inland valleys and floodplains (Bossa et al. 2020; Tran et al. 2021). In Benin, where agriculture in inland valleys and floodplain areas is actively being developed, there is significant potential for lowland rice production. Despite national efforts to increase output, rice supply

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continues to lag behind demand (Namara and Sally 2014; Tondel et al. 2020). Production is largely based on smallholder, rain-fed systems with low yields ranging from 1 to 2 t ha^{-1} (Balasubramanian et al. 2007; Katic et al. 2013). To address these constraints, various interventions such as contour bunds, drainage structures, and Sawah technology have been introduced to boost productivity (Nwite et al. 2008; Depieu et al. 2017). Yet, yields in these environments remain modest, typically below 3 t ha^{-1} (Gbenou et al. 2016), despite a potential of 6 t ha^{-1} or more (Niang et al 2019).

The challenge is further compounded by increasing climate variability and change, which exacerbates water scarcity challenges for rice production, particularly in tropical and subtropical regions like West Africa (Ullah et al. 2019; Meng et al. 2023). In Benin, climatic pressures, coupled with population growth, have intensified the demand for rice, reinforcing the country's dependency on imports. This situation highlights the need for more efficient and sustainable water use in rice systems. Improving rice yield and water use efficiency (WUE) is vital for sustainable production amid increasing water scarcity and climate variability (Mallareddy et al. 2023). Research demonstrates that water-saving practices, like Alternate Wetting and Drying (AWD), enhance WUE while sustaining yields (Wang et al. 2020; Gao et al. 2024). AWD promotes root growth, improves soil aeration, and reduces water loss, thereby optimizing resource use (Huang 2024). Fertilizer management also significantly influences productivity (Dwivedi and Dwivedi 2015). In Benin, rice farmers apply suboptimal fertilizer rates due to cost, access, and knowledge gaps (Niang 2019; Tsujimoto et al. 2019). Predominant use of mineral fertilizers with poor timing reduces nutrient use efficiency, while the use of organic amendment remains limited and inconsistently practiced (Tovihoudji et al. 2022). Organic amendments like compost, biochar, rice straw improve soil structure, microbial activity, and water retention, while mineral fertilizers ensure rapid nutrient availability (Wang et al. 2022; Singh et al. 2024). However, excessive use of mineral fertilizers may lead to leaching risks and poor nutrient uptake (Fontaine et al. 2024). Combining AWD with integrated nutrient management synergistically enhances yield and WUE by improving nutrient availability, root development, and physiological efficiency (Zhang et al. 2023; Lyu 2024).

Table 1 Initial soil chemical and physical properties of the experimental sites

	Matekpo	Sewahoue
Parameters	0–20 cm	0–20 cm
Soil texture (FAO textural triangle)	Clay	Silt Clay loam
Sand (%)	2.86	8.41
Silt (%)	15.08	57.67
Clay (%)	82.06	33.92
Bulk density (g/cm^3)	1.36	1.15
Soil chemical properties		
pH-H2O	5.2	5.4
Organic C (g kg^{-1})	1.74	1.13
Total N (mg kg^{-1})	0.18	0.09
P Bray-1 (mg kg^{-1})	1.9	6.25
Exch. K (cmol+kg^{-1})	0.21	0.04
CEC mmolc dm^3	10.2	8.78

Despite their potential, only a few studies have comprehensively assessed these interactions, particularly in the inland valleys of sub-Saharan Africa, characterized by particular hydrological and soil conditions which require context-specific solutions. A knowledge gap persists regarding how agro-ecological water and nutrient management strategies may jointly optimize productivity and sustainability. Addressing this gap is crucial for developing climate-resilient and resource-efficient rice systems in vulnerable regions.

We hypothesize that combining AWD with organic nutrient management will significantly increase both rice yield and WUE in inland valleys, compared to conventional continuous flooding and sole mineral fertilization. The objective of this study was to identify treatment combinations that align with agro-ecological principles of efficiency and sustainability. Our findings emphasize the importance of WUE as a guiding metric for sustainable intensification, highlighting the role of synergistic interactions between water and nutrient management practices in improving rice productivity in inland-valley systems.

Materials and methods

Experimental site description

The experiments were conducted in inland-valley production systems at two farmer's sites locations: Matekpo and Sewahoue in south west Benin. The Matekpo site (6°19’14.60"N, 1°50’13.40"E) is located in the commune of Grand Popo (southern Benin), in the shallows of the Sazue tributary of the Mono River. The Sewahoue site (6°19’15.60"N, 1°50’13.20"E) is located in the commune of Lalo (southern Benin), in the inland valley of a tributary of the Couffo River. Both regions have a sub-equatorial, bimodal climate with two dry seasons (November–March and July–September) and two rainy seasons (March–July and September–October. The average temperature is 28 °C, and the average annual rainfall is 1300 mm (Tossou et al. 2017). Soil chemical characteristics at the onset of the trials are presented in Table 1 and the cumulative amounts of precipitation of the experimental site are presented in Fig. 1.

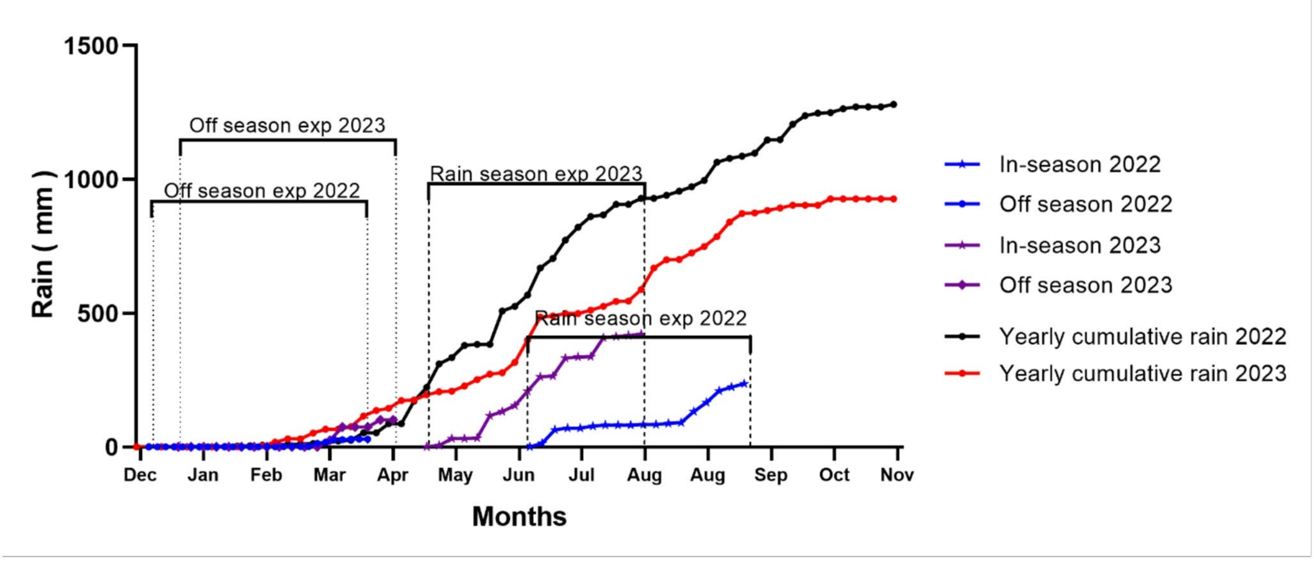

Fig. 1 Cumulative rains at the experimental sites during the rice production cycle

Table 2 Experiment design

Experimental plots	Factors	Levels
Main plot	Season (site)	Matekpo site (in-season) and sewahoue site (off-season)
Sub plot	Water management	Alternate wetting and drying (AWD30, AWD15) soil saturated (SS), continuous flooding (CF)
Sub subplot	N fertilizer sources	Control (C), Mineral fertilizers at the recommended rate (M) Micro-dose of mineral fertilizer (MM) Rice straw (RS) Compost in micro-dose (CO) Compost + rice straw (RSCO) Rice husk biochar + compost (BCO) Biomass of mucuna (BM) only for in-season site

Experimental design and treatments

A split-split-plot design with complete randomization and three replications per site was used to assess the effects of site (Matekpo/in-season and Sewahoue/off-season), water management, and nutrient management practices over the two years (2022 and 2023). The sites were considered at the main plot factor level. Four water management practices were applied in the subplots (Table 2), and the nutrient management practices were implemented in the sub-subplots (seven at Matekpo and eight at Sewahoue). The additional treatment at Sewahoue resulted from the inclusion of Mucuna, which is a common soil fertility management practice in this area. Hence, the Matekpo site had 28 treatments replicated three times while the Sewahoue site had 32 treatments replicated three times. All the factors and their respective levels are summarized in Table 2.

