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Planting Methods and Irrigation the Northern Nile Delta, Egypt Depth Management to Enhance Water Productivity and Yield of Rice in

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IMPROVING crop yield and the productivity of irrigation water (PIW) is essential for sustainable agriculture, particularly in water-scarce regions. This study aimed to evaluate the effects of different planting methods and irrigation depths on water applied, grain yield, and water productivity in rice cultivation under the agro ecological conditions of the Northern Nile Delta, A field experiment was conducted over two consecutive rice-growing seasons (2023 and 2024), using three planting methods, traditional planting (TPM), furrow planting (FPM), and bed planting (BPM) combined with three irrigation depths: 7 cm (D7), 5 cm (D5), and 3 cm (D3). Parameters measured included irrigation water applied ($m^3\ ha^{-1}$), grain yield ($kg\ ha^{-1}$), and PIW ($kg\ m^{-3}$). Statistical analysis revealed significant differences among treatments. BPM recorded the lowest irrigation water applied (9,500 $m^3\ ha^{-1}$), while TPM recorded the highest (13,000 $m^3\ ha^{-1}$). Similarly, water applied increased with irrigation depth from D3 to D7. In terms of yield, TPM and FPM achieved the highest grain yields (11,500–12,000 $kg\ ha^{-1}$), whereas BPM yielded less (10,500 $kg\ ha^{-1}$). D7 produced the highest grain yield (13,000 $kg\ ha^{-1}$), followed by D5 with statistically similar performance, while D3 resulted in significantly lower yield (10,000 $kg\ ha^{-1}$). Despite lower yields, PIW increased under reduced irrigation depths and alternative planting methods, reaching its highest value with BPM and D3 (>1.12 $kg\ m^{-3}$). In contrast, TPM and D7 showed the lowest PIW (0.89–1.02 $kg\ m^{-3}$). Notably, BPM reduced water applied by approximately 27% but resulted in a 6 % yield reduction compared to TPM. These findings suggest that bed planting, particularly when combined with moderate to shallow irrigation depths, can substantially enhance water productivity and may serve as an effective strategy for sustainable rice production in water-limited environments.

Keywords: Water-saving practices, Irrigation water use efficiency, Yield response, Crop performance, Grain quality, Sustainable production.

1. Introduction

In arid and semi-arid regions, irrigated agriculture consumes most available water resources. With rapid population growth, competition among agricultural, industrial, and urban sectors is intensifying, putting additional stress on already limited supplies and raising serious concerns about future food security. Improving crop water productivity (CWP) defined as the yield obtained per unit of water used has therefore become a central goal. **Woolley et al. (2009)** emphasized that progress in CWP can be achieved by integrating improved crop varieties with efficient resource management at both field and system levels.

Rice, one of the world's three major staple crops, provides about one-fifth of global calorie intake (**FAO, 2023**) and is cultivated on more than 195 million hectares, accounting for around 12% of all cropped land (**FAO, 2022**). Agriculture is already the largest consumer of irrigation water, and this demand is projected to rise further with population growth (**Ali, 2017; Ebrahim and Ali, 2018**). Since the primary objective of any irrigation technique is to maximize crop productivity, efficient water management in agriculture is crucial to mitigating water scarcity (**El-Nady and Hadad, 2016**). In Egypt, where water resources are severely constrained, rationalizing irrigation water use has become essential for conserving national water supplies. Effective irrigation management at the farm level is a key component of this strategy (**El-Henawy & Soltan, 2013**). Recent research has shown that for water-intensive crops like rice, optimizing irrigation timing, method, and depth can significantly enhance yields while reducing water waste (**Gao et al., 2024; Mubarak et al., 2025)**. Combining improved planting techniques with regulated irrigation scheduling has emerged as a promising approach to balance high yield targets with water-saving goals (**Dahlgreen and Parr, 2024; Yu et al., 2024**).

Egypt illustrates these challenges clearly. The country's fixed Nile water allocation of 55.5 billion cubic meters per year no longer meets the rising demand created by population growth and agricultural expansion (**Darwesh**

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et al., 2016). Because agriculture consumes the largest share of this allocation, improving water-use efficiency in crop production has become a national priority. Rice (*Oryza sativa* L.) is of great importance as a staple food for millions due to its affordability and nutritional value (**Fouda, 2021**). However, it is also among the most water-demanding cereals. Traditional rice cultivation under continuous flooding requires about 2000 mm of water per season, placing severe pressure on Egypt's limited freshwater resources (**Darwesh et al., 2016)**. Consequently, enhancing water-use efficiency in rice cultivation is critical.

