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RESEARCH

Alternate wetting and drying water management can reduce phosphorus availability under lowland rice cultivation irrespective of nitrogen level

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Abstract The limited availability of phosphorus (P) in the soil, which is affected by soil moisture, has a significant impact on crop production. However, we still do not fully understand how water management and nitrogen (N) addition affect the availability of P in paddy soil. An evaluation of the effects of two water management strategies that is continuous flooding (CF) and alternate wetting and drying (AWD) irrigation along with various nitrogenous fertilizer addition rates (equivalent to 0, 100%, 133%, and 166% recommended dose of N addition) on P availability in paddy soil took place over the course of a 2-year field experiment. The results showed that water management had a significant influence on ferrous iron, microbial biomass P, and soil-available P. However, the addition of N did not affect the availability of P in the soil. When N was added at various rates, AWD consistently reduced the amount of soil-available P compared to CF. This was primarily because AWD increased microbial biomass, which immobilized P and decreased the content of ferrous iron. As a result, the soil's ability to absorb P increased, leading to a decrease in the amount of P available. In conclusion, AWD decreases the amount of available P in paddy soil compared to CF.

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Keywords Alternate wetting and drying · Available P · Continuous flooding · Microbial biomass P · Redox condition · Soil moisture

Introduction

Rice is the primary staple grain crop grown in India, where rice fields are flooded throughout the entire crop growth period (Dash et al., 2015). As the demand for water increases in domestic and industrial sectors, the agricultural sector must allocate some of its water supply to meet the needs of other sectors. Water requirements in paddy can be reduced while increasing water productivity by replacing the continuous flooding (CF) water management system with alternate wetting and drying (AWD) without significantly sacrificing yield. The success and adoption of the AWD system will depend on the following factors: (1) the amount of water saved, (2) the availability of soil nutrients to the crop, and (3) the grain yield produced, compared to the CF system. This study focuses specifically on the second factor, which is nutrient transformation and availability, particularly phosphorus (P) availability and transformation under CF and AWD water management systems.

P is an essential macronutrient for rice, but its availability in the soil has always been a problem due to slow diffusion and high fixation rates (Yigezu et al., 2023). P availability in soil is influenced by three main mechanisms: (1) dissolution and precipitation, (2) absorption and desorption, and (3) biotransformation (Adediran et al., 2021). These mechanisms are affected by the state and condition of the soil, including water flux and oxidation–reduction state. The condition of the soil rhizosphere remains stable in dryland situations, whereas in the water environment of paddy fields, the changing condition of the rhizosphere significantly impacts P availability (Bagheri et al., 2021; Turner & Gilliam, 1976). Therefore, water management in paddy fields directly affects the availability of P for the crop.

Water management and nutrient balance both play crucial roles in determining nutrient availability. Specifically, the application rate of nitrogen (N) under different water regimes can impact the rhizosphere environment and influence P availability in soil. Studies have demonstrated that the continuous use of balanced chemical fertilizers improves soil P availability, rice P sorption, and yield (Bhattacharyya et al., 2015). Changes in soil pH and redox potentials (Eh) in paddy fields under CF and AWD can also affect P availability, as well as P adsorption and desorption properties (Seng et al., 1999). Even in acidic soils, calcium plays a significant role in modulating P dynamics under CF (Scalenghe et al., 2014). However, the excessive use of chemical fertilizers can lead to P build-up in the soil, limiting P availability (Ramaekers et al., 2010). To mitigate these negative effects and improve soil fertility in rice production systems, various agronomic practices, such as straw incorporation and AWD water management, have been implemented (Jiang et al., 2021). However, little is known about the effect of N fertilizer on soil P availability under different water management systems.

Under the CF water management system, the rhizosphere remains anaerobic throughout the rice growing period. This anaerobic condition lowers the redox potential, converts Fe^{3+} to Fe^{2+}, and releases P from insoluble iron phosphate, potentially increasing P availability (Rakotoson et al., 2014). Conversely, reduced conditions can facilitate the sorption of more P by amorphous iron oxides with additional P binding sites, reducing P availability (Zhang et al., 2003). However, since the reduced soil is exposed to aerobic conditions during sampling and experimentation, the increased P availability can be considered an experimental artifact. Estimating P in the laboratory using air-dried soil may lead to an overestimation of P due to increased P precipitation (Brand-Klibanski et al., 2007).

The AWD water management system consists of two phases: drying and wetting. Most studies on soil P availability have focused on the wetting phase, with limited emphasis on P availability during the drying phase. Many researchers have used air-dried soils collected after paddy harvest to assess the impact of water management on soil P availability (Xu et al., 2020), while a few have compared changes in available P and P sorption in flooded soils and their air-dried samples (Maftoun et al., 2006). However, this may not accurately represent the soil's P response to different water management regimes throughout the entire paddy growth period. In actual paddy field conditions during the AWD drying cycle, the soil retains a high level of water content. Therefore, the extent of soil dryness and wetness in samples collected for the study becomes crucial in determining soil P availability. During the drying phase, both the forms of iron and P in the soil undergo changes (Xu et al., 2020). As a result, fresh soil samples collected under different water management systems may provide a more accurate representation of the actual P condition in paddy soils.

Microbial biomass phosphorus (MBP) constitutes a significant portion of the soil organic P pool, accounting for 2–5% of the total organic P content in arable soil (Hedley & Stewart, 1982). MBP is highly active and plays a key role in nutrient cycling. Due to its fast turnover rate, MBP can swiftly enhance P availability. Throughout the life cycle of soil microbes, P availability decreases as a result of immobilization, while P levels in the soil rapidly rise after microbe's death due to rapid mineralization. In anaerobic (flooded) soils, the abundance of Fe^{3+}-reducing bacteria increases (Wang et al., 2019), facilitating the release of P anions through microbiological dissolution of ferric oxides (Maranguit et al., 2017). Conversely, soils under AWD water management exhibit a more diverse and enriched microbial population (Majumder et al., 2021). Previous research has primarily focused on P availability in soil based on absorption–desorption phenomena under different water management systems (Bai et al., 2017), but the relationship between MBP and available P under various water management systems remains unclear.

The present study investigates the influence of water management and N addition on P availability in paddy soil. Its other objective is to examine the relationships between soil-available P, redox state, pH, and MBP under various water management regimes. The hypothesis posits that AWD irrigation, with or without N addition, will decrease P availability in paddy soil compared to CF irrigation. Accordingly, the study aims to achieve the following objectives: (1) to quantify the impact of water management (CF and AWD) on soil P availability, and (2) to determine the potential effect of different N fertilizer application rates on P availability in soil under CF and AWD conditions.

