SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Dynamics of soil fertility and rice productivity in irrigated rice fields under different cropping patterns

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ARTICLE INFO

Keywords:
Nutrient dynamics
Superior varieties
Limiting factors
Water availability
Cultivation

Article history
Submitted: 2025-01-19
Revised: 2025-05-05
Accepted: 2025-05-26
Available online: 2025-06-23
Published regularly: June 2025

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ABSTRACT

Irrigated rice fields serve as the primary land for rice production. Whether continuous rice cultivation or alternating with secondary crops, the cropping pattern in these filelds depends on water supply. These differences in cropping patterns will affect the soil's nutrient dynamics and rice productivity. This research aims to analyze the soil fertility dynamics and rice productivity in irrigated rice fields under different cropping patterns. The study used an oversite design with two factors, namely cropping patterns (rice-rice-rice (R-R-R), rice-rice-corn (R-R-C), and rice-rice-soybean (R-R-S)), and superior varieties (Inpari 23 and Mentik wangi). The results showed that the overall fertility of irrigated rice fields was low, with crucial limiting factors being deficiencies in total N, available P, and K nutrients. Differences in cropping patterns on Inceptisol significantly affect available P. The R-R-R cropping pattern, including the Inpari 23 and Mentik wangi varieties, provided the highest productivity, reaching 6.5-6.9 t ha^{-1}. Selecting the right superior varieties and those by cropping patterns can increase the dry milled grain (MDG) yields by 23.52-30.1% compared to other superior varieties. Sufficient water availability throughout the growing phase can increase rice productivity by 33.3 -56.2% (1.5-2.3 times). Therefore, the key to intensive rice field management is not only to pay attention to soil fertility (nutrient dynamics), fertilization (organic and inorganic), and pest and disease control, but also to ensure the availability of sufficient water during cultivation and to use superior varieties. This research is beneficial for farmers, stakeholders, and the government in efforts to increase food security.

How to Cite: Muslim, R. Q., Suprihatin, A., Fatimah, A. S., Waluyo, Suparwoto, Jumakir, . . . Raharjo, B. (2025). Dynamics of soil fertility and rice productivity in irrigated rice fields under different cropping patterns. Sains Tanah Journal of Soil Science and Agroclimatology, 22(1), 179-190. https://doi.org/10.20961/stjssa.v22i1.98500

1. INTRODUCTION

Rice is a strategic commodity that serves as a staple food for populations worldwide, particularly in Asia and Africa. The average global rice consumption is 70 kg per person per year. Seven Asian countries - China, India, Bangladesh, Vietnam, Myanmar, Thailand, and Indonesia - together contribute more than 80% of the world's rice production (Bhatnagar & Khan, 2024; Zhang et al., 2021). As the primary source of food security, rice production and productivity will always be sought to increase to achieve food sovereignty.

Rice productivity is closely related to soil fertility (Wapongnungsang et al., 2021), which is influenced by soil properties, including the availability of nutrients and water. The availability of nutrients such as N, P, and K is critical to support optimal rice growth (Biswas et al., 2023). The water requirements of lowland rice crops are determined by several factors, such as water requirements for land preparation, during plant growth (evapotranspiration), percolation (infiltration), water layer replacement, and adequate rainfall (Arouna et al., 2023; Luo et al., 2022).

The use of new superior varieties (NSV) rice seeds and site-specific adaptive technologies is one of the most efficient and effective technologies that farmers can adopt (Arinta &

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v22i1.98500

Lubis, 2018; Sudaryono, 2017). The introduction of NSV, with the support of appropriate cultivation technology, can increase yields by 21-54% (Sirappa et al., 2007). Using NSV produces more tillers and longer panicles, leading to increased yield. In addition, NSVs offer resistance to specific pests and diseases, and their grain quality, including taste and texture, aligns with consumer preferences, making them highly desirable in the market (Maryana et al., 2022). Most farmers and consumers prefer for white rice colour, aroma, and fluffier taste (Surdianto et al., 2021).

Irrigated rice fields are prime land for rice production. In irrigated rice fields, water availability strongly influences cropping patterns. Rice fields with a consistent water supply year-round typically follow a rice-rice-rice cropping pattern, whereas fields lacking sufficient water during the dry season tend to adopt a rice-rice-*palawija* (corn or soybean) cropping pattern. Water availability is a factor that greatly influences the success of rice cultivation. Therefore, irrigation systems must respond to farmers' needs, supply and demand must be in line, minimizing water loss, and cropping patterns must be more responsive (FAO, 2007). Pratama and Masitoh (2023) state that optimizing cropping patterns is very important to obtain appropriate planting patterns and optimally utilize water availability.

