

REVIEW ARTICLE

Improving rice yield and water productivity in lowland rice systems: A global meta-analysis exploring the synergy of agro-ecological practices and water management technologies

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Abstract

This meta-analysis evaluated the impact of agro-ecological practices and water management techniques on lowland rice yield and water productivity (WP). A total of 573 observations were collected from 56 articles that met specific criteria from 445 publications. Five water management practices were assessed: continuous flooding (CF), soil saturation (SS), moderate (AWDm) and severe (AWDs) alternate wetting and drying, and the aerobic rice system (ARS). The response ratios (RRs) of yield and WP were compared for crop management, soil fertility, weed control and evaporation. The integration of agro-ecological practices such as short-cycle rice varieties, crop rotation, organic nutrient application and mechanical weeding with water management led to similar yields across CF, SS, AWDm and AWDs, with ARS consistently yielding the lowest yields. However, medium- and long-cycle varieties under AWDs experienced yield losses of 11 and 13%, respectively. Mineral fertilizer combined with AWDs resulted in a 14% lower yield than did CF. Mechanical weeding increased the rice yield and WP by 10 and 10% in SS, and only WP by 35% in AWDs, whereas chemical weeding decreased the yield by 13% in AWDs. Crop rotation enhanced yield and WP by 13 and 12%, respectively, under AWDm compared to that under CF. WP was greater under AWDs (36%) and AWDm (12%) than under CF.

KEYWORDS

agro-ecology, rice production systems, water management practices, West Africa

Résumé

Cette méta-analyse a évalué l'impact des pratiques agro-écologiques et des technologies de gestion de l'eau sur le rendement et la productivité de l'eau du riz de bas-fonds. Un total de 573 observations ont été collectées de 56 articles répondant à des critères spécifiques tirés de 445 publications. Cinq pratiques

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de gestion de l'eau ont été évaluées: l'Inondation Continue (IC), la Saturation du Sol (SS), l'irrigation intermittente Modérée (IIM) et Sévère (IIS), et le Système de Riz Aérobie (SRA). Les Ratios de Réponse (RR) du rendement et de la productivité de l'eau (PE) ont été comparés selon la gestion des cultures, la fertilité du sol, la lutte contre les adventices et l'évaporation. L'intégration de la gestion de l'eau avec des pratiques agro-écologiques telles que les variétés de riz à cycle court, la rotation des cultures, l'application d'engrais organiques et le désherbage mécanique a conduit à des rendements similaires pour IC, SS, IIM et IIS, SRA donnant systématiquement des rendements les plus faibles. Cependant, les variétés à cycle moyen et long sous IIS ont subi des pertes de rendement de 11 et 13%, respectivement. L'engrais minéral combiné à l'IIS a donné un rendement inférieur de 14% à celui de IC. Le désherbage mécanique a augmenté le rendement du riz et la PE de 10 et 10% respectivement pour SS et seulement PE de 35% pour IIS, tandis que le désherbage chimique a diminué le rendement de 13% en IIS. La rotation des cultures a amélioré le rendement et la productivité de l'eau de 13 et 12%, respectivement, sous IIM comparé à celle sous IC. La productivité de l'eau était plus élevée sous IIS (36%) et IIM (12%) comparé à IC.

MOTS CLÉS

pratiques de gestion de l'eau, systèmes de production de riz, agroécologie, Afrique de l'Ouest

1 | INTRODUCTION

Most crop production systems aim to maximize yield while optimizing resources (Allakonon et al., 2022). As a primary production resource, water influences the crop production process, particularly crop yield. Water availability for crop production is typically driven by rainfall variability (Rosa et al., 2020) and by competition between different sectors (Malek et al., 2018). Water productivity (WP) is considered a basic performance criterion of the crop production process and is generally defined as crop yield per cubic meter of water consumption (Kambou et al., 2014). Considering the impact of climate change on water availability in water-stressed regions worldwide, high WP in crop production is crucial for achieving global food security (Suna et al., 2023). Efficient water management that aims to increase WP during crop production is therefore pivotal for developing climate-resilient production systems (Liu et al., 2022).

Rice is an important staple cereal for ensuring global food security (Khan et al., 2021), and its productivity largely depends on water management. More than 75% of global rice production occurs under continuous flooding (CF) conditions in rain-fed or irrigated systems of lowlands and uplands (Bo et al., 2022). Rice production under CF conditions requires large amounts of water due

to significant water loss through percolation (Dunn & Gaydon, 2011). The strong dependence of rice production performance on water management also makes rice production very vulnerable to climate change in several parts of the world (Wassmann et al., 2009). Climate variability under rice cultivation often manifests as high temperatures and long periods of drought but also as floods that lead to the complete submersion of rice plants (Silalertruksa et al., 2017).

Various water management alternatives linked to CF, including soil saturation (SS) without ponding, alternate wetting and drying (AWD), and maintaining fully aerobic soil, are used to reduce water consumption in rice crop fields. SS without ponding can reduce water use by preventing losses of ponding water on the soil surface. The water suction tension in this case often ranges between 0 and 5 kPa (de Borja Reis et al., 2018). Under these conditions, evapotranspiration is reduced, but yields remain similar to those of the CF plots (Datta et al., 2017). In AWD practices, water is supplied until a water layer occurs on the surface, which disappears due to evapotranspiration and infiltration before subsequent irrigation (Sriphirom et al., 2019). This practice has been categorized into two levels: moderate AWD and severe AWD. Under moderate AWD, the suction tension varies between 0 and 15 kPa (Li et al., 2018), and the rice yield

(RY) is significantly equal to or even greater (by 7–15%) in moderate AWD than in CF (Maneepitak et al., 2019), reducing water consumption by 16–23%. The WP in moderate AWD systems is improved by 20–46% compared to that in CF systems (Maneepitak et al., 2019; Thakur et al., 2018). In severe AWD, the maximum suction tension exceeds 15 kPa before irrigation (Li et al., 2018). Under severe AWD, the soil suction tension varies between 15 and 80 kPa, and no ponded water occurs on the soil surface. This practice causes 5% yield losses and reduces water use by 23% compared to CF (Carrijo et al., 2017). Yield is generally lower in fields that maintain aerobic soil conditions (aerobic rice systems [ARSs]) than in fields under CF management. Carrijo et al. (2017) quantitatively compared AWD practices to CF practices while linking them to natural factors. Similarly, Datta et al. (2017) compared all water management practices (WMPs) to those of CF qualitatively without considering other factors.

Agro-ecology encompasses an array of systems or components facilitating sustainable agricultural production (Ewert et al., 2023). It focuses on the system level, integrating aspects of crop production with different production resources and environmental impacts. It advocates production methodologies that incorporate organic constituents, diversification through rotation or intercropping, resource conservation (particularly water), and the minimization of synthetic inputs, all with the overarching goal of environmental preservation (Lestrelin & Jaouadi, 2022). In terms of nutrient management, those derived from organic sources are regarded as agro-ecological due to their role in soil rejuvenation (Aguilera et al., 2020). For rice production, the combination of AWD with organic amendments (such as compost and biochar) can be considered an agro-ecological WMP. Compared with CF, this practice has a strong potential to improve RY (Haque et al., 2021; Sriphiroom et al., 2020, 2021).

Nevertheless, in the previously cited studies that explored the potential of alternative WMPs for rice productivity and WP and the scope for agro-ecological practices in rice production systems, the synergetic effects between WMPs on the one hand and other agro-ecological practices (crop diversity, fertilizers and biodiversity) on the other have not been fully investigated. Therefore, a more in-depth analysis is needed to examine the effect of water management alongside agronomic factors on RY and WP.