Materials and methods

Experimental site

The field experiment was conducted during the winter (*rabi*) seasons of 2021 and 2022 at the ICAR-Indian Institute of Water Management research farm in Mendhasal, Bhubaneswar, India. The research farm is located at 20°30′ N latitude and 87°48′ E longitude, in an irrigated lowland rice cultivation area (Fig. 1). The soil at the experimental site belongs to the Aeric Haplaquepts soil classification and has a silty clay–loam texture. Surrounding the experimental field are lowland rice fields, with three sides bordered by them and the fourth side by a road. The farm receives irrigation water from a canal regulated by the Deras Minor Irrigation Canal Command Area.

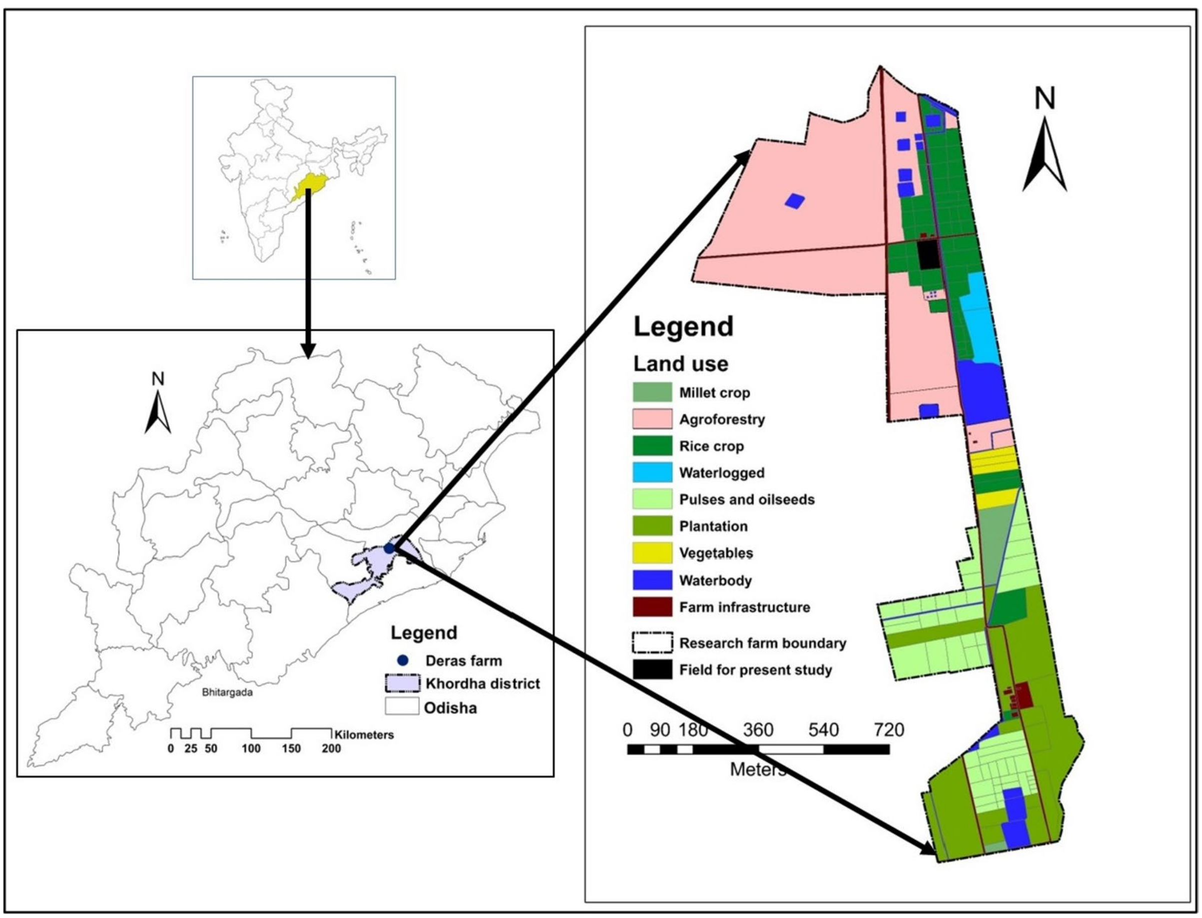


Fig. 1 Map of the study area showing the experimental plots and land use of the farm

Prior to commencing the experiment, soil samples were collected from the experimental plots and analyzed for their physico-chemical characteristics. Throughout the experiment, measurements were periodically taken of surface soil moisture (0–20 cm), available P, MBP, and Fe^{+2} content.

Treatments and design of the experiment

Throughout the entire cropping season, two water management strategies were implemented: (1) CF and (2) AWD. After transplanting and until the tillering stage of the crop growth, the depth of the ponded water on the field was maintained in both the CF and AWD regimes between 10 and 50 mm. Following this, the water level in the CF treatment was allowed to vary roughly between 10 and 100 mm. In the AWD treatment, which was started 27 DAT, the irrigation was scheduled using International Rice Research Institute (IRRI) pipe where 5 days drying period was observed. The AWD regimes had a maximum water depth of 100 mm (any excessive rainfall was drained off). The ponded water level decreased below the field surface during the drying phase when it was not submerged.

N fertilizer dosages were 0, 90, 120, and 150 kg ha^{-1}. For each subplot, N was added as urea in three splits: 50% as basal, 25% at 20 days after transplanting (DAT), and 25% at the panicle initiation stage. All treatments received a basal dose of P and K at a rate of 50 kg ha^{-1}. At the final harrowing, which was 1 day prior to transplanting, all basal fertilizers were incorporated into the soil.

The treatments were designed as a split plot with water regime as the main plot and N rate as the subplot in completely randomized blocks (Fig. 2). Treatment combinations were replicated four times. The plot measured 150 m^2. Two to three seedlings (23 days old) per hill of MTU 1010 paddy variety (120 days duration) were transplanted with spacing of 20 × 10 cm. Plots were routinely hand-weeded and treated with pesticides to prevent insect and pest damage. In the experiment, there was no discernible crop damage. When the paddy crop reached maturity, it was cut, and the dry yield of grain and straw was calculated. For each treatment, the water productivity of the paddy was calculated.