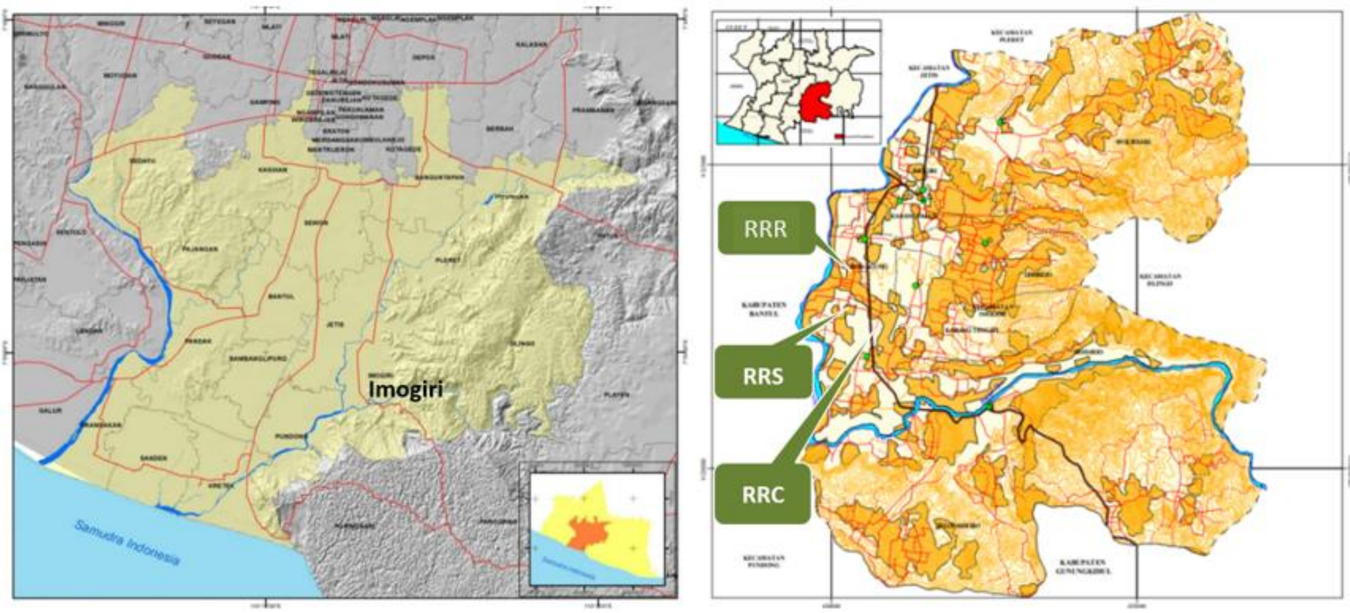
Rice intercropping with *palawija* involves reduction and oxidation processes because the field is flooded when rice is planted and then dried when *palawija* is planted. The alternation of aerobic and anaerobic conditions in rice fields is an effective natural control that regulates the biological and non-biological balance so that the soil becomes healthy and remains productive. These differences in cropping patterns will impact the soil's nutrient dynamics and rice productivity. Research by Reddy YR et al. (2022) also demonstrated that different cropping sequences, irrigation levels, and fertilizer applications can significantly influence soil fertility. Proper crop rotation and irrigation practices were shown to enhance soil nutrient content, increase productivity, and optimize irrigation water use. This study aims to analyze soil fertility dynamics and rice productivity in irrigated rice fields under different cropping patterns. Research involving cropping patterns in paddy fields remains limited, making the findings of this study a valuable contribution to understanding soil fertility dynamics and rice productivity under different cropping patterns.

2. MATERIAL AND METHODS

2.1. Research Location

The research was conducted from November 2022 to February 2023 in irrigated rice fields in Sriharjo Village, Bantul Regency, Special Region of Yogyakarta. The source of irrigation comes from the Canden Kiri dam, the Opak River. The study used an oversite design, with two factors and three replications. Factors tested: 1) Cropping patterns, there are three cropping patterns: rice-rice-rice (R-R-R) in Kebon Agung Hamlet 7°55'58.1"S, 110°22'17.8"E with an altitude of 90 m asl, rice-rice-corn (R-R-C) in Demen Hamlet 7°56'27. 5"S, 110°22'31.3"E at an altitude of 90 m asl, and rice-rice-soybean (R-R-S) in Miri Hamlet 7°56'17.3"S, 110°22'16.3"E at an altitude of 102.55 m asl (Fig. 1), and 2) superior varieties, namely Inpari 23 (NSV) and Mentik wangi (local superior varieties).

The average annual rainfall in Bantul Regency for 10 years is 1,613 mm yr^{-1}, with a maximum rainfall of 321.5 mm in February. The lowest rainfall was 0 mm in August (Fig. 2). The average wet month was 5.7 months, the average humid month was 0.6 months, and the average dry month was 5.8 months. The average monthly temperature was about 26.1°C.



Remarks: Bantul Regency Administrative Map (left) (RBI Digital Map scale 1:25.000, Bantul Sheet, 1999), Imogiri Regency (right) (RBI Digital Map scale 1:25.000, Imogiri Sheet, 1999)

Figure 1. Location of rice-rice-rice (R-R-R), rice-rice-corn (R-R-C), and rice-rice-soybean (R-R-S) land areas in Sriharjo Sub-district, Imogiri District, Bantul – D.I Yogyakarta

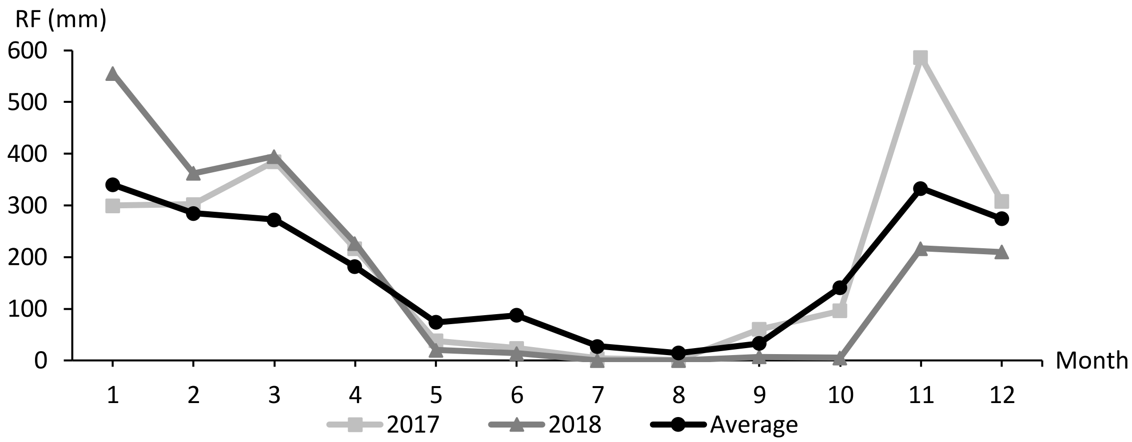


Figure 2. Average rainfall in the study area

Table 1. Existing farmers' technology for irrigated rice fields at the study location