The aim of this research was to elucidate the WMPs implemented in lowland rice cultivation. Second, it identifies the agro-ecological practices in lowland rice production systems and synthesizes the effect of the combination of potential agro-ecological and water

management techniques on the performance of lowland rice systems at a global scale. To achieve these objectives, a literature-based meta-analysis was implemented to evaluate the effect of WMPs on yield and WP in association with the effects of crop management, nutrient management, mulching, weed management and natural soil factors. We also discuss the contribution of agro-ecology to improving yields and WP in relation to WMPs. The meta-analysis conducted in this study is a quantitative review that specifically assesses the response of grain yield and WP to different WMPs and agro-ecological practices. It draws upon 573 observations extracted from 56 papers published between 2000 and 2021. The analysis employs the response ratio (RR) as a metric for quantifying the variability in RY or WP attributed to these practices. An RR greater than 0 ($RR > 0$) indicates an increase, while an RR less than 0 ($RR < 0$) indicates a decrease. An RR equal to 0 indicates that the yields and WP in the treatments are not significantly different from those observed under CF conditions.

2 | MATERIALS AND METHODS

2.1 | Article selection criteria

This meta-analysis focused on WMPs implemented in lowland rice production systems. Rice is often cultivated in wetlands, including inland plains and inland valleys. Only field experiments comparing CF to other WMPs were considered in this meta-analysis. Figure 1 shows the process of document search, selection and analysis for the meta-analysis, and Table 1 shows the number of papers per main factor studied.

2.2 | Data collection

Environmental and agronomic data were retrieved from each selected scientific paper. The data set includes information on WMPs, RY, WP, crop planting (direct sowing or transplanting), crop density and climate (average rainfall and evapotranspiration). Five WMPs were identified and considered in lowland rice systems: CF, SS, moderate AWD (AWDm), severe AWD (AWDs) and ARS. The WMPs were classified according to the soil water tension (SWT). CF always has a suction tension of 0 kPa, and SS is characterized by a maximum SWT of -5 kPa before irrigation. For AWDm, the maximum SWT was -15 kPa before irrigation. When the SWT exceeds -15 kPa, AWDs is considered. No ponded water was observed in aerobic practices, and the maximum SWT varied between -15 and -80 kPa.

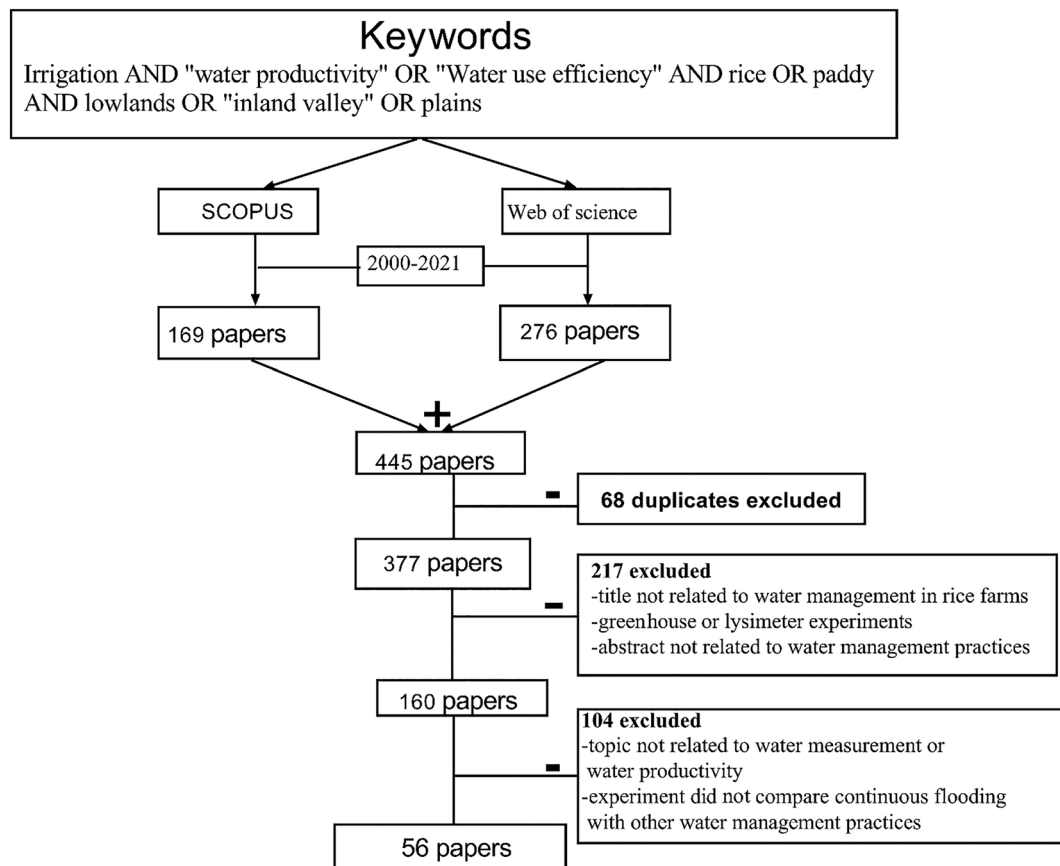


FIGURE 1 Procedure of the literature search, screening, selection and internalization for data analysis.

Climate information, including average rainfall and evapotranspiration, was collected. When climate data were not available, they were retrieved from the FAO software Climwat 2 and Cropwat 8 based on the geographic coordinates of the study sites. Climate zones were identified based on the drought index determined by dividing the annual rainfall by the annual reference evapotranspiration (Sahin, 2012). Additional data were collected regarding the season of the experiment (dry or wet) and the water regime (irrigated, rain-irrigated or rain-fed).

Data on soil properties (physical and chemical) for each study site were collected from the SOILGRID database (Hengl et al., 2017). The soil textures were classified as fine, medium, or coarse according to Yu et al. (2021). The soil organic matter (SOM) content was divided into three groups based on a range of 10 g kg^{-1} : Group 1 ($\text{SOM} < 10 \text{ g kg}^{-1}$), Group 2 ($10 \leq \text{SOM} \leq 20 \text{ g kg}^{-1}$) and Group 3 ($\text{SOM} > 20 \text{ g kg}^{-1}$). The soil pH was classified into three classes: acidic ($\text{pH} < 6.5$), neutral ($6.5 < \text{pH} < 7.5$) and alkaline ($\text{pH} > 7.5$).

Through crop management analysis, we assessed various factors, including planting techniques, planting density, rice variety or genotype (cycle length), and the

timing of WMP application and crop rotation. Two main planting methods were considered: direct sowing and transplanting. Plant densities were categorized into five classes: ≤ 25 ; $[25, 50]$; $[50, 75]$; $[75, 100]$; and > 100 plants m^{-2} . Rice genotypes were categorized based on their production cycle length as defined by the rice knowledge bank. This classification included short-cycle varieties (with a duration of fewer than 120 days), medium-cycle varieties (with a duration between 120 and 140 days) and long-cycle varieties (with a reproductive cycle exceeding 140 days) (Kouassi et al., 2020; Phan et al., 2018; Won et al., 2020).

Soybean, wheat or maize preceded rice cultivation in some plots. Due to the limited number of treatments in which soybeans preceded rice, categorization by crop family was not feasible, thus encompassing the entire practice under the term 'rotation'. Plots with rice cultivation without succession but with another crop were labelled 'no rotation'. Mulching is also considered a water-saving practice in agriculture. The mulching materials can be of vegetable or plastic origin.

This meta-analysis incorporated two primary fertilizer sources: organic fertilizers (including crop residues, domestic and industrial waste, animal by products, etc.)

TABLE 1 The number of papers per main factor studied.