Soil sampling and analysis

This study employed two water management strategies: CF and AWD irrigation. The AWD treatments underwent seven cycles of wetting and drying throughout the crop growth period. Generally, the AWD treatment received irrigation 5 days after the drying period (DDP), depending on the soil type. Soil samples were collected twice during each wetting–drying cycle for the AWD treatments: once at 3 DDP and again at 5 DDP. The AWD and CF treatments were sampled simultaneously.

The soil moisture content of the AWD treatments was measured using the gravimetric method. Throughout the sampling periods, the soil moisture content of the AWD treatments remained consistent. However, measuring chemical parameters in the CF treatments posed a challenge due to the submerged condition. To achieve uniform soil moisture content in the CF treatments, the surface water was removed by centrifuging the soil for 10 min at 3600 rpm after measuring the initial weight of the fresh soil. The soil samples were then subjected to the oven-drying method to assess their moisture content.

Each soil sample was divided into two portions. Within a week, one portion of fresh soil was used to determine the available P, pH, MBP, and ferrous iron. The concentration of these parameters was calculated based on the soil water content of each fresh soil sample. After air drying, another component was used to calculate the amount of available P and MBP. The pH of the soil was measured using a pH meter with a 1:2.5 (w/v) soil-to-water ratio. Fresh soil equivalent to 10 g of dry soil, adjusted according to the water content of each soil sample, was weighed, and the corresponding volume of water was added. The available P content was measured using the molybdenum antimony spectrophotometric method, involving the extraction of soil samples with Brays solution, as described by Bray and Kurtz (1945). The MBP was determined following the method described by Brookes et al. (1982). The ferrous iron content was calculated using the phenanthroline colorimetric method, as outlined by Asami and Kumada (1959).

Statistical analysis

One-way analysis of variance (ANOVA) was used to compare the differences among the soil variables,

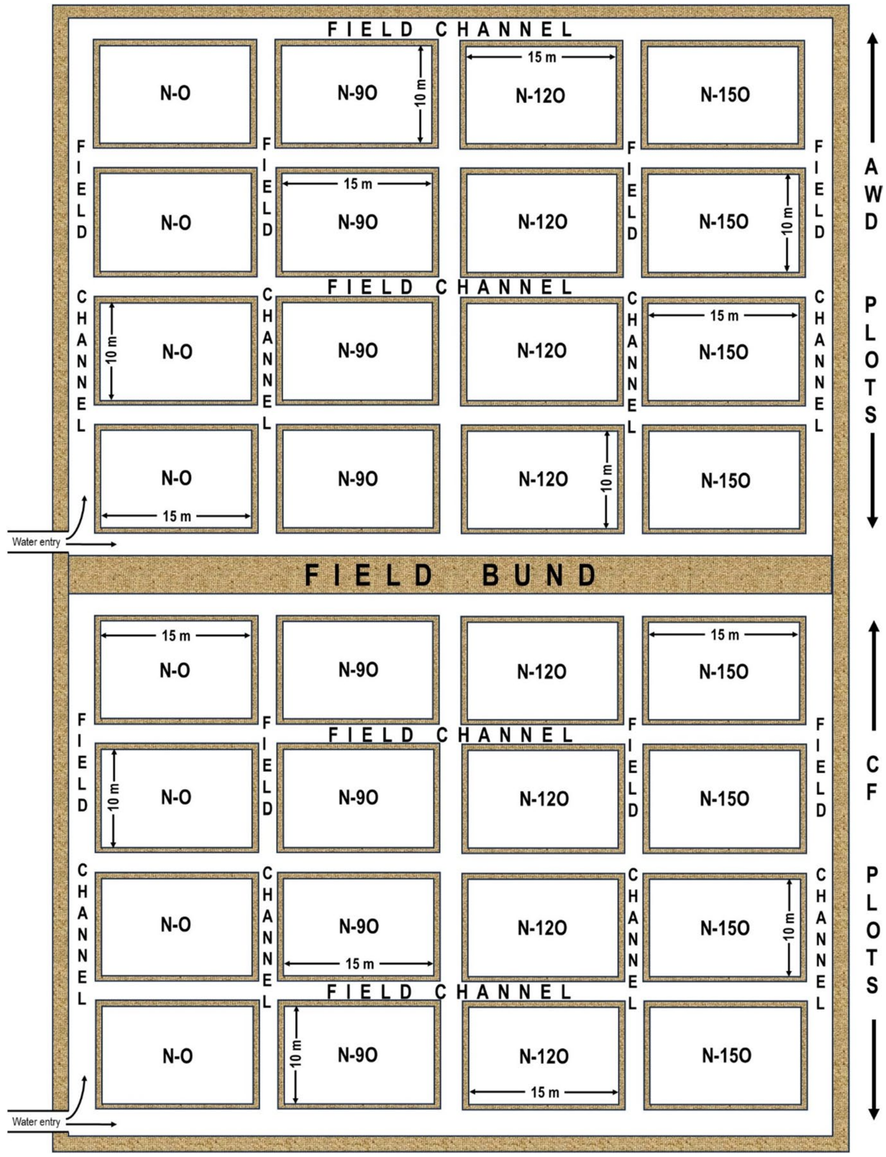


Fig. 2 Layout of the experimental plots showing the field channels, bunds, and treatments

including available P in fresh soil, available P in air-dried soil, pH, MBP, and ferrous iron, for each sampling period under the two water management regimes. The means were compared using a least significant difference (LSD) test at a significance level of $p = 0.05$. Furthermore, a two-way ANOVA was conducted for each sampling period to assess the statistical differences between water management and N addition. To examine the correlations between the measured variables under the two different water management regimes, the Pearson test (two-tailed) was employed at a significance level of $p = 0.05$.