No.	Component	Existing farmers' technology
1	Varieties	Using superior varieties that are in demand by farmers and consumers (Inpari 23 and Mentik wangi)
2	Seeds	Quality seeds with high germination power (by soaking the seeds in a 0.2% salt solution and then removing the floating seeds). Using young seeds (< 14 days after germination)
3	Number of seeds	1-2 stems per hole
4	Fertilization	N, P, and K fertilizers as basic fertilizers, each as much as 100 kg Urea ha^{-1}, and 300 kg NPK Phonska ha^{-1}. Urea as a follow-up fertilizer at of 35, and 45 DAP, each as much as 25 kg Urea ha^{-1}.
5	Organic matter	The remaining plant litter from the previous season's crop is buried in the ground with a tractor.
6	Irrigation	from *Canden Kiri* Dam, Opak River, always flooded or depending on irrigation water availability.
7	Weed	Mechanically, using a *gasrok* tool twice, muddy soil conditions at 15 and 40 DAP
8	Pests dan Diseases	According to the farmer's ability, the pests that frequently appear during the research are golden snails, controlled manually by collecting snails in the field and installing bamboo sticks as a place for golden snail eggs to stick to, so that it is easier to destroy golden snail eggs to stop the development of golden snails
9	Harvest	Manually using a sickle and fell out using an oil-fueled thresher

2.2. Rice Cultivation Technology

The research was carried out when entering Planting Season (PS) I (rainy season (RS) in 2022), R-R-R field was carried out after the rice harvest in PS III (dry season (DS) in 2021), while R-R-S and R-R-C fields were carried out after the soybean and corn harvests in PS III. The rice crop management follows the existing farmer's technology (Table 1). The distance between rows and plants in the rows of the rice plants used a tile planting system (20 × 20 cm). The experimental plot size used was approximately >300 m^2 per plot.

2.3. Soil and Plant Analysis

Soil sampling was taken at five points per treatment plot, taken six times, namely before tillage (initial soil), and at each phase of plant growth (<14 DAP, tillering, primordial, grain filling, and harvest). Soil analysis included soil physical properties (texture and soil moisture content) and soil chemical properties (pH, organic C, CEC, BS, total N, available P, and available K). Dry milled grain (MDG) samples were taken in 2.5 m x 2.5 m tiles in each experimental plot.

2.4. Data Analysis

The data obtained were analyzed using analysis of variance (ANOVA) and continued with the Honestly Significant Differences (HSD) test at 5%, to compare the effect of each treatment. Correlation analysis is used to see the closeness of the relationship between the parameters analyzed. Data analysis was performed using SAS 9.1.3. Portable.

3. RESULTS

3.1. Nutrient Dynamics in Irrigated Rice Fields Under Different Cropping Patterns

The geomorphological unit of Imogiri District is included in the fluvial plain, which result from the sedimentation process of alluvial material from the Opak River (West) and the Oyo River (East). As a result, the soil type in the area is dominated by Inceptisols (Aziez, 2017; Romdhoni et al., 2023). The R-R-C and R-R-R fields have a loam texture with the distribution of sand, silt, and clay being 31.15-33.47%, 41.58-44.43%, and 24.43-24.95%, respectively. The R-R-S field has a clay loam texture with sand, silt, and clay distribution of 37.82%, 33.16%, and 29.02%, respectively (Fig. 3).

Table 2. The chemical properties of irrigated soil conditions under different cropping patterns

Parameter	Unit	Cropping pattern		
		R-R-R	R-R-C	R-R-S
pH		5.71 sa	6.09 sa	6.19 sa
SOC	g 100^{-1} g^{-1}	1.44 l	1.10 l	1.28 l
CEC	c mol (+) g^{-1}	63.93 vh	53.55 vh	64.90 vh
BS		16 l	24 l	23 l
Total N	g 100^{-1} g^{-1}	0.06 vl	0.21 vl	0.12 vl
Available P	mg kg^{-1}	24.36 m	33.06 h	17.91 m
Available K	c mol (+) g^{-1}	0.02 vl	0.02 vl	0.02 vl

Remarks: R-R-R=rice-rice-rice, R-R-C=rice-rice-corn, R-R-S=rice-rice-soybean, CEC=cation exchange capacity, BS=base saturation, sa=slight acid, l=low, vh=very high, vl=very low, m=moderate; soil criteria follow Eviati et al. (2023)

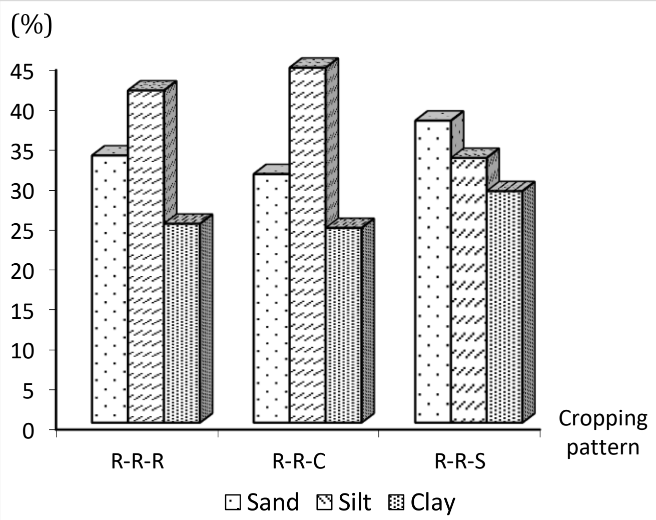
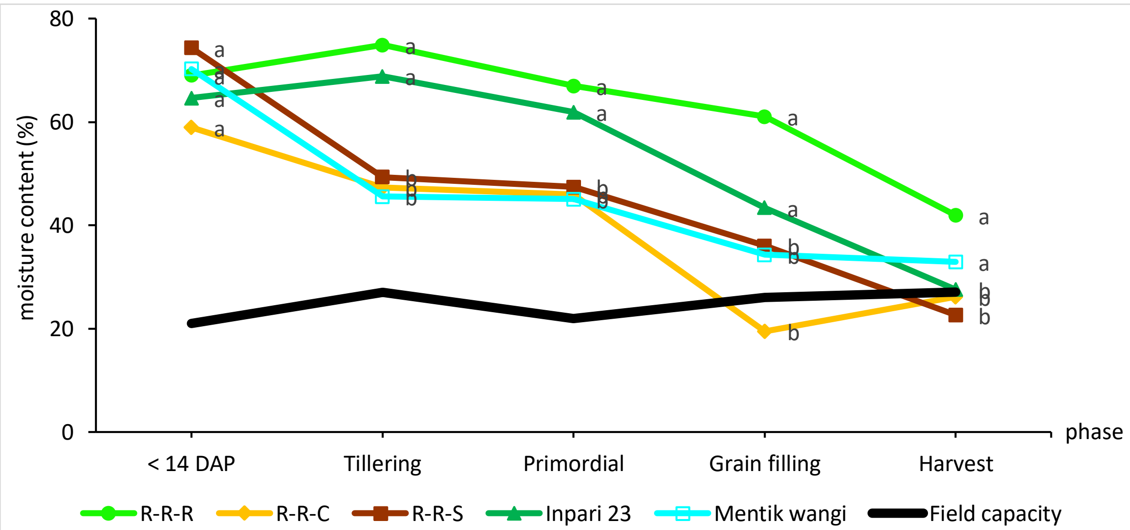