Water management practices	Water timing		Season		Water regime		Crop establishment		Climate zone		Nutrients		Biodiversity	
	NP	Variants	NP	Variants	NP	Variants	NP	Variants	NP	Variants	NP	Variants	NP	Variants
CF	56	Vegetative phase	7	Wet	41	Irrigation	27	Direct sowing	16	Humid	40	Mineral	42	No rotation
SS	8	Reproduction phase	14	Dry	19	Rain + irrigation	35	Transplanted	48	Dry-humid	6	Organic	6	Rotation
AWDm	23	Whole season	39			Rain	4			Semi-arid	4	Mixture	12	
AWDs	23									Arid	4			
ARS	14									Hyper-arid	2			

Abbreviations: ARS, aerobic rice system; AWDm, moderate alternate wetting and drying; AWDs, severe alternate wetting and drying; CF, continuous flooding; NP, number of papers; SS, soil saturation.

and mineral fertilizers. Additionally, fertilizers derived from the combination of both organic and mineral sources were analysed and referred to as mixed fertilizers. Both individual and combined fertilizer sources were included in the study. Weed management practices included chemical control, mechanical control (hand hoeing or machine weeding) or a combination of both practices. Subsequently, we retrieved information on agronomic practices from the selected papers. We categorized the practices into crop management, soil fertility management, diversity and weed control, as well as direct soil evaporation control practices. In Table 2, we describe the assumptions that were made regarding agro-ecological practices, including the transitional potentialities of the variants of these practices.

2.3 | Data analysis

2.3.1 | Response variables

RY and WP were considered response variables in the analysis. RY was defined as the amount of rice grain collected after harvest per unit area. WP refers to the ratio of RY to the total amount of water from irrigation and precipitation and was calculated according to Kambou et al. (2014) as follows:

$$WP = \frac{\text{Grain yield}}{\text{Amount of water used}} \quad (1)$$

2.3.2 | Effect sizes and associated variance

The RRs were calculated according to Hedges et al. (1999) and Lajeunesse (2015) to evaluate the effect of treatment on RY and WP as follows:

$$\ln(RR) = \ln \left(\frac{x_t}{x_c} \right) \quad (2)$$

where x_t represents the RY or WP for a treatment and x_c represents the control.

The standard deviations (SDs) of the means of the RY and WP were recorded. The standard error (SE) was recorded and converted to the SD as follows:

$$SD = SE\sqrt{n} \quad (3)$$

where n is the number of replications.

TABLE 2 Agro-ecological practices identified.

Agro-ecological assumption	Crop management	Soil nutrient management	Weed control	Evaporation control (mulching)
Potentially	Planting density Genotype Timing/phase of water management Rotation	Organic	Manual	Residue
Transitional		Mix	Mix	No
No agro-ecology		Inorganic	Chemical	Plastic

Then, the intra column variance (Var) associated with each RR value was computed from the SD associated with each yield (Equation 4):

$$\text{Var} = \frac{SD_t^2}{n_t * x_t^2} + \frac{SD_c^3}{n_c * x_c^2} \quad (4)$$

where n_t and n_c represent the number of replicates of the considered treatment or control, respectively. SD_t and SD_c represent the associated SDs.

As most of the papers considered did not report the SE for WP for the control and treatments, the variance weight was estimated as the ratio of the number of replications to twice the number of observations (Carrizo et al., 2017):

$$\text{Weight} = \frac{n_{\text{rep}}}{2 * n_{\text{obs}}} \quad (5)$$

where n_{rep} refers to the number of replications of the experiment and n_{obs} is the number of observations recorded. The variance of the sum effect was estimated as the reciprocal of the sum of the weights, and the 95% confidence interval (CI) for the effect was calculated as follows:

$$\text{Lower limits} = m - 1.96 * \sqrt{Vm} \quad (6)$$

$$\text{Upper limits} = m \mp 1.96 * \sqrt{Vm} \quad (7)$$

where m and Vm are the cumulative effect and its variance, respectively.

The statistical analyses were performed using the OpenMEE statistical software (Wallace et al., 2017). OpenMEE is an open-source ecological and evolutionary meta-analysis software package that includes the 'metaphor' package (Team, R. C., 2013; Wallace et al., 2017; Wickham et al., 2024).

The study site location map was created on QGIS 3.24.2 utilizing the International Union for Conservation of Nature (IUCN) database.

3 | RESULTS

3.1 | Overview of selected studies

The database search yielded 445 articles, and only 56 articles met the selection criteria. Among the collected articles, 83% were from Asia, 13% from Africa, and the remainder from the Mediterranean region, with one document from Latin America (Figure 2).

3.2 | Effect of WMPs on RY and WP across different climates, water regimes, and seasons

RY was 49% lower under the irrigated ARS (Figure 3a) than under CF, while WP increased by 70% under AWDs and by 32.1% under rain-irrigated and rain-fed conditions with supplemental irrigation. Similarly, the WP under the ARS mode increased by 39% under irrigation and 29% under rain-fed conditions with supplemental irrigation (Figure 3b). Regardless of the climatic zone, RY was consistently lower in the ARS treatment than in the CF treatment, with no significant difference in RY between the AWDm, SS and CF treatments in the humid, dry-subhumid, semi-arid and arid zones (Figure 3c). WP was greater under the ARS, AWD and AWDm treatments than under the CF treatment in all the climatic zones, while the SS treatment showed no differences between the ARS, AWD and AWDm treatments and CF in the humid zone (Figure 3d).

RY increased by 5% in the rainy season under AWDm (Figure 3e), with yield losses of 15 and 8% under AWDs in the dry and wet seasons, respectively. In addition, the RY decreased by 14 and 40% under the ARS treatment in

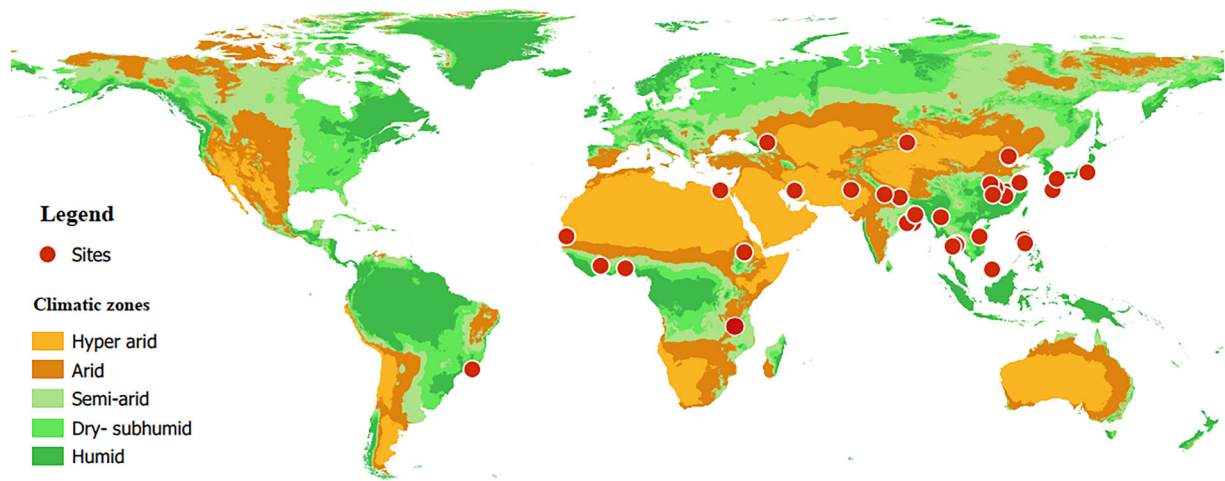


FIGURE 2 Location map of the study sites and classification of climatic zones.