Site or season factor

The experiments at Matekpo were carried out during two consecutive in-seasons: the short rainy season from June to October 2022 and the long rainy season from April to July 2023. The experiments at Sewahoue were conducted during two consecutive off seasons: from November 2022 to March 2023 and from November 2023 to March 2024 further referred to as the 2022 and 2023 dry seasons, respectively. Thus, the site factor reflects not only the effect of location but also a season effect, with Matekpo representing the in-season and Sewahoue the off-season variants. Hereafter, the site effect will also be referred to as season effect.

Water management practices

Irrigation was supplementary in in-season and full in off-season. Field irrigation was performed using surface water resources in the in-season field and groundwater in the dry season. Water management practices included (i) Continuous Flooding (CF), (ii) Soil Saturation (SS), (iii) moderate (AWD15), and (iv) severe (AWD30) Alternate Wetting and Drying. The plots under CF were irrigated every two days, i.e., additional water was supplied to maintain water level between 20 mm and 50 mm. The SS, AWD15 and AWD30 plots were irrigated when the soil water suction reached −5 kPa, -15 kPa and −30 kPa, respectively. A water depth of 2 mm was maintained for all treatments during the first two weeks after transplanting to favor the establishment of the young plants before starting water management practices started.

Nutrient management practices

Nutrient management practices included: (i) Control (with no fertilizer, C), (ii) recommended dose of NPK (M), (iii) Micro-dosing of NPK (MM), (iv) Compost at 5 t DM ha^{-1} (CO), (v) Rice Straw at 9 t DM ha^{-1} (RS), (vi) Biochar at 5 t DMha^{-1} plus Compost at 2.5 t DM ha^{-1} (BCO), (vii) Rice Straw at 4.5 t DM ha^{-1} plus Compost at 2.5 t DM ha^{-1} (RSCO) and, (viii) Mucuna biomass (applied only for off-season, BM). The compost was applied in micro-doses in bands at 5 t DM ha^{-1}, 15 Days After Transplanting (DAT). The rice straw was incorporated during land plowing. Biochar was made using a conventional pyrolysis process from rice husks and was incorporated at 7 days before transplanting. The recommended dose (M) of mineral fertilizers consisted in the application through a uniform broadcast method of 200 kg ha^{-1} of NPKSB (14-23-14-5-1) at 15 DAT followed by 75 kg ha^{-1} of urea 75 DAT. The NPK micro-dose (MM) treatment consisted of reducing the recommended dose of mineral fertilizers by 25%, resulting in 150 kg ha^{-1} of NPKSB at 15 DAT plus 56.25 kg ha^{-1} of urea at 75 DAT, applied through a banding method. *Mucuna pruriens* was cultivated in a separate plot for 6 weeks, after which the biomass was harvested, dried, and incorporated at a rate of 7.5 t ha^{-1} in the BM treatment.

Other crop management practices

The total area of the experimental plot was 2000 m^2 for Matekpo site and 2400 m^2 for Sewahoue (including the footprint of bunds and water distribution channels), with individual plot units measuring 4 × 3 m. At the onset of the experiment, land plowing was done manually (15 to 20 cm depth) using a hoe. Land leveling by hoeing was done to ensure water distribution uniformity of 90%. In the in-season, rice (IR 841) seeds were sown in the nursery on June 1, 2022 and March 28, 2023. Rice seeds were sown in a nursery on November 23, 2022, and December 1, 2023 during off season. The 16-day-old young rice plants were transplanted at a density of 16 plants m^{-2} (0.25 m x 0.25 m) with 1 plant per hill, corresponding to 160,000 plants ha^{-1}. A biological pest control based on neem leaves was carried out. The leaves of neem (*Azadiarata indica*) were crushed and soaked in water, to which two pieces (150 g) of local soap were added, and left to mix for 21 days. The extract was sprayed on the plot every seven days whenever caterpillars were found on rice plants. Plots were manually weeded at 14 and 74 DAT.

Installation of measurement equipment

At both sites, polythene films were installed to a depth of 60 cm beneath the soil surface and 40 cm inside the bunds to limit seepage and nutrient transfer between experimental plots. The primary channel was installed along the contour lines generated from the Digital Terrain Model (DTM) obtained from GADM database and using the coordinates of the site on global mapper and Q-GIS 3.22.1. Two bunds bordered this channel, and the space between them served as the water supply channel. The bottom was compacted with a layer of clay to reduce seepage in the canal. The secondary channels were also earth-made, and constructed perpendicular to the primary channel, with a smaller cross-section than the primary channel. The plots were bordered by soil bunds. Water supply to the plots was provided through canals, which are connected to the plots via PVC pipes that serve as a link between the canal and the individual plots.

An automatic rain gauge was installed on each site to collect rainfall amounts. To monitor irrigation and drainage water levels, 12 limnimeter were placed at a depth of 30 cm, with 120 cm of clearance for readings. Three surface limnimeter were allocated for each water management practice. Additionally, twelve piezometers were installed, and distributed at a rate of three per water management level (and one per replicate). Each piezometer was 200 cm long, with 160 cm below ground level and 40 cm within the soil bund, and was used to monitor the groundwater table. Percolation was monitored using a vertical lysimeter, constructed according to previous studies (Tan et al. 2013). The lysimeter consisted of a 16 cm diameter pipe, 100 cm long, 55 cm below ground level, and 45 cm above. The pipe bottom was sealed, featuring 4 rows of 6 rounded holes of 0.6 cm diameter each, facilitating percolation observation. Vertical water movement was investigated using PVC water monitors, 60 cm in length, perforated for 30 cm below ground level. Suction measurements were done daily between 12 AM and 3 PM using gauge tensiometers, positioned at 15 cm depth on mineral fertilizer plots across each water management level. Limnimeters, piezometers, lysimeters, and water monitors were replicated three time by each water management of each water management variant. Daily vertical percolated water amounts were collected between 7 and 8 AM. using a battery-powered vacuum pump. Similarly, water levels before and immediately after water supply, were recorded. Monitoring of water levels throughout the rice crop cycle occurred daily using water monitors, while groundwater levels were measured daily using a water level dip meter. All of the equipment are indicated in Fig. 2.