Figure 3. Distribution of sand, silt and clay fraction on irrigated rice soil under different cropping patterns

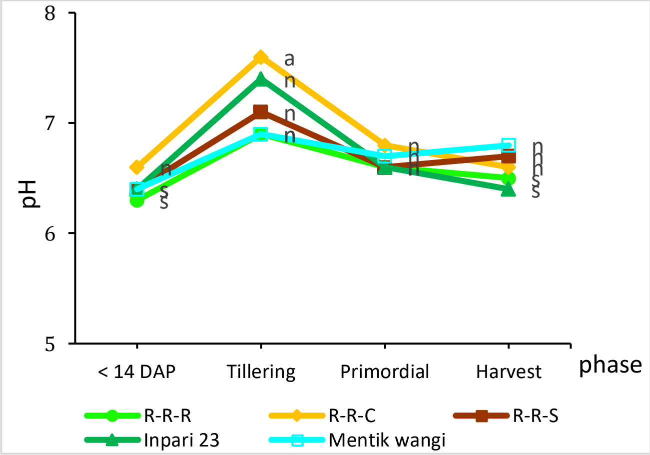
Irrigated rice fields with different planting patterns have almost the same distribution of chemical properties, except for the available P nutrient content. These paddy fields have slightly acidic soil pH, low organic matter content and BS value, and very low total N and available K contents, but have very high CEC values (Table 2). Based on Figure 4, the condition of the length of field capacity in irrigated rice fields is 20-30%.

The pH dynamics of irrigated paddy soils under different cropping patterns have the same trend during the plant growth phase (Fig. 5), namely in the early growth phase (<14 DAP), irrigated paddy soils have a slightly acidic pH, and experienced an increase in pH during the active tillering phase, which became neutral in R-R-R and R-R-S fields, even alkaline in R-R-C fields. However, when entering the primordial phase, the pH of the irrigated rice field soil tends to decrease, especially in the R-R-C field, while the R-R-R and R-R-S fields and the Inpari 23 and Mentik wangi varieties have a more stable pH in the neutral. The pH of the irrigated rice field soil continues to decrease until harvest at a slightly acid pH condition for R-R-R and R-R-C fields and planting Inpari 23, while for R-R-S field and planting Mentik wangi varieties is more incommutable at neutral pH conditions.

The dynamics of soil organic C (SOC) levels in irrigated rice fields also showed almost the same trend as soil pH. During the early growth phase (<14 DAP), SOC levels were low in the range of 1.34-1.43%, then there was a very significant increase when entering the tillering phase (± 25 DAP) even to moderate in R-R-R and R-R-S fields and when planting Mentik wangi varieties in the range of 2.49-2.57%. However, there was a decrease to low SOC levels when entering the primordial phase, and a tendency to increase when entering the harvesting phase, although it was still in the range of low SOC levels in all cropping patterns and planting of Mentik wangi (Fig. 6).



Remarks: the dots followed by different letters indicate a significant difference (HSD, α = 0.05)
Figure 4. Soil moisture conditions on irrigated rice fields during the plant growth phase



Remarks: a=alkaline, n=neutral, s=slight acid
Figure 5. Dynamics of soil pH in irrigated rice fields during the plant growth phase

The highest levels of available P nutrients in the soil were found in irrigated rice fields with the R-R-C cropping pattern, which were around 17.790-18.905 g P_2O_5 kg^{-1} (moderate), followed by the R-R-S field of 14,266-14,881 g P_2O_5 kg^{-1} (low), and the lowest content in the R-R-R field of 1,755-7,439 g P_2O_5 kg^{-1} (very low) (Fig. 7). Table 3 shows that the total amount of available K nutrients in the soil of irrigated rice fields at harvest time increases by 5-8 times (565-827%) compared to the conditions during early growth phase (<14 DAP).