Results

Initial soil properties

Before the start of the experiment, the surface (0–20 cm) soil samples from the CF and AWD fields were collected and analyzed for their physical and chemical properties and presented in Table 1. Within the 0–20 cm soil layer, the soils at the experimental site had a coarse texture with 61.5% sand and 19.3% clay in the CF field and 63.3% sand and 18.2% clay in the AWD field. When compared to the CF field,

Table 1 Basic soil properties at the start of the experiment

Soil parameters	CF field	AWD field
pH	5.82	5.83
EC (dS m^{-1})	0.41	0.44
Soil organic carbon (g kg^{-1})	5.32	5.54
Total N (mg kg^{-1})	1270	1310
NH_4 N (mg kg^{-1})	4.24	4.22
NO_3 N (mg kg^{-1})	7.02	7.09
Available P (mg kg^{-1})	6.61	6.64
Available K (mg kg^{-1})	81.9	82.4
Sand (%)	61.5	63.3
Silt (%)	19.2	18.5
Clay (%)	19.3	18.2
Bulk density (Mg m^{-3})	1.45	1.44
Soil moisture at field capacity (m^3 m^{-3})	0.34	0.35
Soil moisture at wilting point (m^3 m^{-3})	0.12	0.12
Saturated hydraulic conductivity (cm h^{-1})	0.41	0.44

the AWD field's sand content was just 2.9% higher. In the CF and AWD fields, the soils had pH values of 5.82 and 5.83 and electrical conductivity (EC) values of 0.41 and 0.44 dS m^{-1}, respectively, were recorded. They were also non-saline. With values of 5.32 g kg^{-1} in the CF field and 5.54 g kg^{-1} in the AWD field, the soil organic carbon content was low. For the CF and AWD fields, the bulk densities were 1.45 and 1.44 Mg m^{-3}, respectively. In the CF and AWD fields, the wilting point soil moisture content was 0.12 m^3 m^{-3}, while the field capacity soil moisture was 0.34 and 0.35 m^3 m^{-3}. For both fields, the available soil moisture content was 22 and 23%. For the CF and AWD fields, the saturated hydraulic conductivity was 0.41 and 0.44 cm h^{-1}, respectively. The soils had medium levels of P and potassium but low available N. Therefore, the fertility status of the experimental field can be considered as low to medium (Sathish et al., 2018).

Water management and soil water storage

The daily rainfall and ponded water depths for CF and AWD in the field are depicted in Fig. 3. The water depth in CF varied roughly between 10 and 100 mm, while in AWD it ranged between − 102 and 101 mm. The shallow groundwater depths varied between 90 and 280 cm below the surface up until 1 week before harvest. The percentage of days without standing water in AWD was 42% of the crop-growing period, whereas it was 31% when compared to the CF treatment. During the crop-growing season, 1322.5 mm and 1092.5 mm of water were added under the CF and AWD water management treatments, respectively. Therefore, AWD water management can conserve 17.4% more water than CF.

At the initial stages of the crop growth, both the water management treatments (CF and AWD) received same amount of water as irrigation up to twenty-one DAT. After that, drying was applied in AWD treatments. Figure 4 shows the moisture

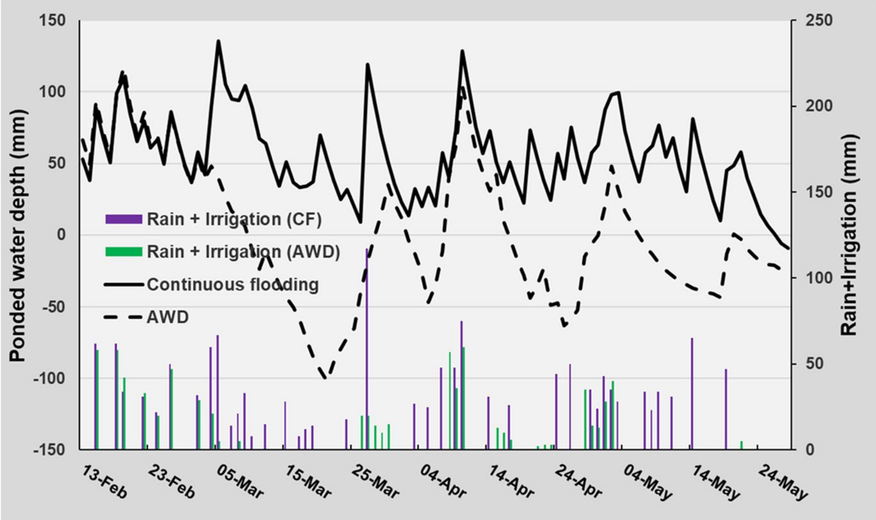


Fig. 3 Temporal variation of ponded water depth in continuous flooding and alternate wetting and drying irrigation methods and daily rainfall and irrigation applied to paddy during the crop growth period

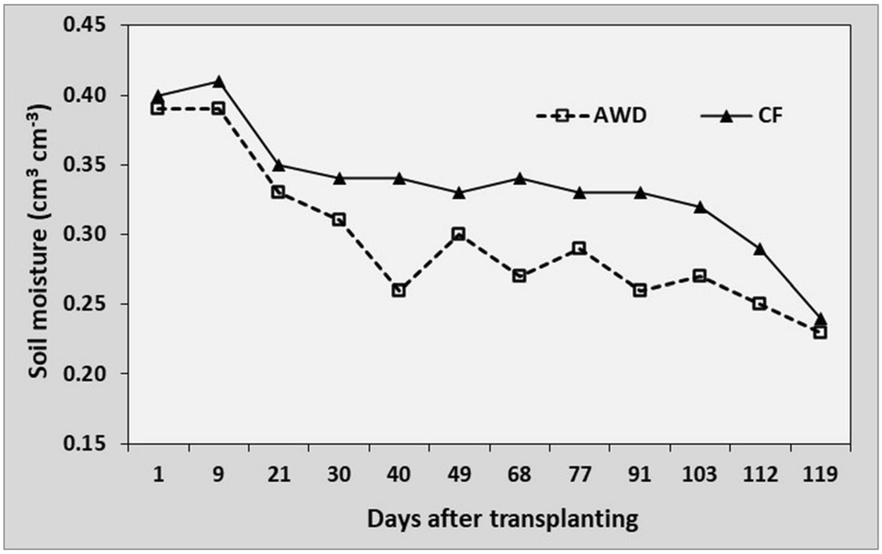


Fig. 4 Temporal variation of soil moisture content under continuous flooding and alternate wetting and drying irrigation managements

distribution of the surface soil under two water management treatments throughout the crop-growing period. At the initial stages of the crop growth, there was no difference of soil moisture for the two water management treatments. After 21 DAT, the soil moisture of AWD reduced continuously up to 46 DAT as compared to CF water management. After 100 DAT, the fields were not watered and the soil moisture under CF treatment reduced and at the harvest the surface soil moisture of both the treatments remained nearly similar. Under AWD water management treatment, 11.7% lower soil moisture was observed in the rhizosphere as compared to CF water management treatment during the total crop growth period. Variable rate of addition of nitrogenous fertilizer did not show any effect on the water storage in the rhizosphere.