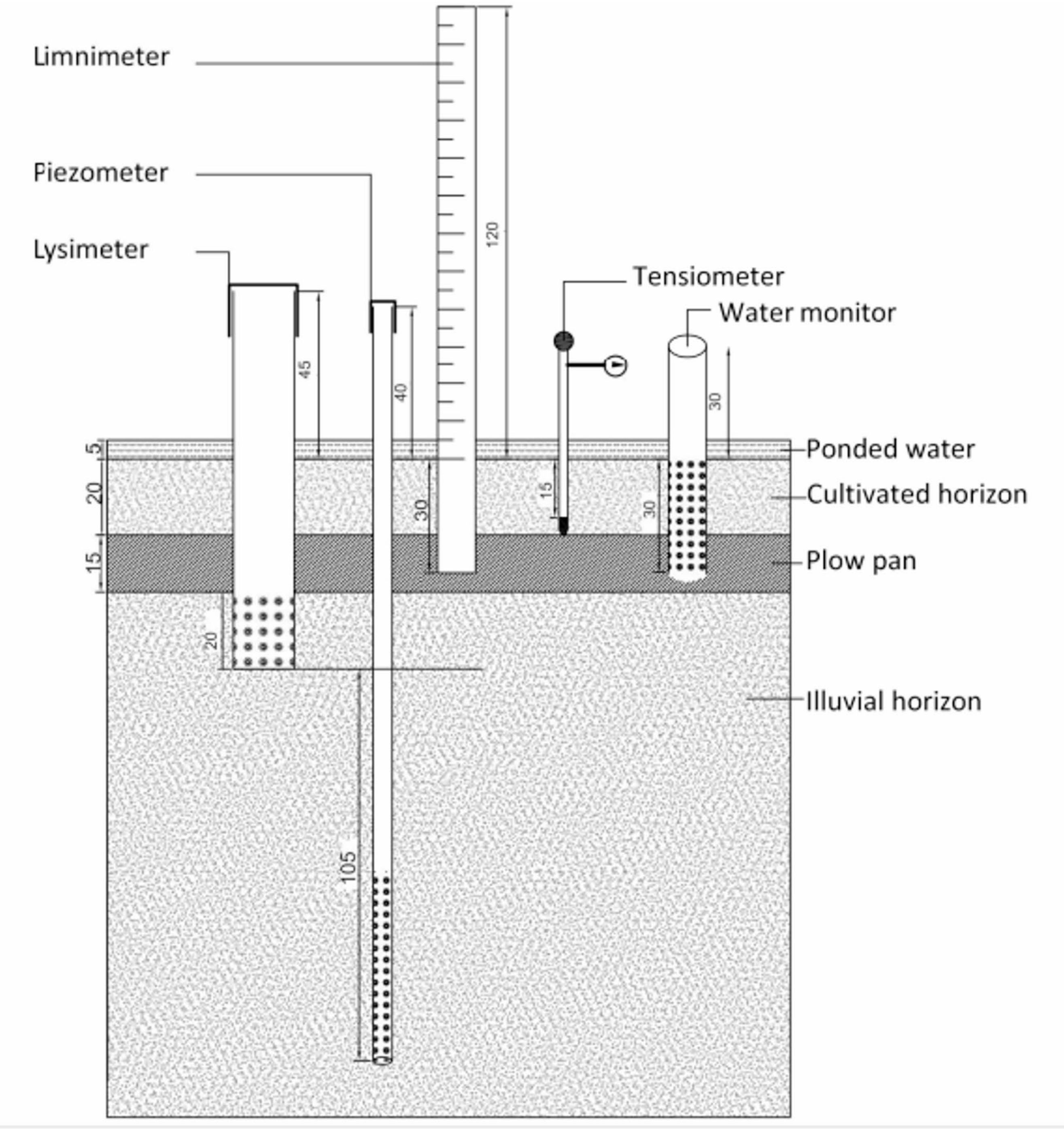

Fig. 2 Installation of the different water measuring equipment (lengths in cm)

Table 3 Chemical composition of organic amendments

	Unit	Mucuna	Compost	Biochar	Rice Straw
pH/H2O	1:2.5	8	6.2	6.5	7.3
Organic carbon	%	1.17	5.25	5.55	41.60
N-total	%	0.07	1.60	1.64	1.16
P-total	%	0.02	1.12	0.46	0.14
K-total	%	0.09	0.77	1.44	1.61
C/N	-	16.71	3.28	3.38	35.86

Soil data collection and organic fertilizer analysis

Soil samples were collected in 2022 and 2023 from a depth of 20 cm, both before nutrient application and at harvest, using a standard soil auger from randomly selected points within the middle rows of each plot. Visible organic residues were manually removed, and the samples were thoroughly mixed to create composite samples, which were then subsampled for analysis. The soil pH was measured in a 1:2.5 (Takamoto et al. 2023). Available phosphorus was quantified using the Bray-1 extraction method, while exchangeable potassium was measured through ammonium acetate extraction at pH 7 (Wuenscher et al. 2015). Soil texture was analyzed using the hydrometer method, which determined the proportions of sand, silt, and clay (Huluka and Miller 2014). Fertilizer samples, including Mucuna biomass, compost, biochar, and rice straw, were collected, air-dried or oven-dried at 60–70 °C, and ground to pass through a 2 mm sieve for homogeneity (Munthali 2019). Organic carbon was determined by the Walkley and Black's method (van Reeuwijk 1993). Total nitrogen was quantified by the Kjeldahl methods using a mixture of salicylic acid, sulphuric acid (H_2SO_4) and selenium for the digestion. These digested samples were subjected to an auto-analyzer using the colorimetric method based on the Bertholet reaction (Houba et al. 1995). The same digest was used for total P and K determination. Total P was determined by the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid. The total K was determined with flame emission spectrophotometry (Houba et al. 1995). All analyses were conducted at the soil and plant analysis laboratory of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Sadore, Niger.

Water balance components calculations

Rainfall (R) was quantified by cumulating water amounts recorded during individual precipitation events throughout the production cycles. Irrigation (Ir) was determined by summing the total volume of water applied throughout the cycle. The presence of polyethylene film restricted lateral runoff (L), resulting in negligible runoff throughout two production cycles. Surface drainage (D) was assessed by the sum of the volume of water drained during each production cycle. The water balance equation provides a comprehensive approach to evaluate water fluxes in the lowland rice cultivation system (Fig. 3).

The percolation (Per) was calculated by dividing the volume of discharged water collected daily by the cross-sectional area of the lysimeter. The daily percolation rate (DP, mm day^{-1}) was estimated from the head of water collected in the lysimeter as the daily successive difference in the water table inside the percolator (Tsubo et al. 2006; Takeda et al. 2019).

$$\mathrm{DP} = \frac{1}{n}\sum\nolimits_{i=1}^{n}(h_i - h_{i+1}) \tag{1}$$

where h_i is the water level in the lysimeter at day *i* and *n* is the number of days through the production cycle.

Depletion, recharge, and neutrality of the groundwater body of the agricultural plot can be analyzed by assessing the incoming and outgoing water fluxes of the field (Fig. 2). Depletion occurs when pumping to sustain cultivation exceeds recharge (Schmitter et al. 2015). Recharge happens when a portion of irrigation water is not utilized by crops, and percolates into the deep soil, thereby contributing to groundwater replenishment (Maréchal et al. 2023). In this case, recharge is synonymous with percolation. The daily variation of the groundwater table as measured by the piezometer (ΔG) represents the field level recharge or its depletion. This assumes that the seasonal water storage changes on top of the flow pan and above the groundwater tables are negligible compared to the water storage change