3.2. Irrigated Rice Productivity Under Different Cropping Patterns

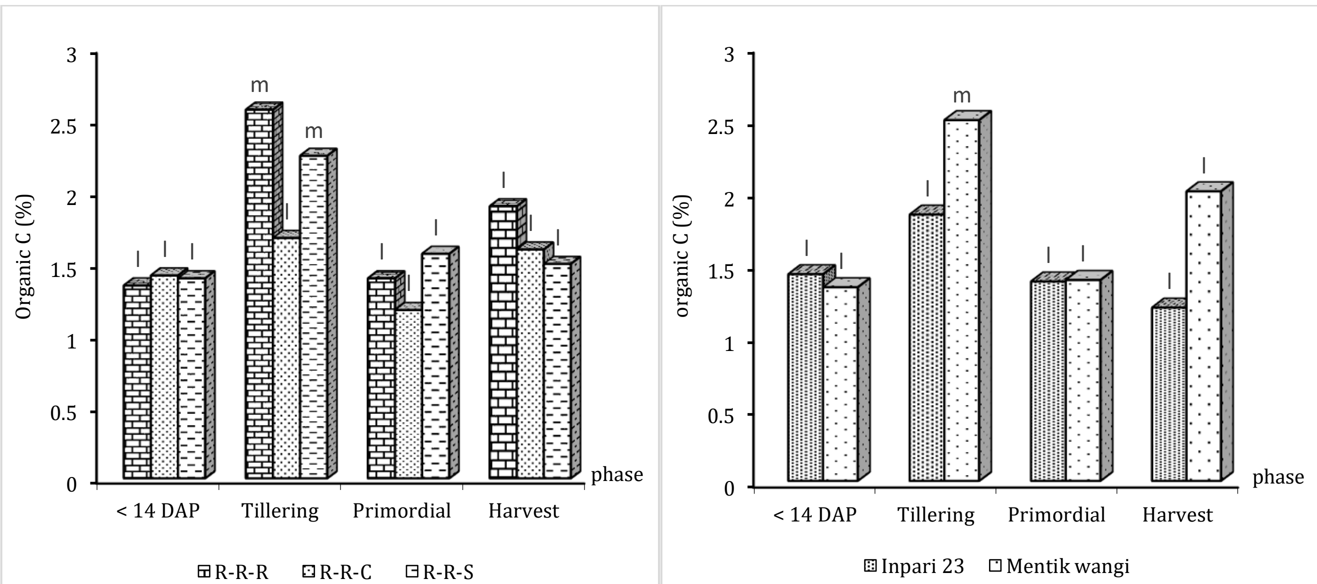
Table 4 shows that the cropping pattern and the use of superior varieties significantly interact with the level of MDG rice yields in irrigated rice fields. The highest MDG results were obtained in the R-R-R field using both Inpari 23 and Mentik wangi varieties, reaching 6.93 and 6.53 t ha^{-1}, respectively. The lowest MDG results were obtained in the R-R-C field. This shows that sufficient water during the growth phase of rice plants in the R-R-R field can increase rice productivity by 33.3-56.2% (1.5-2.3 times) compared to the R-R-C and R-R-S fields.

Table 5 shows some of the observed soil parameters and crop production that are very significantly positively and negatively correlated, namely in the early growth phase (<14 DAP), primordial, grain filling, and harvest. The sand and clay fractions are very significantly negatively correlated with the silt fraction, with R values of -0.99452 and -0.99003, respectively. The sand fraction is very significantly positively correlated with the clay fraction, with R=0.96989. The distribution of sand, silt, and clay fractions is correlated with 1) base saturation during early growth phase (<14 DAP), 2) available P during early growth phase (<14 DAP) and harvest, 3) soil moisture content during primordial, grain filling and harvest phases, and 4) MDG.

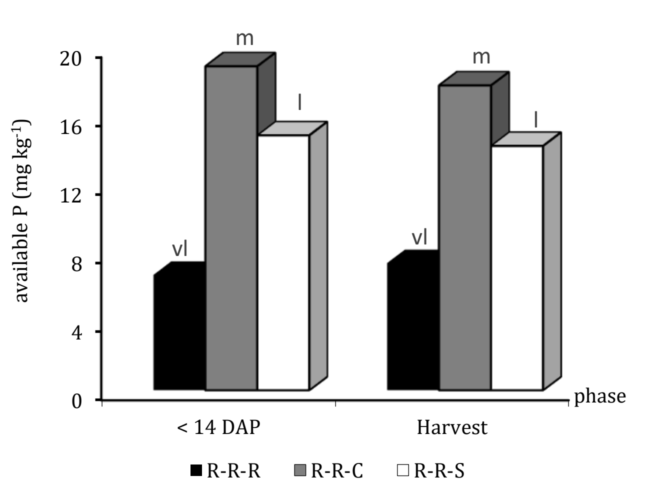
Total N content in the early growth phase (14 DAP) had a very significant, strong positive correlation with pH and base saturation, but a very significant, strong negative correlation with SOC and a very significant, strong positive correlation with available P at harvest. This shows that the higher total N content in the early growth phase (<14 DAP) is followed by an increase in pH, base saturation, during early growth (<14 DAP), and available P at harvest, but SOC content in the early growth phase (<14 DAP) decreases. Similarly, base saturation during early growth (<14 DAP) is also very significantly negatively correlated with SOC during early growth (<14 DAP). Soil available K at harvest was very significantly positively strongly correlated with pH and SOC (Table 5).

The MDG yield in irrigated rice fields is very significantly positively strongly correlated with sand and clay fractions, but very significantly negatively strongly correlated with silt fractions (Table 5).

Available P parameters during early growth (<14 DAP) and at harvest were very significantly negatively correlated with MDG (Table 5).



Remarks: m=moderate, l=low
Figure 6. Soil organic C dynamics of irrigated rice fields under different cropping patterns (left) and superior varieties used (right)



Remarks: m=moderate, l=low, vl=very low

Figure 7. Available P on irrigated rice fields under different cropping patterns

Table 3. Available K in irrigated paddy fields under different cropping patterns

Treatment		Available K (c mol (+) kg-)	
		Phase	
		< 14 DAP	Harvest
Cropping patterns:	R-R-R	0.016 vl	7.318 vh
	R-R-C	0.016 vl	6.514 vh
	R-R-S	0.018 vl	7.048 vh
Varieties:	Inpari 23	0.020 vl	5.653 vh
	Mentik wangi	0.010 vl	8.267 vh

Remarks: DAP=day after planting, R-R-R=rice-rice-rice, R-R-C=rice-rice-corn, R-R-S=rice-rice-soybean, vl=very low, vh=very high; soil criteria follow Eviati et al. (2023)

4. DISCUSSION

Irrigated rice fields in the study area had inadequate soil fertility (BS <35%), with total N, available P, and K soil nutrients being the main limiting factors. Irrigated rice fields with R-R-R and R-R-S cropping patterns have moderate soil available P levels, whereas R-R-C fields have high available P levels (Table 2). This may be related to the distribution of clay and silt fractions in the R-R-R and R-R-S fields, which have a higher percentage than the R-R-C fields. High-clay soils have more fine particles holding water and nutrients than sandy or low-clay soils (Dou et al., 2016). Therefore the soil is not easily infiltrated or permeable to water and has a high bulk density (Surya et al., 2017). The loam soil texture in the study area has a sequence distribution of sand, silt , and clay fractions in the range of 23-53%, 28-50%, and 8-28% respectively. Meanwhile, the clay loam soil texture has sequence a distribution of sand, silt , and clay fractions in the range of 20-45%, 15-53%, and 28-40% respectively (Eviati et al., 2023). Loam and clay loam textured soil has poor permeability (class 4) (Othmani et al., 2023). This shows that irrigated rice field soils have low drainage and porosity (Eviati et al., 2023; Othmani et al., 2023). The correlation between MDG and soil texture (Table 5) indicates that the distribution of soil fractions affects rice productivity in irrigated rice fields, and the higher the sand and clay fractions in the topsoil layer, the higher the rice productivity.