Availability of soil P

Water management had a significant impact on the available P content of the soil, both when it was fresh and when it had been air-dried. Additionally, there were no discernible effects of adding fertilizer N on the amount of available P (Table 2). The available P content was higher in CF than in AWD for both fresh and air-dried soil. The average available P content in fresh AWD soil decreased by 20.9% compared to CF. Furthermore, there was a 10.2% decrease in the average available P content of air-dried soil. The available P content of the soil increased after air drying, with an increase of 8.4% for CF and 22.9% for AWD. The increment varied under the two water management regimes at seven sampling intervals, indicating that the P status of fresh soil could not be accurately represented using air-dried soil under different water management regimes.

During the drying cycle of AWD, soil samples were collected at 3 DDP and 5 DDP, and the available P content was measured for both fresh and dry soil. There was no significant difference in the available P content during these two drying periods when measured with dry soil samples. However, when the available P content was measured with fresh soil samples, a significant difference in the availability of P content was observed between these two drying periods. The available P content during 3 DDP was 7.68 mg kg^{-1}, while during 5 DDP it was 6.71 mg kg^{-1} (Fig. 5). Therefore, there was a 12.6% decline in the availability of P content due to the extension of the drying period.

Soil pH and MBP

The pH of the soil was not significantly affected either by the addition of N fertilizer or by water management. Overall, the pH of all treatments ranged from 5.87 to 5.92 across seven sampling intervals, indicating a low to intermediate acidity level.

Table 2 ANOVA table shows the variation of available phosphorus, microbial biomass phosphorus and ferrous iron under various irrigation and nitrogen managements

Parameters	Fresh soil-P (mg kg^{-1})	Dry soil-P (mg kg^{-1})	MBP (mg kg^{-1})	Ferrous-Fe (mg kg^{-1})
Irrigation				
CF	8.48	9.19	24.55	81.59
AWD	6.71	8.25	33.71	54.93
LSD for irrigation	0.33 ($p=0.000$)	0.41 ($p=0.004$)	0.94 ($p=0.0000$)	1.12 ($p=0.0000$)
N level (kg ha^{-1})				
0	7.69	8.83	26.78	68.24
90	7.59	8.71	28.61	68.45
120	7.55	8.72	29.95	68.35
150	7.54	8.64	31.18	68.99
LSD for N level	NS ($p=0.31$)	NS ($p=0.058$)	0.584 ($p=0.0000$)	NS ($p=0.68$)
Irrigation × N level				
CF × N0	8.58	9.43	23.43	81.71
CF × N90	8.48	9.18	24.25	81.63
CF × N120	8.45	9.16	25.00	81.45
CF × N150	8.48	9.02	25.53	81.58
AWD × N0	6.79	8.23	30.13	54.78
AWD × N90	6.72	8.23	32.95	55.28
AWD × N120	6.66	8.28	34.91	55.25
AWD × N150	6.68	8.25	36.83	54.41
LSD for irrigation × N level	NS ($p=0.99$)	0.27 ($p=0.02$)	1.02 ($p=0.0000$)	NS ($p=0.60$)

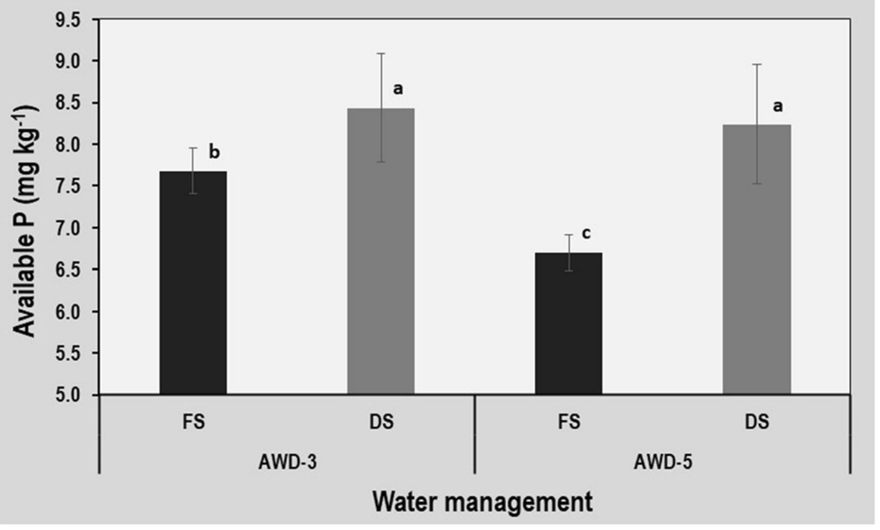


Fig. 5 Variation of available soil P in fresh and dry soil samples under various water management treatments. Note: FS, fresh soil; DS, dry soil; AWD-3, alternate wetting and drying at 3 DDP; AWD-5, alternate wetting and drying at 5 DDP. Error bars are the standard error; treatments with different alphabet indicate significant difference at $p<0.05$

Water management had a significant impact on the P content of the soil's microbial biomass during the seven sampling intervals. Moreover, the addition of N fertilizer also had a significant effect on the level of microbial biomass P (Table 2). Compared to CF, AWD increased the P content of the microbial biomass by 37.3%. Both CF and AWD water management regimes showed an increase in MBP with the addition of N fertilizer. Under CF, the MBP increased by 3.5% and 9.0% as N levels increased from 0 to 90 and 0 to 150 kg ha^{-1}, respectively. Similar increases were observed for the AWD water management system, with an increase of 9.4% and 22.2%, respectively.

The level of MBP varied significantly between different stages of the drying cycle under the AWD water management treatment. At 3 DDP, the MBP was 30.1 mg kg^{-1}, which increased to 33.7 mg kg^{-1} during 5 DDP (Fig. 6). Therefore, there was an 11.9% increase in MBP with an increase in the drying period from 3 to 5 days. The MBP was also measured during the same stages under the CF treatment, but no significant difference in the MBP level was observed.

Redox state of the soil as evidenced by iron content

The management of water had a significant impact on the soil's redox state. When comparing AWD treatments to CF treatments, the average total reductant content dropped by 13.1% (data not shown). The addition of N fertilizer had no noticeable effect on the total reductant content under both CF and AWD water management regimes. However, water management had a significant effect on the amount of soil ferrous iron. The average ferrous iron content in AWD treatments was 32.7% lower compared to CF treatments (Table 2). The addition of N fertilizer did not significantly affect the availability of ferrous iron.