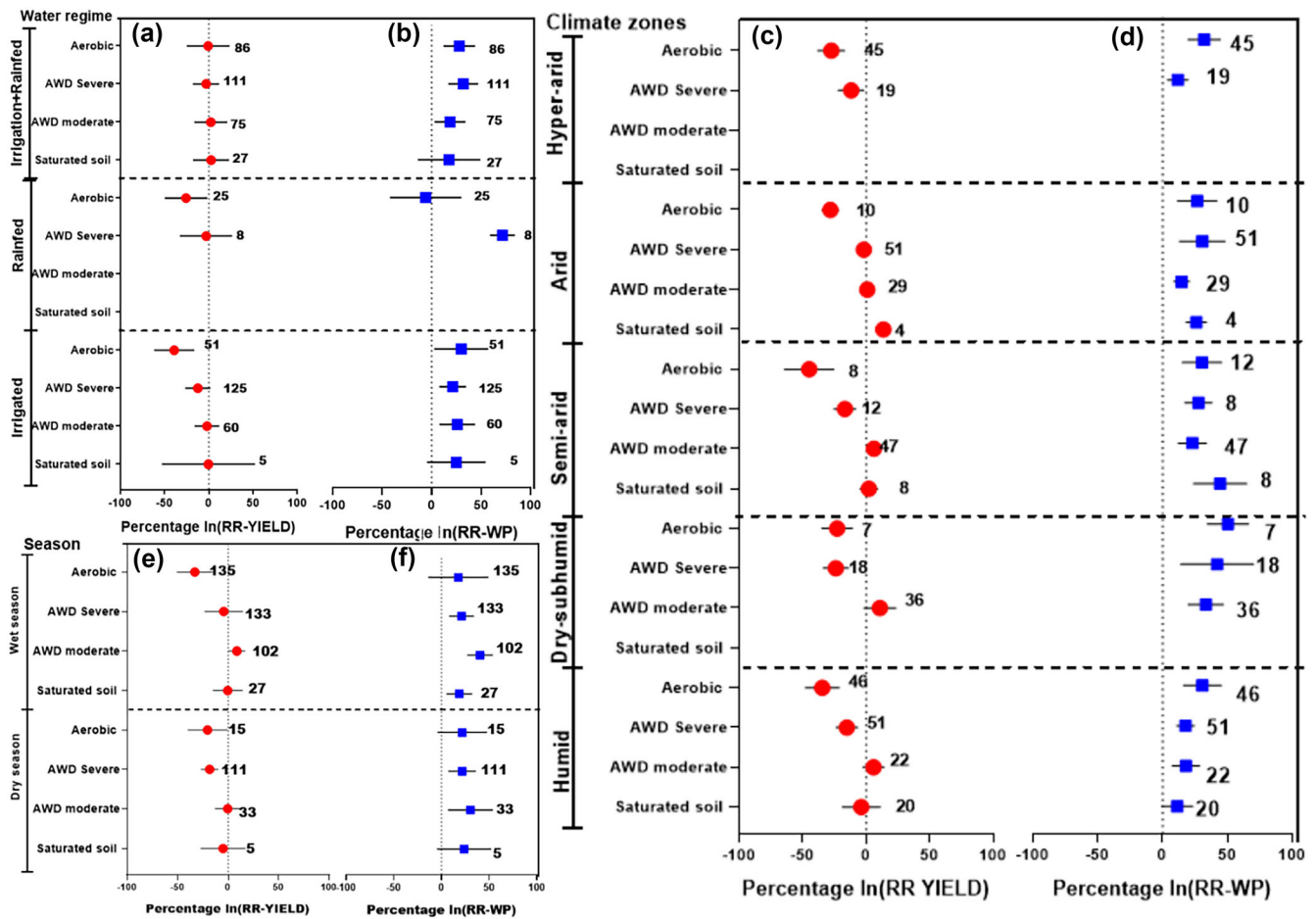


FIGURE 3 Effect of water management practices on rice yield (RY) and water productivity (WP) as a percentage change for different water regimes (a, b), climate zones (c, d) and seasons (e, f). AWD, alternate wetting and drying; RR, response ratio.

the dry and rainy seasons, respectively, while the WP increased by 37 and 21% in the dry season under the AWDm treatment and AWD treatment, respectively

(Figure 3f). WP also increased by 22, 42 and 15% in the wet season under AWDm, AWDs and ARS, respectively, compared to that under CF.

3.3 | Effect of WMPs according to soil intrinsic properties

RY was not influenced by soil texture under the SS and AWDm practices when compared to CF (Figure 4a). However, RY under AWDs was lower than that under CF, on coarse and medium soil textures, but it was not affected when the soil texture was fine. In contrast, the yield loss in rice grains was greater when the texture was fine. The best WP was observed in medium-textured soils under SS, AWDs and ARS, while it was better in fine-textured soils under AWDm (Figure 4b).

RY recorded under SS, AWDm and AWDs practices was not significantly different from that under CF in acidic soils (Figure 4c). However, under AWDm and AWDs, the RY decreased by 16% in alkaline soils. Similarly, the RY recorded under the ARS treatment was lower than that under the CF treatment regardless of the soil pH (Figure 4c). The greatest yield loss (47%) in rice grains under the ARS treatment was observed in alkaline soils. WP improved under severe AWD in acidic and neutral environments and increased only under the ARS treatment in alkaline soils (Figure 4d).

The RY was lower in the ARS and AWDs treatments than in the CF treatment regardless of the SOM content. The yield loss decreased when the SOM content ranged from 10 to 20 g kg⁻¹ in AWDs and ARS treatments (Figure 4e). The AWDm practice was adaptable to all SOM levels, and the RY was lower in the ARS and AWDs than in CF regardless of the SOM content (Figure 4e). On the other hand, the WP on the AWDs and AWDm was higher than that of CF for SOM < 10 g kg⁻¹ and SOM > 20 g kg⁻¹ (Figure 4f).

3.4 | Effect of agro-ecological practices combined with water management techniques on RY and WP

3.4.1 | Crop management

The length of the rice growth cycle did not significantly affect the RY under SS or AWDm compared to that under CF (Figure 5a). For short-cycle rice varieties, the RY under AWDs was almost the same as that under CF. Meanwhile, the RY decreased by 11 and 13% for the medium- and long-cycle varieties, respectively, when grown under AWDs. RY under the ARS treatment decreased by 19, 20 and 28% for the short- to long-cycle varieties, respectively. WP increased by 23% for the medium-cycle varieties under the AWDm treatment. For the plots under AWDs, the increase in WP was 27% (Figure 5b).

RY increased by 10% under AWDm for density class [25, 50] plants m⁻² and remained unaffected for the other density classes compared to that under CF. However, the RY decreased under AWDs by 8, 7, 188 and 19% for density classes [25, 50], [50, 75], [75, 100], and >100 plants m⁻², respectively, compared to that under CF. Moreover, the RY did not change for density classes below 25 plants m⁻². The yield loss associated with ARS was approximately 27, 26 and 52% for density classes <25, [25, 50] or >100 plants m⁻², respectively. With a class density of [75, 100], the yield did not significantly differ between the ARS and CF treatments (Figure 5c). In addition, WP improved by 10% under AWDm for a class density of [25, 50] plants m⁻². It improved by 51% for densities below 25 plants m⁻² but decreased by 8 and 18% for medium-density classes [25, 50] and [50, 75], respectively. Similarly, WP increased by 41% for densities below 25 plants m⁻² and decreased by 26% for densities belonging to [25, 50] plants m⁻² (Figure 5d).

RY decreased by 15% under AWDs and 39% under ARS when rice was transplanted compared to that under CF (Figure 5e). However, for the directly sown rice, the RY decreased by 15% under AWDs, while the RY was not significantly different under ARS, AWDm and SS compared to that under CF. The WP improved by 24, 38 and 201% under AWDm, AWDs and ARS, respectively, when rice was transplanted compared to that under CF (Figure 5f). Similarly, the WP improved by 55 and 37% in ARS and AWDs while there was no significant difference between the WP of the AWDm, SS and CF treatments in the plots where the rice was sown directly on the plots (Figure 5f).

Crop rotation enhanced the RY by 13% in the AWDm plots compared to that in the CF plots. Conversely, the RY was lower than that in the CF plots in the AWD plot crop rotation (Figure 5g). Similarly, RY values were markedly lower in plots without crop rotation than in those with AWD (-12%) and ARS (-40%) cropping sequences. Moreover, crop rotation increased WP by 12% in the AWDm plots, while it decreased WP by 20% in AWDs under plots without rotation (Figure 5h).