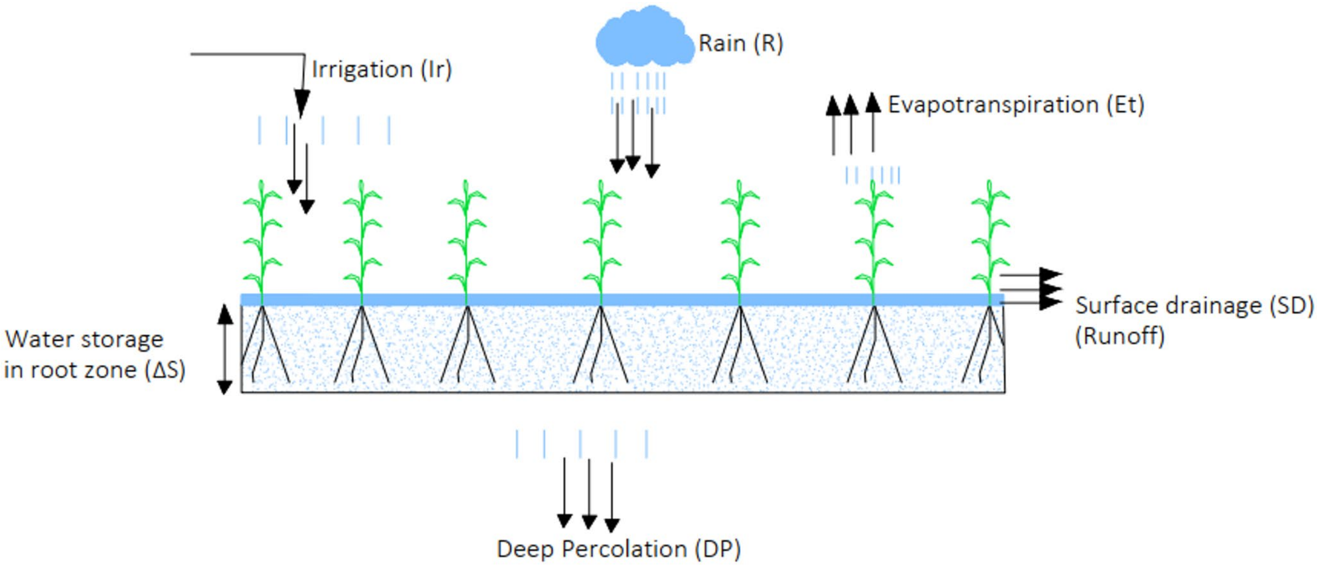

Fig. 3 Water balance and component approaches

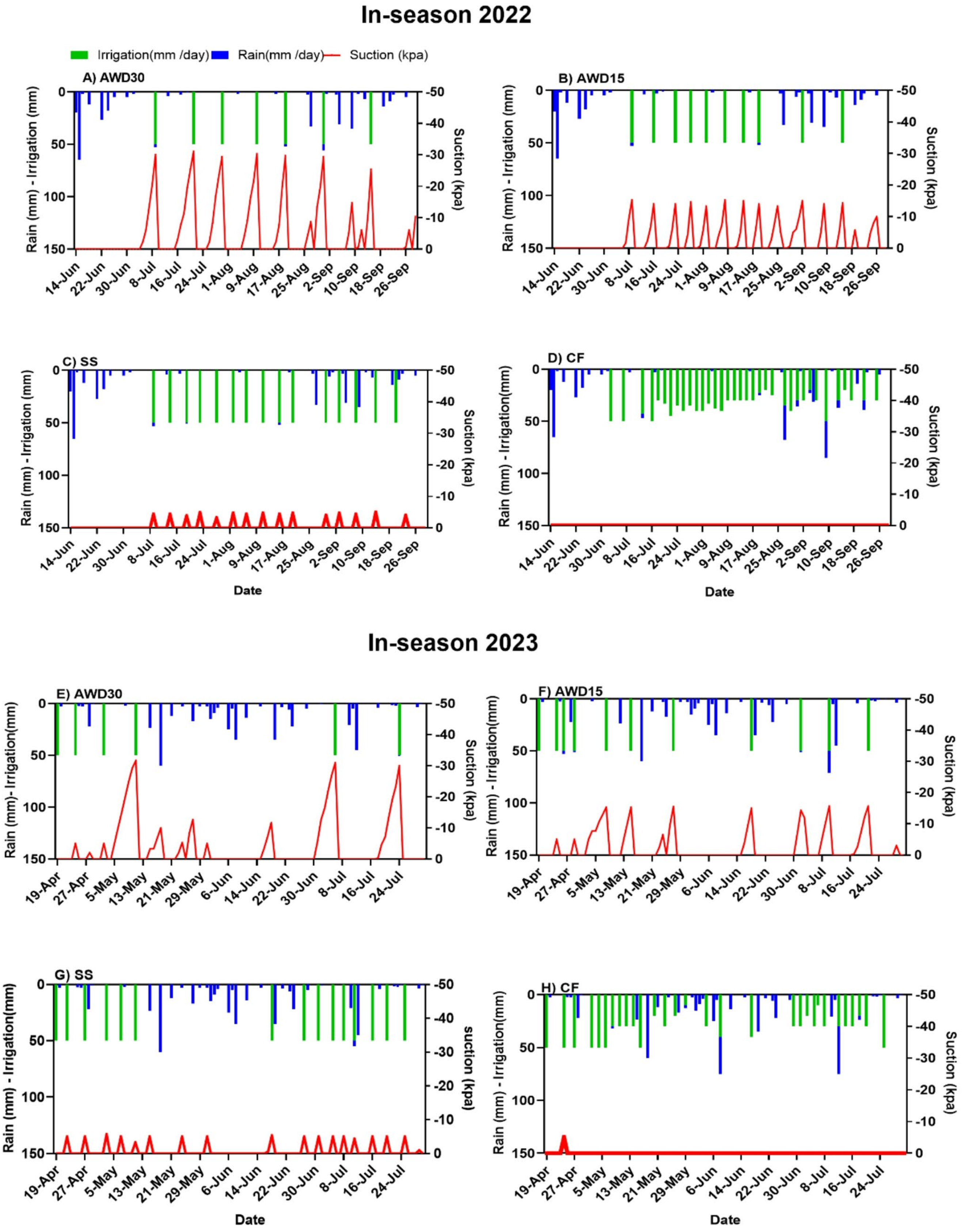

Fig. 4 Rainfall, irrigation events, and soil water suction (15 cm depth) during the in-season periods of 2022 and 2023 (Blue bars represent rainfall amounts per event, green bars indicate irrigation amounts per application date, and the red line shows soil water suction prior to each irrigation event)

in the groundwater level. Soil water storage change (ΔS) represents the variation of water content within the soil profile over time. Volumetric soil water contents were estimated from soil suction data using the Van Genuchten soil water retention model fitted with available measured data (Tian et al. 2018). Hence, ΔS was calculated as follows:

$$\Delta S = \Delta \theta . \Delta z \tag{2}$$

where Δθ is the change in volumetric water content at 15 cm depth between two days. Δ z is the considered soil depth of root zone (15 cm).

Considering all the hypotheses, the actual evapotranspiration was deducted from the field water balance equation as follows (Schmitter et al. 2015):

$$\mathrm{ETa} = \mathrm{R} + \mathrm{Ir} - \mathrm{DP} - \mathrm{SD} - \mathrm{DS} \tag{3}$$

Water use efficiency is the yield ratio to the total amount of water used by the crop (Schmitter et al. 2015)

$$WUE\ (kg\ /m3) = \frac{Grain\ yield\ (kg)}{ETa\ (\mathrm{m3})} \tag{4}$$

Crop performance

Paddy and rice straw yields were evaluated at crop maturity by cutting all stalks on a square of 1 m² (1 × 1 m) per experimental plot. Paddy and straw sub-samples were oven dried to a constant mass at 70 °C for 72 h. Paddy and straw yields were expressed on a dry matter basis.

Statistical analysis

The dataset was analyzed using R software (Version 4.4.4, Core Team). The normality of data was checked using the Shapiro-Wilk test, and the homogeneity of variances was tested using Levene's test. Variables that violated these assumptions underwent transformations using the PROC TRANSREG Box-Cox transformation with an optimal lambda parameter. The involved factors were the year, season, water management, and fertilizer treatments. Year, season, water and nutrients were treated as fixed effects to assess crop performance. Replications were considered as random effect factors. The primary analytical approach focused on analyzing variance (ANOVA) using the PROC GLM procedure. Post-hoc analyses were conducted using the Least Significant Difference (LSD) method when F probabilities fell below 0.05, enabling detailed comparisons of treatment means. Comparisons were conducted using the Agricolae package, taking into account the split-split plot design and all factors. LSD tests were performed initially for each factor separately and then for the interaction between water and fertilizer according to the model.

Results

Water balance and components

Rainfall and irrigation patterns

During both cropping seasons, variations in rainfall and irrigation patterns were observed across the fields, influenced by environmental conditions and water management practices. The in-season experiments received significantly higher rainfall, with a total of 248 mm from 31 rainfall events in 2022 (Fig. 4A, B, C and D) and 421 mm from 37 events during the 2023 rainy season (Fig. 4E, F, G and H). In contrast, the off-season experiments recorded substantially lower rainfall, with 63.26 mm from 9 events in 2022 (Fig. 5A, B, C and D) and a slight increase to 101 mm from 3 events in the subsequent period (Fig. 5E, F, G and H).

Irrigation frequency varied between season. For the in-season experiments in 2022, irrigation was applied as follows: AWD30 every 10 days, AWD15 every 7 days, SS every 5 days, and CF every two days (Fig. 4-from A to F). In the off-season experiments, irrigation was applied more frequently: AWD30 every 8 days, AWD15 every 6 days, saturated soil every 4 days, and CF daily. Supplemental irrigation volumes also differed significantly, ranging from 350 to 1135 mm for the in-season (Fig. 4) experiment and from 600 to 2938 mm for the off-season experiment (Fig. 5), with the latter consistently receiving higher water inputs in both years.

The total water input (rainfall + irrigation) for the in-season experiments in 2022 was 598, 748, 998, and 1383 mm for the AWD30, AWD15, SS, and CF treatments, respectively. These values increased in 2023 to 721, 971, 1171, and 1421 mm for the same treatments. Similarly, for the off-season experiments, the total water input in 2022 was 663 mm, 863 mm, 1113 mm, and 3001 mm for the AWD30, AWD15, SS, and CF treatments, respectively. In 2023, these values were 751 mm, 1001 mm, 1351 mm, and 2461 mm for the respective treatments.