Within the drying cycle of the AWD water management treatment, the ferrous iron content exhibited significant variation. At 3 DDP, the Fe^{2+} content was 77.4 mg kg^{-1}, but it decreased significantly to 54.9 mg kg^{-1} at 6 DDP (Fig. 7). Therefore, within a span of 2 days, there was a 29.1% decrease in the ferrous iron content in the paddy field.

Relationships between soil properties and soil water content

In AWD treatments, the soil water content showed a significant correlation with the levels of available P, MBP, and ferrous iron (Fig. 8). As the soil water content increased, the amounts of available P and ferrous iron also increased, while the amount of P in the microbial biomass decreased. However, there was no significant correlation observed between pH and soil water content. The available P content of the soil under AWD was not affected by other soil characteristics such as pH, MBP, and ferrous iron (Table 3). On the other hand, in CF treatments, there was a negative correlation between the amount of soil-available P and the amount of MBP, while a positive correlation was found between the amount of soil-available P and the amount of ferrous iron. In CF treatments, there was a negative correlation between soil MBP content and other soil properties, whereas a positive correlation was observed between soil MBP and available P under AWD treatment. This indicates that high reducibility leads to a reduction in microbial activity.

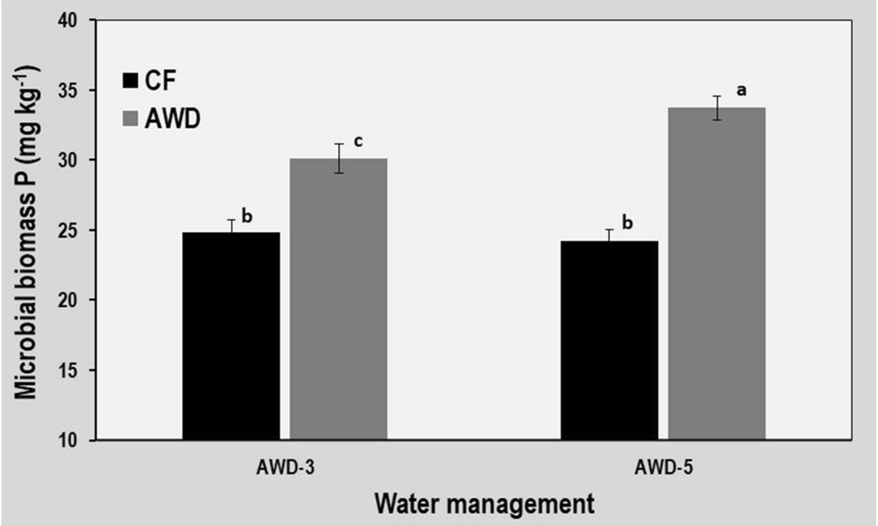
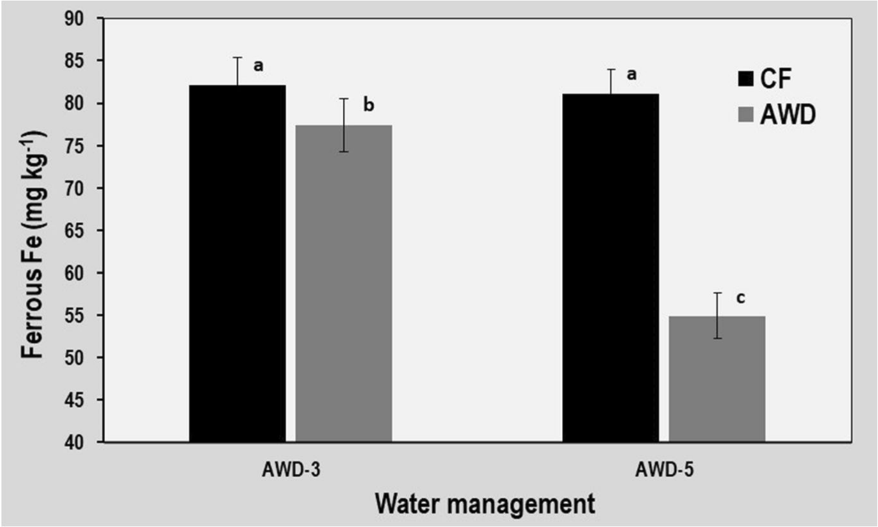


Fig. 6 Variation of soil microbial biomass P under continuous flooding and two alternate wetting and drying stages. Note: CF, continuous flooding; AWD-3, alternate wetting and drying at 3 DDP; AWD-5, alternate wetting and drying at 5 DDP. Error bars are the standard error; treatments with different alphabet indicate significant difference at $p < 0.05$

Fig. 7 Variation of ferrous iron content under continuous flooding and two alternate wetting and drying stages. Note: CF, continuous flooding; AWD-3, alternate wetting and drying at 3 DDP; AWD-5, alternate wetting and drying at 5 DDP. Error bars are the standard error; treatments with different alphabet indicate significant difference at $p < 0.05$



Discussion

With the exception of MBP content, the soil parameters in CF remained relatively stable over the sampling periods, while the parameters in AWD changed significantly over time (Table 2). This indicates that AWD has a greater impact on soil parameters compared to CF. Redox potential changes as a result of changes in soil water content (Sagi-Ben Moshe et al., 2012). Fe^{2+} content can more accurately characterize the soil redox status than Eh, which is challenging to measure by a potentiometer due to the different dryness of soil samples. AWD involves cycles of flooding and drying of the soil. When the soil is flooded, the lack of oxygen creates anaerobic conditions, leading to an increase in total reductants and ferrous iron content (Maranguit et al., 2017). On the other hand, during the drying period in AWD, the soil gradually transitions from anaerobic to aerobic conditions, resulting in a decrease in ferrous iron content.

We also observed that AWD decreased the available P content in the soil compared to CF, which can be attributed to the decrease in ferrous iron content and an increase in MBP (Table 2). The decrease in ferrous iron suggests the production of ferric ions, which can react with P to form insoluble ferric phosphate. Additionally, the reduction in soil reducibility during AWD may have promoted microbial activity, leading to increased retention of P by microorganisms. Our findings also showed that available P was negatively correlated with MBP and positively correlated with ferrous iron under AWD (Table 3). This suggests that water management practices can affect the availability of P in the soil through their influence on microbial activity and iron content.