3.4.2 | Effect of the crop stage receiving irrigation techniques and soil evaporation control (mulching)

RY was not significantly different between the AWDm, SS and CF treatments (Figure 6a). However, the RY decreased slightly by 14% in AWDs when this practice was applied during the reproductive phase or throughout the rice crop cycle. A similar observation to that of the

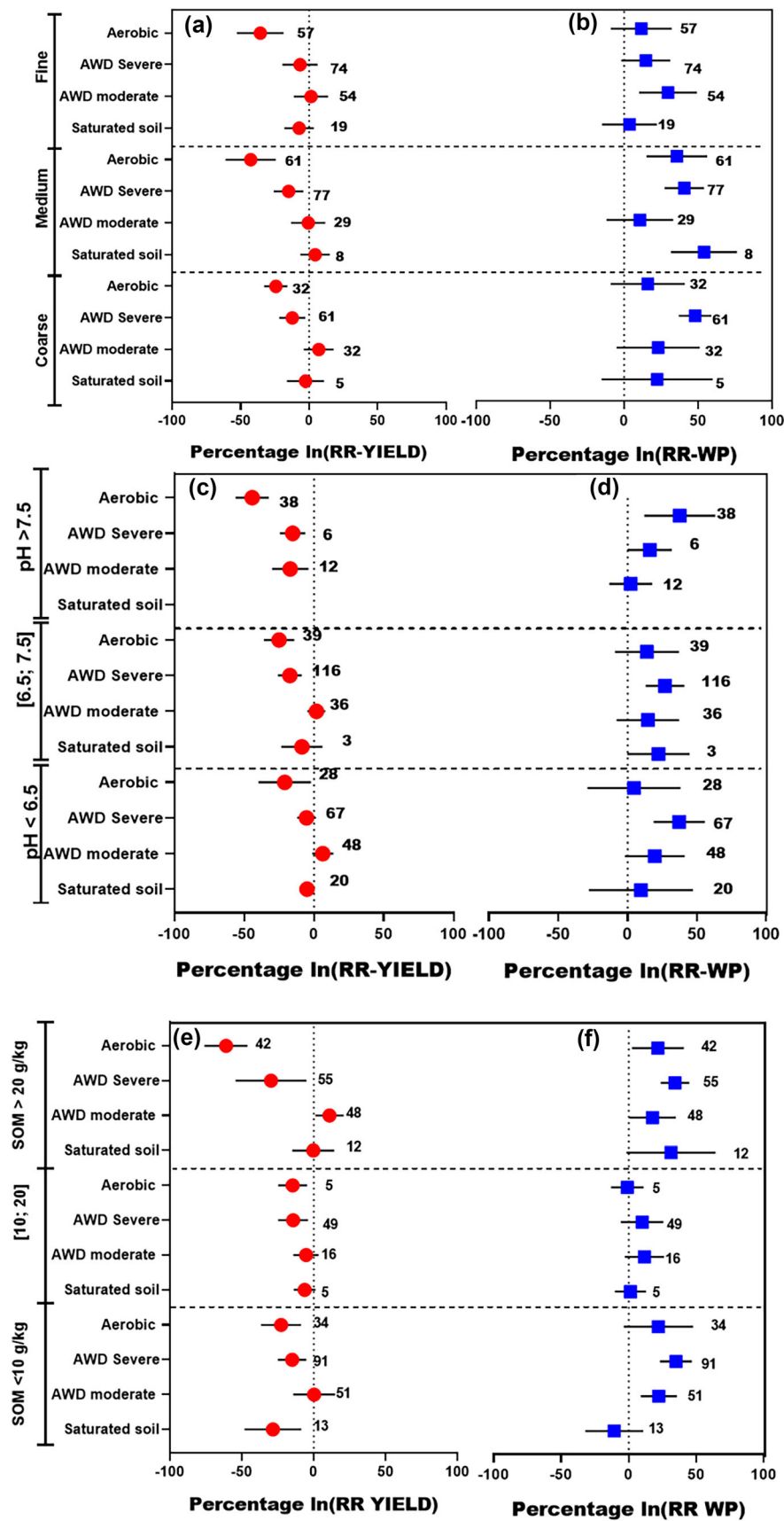


FIGURE 4 Effect of water management practices on rice yield (RY) and water productivity (WP) as a percentage change for different soil textures (a, b), pH values (c, d) and soil organic matter (SOM) (e, f). AWD, alternate wetting and drying; RR, response ratio; SOM, organic matter content.

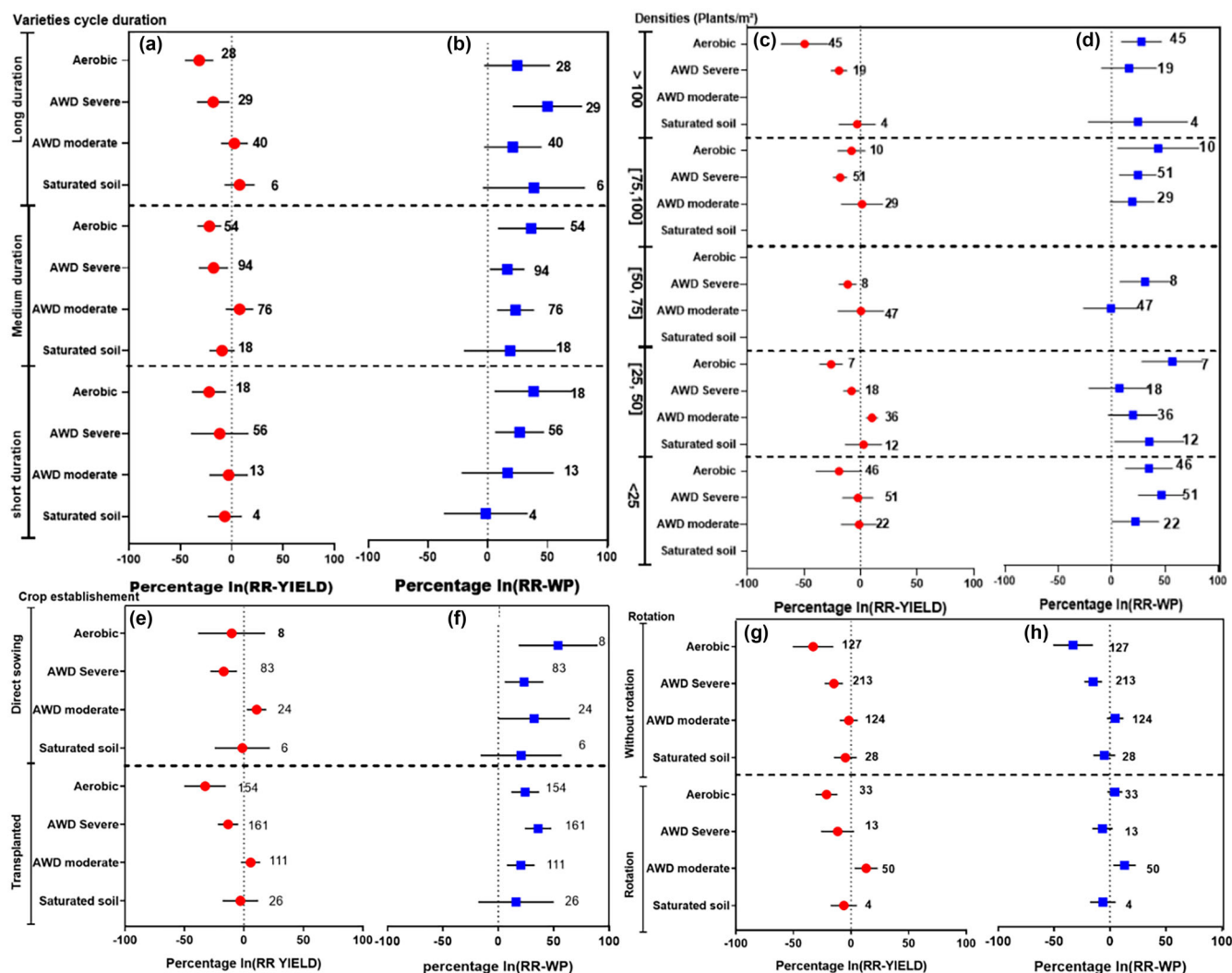


FIGURE 5 Effect of water management practices on rice yield (RY) and water productivity (WP) as a percentage change for different rice variety cycle lengths (a, b), crop densities (c, d), crop establishment methods (e, f) and crop rotations (g, h). AWD, alternate wetting and drying; RR, response ratio.