Percolation and evapotranspiration

Percolation losses were significantly influenced by season, water management, and their interactions, though no significant variation was observed between years alone ($p < 0.001$; Table 4). On average, percolation was higher during the in-season (357 mm) compared to the off-season (327 mm)

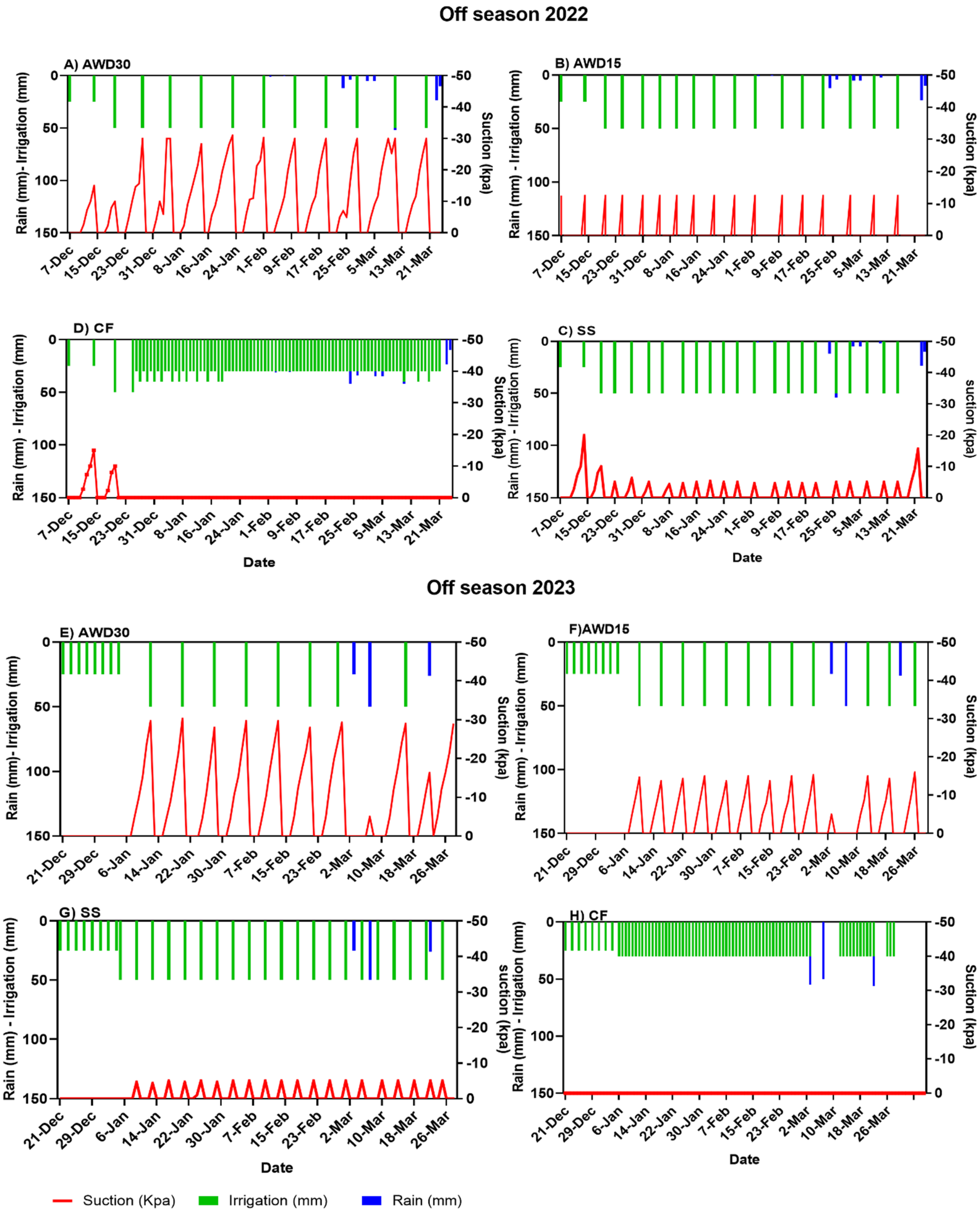

Fig. 5 Rainfall, irrigation events, and soil water suction (15 cm depth) during the off-season periods of 2022 and 2023 (Blue bars represent rainfall amounts per event, green bars indicate irrigation amounts per application date, and the red line shows soil water suction prior to each irrigation event)

Table 4 Analysis of variance of percolation and actual evapotranspiration as affected by year, season and water and nutrient management practices in 2022 and 2023

	Percolation			Eta	
	DF	F value	Pval	F value	Pval
Year (Y)	1	101.92	1	318.67	1
Season (S)	1	109.99	0.0001***	29262.05	0.0001***
Water (W)	3	13986.55	0.0001***	45037.49	0.0001***
Y*S	1	1430.52	0.0001***	701.01	0.0001***
Y*W	3	120.73	0.0001***	3644.07	0.0001***
S*W	3	26.55	0.0001***	21847.28	0.0001***
Y*S*W	3	510.83	0.0001***	1470.24	0.0001***

(Fig. 6A). Among water regimes, CF exhibited the highest percolation, nearly double that of SS, threefold greater than AWD15, and fourfold greater than AWD30 (Fig. 6B).

Season-by-year interaction revealed that in 2022, percolation rates did not significantly differ between seasons. However, in 2023, in-season percolation (468 mm) was significantly higher than off-season values (379 mm) (Fig. 6C). The year-by-water management interaction showed that AWD15 and AWD30 had comparable percolation in 2022, each nearly three times lower than CF. In 2023, CF still had the highest percolation, 2.4 times greater than AWD15 and 3.5 times greater than AWD30. Across both years, SS consistently exhibited percolation losses 1.6 times lower than CF (Fig. 6D).

The interaction between season and water management was also significant ($p<0.001$, Table 4). Percolation under AWD15 and AWD30 was higher during the in-season (226 mm and 167 mm, respectively) than the off-season (183 mm and 147 mm). Conversely, CF and SS had similar percolation losses across both seasons. A three-way

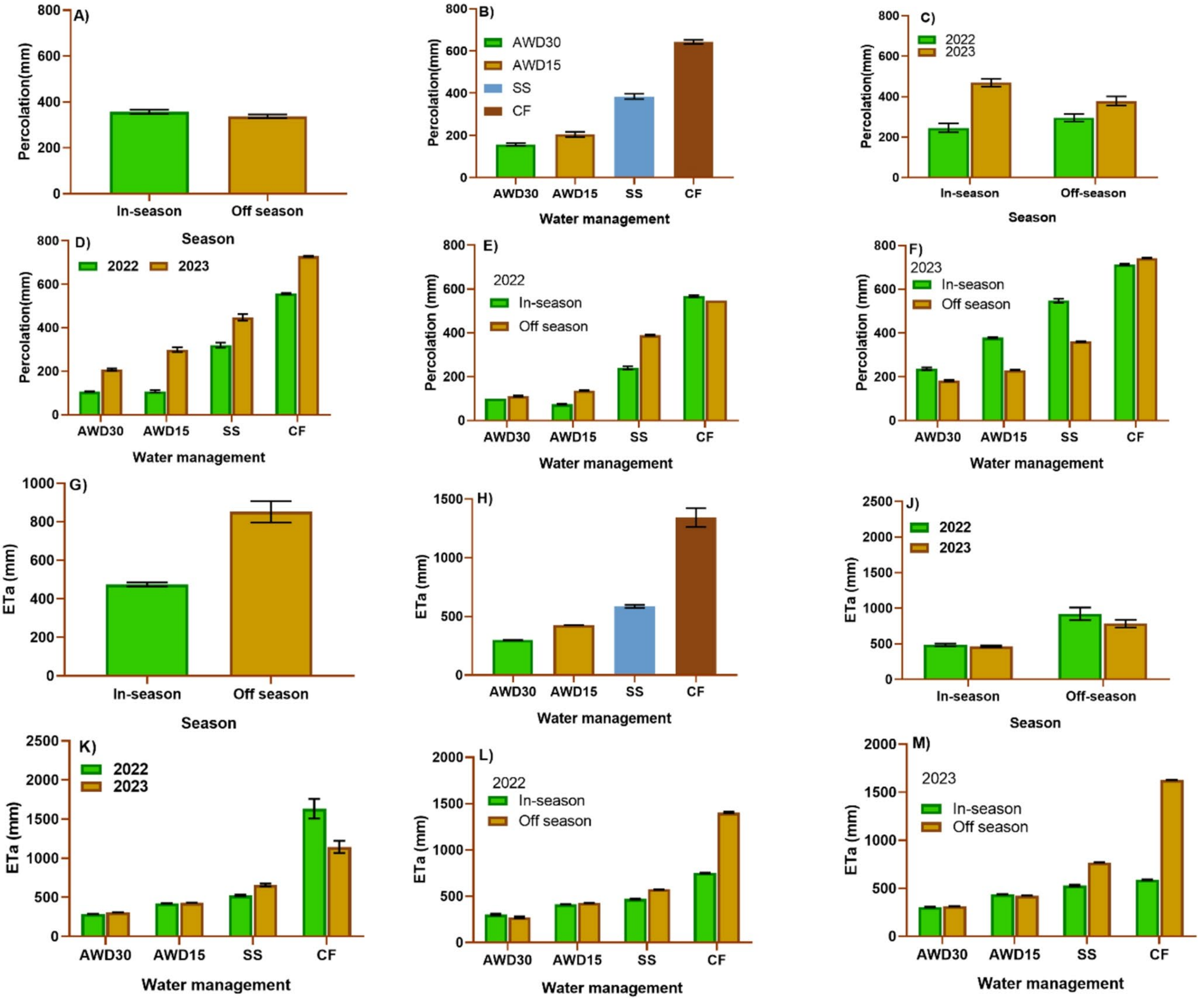

Fig. 6 Effect of season, year and water management practices on percolation (**A** to **F**) and ETa (**G** to **M**)

interaction (year × season × water management) further highlighted differential patterns. In 2022, percolation under AWD30, AWD15, and SS was higher in the off-season, while CF exhibited higher losses during the in-season. In 2023, the reverse trend was observed for AWD30, AWD15, and CF, whereas SS maintained relatively stable values (Fig. 6E and F).