The pH of the soil after flooding and drying was influenced by factors such as initial soil pH, organic matter content, cation exchange capacity, and the duration of the water management process. According to a predictive model developed by Ding et al. (2019), the pH of neutral-to-acidic soils initially decreased during the flooding period and then increased to around 7.0. However, our results do not align precisely with this pattern. In our study, all the treatments showed slightly acidic pH values. Changes in pH did not significantly impact the available P content in the soil within this acidic pH range (Wang et al., 2021). It is worth noting that the effects of water management on P availability can vary depending on soil type. Studies conducted on alkaline soil have shown different results, where AWD increased the available P content (Bagheri et al., 2021). This discrepancy is likely due to the different soil conditions and pH levels. Soil in the present study had a pH of 5.83, whereas their experiment's soil had an alkaline pH of 8.50. In acidic to neutral soils, iron-bound P (Fe–P) and aluminum-bound P (Al-P) predominate, while calcium-bound P (Ca-P) predominates in alkaline and calcareous soils (Aboulfazli et al., 2012).

We did not find a clear relationship between N fertilizer addition rates and soil P availability during the growing season. It might be as a result of lack of

Fig. 8 Relationships between soil water content and (**a**) available fresh P, **b** available dry P, **c** microbial biomass P, and (**d**) ferrous iron under AWD irrigation system

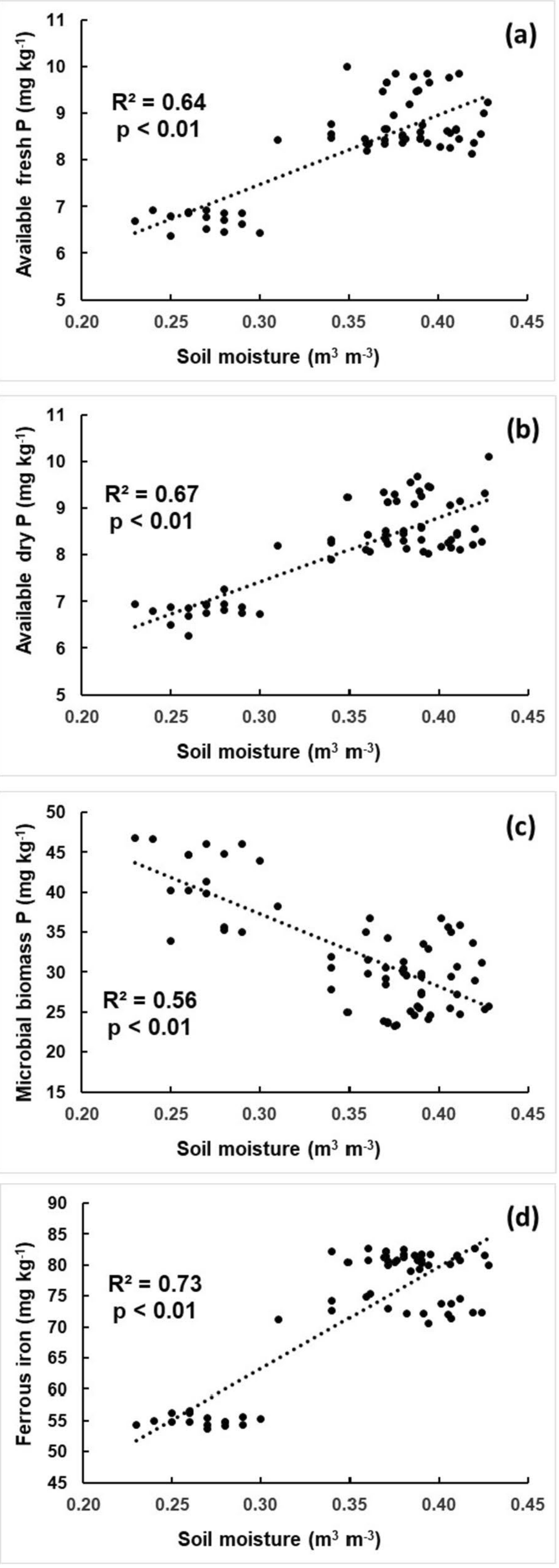


Table 3 Correlations between selected soil properties under continuous flooding (CF) and alternate wetting and drying (AWD) water management systems

Water management	Soil parameters	AWD			
		AP (Fresh)	AP (Dry)	MBP	Fe^{2+}
CF	Available P (fresh)		−0.322	−0.283	0.047
	Available P (dry)	0.311		0.212	0.026
	Microbial biomass P	−0.483*	−0.573*		0.019
	Fe^{2+}	−0.061	0.457*	−0.149	

antagonism between N and P. However, high N levels can promote root growth, organic matter decomposition, and microbial activity, which can indirectly influence P availability in the soil. Previous research has indicated that soil organic matter can reduce the sorption of P in multiple ways. It can form complexes with metal ions like iron (Earl et al., 1979), compete for P sorption sites, and modify the binding energy of adsorbed P (Fink et al., 2016). Another hypothesis proposed by Guppy et al. (2005) suggests that the increase in available P observed in sorption–desorption experiments might be due to the release of P from organophosphorus materials, rather than the competitive sorption sites of organic matter and P. Based on these findings, it is possible that in soils with high N addition rates, the availability of P could be significantly increased when microorganisms fully mineralize organic matter. However, when comparing the effects of nitrogenous fertilizers to water management, the changes in soil redox indicators (ferrous iron) caused by N addition were found to be insufficient. In order to substantially alter P availability, it may be necessary to dramatically change the soil's redox status, especially the concentration of ferrous iron, through N addition. Therefore, it can be inferred that N addition had no discernible impact on soil P availability under both water management systems.

After air drying under both water management systems, the available P content in fresh soil increased, which aligns with the findings of a previous study (Bagheri et al., 2021). However, the increase in available P varied between the two water management regimes at different sampling times. In our study, we also measured the microbial biomass P in air-dried soil, but most of the values were too low to be accurately quantified. Therefore, the observed increase in available P after soil air drying may be attributed to the death of soil microorganisms (Brookes et al., 1982). It is important to note that the increase in available P in air-dried soil could be limited by the possibility that mineralized P becomes partially fixed by soil clay and metal oxides once the microorganisms have died.

When soil water content drops from its water-holding capacity to air drying, the mineralization of organic P by phosphatase may have an impact on the availability of P in the soil. During this time, the conversion of Fe^{2+} to Fe^{3+} and an increase in the formation of insoluble phosphate may also have an impact on P availability. The availability of P is also influenced by changes in soil P sorption characteristics. This suggests that using air-dried soil to determine available P under different water management systems may not fully account for the variations observed.