CF could be made for the ARS when applied during the vegetative, reproductive and whole seasons. Compared with the observations of RY, those of WP were similar among all WMPs when applied in the vegetative phase. Nevertheless, the WP increased by 26, 33 and 23% under AWDm and AWDs and ARS, respectively, when applied throughout the culture cycle (Figure 6b). The yield loss under the ARS treatment was approximately 31% under the grass mulch treatment, 30% under the plastic mulch treatment and 68% under the soil without mulch treatment (Figure 6c). Mulching improved by 16% (AWDm), 70% (AWDs) and 67% (ARS) compared to CF. WP improved by 79% under AWDm but was not significantly affected by other WMPs under plastic mulch. For the AWDm, AWDs and ARS plots without mulch, the WP was 21, 27 and 26% higher, respectively (Figure 6d).

3.4.3 | Effects of soil nutrient management and weed control

The fertilizer sources did not significantly affect the RY under SS or AWDm conditions (Figure 7a). However, the application of mineral fertilizers resulted in yield reductions of approximately 14 and 40% under AWDs and the ARS, respectively. The yield reduction amounted to only 16% under the ARS treatment supplemented with organic fertilizers. Moreover, when organic and mineral fertilizers were combined, the RY decreased by 32% under the ARS treatment but did not significantly differ from that under the CF treatment under the SS and AWD treatments. With the application of inorganic fertilizers, the WP increased by 28% under ADWs. WP was 80 and 85% greater under AWDs and ARs, respectively, than under CF when both fertilizer sources were mixed (Figure 7b).

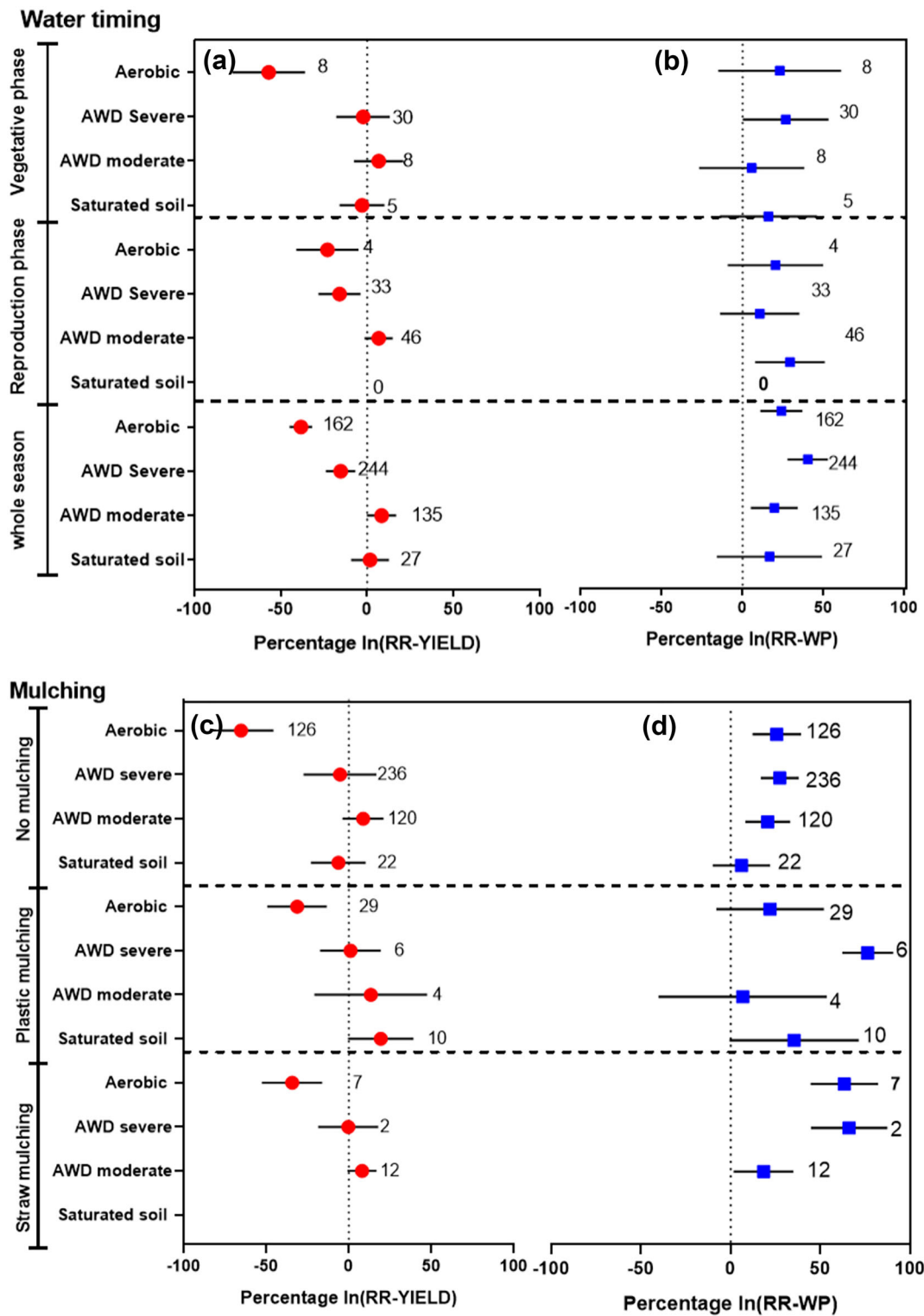


FIGURE 6 Effect of water management practices on rice yield (RY) and water productivity (WP) as a percentage change for different water timings (a, b) and mulching practices (c, d). AWD, alternate wetting and drying; RR, response ratio.

RY increased by 10% in plots with mechanical weed control under SS compared to those under CF (Figure 7c). Similarly, the RY under AWDm increased by 11% in plots where chemical weed control was employed

and remained unchanged under the other WMPs. Moreover, RY decreased by 20% under chemical weed management and by 18% under mixed weed management. With respect to ARS, the RY remained unchanged