Evapotranspiration (ETa) did not significantly differ between years but was significantly higher in the off-season (852 mm) than in-season (474 mm) (Fig. 6G). Water regimes had a significant effect on Eta, where CF had the highest values (1343 mm), being 2.3 times higher than SS, 3 times higher than AWD15, and 4.5 times higher than AWD30 (Fig. 6H).

Interactions between year and water regime showed consistent ETa under AWD15 and AWD30, while SS and CF exhibited variability. CF recorded higher ETa in 2022 (1500 mm) compared to 2023 (1143 mm), whereas SS increased in 2023 (Fig. 6K). Season-by-management interaction revealed greater off-season ETa under CF and SS than in-season. AWD15 and AWD30 had comparable ETa across seasons (Fig. 6L and M). The three-way interaction also confirmed greater interannual variability under CF and SS than under AWD practices (Table 4).

Rice yield

Rice yield did not differ significantly between years unlike across to season ($p<0.001$; Table 5). In-season rice yield (3.3 t/ha) were higher than those of off-season (3.1 t/ha) (Fig. 7A). Significant differences were also observed across water management practices ($p<0.001$; Table 4). Yields achieved under CF, SS, and AWD15 were comparable (3,46 t/ha on average) but significantly higher than that recorded under AWD30 (2.47 t/ha) (Fig. 7B). Nutrient management also significantly influenced yield ($p<0.001$; Table 4)., with the highest yield observed under M (4.01 t/ha), followed by BCO (3.77 t/ha), CO (3.6 t/ha), and RSCO (3.52 t/ha). The lowest yield was recorded in the control plots (2.15 t/ha) (Fig. 7C).

All water management practices showed similar yield at both seasons (3.54 t/ha) except for AWD30 which showed significantly lower yield in the off-season (2.06 t/ha) compared to in-season (2.9 t/ha) (Fig. 7D). Interaction across seasons, water management, was significant ($p<0.001$; Table 5). Yield recorded under CF, SS and AWD15 were similar (3.54 t/ha) for both seasons, but AWD30 (2.9 t/ha) yields in the in-season were 28% higher than those of AWD30 (2.06 t/ha) at off-season (Fig. 7E). Interaction across year, season and water management indicated a significantly difference in yield (($p<0.001$; Table 5). In 2022, CF, SS, and AWD15 resulted in comparable yields across season (3.54 t/ha), while AWD30 was 30% higher in the in-season (2.74 t/ha) compared to off-season (2.02 t/ha). But in 2023, there was a slight difference among CF, SS and AWD15 (Fig. 7F).

Interaction between year and nutrient management practices induced a significant difference in yield ($p<0.001$; Table 5). In 2022, the M treatment resulted in the highest yield (4.54 t/ha), followed by BCO (3.95 t/ha), while CO and RSCO produced similar yields (3.6 t/ha) (Fig. 7G). In 2023, there were no significant yield differences among M, BCO, CO, and RSCO (3.59 t/ha), although yields recorded under BM increased by 21% compared to the first year (3.3 t/ha vs. 2.59 t/ha) (Fig. 7H). The interaction between season and fertilizer indicated that in-season rice consistently produced higher yields under CO (3.76 t/ha), MM (3.27 t/ha), RS (2.7 t/ha), and RSCO (3.68 t/ha) compared to those of off-season, where CO, MM, RS, and RSCO yields were 3.43 t/ha, 2.65 t/ha, 2.42 t/ha, and 3.36 t/ha, respectively. However, rice grain yields were similar for M, BCO (3.88 t/ha) on average in the both seasons (Fig. 7I). Season * water interaction was significant. Interaction across year, season and nutrient management indicated a significant difference in yield ($p<0.001$; Table 5). Yields achieved under the M treatment were significantly higher than those recorded under BCO, CO, and RSCO in both season in 2022, with in-season showing yield advantages of 10%, 20%, and 22%, respectively, and off-season experiment showing advantages of 14%, 21%, and 16%, respectively. Fertilizers application in 2022 significantly increased yields, with plots receiving M, BCO, RSCO, and CO producing 1.86, 1.75, 1.63, and 1.67 times more yield, respectively, than the control. In 2023, although no significant yield differences were observed among M, CO, RSCO, and BCO treatments, fertilizer application still resulted in yield increases of 1.70 and 1.44 times on average at off-season and in-season,

Table 5 Paddy and straw yield variation in response to year, season, water and nutrient management

	Yield		WUE	
	F value	Pr(>F)	F value	Pr(>F)
Year (Y)	3.4714	1	39.775	1
Season (S)	26.9017	0.0001***	513.5092	0.001***
Water (W)	153.5116	0.0001***	887.2596	0.001***
Fertilizer (F)	139.1413	0.0001***	75.273	0.001***
Y*S	1.4213	0.2344	416.4666	0.001***
Y*W	0.9762	0.4046	53.1715	0.001***
Y*F	24.7364	0.0001***	84.9275	0.001***
S*W	47.0309	0.0001***	27.2208	0.001***
S*F	5.4889	0.0001***	54.9968	0.001***
W*F	21.9878	0.0001***	12.1805	0.001***
Y*S*W	11.4978	0.0001***	34.9489	0.001***
Y*S*F	10.2167	0.0001***	42.8327	0.001***
Y*W*F	5.8606	0.0001***	8.8217	0.001***