Our study showed that AWD reduced the availability of P in paddy soil compared to CF. This differs from some studies that have reported increased rice production and P use efficiency under AWD. The lower water content and soil reducibility during the AWD drying period create conditions that promote root development and nutrient sorption in rice plants. Additionally, high concentrations of ferrous iron under CF can be detrimental to rice growth and grain yield (Fageria et al., 2008).

One limitation of our study is that we used different drying levels in the AWD treatment, which may have affected the consistency of soil parameter responses. Future research could consider collecting soil samples at the same drying level during each cycle to assess the variation in available P content. The complexity of the field soil environment, including the presence of oxygen and root exudates in paddy soil, adds further challenges to understanding these processes.

Strategies to increase P availability

AWD irrigation management reduces the water requirement of paddy by 17.4% over CF irrigation.

But it reduces the P availability to plants. To overcome this problem, different strategies can be adopted and depicted in Fig. 9. The strategies are discussed below:

P fertilization: To make up for the decreased P availability caused by AWD, more P-based fertilizers should be used. Based on the existing soil P levels and crop requirements, a soil test can be done to determine the proper amount of P fertilizer required. It is necessary to apply fertilizers containing easily accessible forms of P, such as superphosphate or diammonium phosphate, and the application rates must be modified correspondingly.

Organic matter amendments: To increase the availability of P in the soil, organic matter should be added. Apply organic amendments that can promote nutrient cycling and increase soil organic carbon content, such as compost manure. P is released more readily for plant sorption and is kept in the soil longer by organic matter.

P-solubilizing microorganisms: It will be beneficial to introduce these organisms to the paddy soil. By converting insoluble forms of P into soluble forms, these advantageous bacteria increase the availability of P to plants. To increase P solubility and uptake, utilize microbial inoculants or organic amendments that include these microorganisms.

P stabilizer addition: Adding P stabilizers in addition to fertilizer applications is an option. These items can assist in lowering P fixation and raising P availability in soil. In order to stop soil minerals from bonding with P and retain it in a soluble form for plant uptake, P stabilizers form complexes with them.

Soil pH adjustment: Adjusting the pH of the soil is necessary to keep it in the ideal range for P availability, which for paddy fields is usually between 6 and 7. Based on the recommendations of the soil test, appropriate amendments like lime or press mud can be utilized in acidic soils.

Crop residue management: Appropriate residue management techniques must be used to recycle nutrients from the previous crop, especially P. After harvest, crop leftovers are to be integrated into the soil to increase organic matter and nutrient cycling.

Water management modifications: The AWD procedures might be modified to increase P availability. Here are some changes to take into account:

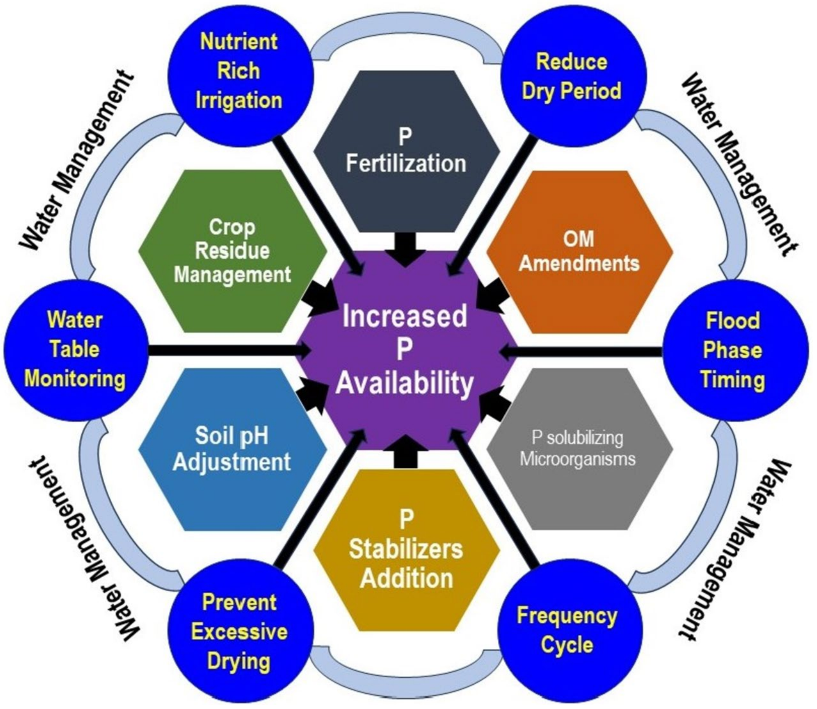


Fig. 9 Strategies to increase P availability in soils under AWD water management technique

Water management modifications: The AWD procedures might be modified to increase P availability. Here are some changes to take into account:

- Dry periods can be shortened during AWD to lessen the amount of P that becomes immobilized in the soil.
- The flooding phase to be timed to coincide with critical growth stages of the paddy crop when P demand is high.
- To encourage P release from organic matter and improve its availability to plants, the frequency of flooding and draining cycles to be enhanced.
- Prevent excessive drying, which can result in P fixation, by sensor-based soil moisture monitoring.
- Where there is a high capillary rise of water, irrigation can be planned by keeping an eye on the water table.
- Nutrient rich irrigation can be given to the paddy crop under AWD water management to compensate the reduction in P availability

It is important to note that reversing reduced soil P availability may take time, and it is crucial to monitor soil nutrient levels regularly to assess the effectiveness of the strategies employed.

Conclusions

The reduction in soil water content during AWD compromises soil reducibility and boosts microbial activity. These changes contribute to an increase in the fixation of soil P as microbial biomass P, resulting in a decrease in ferrous iron content and a reduction in the amount of available P. The addition of nitrogenous fertilizers at different rates does not significantly affect the availability of soil P during the crop-growing season. Thus, it is the water management strategy that has a significant impact on the availability of P in paddy soil. Regardless of the application of nitrogenous fertilizers, AWD consistently reduces the available P in the soil when compared to CF practices.

Author contribution Partha Pratim Adhikary: conceptualization, experimentation, data analysis, writing, reviewing, editing; Sheelabhadra Mohanty: experimentation, reviewing; Sachin Kanta Rautaray: reviewing; Narayanan Manikandan: experimentation, reviewing; Atmaram Mishra: supervision. All authors have read and agreed to the published version of the manuscript.

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Data availability The data presented in this study are available upon request from the corresponding author.

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Consent to participate Not applicable.

Conflict of interest The authors declare no conflict of interest.

Competing interests The authors declare no competing interests.

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