The soil water holding capacity is influenced by soil texture, aggregation, organic matter content, and overall soil structure (Rai et al., 2017). The soil moisture content of irrigated rice fields is always above the soil moisture content of its field capacity during the plant growth phase, except during the grain filling phase in the R-R-C field and harvest in the R-R-S field. The soil moisture content of irrigated rice fields during grain filling is most significant and has a strong positive correlation with MDG. Meanwhile, in the harvest phase, the soil moisture content is very real and has a strong negative correlation with MDG (Table 5). This shows that the higher the soil moisture content of irrigated rice fields during the grain filling phase, the higher the rice productivity will be, but excessive water availability at harvest time may reduce rice productivity in irrigated rice fields. Dry soil conditions can accelerate the rice grain filling rate compared to well-irrigated soils (Li et al., 2016). Soil drying during the rice grain filling phase can promote root growth, leading to optimal nutrient uptake, accumulating soluble carbohydrates, and promoting rapid remobilization of these assimilates into grains (Maneepitak et al., 2019).

Flooding of rice fields from the beginning of planting can increase the soil pH after 1 month, i.e. during the active tillering phase (± 25 DAP) in R-R-R and R-R-S fields, while in R-R-C fields there was an increase in pH after 14 DAP, i.e., the soil pH became neutral. The findings of Ding et al. (2019) showed that the inundation process in paddy fields can increase the pH of acidic soils to near neutral, and conversely, the pH of alkaline soils will decrease to near neutral. Soil pH decreased from the primordial phase to harvest. The decrease in soil pH in the early growth phase (<14 DAP), primordial, and harvest is probably also related to the timing of N fertilizer application, which was given at the beginning (basal fertilizer) and continued with additional fertilizer given after active seedlings at 35 and 45 DAP. This aligns with the findings of Zhou et al. (2014) and Ghimire et al. (2017), who stated that N fertilization generally decreases soil pH. The primary mechanism of soil pH reduction due to nitrogen fertilization is the NH_4^+ nitrification process, which produces hydrogen ions (H^+) as ammonium (NH_4^+) is converted to nitrate (NO_3^-), thereby lowering the soil pH (Guo et al., 2010; Zhou et al., 2014).

Table 4. Yields of milled dry grain from irrigated rice fields under different cropping patterns

Treatment	Milled dry grain (t ha-1)		
	Inpari 23	Mentik wangi	Average
R-R-R	6.93 a	6.53 a	6.73
R-R-C	3.47 bc	2.43 c	2.95
R-R-S	3.89 bc	5.09 ab	4.49
Average	4.76	4.68	(+)

Remarks: R-R-R=rice-rice-rice, R-R-C=rice-rice-corn, R-R-S=rice-rice-soybean, (+)=significant interaction, the means followed by different letters indicate a significant difference (HSD, α = 0.05)

Table 5. Result of correlation analysis between parameters observed

Parameter	initial analysis			Plant growth phase < 14 DAP			
	Sand	Silt	Clay	pH	BS	SOC	av P
Initial:							
- Sand		-0.99452**	0.96989**	ns	-0.58543*	ns	-0.66223**
- Silt			-0.99003**	ns	0.60907**	ns	0.70626**
- Clay				-0.47586*	-0.63036**	ns	-0.75333**
< 14 DAP:							
- Total N	ns	0.48675*	-0.56541*	0.61313**	0.622**	-0.61309**	0.47334*
- SOC				0.47699*	-0.64435**		ns
Harvest:							
- MDG	0.62802**	-0.68793**	0.7567**	-0.52427*	ns	ns	-0.73645**

Parameter	Plant growth phase: Primordial	Grain filling	Harvest			
	SMC	SMC	SMC	av P	pH	SOC
Initial:						
- Sand	0.59642**	0.51870*	0.59816**	-0.56431*	ns	ns
- Silt	-0.62033**	-0.57813*	-0.60328**	0.60272**	ns	ns
- Clay	0.64178**	0.64816**	0.59971**	-0.64400**	ns	ns
< 14 DAP:						
- Total N	ns	-0.48005*	ns	0.67744**	ns	ns
Harvest:						
- av K	ns	ns	ns	ns	0.60139**	0.61701**
- MDG	ns	0.63669**	-0.63639**	ns	ns	ns

Remarks: **=very significant, *=significant, ns=not significant, DAP=day after planting, av P=available P, BS=base saturation, SMC=soil moisture content, av K=available K, MDG=milled dry grain

In addition, oxidation microbes in rice fields, which oxidizes urea compounds, contribute to acid formation (Zhou et al., 2014).

The presence of SOC in irrigated rice fields in the early growth phase is due to grass growing in the rice fields and the return of crop residues from the previous crop season, which are buried/turned during soil cultivation using a two-wheeled tractor. The results of the research of Jin et al. (2020) stated that returning straw to the land can increase organic matter content, soil quality, and annual crop yields, added by Yan et al. (2020) stated that labile organic carbon, particulate organic carbon, dissolved organic carbon, and microbial biomass carbon which affect improving the physical and chemical properties of the soil.

As the crop enters the tillers stage, the SOC content rises across all crop patterns and the use of superior varieties, both Mentik wangi and Inpari 23 (Fig. 6). This is thought to be related to a very significant increase in the number of tillers compared to early growth. The higher the number of shoots in the rice plant, the greater the root volume, which will have an effect on increasing root activity and various processes in the root area. The increase in SOC in the R-R-C field was not as significant as in the R-R-R and R-R-S fields. This may be due to the fewer number of tillers in the R-R-C field compared to the R-R-R and R-R-S fields.