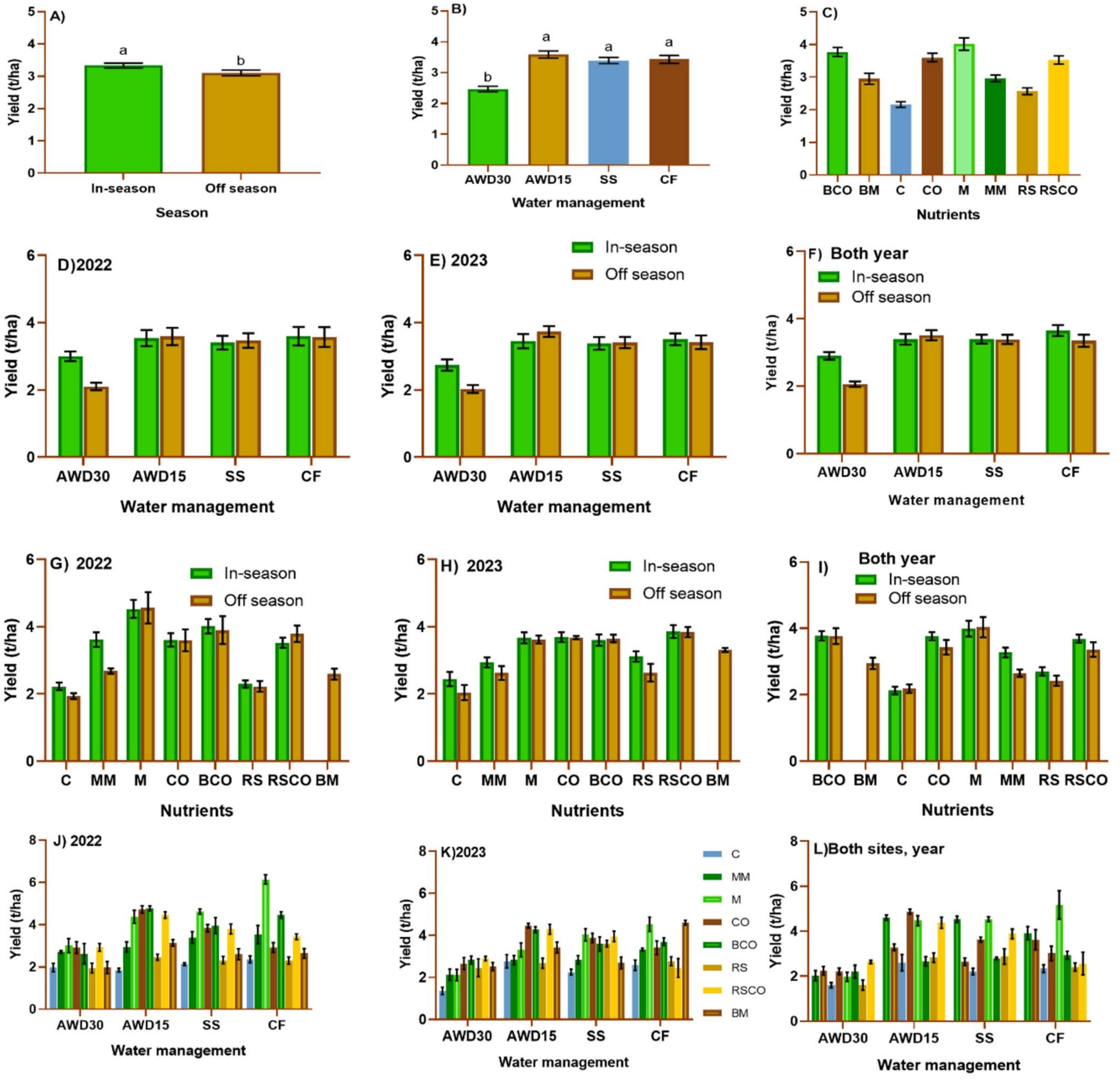

Fig. 7 Rice grain yield according water management and field

respectively. Yields under the Mucuna treatment were 42% higher in 2023 compared to 2022 (Fig. 7D, H and I).

A synergy between water and nutrient management was observed. Mineral fertilizers (M and MM) performed better under CF and SS conditions, whereas organic fertilizers (BCO, CO, and RSCO) showed higher efficacy under AWD treatments, particularly AWD15, in both years. This demonstrates the complementary roles of water and nutrient management in optimizing rice yields (Fig. 7J, K and L).

Water use efficiency (WUE)

Water use efficiency (WUE) did not significantly differ between years, but significant differences were observed between season ($p<0.001$; Table 5). WUE was higher in the in-season (1.16 kg/m³) compared the off-season (0.87 kg/m³) (Fig. 8-A). Water management significantly influenced WUE ($p<0.001$; Table 5). WUE observed under CF (0.5 kg/m^3) were respectively 2.6, 2.4, and 1.8 times lower than AWD30 (1.3 kg/m^3), AWD15 (1.2 kg/m^3) and SS (0.9 kg/m^3) (Fig. 8B). Nutrient management induced significant

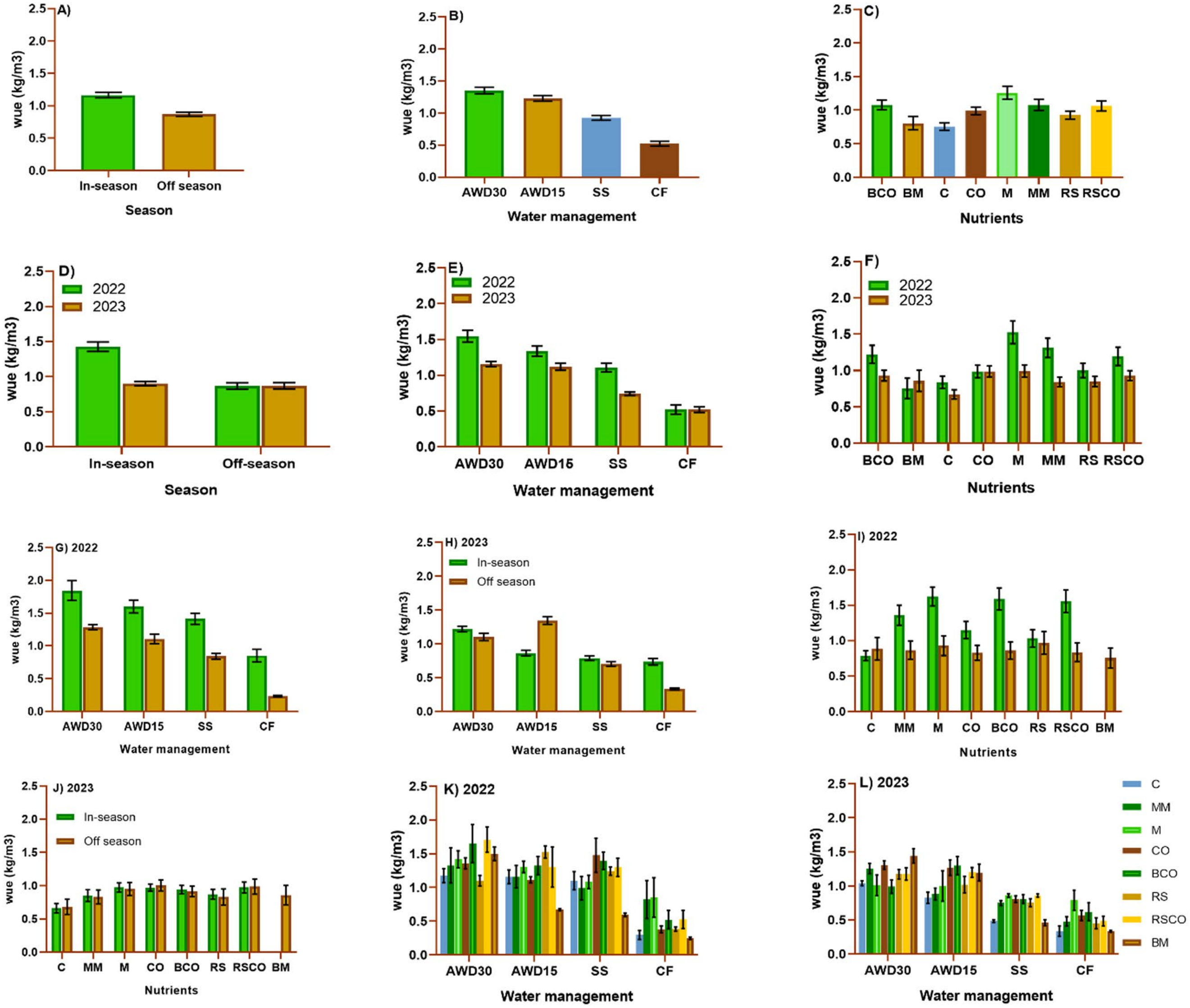

Fig. 8 WUE variation according year, seasons water and nutrient management strategies

difference in WUE ($p<0.001$; Table 5). WUE were higher for M (1.2 kg/m³) followed by BCO, CO and RSCO which were similar (1.06 kg/m³). The lowest WUE was identified under the control (C, 0.75 kg/m³) (Fig. 8C).

The interaction between year and season significantly affected WUE. In 2022, WUE was higher in the in-season (1.4 kg/m³) compared to off-season (0.87 kg/m³), whereas in 2023, no significant difference was observed between seasons (0.9 kg/m³ on average) (Fig. 8D). There was a significant interaction between water management and years. In 2022, WUE was higher under AWD30 (1.5 kg/m³), followed by AWD15 (1.3 kg/m³) and SS (1.1 kg/m³). In 2023, WUE decreased to 1.1 kg/m³ for AWD30 and AWD15 and to 0.7 kg/m³ for SS. However, under CF, WUE remained consistent between both years at 0.52 kg/m³ (Fig. 8E). The interaction between year and nutrient management also influenced WUE significantly. In 2022, the highest WUE was observed with mineral fertilizer (M, 1.5 kg/m³), followed by BCO and RSCO both similar (1.15 kg/m³). In 2023, M, BCO, RSCO, and CO resulted in similar WUE values (0.9 kg/m³) (Fig. 8F). The interaction between season and water management showed that WUE was higher on in-season under AWD15 (1.5 kg/m³), SS (1.1 kg/m³), and CF (0.8 kg/m³) compared to off-season, where WUE under AWD15, SS, and CF was 1.1 kg/m³, 0.8 kg/m³, and 0.2 kg/m³, respectively. However, WUE under AWD30 was similar between the both seasons (1.2 kg/m³) (Fig. 8G). Season and nutrient management interaction also caused significant differences in WUE. On in-season, WUE was higher under M (1.5 kg/m³), followed by MM (1.3 kg/m³), BCO (1.2 kg/m³), RSCO (1.2 kg/m³), and CO (1.0 kg/m³). But at off-season, WUE was similar across M, BCO, CO, and RSCO (0.9 kg/m³) (Fig. 8H).