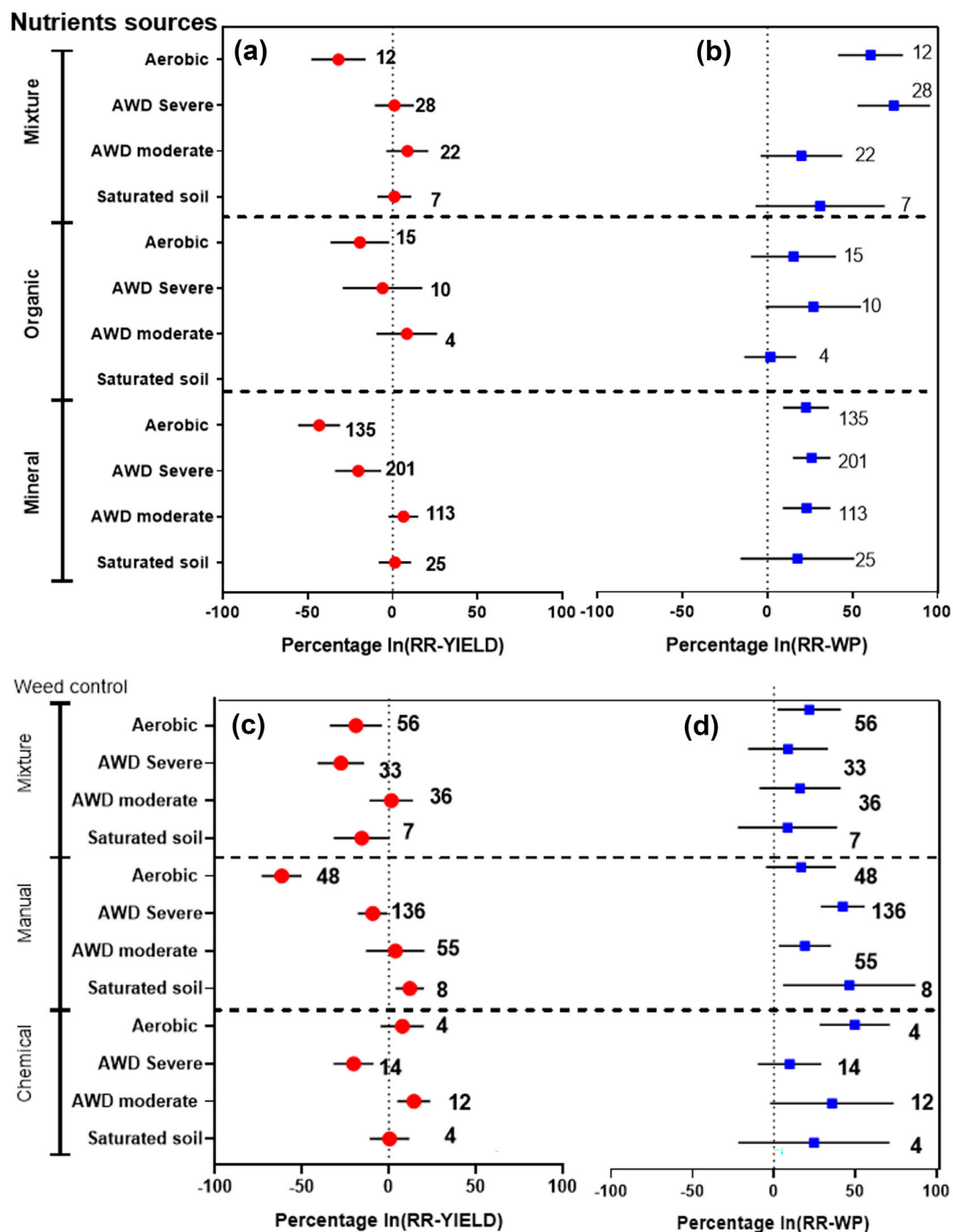


FIGURE 7 Effect of water management practices on rice yield (RY) and water productivity (WP) as a percentage change for different nutrient sources (a, b) and weed control methods (c, d). AWD, alternate wetting and drying; RR, response ratio.

under chemical weed control but decreased by 61% under manual weed control compared with that under CF and by 19% under mixed control. WP improved by 42% for AWDs under manual weed management. This percentage also increased by 52% under the ARS treatment, where weeds were controlled with chemicals (Figure 7d).

4 | DISCUSSION

4.1 | Effect of WMPs according to climate, water regime and season

Using a meta-analysis method, this study quantitatively analysed the effect of WMPs on grain yield and WP in

lowland rice production. The study also considered the impact of other factors that interact with WMPs on yield and WP. Figures 2 and 3 illustrate that rice is produced in all climate zones, with more than 80% of the documents originating from Asian countries. This finding aligns with previous work by Fukagawa and Ziska (2019), which estimated that 90% of the world's rice production comes from Asia. Our study identified five WMPs (ARS, AWDs, AWDm, SS and CF) in all climate zones. However, regardless of the climatic zone, the RY under the ARS and AWDs was lower than that under CF, while the RY under AWDm and SS was similar to that obtained under CF. This finding suggests that various WMPs can be applied worldwide. Notably, all practices resulted in higher WP than did CF. CF practices consumed significant amounts of water, although they contributed to higher yields.

4.2 | Effect of WMPs and soil characteristics

The soils identified in the papers have been classified into three groups: coarse-textured (sand, loamy sand, sandy loam), medium-textured (loam, silt loam, silt, sandy clay loam) and fine-textured (clay loam, silty clay loam, sandy clay, silty clay and clay) (Moebius-Clune, 2016). The results show that the RY of SS and AWDm practices did not differ significantly from that of CF, regardless of the soil texture (Figure 4a). However, the RYs obtained under AWDs practices were lower than those obtained under CF on coarse- and medium-textured soils but remained similar to those under CF on fine-textured soils. Fine-textured soils, characterized by a high clay content, had a greater water-holding capacity and slower water infiltration rates, which contributed to sustaining plant growth under AWDs.

Our study revealed that the RY under acidic soil conditions was similar under SS, AWDm and AWDs compared to that under CF, while the yield under acidic soil conditions was lower than that under CF in alkaline soils (Figure 4c). Alkaline soils often have a high exchangeable sodium content (Carrijo et al., 2017), leading to a reduced water infiltration rate, hydraulic conductivity and soil water diffusivity (Mölders et al., 2003). This could explain the low RY observed in alkaline soils. Previous studies have indicated that water management does not significantly reduce RY under acidic conditions (Carrijo et al., 2017; Linquist et al., 2013). The acidity and alkalinity of the soil can be attributed to the lack of organic matter, which typically improves soil chemical properties and consequently yields (Bot & Benites, 2005). A deficiency in organic matter resulted in a decrease in RY in SSs (Figure 4e).

4.3 | Effect of agroecological WMPs and agronomic practices

4.3.1 | Crop management

The influence of rice crop cycle length on yield (RY) under different WMPs, namely SS, AWDm and AWDs, was evaluated and compared with that under CF (Figure 5a). Notably, compared with CF with short and medium rice genotypes, no significant impact on RY was observed for SS or AWDm or AWDs. However, an extended cycle length (>120 days) led to a notable 12% decrease in RY under AWDs. Short-cycle varieties are recommended from an agro-ecological standpoint due to their lower water demand, reduced weeding requirements and potential for multiple cropping cycles within a year. This finding corroborates prior research by Jagannath et al. (2013), indicating that short-cycle rice varieties exhibit reduced sensitivity to RY reduction in AWDs scenarios compared to long-cycle varieties. Additionally, these varieties demonstrate enhanced drought resistance and shorter production periods, consistent with findings from Mackill et al. (2012) and Dar et al. (2020).

Furthermore, the choice between direct seeding and transplanting significantly influenced RY and WP. Compared with CF, direct seeding notably increased RY by 7% in AWDm and minimized yield losses in AWDs and ARSs (Figure 5e). This method alleviated the stress associated with transplanting, ensuring uniform plant distribution and enhancing water and nutrient uptake. Conversely, despite being labour intensive, transplanting offered advantages in terms of water management and crop establishment. Transplanted rice plants experienced reduced water and nutrient stress during establishment, contributing to improved RY and WP (Figure 5f). Notably, a slight improvement in RY (10%) was observed under AWDm at a planting density of 25–50 plants m^{-2} (Figure 5c). Consistent with research from China and Iran, optimal planting density plays a pivotal role in maximizing RY while minimizing water usage. This finding resonates with the conclusions drawn by Ahmed et al. (2023), who modelled various treatments that combined planting density and AWDm. The observed increase in yield losses at high planting densities under AWDs and AWDm may be attributed to heightened competition for water resources, leading to accelerated soil water depletion. Similar trends were noted for the ARS, with no significant difference in yield observed when the sowing density ranged between 75 and 100 plants m^{-2} . Studies have indicated that a high seeding rate can mitigate yield losses under conditions of high water stress induced by AWDs and AWDm, ensuring more efficient

resource utilization (Xu et al., 2019). Additionally, a comparison between directly sown and transplanted rice at equivalent densities consistently revealed higher yields and WP in directly sown plots (Ishfaq et al., 2020). Although transplanting offers water conservation benefits, particularly during the nursery stage, compared to direct seeding (Dossou-Yovo & Saito, 2021), the selection between methods should consider factors such as water availability, labour resources and overall resource management strategies to optimize crop yield and WP (Mishra & Salokhe, 2008; Tuong et al., 2005).