At the tillering phase, there was an increase in SOC content when the Mentik wangi varieties were planted, which was very significantly higher than Inpari 23 (Fig. 6). This is thought to be related to the higher number of tillers in Mentik wangi compared to Inpari 23. Several research results show that Mentik wangi has more tillers than Inpari 23. The number of tillers in Mentik wangi is about 9 tillers (Qoni'ah et al., 2021), 10 (Pratiwi et al., 2018), 11 (Yunus et al., 2018), 15-16 (Hakim, 2021), 19 (Faisal et al., 2024), 20-21 (Kristamtini et al., 2011), even up to 29 tillers (Syafrullah, 2019). While Inpari 23 has about 3 tillers (Dewi et al., 2021), 5 (Nugroho et al., 2021), 6 (Pratiwi et al., 2018), 9 (Agustiani et al., 2018), 10 (Susanto et al., 2017), 11 (Wibawa & Sugandi, 2017), 16 (Sutaryo & Pramono, 2016), dan 17-18 (Chairunnisak et al., 2018; Marzuki et al., 2016). The very significant increase in SOC when the Mentik wangi varieties were planted can be attributed to increased root activity and rhizodeposition, which increased microbial biomass (Jones et al., 2004) much more than in Inpari 23. Rhizodeposition is the process by which organic compounds from plant roots are released into the soil (e.g., root exudates, loss of root caps and marginal cells, and mucilage, Jones et al. (2009). Rhizodeposition significantly affects microbial activity and enhances SOC decomposition, referred to as the rhizosphere priming effect (RPE) (Huo et al., 2017; Kuzyakov, 2002, 2010). Therefore, rhizodeposition directly contributes to SOC formation (Sokol et al., 2019; van Hees et al., 2003), reaching 15% of SOC allocation, which is influenced by plant species and environmental conditions (Pausch & Kuzyakov, 2018). Soil microbes utilize rhizodeposition through in vivo microbial pathways for SOC formation (Islam et al., 2022; Liang et al., 2017; Sokol & Bradford, 2019).

The subsequent decline in SOC on entry into the primordial phase is thought to be related to microorganisms' decomposition of organic matter. At this time, increased microbial activity could be due to the addition of urea fertilizer at 45 HST (Table 1) and reduced carbon input. During the harvesting phase, there was a tendency for SOC levels to increase in all cropping patterns. This is thought to be related to the contribution of crop residues and some dead seedlings.

SOC levels tend to increase during harvest phase, when planting the Mentik wangi varieties. This is likely related to the greater number of productive tillers in Mentik wangi compared to Inpari 23, and a reduction in the number of tillers as the harvesting phase approaches. Reducing the number of tillers will contribute organic matter to irrigated rice fields as the tillers die and decompose, increasing the SOC content at harvest. The study's results by Yin et al. (2025) stated that during the plant life cycle, root litter and rhizodeposition have an efficiency of plant carbon incorporation into SOC of 10 and 12 times that of shoot litter, respectively. Therefore, root litter plays an important role in forming new SOC, although its amount is minimal compared to shoot litter.

The application of NPK fertilizer does not increase the levels of available P in irrigated rice fields from the early growth of plants to harvest. This shows that the supply of NPK fertilizer to meet the soil P nutrient needs of rice plants in irrigated rice fields is very effective for growing and producting of rice plants, especially in R-R-R fields, as evidenced by the highest productivity obtained in these fields. The status of availability of available P nutrients in each irrigated rice field (Fig. 7) is closely related to the soil pH in each irrigated rice field (Fig. 5). These results show that the higher the soil pH, the higher the available P content of irrigated rice field soils up to a neutral pH of 6.6, with moderate criteria. However, once the soil pH reaches a value of 6.7, the available P content of irrigated rice field soils drops to low levels. This align with the conclusion of Barrow (2017), and Penn and Camberato (2019), who stated that the increase in soil available P is consistent with the increase in soil pH approaching neutral, which has become a general guideline.

The results of the study by Adhikary et al. (2023) showed that P availability was not affected by N fertilization, but intermittent irrigation practices accompanied by N fertilization in rice fields could increase soil microbial biomass. Increased microbial activity causes P retention by microorganisms, reducing soil available P. Therefore, there is no need to apply P fertilizer for the next planting season, but it is necessary to add organic fertilizer such as manure, compost, or other organic materials to increase the productivity of rice and irrigated rice fields.

The content of residual K nutrients in the soil is very high, reaching 5,653-8,267 cmol (+) kg^{-1}. If this condition continues by returning the rest of the rice crop in the form of straw and composting it directly on the rice field until it is finally buried in the soil with a tractor, it will provide K nutrients for the next planting season. The study by Zhang et al. (2021) demonstrates that incorporating straw into the soil can enhance potassium (K) availability in the short and long term while contributing to the soil's ability to sustain potassium supply for crops. At the harvest phase, the Mentik wangi varieties resulted in higher available K than Inpari 23 (Table 3). According to the correlation in Table 5, available K is strongly associated with pH and SOC. The Mentik wangi varieties exhibited higher pH and SOC values, which likely enhanced K solubility, thereby increasing available K. A similar trend was observed in the cropping pattern treatments, where the R-R-C field had lower available K than R-R-R and R-R-S fields. Based on pH trends during the growth phases, the R-R-C field experienced the most significant pH decline from the tillering to harvest phase, which is suspected to have reduced the availability of base cations, including K.