Table 5 further highlights significant interaction of year, season and water management practices and year. In 2022, WUE under AWD30 and AWD15 during the in-season was 30% and 46% higher, respectively, compared to CF. In the off-season, WUE recorded under AWD15 was 79% higher than CF at the same season. In 2023, AWD15 achieved the highest WUE at on off-season compared to other practices (Fig. 8I). For in-season experiment, WUE under AWD15 was 39% higher than CF, while that of off-season, WUE under AWD15 was 75% higher than CF. The interaction of year, season nutrient management showed that in 2022, all nutrient treatments performed better on in-season compared to off-season. In 2023, WUE was similar for BCO, CO, M, and RSCO for both seasons. Notably, combining Mucuna biomass (BM) with AWD15 improved WUE by 30% in 2023 compared to 2022. The combined effects of water and nutrient management demonstrated that the highest WUE was achieved under CF when combined with mineral fertilizer (CF + M). In contrast, water-saving practices combined with organic nutrients, such as AWD30 + BCO, AWD30 + CO, AWD30 + RSCO, and AWD30 + RS, achieved efficient outcomes (Fig. 8K and L).

Discussion

Water input, Percolation, and evapotranspiration under different water management practices

Although a site effect could have been considered, the observed differences are more likely attributed to seasonal variation rather than location-specific factors, as both sites share similar soil textural properties. Seasonal climatic conditions, particularly rainfall variability, emerged as the primary driver of differences in water requirements and management practices. In-season trials received substantially more rainfall (248 mm in 2022; 421 mm in 2023) than off-season trials (63.26 mm in 2022; 101 mm in 2023), resulting in significantly different irrigation needs. Off-season experiments required higher supplemental irrigation (600–2938 mm) compared to in-season (350–1135 mm), emphasizing the need for season-specific irrigation strategies (Thorp et al. 2010; Zhang et al. 2022; Dolaptsis et al. 2024).

Continuous flooding (CF) consistently had the highest water inputs (663–3001 mm off-season; 598–1421 mm in-season), corroborating its association with excessive percolation and evaporation losses (Ghorbani et al. 2019; Idris 2020). In contrast, alternate wetting and drying (AWD15, AWD30) reduced water inputs by 1.84–2.31 times in-season and 1.3–1.6 times for off-season, extending irrigation intervals to 6–10 days. These findings confirm AWD's water-saving potential (Carrijo et al. 2017, 2018; Sounon Orou et al. 2024), particularly in water-scarce settings (Cheng et al. 2022; Gao et al. 2023).

Percolation losses and evapotranspiration (ETa) were highest under CF. However, AWD significantly reduced percolation losses and ETa, consistent with previous studies (Tan et al. 2013; Schneider et al. 2019). ETa under AWD15 (484–939 mm) aligned with values reported in similar systems (Tsubo et al. 2005; Djaman et al. 2017), reinforcing the efficiency of AWD in improving water use without compromising crop performance.

Effects of season, water management, and nutrient management practices on rice yield

Rice yield was higher in the in-season (3.3 t/ha) than in the off-season (3.1 t/ha), likely due to favorable agronomic and environmental conditions. Greater rainfall and lower evapotranspiration during the in-season supported optimal crop growth and grain filling, reducing water stress (Datta et al. 2017). In contrast, the off-season experienced limited water availability and higher temperatures, thereby impairing photosynthesis and nutrient uptake (Bowles et al. 2018). Supplemental irrigation during the off-season often fails to fully compensate for natural in-season conditions (Jiang et al. 2021), emphasizing the need for adaptive strategies such as drought-tolerant varieties and efficient irrigation (Arouna et al. 2023).

In 2022, CF, SS, and AWD15 had similar yields across seasons, outperforming AWD30, highlighting the importance of maintaining sufficient soil moisture in rice systems. AWD30 performed 30% better in-season than off-season due to favorable rainy-season microclimates. Rice's sensitivity to water deficits is well-documented, with severe stress reducing biomass and photosynthesis (Bouman et al. 2007). In 2023, AWD15 outperformed CF by 7.4% during the off-season, confirming AWD15's efficiency under moderate stress (Sounon Orou et al. 2024).

Fertilizer application significantly affected yields. In 2022, mineral fertilizers outperformed organic amendments due to faster nutrient release (Myint et al. 2010). However, in 2023, no significant differences were observed, likely reflecting cumulative organic benefits (Diacono and Montemurro 2011). Mineral fertilizers were more effective under CF and SS, while organic amendments performed better under AWD, improving soil structure and water retention (Brempong and Addo-Danso 2022). Notably, CF + BM treatment yielded 4.6 t/ha in 2023 versus 2.64 t/ha in 2022, indicating improvements in soil health and plant adaptation. These results confirm that integrating mineral and organic fertilizers under efficient water regimes like AWD enhances water use efficiency and sustains productivity (Asadi et al. 2021).

Effects of season, water management practices, and nutrient management on rice yield and water use efficiency

WUE was significantly higher in the in-season (1.16 kg/m³) than the off-season (0.87 kg/m³), reflecting the influence of climatic conditions on crop water productivity. Moderate in-season temperatures and water availability likely improved photosynthesis and nutrient uptake, reducing irrigation needs (Farooq et al. 2023). In 2022, WUE peaked at 1.4 kg/m³ in-season versus 0.87 kg/m³ in off-season, suggesting high evaporative demand and irrigation variability reduced efficiency during the dry season (Almeida et al. 2024). In 2023, no significant seasonal difference (avg. 0.9 kg/m³) may reflect improved water management or residual soil effects from continuous cultivation.

Season and irrigation practices significantly impacted WUE ($p < 0.001$). AWD30 and AWD15 achieved the highest values (1.3 and 1.2 kg/m³), outperforming CF (0.5 kg/m³), while SS reached 0.9 kg/m³. AWD's superior performance is attributed to improved root aeration, reduced waterlogging, and enhanced nutrient uptake (Mallareddy et al. 2023). In contrast, CF likely caused excess water losses and anaerobic stress. Seasonal-climate interaction was evident: in 2022, AWD30 (1.5 kg/m³) and AWD15 (1.3 kg/m³) outperformed SS (1.1 kg/m³); all declined in 2023, indicating sensitivity to climatic variability.

Fertilization also influenced WUE. In 2022, mineral fertilizers (M) showed the highest WUE (1.5 kg/m³), exceeding organic amendments (BCO, RSCO: 1.15 kg/m³) due to immediate nutrient release. In 2023, WUE among M, CO, RSCO, and BCO treatments converged (0.9 kg/m³), possibly due to nutrient leaching or improved soil conditions from organic amendments. Organic inputs showed greater consistency across seasons, especially in the off-season, supporting resilience under water stress (Chu et al. 2015). These findings highlight the synergistic role of AWD and organic amendments in enhancing sustainable WUE.

Conclusion

This study demonstrates that combining alternate wetting and drying (AWD) at −15 kPa with organic nutrient amendments enhances rice yield and water use efficiency (WUE) in inland valleys of Benin. In-season conditions led to higher yields and WUE than off-season, largely due to favorable rainfall and reduced evapotranspiration. AWD15 achieved comparable yields to continuous flooding (CF) while substantially reducing water input. Mineral fertilizers performed best under CF, while organic amendments were more effective under AWD, especially AWD15. These findings highlight the importance of tailoring irrigation and nutrient strategies to seasonal conditions for sustainable rice production.

However, the study's applicability is subject to certain limitations. The results are based on two sites with distinct hydrological contexts, which may limit broader generalization. Additionally, the short two-year study period constrains the assessment of long-term soil fertility and climate variability effects. Future research should explore multi-season trials across diverse agroecological zones to validate these findings and refine recommendations.

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Author contributions SOUNON wrote the main manuscript text and prepared figures. ADJOGBOTO, TOVIHOUDJI, and ZAKARI reviewed the manuscript. AKPONIKPE and VANCLOOSTER , supervised the experimentation, writing, and review of the main manuscript text All authors reviewed the manuscript.

Data availability The data is available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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