The comparable performance among AWDm and AWDs, SS and CF in plots implementing crop rotation underscores the positive impact of crop rotation on soil fertility and microbial development. Crop rotation, as a fundamental agro-ecological practice, enhances soil health and biodiversity, fostering a diverse microbial community crucial for nutrient cycling, soil structure enhancement and pest control (Sourisseau et al., 2021). This microbial diversity supports the proliferation of beneficial soil organisms, contributing to improved soil fertility and the suppression of detrimental pests and diseases, thereby enhancing overall crop performance (Malézieux et al., 2022). Previous research has indicated that culture rotation combined with AWD increases RY by 24–46% (Xuan et al., 2012).

4.3.2 | The crop stage receiving irrigation techniques

The notable increase in RY across all WMPs, ranging from AWDs to CF, underscores the sensitivity of rice crops to water availability (Bouman et al., 2007). Under conditions of ample water, such as CF, RYs tend to peak due to minimized water stress during critical growth phases. Intriguingly, when WMPs were solely applied during the vegetative phase, the RY remained relatively consistent across CF, SS, AWDm and AWDs, despite variations in soil moisture levels (Figure 6a). This phenomenon can be attributed to the moderate water requirements of rice during vegetative development (Djaman et al., 2017). Moreover, AWD systems stimulate rice tillering, leading to increased tiller numbers and the potential for heightened RY during the vegetative stage (Sriphirom et al., 2020). Conversely, water stress incurs substantial yield losses during the reproductive phase, which is evident in AWDs and ARS practices (Figure 6a). Carrijo et al. (2017) conducted a meta-analysis revealing a 23% reduction in RY under AWDm and AWDs compared to CF. Hence, effective water management during the reproductive phase becomes paramount for maximizing RY and overall productivity. The adoption of AWDm

has proven effective in curbing water losses through evaporation and percolation while maintaining relatively high yields (Hoang et al., 2019; Silalertruksa et al., 2017; Tan et al., 2015). AWDm practices resonate with agro-ecological principles, emphasizing resource efficiency to achieve sustainable agricultural production. By embracing AWDm, farmers can boost productivity with fewer external inputs, particularly water. The diminished yields observed in severe AWD (AWDs) and ARS practices due to heightened water stress are counterbalanced by relatively higher WP, indicating more efficient water utilization despite reduced yields. This aligns with agro-ecological objectives of optimizing resource utilization. Furthermore, the timing of WMPs during the vegetative, reproductive or entire crop cycle significantly influences agro-ecological principles. AWDm practices play a pivotal role in this regard by facilitating efficient water utilization across different growth stages of crops. For rain-fed rice cultivation, it is imperative for farmers and rural development stakeholders to synchronize the cropping calendar with water requirements, particularly during the reproductive phase, ensuring an adequate water supply. This may necessitate meticulous planning and planting timing to coincide with periods of ample rainfall or the implementation of effective water management strategies to mitigate water stress during critical growth stages. Integrating such practices can enhance the resilience and sustainability of rain-fed rice production systems in line with agro-ecological principles.

Mulching had no significant effect on RY or WP compared to CF (Figure 6c). However, previous studies have yielded mixed results regarding the impact of mulching on rice production and water use efficiency. For instance, He et al. (2013) observed that plastic mulching did not enhance yield but contributed to better water conservation and higher WP. Plastic mulches were found to augment WP in SSs compared to CF (Tao et al., 2006). Similarly, Maneepitak et al. (2019) reported a greater RY in mulched plots under AWDm than under CF. Additionally, WP was significantly greater under AWDm with plastic mulch than under CF (Figure 6d). Finally, Hoang et al. (2019) reported that combining mulching with AWDm improved WP by 0.37 kg m⁻³ compared to CF.

4.3.3 | Soil nutrient management and weed management

The RY in WMPs exhibiting suction tension below –15 kPa was lower than that in CF in soils where mineral fertilizers were applied (Figure 7a). However, for organic and mixed fertilizers, the RY under AWDs, AWDm and SS did not significantly differ from those

under CF. Organic fertilizers, such as crop residue recycling, contribute to enhancing soil cohesion, thereby improving soil infiltration and water retention capacity (Li et al., 2018). Additionally, organic fertilizers aid in soil carbon sequestration (Verma et al., 2020), increase soil water storage capacity, decrease soil bulk density and facilitate root penetration into deeper layers (Mueller et al., 2012), potentially mitigating the effects of water scarcity in rice cultivation. Numerous studies have demonstrated that organic fertilizers enhance yields under AWD conditions (Dawe, 2005; Islam et al., 2018), particularly in intensive rice systems (Gbenou et al., 2016; Serpantié, 2013). However, the slow decomposition rates of organic fertilizers may pose challenges to nutrient availability, particularly nitrogen immobilization, which adversely affects yields (Bird et al., 2001). To address this issue, organic fertilizers are often incorporated into the soil during land preparation, with additional nitrogen supplements, such as urea, applied during the reproductive stage to meet crop nutrient demands (Wei et al., 2016). Combining organic and mineral fertilizers is a strategy for mitigating nutrient deficiencies and optimizing nutrient availability throughout the season. Studies have shown that such combinations can significantly improve WP, with up to 80% improvement in AWDs and 85% greater productivity in the ARS than in CF plots (Figure 7b). These findings are consistent with previous research, such as that conducted by Singh (2013), who also reported substantial improvements in WP with the combination of fertilizer sources and AWD practices in lowland areas. In contrast to plots receiving mineral fertilizers, WP increased by 28% in AWDm severe (Figure 7b) compared to CF. Moreover, integrating organic fertilizers with AWD practices, as seen in systems such as the System of Rice Intensification (SRI), has shown even greater WP gains, reaching up to 61% compared to conventional production systems (Uphoff et al., 2011).

Our results demonstrated a 10% increase in RY under chemical weed control compared to mechanical control under the AWDm system. Conversely, reliance on chemical weed control contributes to a reduction in rice yield in AWDs (Figure 7c). Moreover, WP was greater under AWDm and AWDs (42%) than under CF when manual weed control was employed. Weed management, in addition to water and nutrient management, is crucial in rice production systems because it significantly impacts crop growth and yield (Rodenburg & Johnson, 2009). CF practices inherently suppress weed growth due to continuous field inundation, effectively smothering weeds (Itoh et al., 2011). However, in water-saving techniques such as AWDm, drying periods create favourable conditions for weed proliferation, leading to

increased labour requirements for weed control (Husain et al., 2009; Pandey et al., 2020). Employing herbicides for weed control can effectively mitigate weed competition and improve yield outcomes. Manual weeding not only removes weeds but also aerates the soil, facilitating better water infiltration and rice development. The synergistic relationships between soil, water and plants underscore the importance of manual weed control in agro-ecological production systems. Adopting agro-ecological principles in weed management suggests favouring manual weed control or judicious use of herbicides, particularly before sowing or transplanting, to minimize environmental impact and promote sustainable weed management practices. By integrating manual weeding with water management strategies, farmers can optimize weed control while conserving water resources and enhancing overall crop productivity in a manner that aligns with agro-ecological principles.

5 | CONCLUSION

This meta-analysis assessed the RR of RY and WP to lowland rice cultivation according to WMPs and interactions with agro-ecological practices (crop and nutrient, weed management practices). The WMPs implemented in lowland rice production include CF, SS, AWDm, AWDs and the ARS. Compared with CF, AWDm (−15 kPa at 15 cm depth) improved RY and WP. In contrast, AWDs reduced RY but maintained high WP. RY is always lower in the ARS treatment than in the CF treatment. Based on the principles of sustainable agriculture that aims to maintain productivity with optimal use of resources, AWDm practices could be strongly recommended. It allows for a water savings of 23% and a 25% improvement in WP compared to CF. We found that the following agro-ecological practices should be associated with water-saving practices: crop management practices (short-cycle varieties, transplanting and low planting density) and agronomic practices (organic fertilizers, manual or mechanical weed management, straw mulching for soil evaporation control) to increase yields and WP.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data are available under request.

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