Planting the superior Mentik wangi variety in the R-R-S field can increase MDG rice productivity by 1.31 times compared to Inpari 23, or an increase of 23.52%. On the other hand, using Inpari 23 in the R-R-C field can increase rice productivity by 30.1%. The introduction of NSV, with the support of appropriate cultivation technology, can increase yields by 21-54% (Sirappa et al., 2007). The Mentik wangi variety is resistant to blast disease, and in conditions of blast disease outbreaks, planting the Mentik wangi variety is more profitable than planting the Mekongga varieties (Yulianto, 2017). Inpari 23 is resistant to pests and diseases (such as brown planthopper, bacterial leaf blight pathotype III), moderately resistant to pathotype IV and susceptible to pathotype VIII (Nugroho et al., 2021). Rice productivity in irrigated rice fields under different cropping patterns and using superior rice varieties can still be increased through improved rice cultivation technology, namely ICM (Integrated Crop Management). However, Inpari 23 and Mentik Wangi have the same productivity in the R-R-R field, but Inpari 23 tends to be more productive than Mentik Wangi when planted in the R-R-C field. In contrast, the productivity of Mentik Wangi is generally higher than that of Inpari 23. The results of the data measurements indicate that an important influencing factor is related to the dynamics of soil moisture in each cropping pattern. Soil moisture in R-R-R fields consistently maintains the highest moisture content from early growth to harvest. This indicates that the water requirements of the rice plants can be adequately met in the R-R-R field. Conversely, soil moisture conditions in the R-R-S field fall below the field's capacity during the harvest phase, resulting in unmet water demand as harvest approaches, which reduces production compared to the R-R-R field. In addition, soil moisture conditions in Inpari 23 consistently exceed those in Mentik Wangi, except during the harvest period.

These differences in productivity can be attributed to both technical and non-technical factors. Technical factors related to the ability and consistency of cooperating farmers in applying PTT technology to irrigated rice fields, particularly during the crop management phases (such as pest management and water regulation) from initial growth to harvest. Non-technical factors relate to the dynamics of soil properties (including physical and chemical parameters) in each field. Previous research conducted by Xu et al. (2023) demonstrated that variations in cultivation patterns significantly affect the physicochemical properties and paddy soil microbial diversity at different depths. The results of the study Wang et al. (2023) concluded that the application of rice and legumes cropping pattern gives better results compared to the continuous planting of the same type of crop. An effective soil management practice is a cropping pattern that enhances microbial activity and improves soil structure.

Irrigated rice production using VUB Inpari 23 and Mentik Wangi in the R-R-C field had the lowest productivity compared to the R-R-R and R-R-S fields. This is likely to be closely related to several parameters in the R-R-C field, including 1) the lowest available SOC and K content, but the highest available P content compared to other cropping patterns. According to Bozarovich et al. (2023), an average of 20-24 kg of nitrogen, 8-13 kg of phosphorus, and 25-32 kg of potassium are required to produce 1 tonne of cereal. This indicates that the demand for K nutrients is significantly higher than for N and P nutrients. 2) an increase in soil pH to alkaline levels during the tillering phase, which has a major impact on the development of tiller numbers, and 3) soil moisture conditions at the start of the rice grain filling phase, which are below field capacity (the lowest soil moisture conditions compared to other cropping patterns). Water is critically needed at this stage to produce full grains.

Zaini et al. (2009) stated that the basic components of ICM technology for paddy fields include (1) superior varieties, (2) healthy and quality seeds, (3) efficient fertilization, (4) application of Integrated Pest and Disease Control (IPDC) according to target pests, and selection of technology components including (a) planting management, (b) early maturing rice seedlings, (c) organic fertilizer, (d) intermittent irrigation, (e) liquid fertilizer, and (f) harvest and post-harvest handling. The results of the study by Kristamtini et al. (2011) showed that planting the Mentik wangi variety using ICM technology was able to produce 9.22 t ha^{-1}. This potential productivity can be achieved based on the description of the Mentik wangi variety. In this study, the highest recorded yield was 6.53 t ha^{-1}. This productivity is already above the average of the Mentik wangi variety description, which is 4.18 t ha^{-1}. The productivity of Mentik wangi could not reach its potential productivity, possibly due to the attack of snail pests during the early growth phase and the attack of brown plant hopper pests since the flowering phase, which greatly affected the decline in rice productivity. This is also likely due to differences in study site locations and planting times, which affected climatic and soil conditions, thereby preventing the rice varieties from reaching their maximum potential despite receiving similar irrigation and fertilization treatments. The results of the study Nugroho et al. (2021) on Inpari 23 and Yulianto (2017) on Mentik wangi also had average productivity of about 6.9 t ha^{-1} and 6.8-6.9 t ha^{-1}, respectively.

Based on the correlation analysis, MDG was strongly associated with soil texture, including sand, clay, and silt content. Among these, clay content influences nutrient absorption and rice crop productivity, as it plays a critical role in determining the soil's cation exchange capacity (CEC). Additionally, soil texture affects soil structure and microbial activity, supporting plant growth. This finding is consistent with the study by Ye et al. (2024), which also reported that soils with higher clay content resulted in greater yields, as finer textures facilitate the mineralization of soil organic matter and enhance microbial activity.

MDG also exhibited a strong correlation with soil moisture content (SMC). MDG was positively correlated with SMC during the grain-filling stage, indicating that adequate water availability is essential during this phase for optimal grain filling. However, MDG was negatively correlated with SMC during the harvest stage, reflecting the reduced water requirement at this stage, which aligns with the common practice of draining paddy fields before harvest.

Furthermore, MDG negatively correlated with soil pH and available phosphorus during the period before 14 days after planting (DAP). Increasing available P during early growth (<14 DAP) in irrigated rice fields did not increase rice productivity. Soil-available P nutrients are required by plants, especially during the vegetative phase (early growth to active tillering) (Murnita & Taher, 2021). However, a lack of available P nutrients can disrupt physiological metabolic processes and cause leaves to become narrower (Bozarovich et al., 2023). Soil pH 14 days after planting (DAP) also showed a negative correlation with MDG, likely because this stage represents the early phase of plant growth, during which the observed correlation may be biased or less representative.

5. CONCLUSION

Differences in cropping patterns on Inceptisols majorly impact available P content. The rice-rice-soybean cropping pattern has a finer soil texture, while the rice-rice-corn cropping pattern has a higher available P content. Irrigated rice fields with different cropping patterns have almost the same distribution of chemical properties, such as slightly acidic soil pH, low organic matter content and BS value, very low total N and available K content, but have very high CEC value. Cropping patterns affect plant productivity more, particularly when considering water availability. Selecting the right superior varieties and those by cropping patterns can increase MDG yields by 23.52-30.1% compared to other superior varieties. Sufficient water availability throughout the growing phase can increase rice productivity by 33.3-56.2% (1.5-2.3 times).

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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