Studies have explored alternative irrigation and planting methods to reduce water input without compromising yield. **Devinder et al. (2005)** found that planting rice on raised beds with furrows lowered water requirements by about 60 cm compared to puddled systems while improving yield components. Bouman and **Tuong (2001)** showed that maintaining short non-flooded periods conserved water without reducing yields. **Ashouri (2012)** reported that an 8-day irrigation interval decreased water use by 18% while sustaining grain yields comparable to continuous flooding. **Abdel-Ghany (2020)** further demonstrated that drip irrigation in arid zones cut water use by up to 59% while maintaining yields, though cost and technical challenges limit its large-scale adoption in rice systems**. Singh et al. (2002**) uses served that transplanted rice required 1608 mm of irrigation water plus 360 mm for land preparation, whereas dry-seeded rice on raised beds reduced irrigation use by 35–51% depending on soil moisture conditions. Similarly, **Meleha et al. (2008)** found that bed planting improved yields by 4%, productivity of irrigation water (PIW) by 66%, and water savings by 38%. **El-Atawy (2012)** also reported that transplanting rice near the bottom of beds enhanced grain yield and PIW by 3.45% and 58.1%, respectively, while reducing irrigation water application (IWA) by 35.2%.

Field-based approaches such as raised-bed planting, furrow irrigation, and alternate wetting and drying (AWD) are particularly promising for large-scale rice cultivation in Egypt. These methods conserve water, improve soil aeration and root growth, and enhance infiltration, thereby increasing water-use efficiency while sustaining productivity (**Swelam, 2016; FAO, 2016**). Studies have shown that raised-bed systems can cut irrigation water use by 25–40% without yield reduction, and in some cases even increase yields (**Atta et al., 2005; FAO, 2016**). Improving irrigation water productivity is therefore essential for sustaining rice production and preserving Egypt's scarce water resources under mounting climatic and socioeconomic pressures (**Molden et al., 2001; Rijsberman, 2006).**

Building on this context, the present study evaluates the combined effects of three transplanting methods traditional flat transplanting, furrow transplanting, and raised-bed transplanting and three irrigation depths (7, 5, and 3 cm) on grain yield and irrigation water productivity of the rice cultivar *Giza 178* under the agroecological conditions of the Northern Nile Delta.

2. Materials and Methods

2.1. Experimental site

A field experiment was carried out during the 2023 and 2024 summer rice-growing seasons at the Crops Water Requirement Research Field, Sakha Agricultural Research Station, Kafr El-Sheikh Governorate, Egypt (31°07′ E, 30°57′ N; 6 m above sea level). This site is representative of the typical agroecological conditions of the Northern Nile Delta region. The nursery area (200 m²) was ploughed, thoroughly dried, and leveled. Prior to plowing, 6 kg of calcium superphosphate (15.5% P_2O_5) was applied, followed by 7.0 kg of ammonium sulfate (20.6% N) after plowing. In addition, 0.65 kg of zinc sulfate was mixed with fine soil to ensure uniform distribution. Rice seeds were soaked in fresh water for 24 h and then incubated for 48 h to promote early germination. During both seasons, pre-germinated seeds were broadcast on May 1st at a seeding rate of 25.0 kg ha^{-1} in the nursery, which was maintained at a water depth of 2–3 cm. All other nursery management practices were performed according to standard recommendations. The rice cultivar *Oryza sativa* L. cv. Giza 178 was obtained from the Agricultural Research Center (ARC), Egypt.

2.2. Soil Physical and Chemical Properties

According to **Sparks (2020),** soil samples collected before cultivation at depths of 0–15, 15–30, 30–45, and 45–60 cm revealed that the soil was clay in texture (27.25% sand, 25.63% silt, and 47.13% clay). Field capacity ranged from 38.0% to 47.0%, while the permanent wilting point was 20.8–25.3%, resulting in available water content of 16.1–21.7%. Bulk density was uniform (1.16–1.30 Mg m^{-3}). The soil was slightly alkaline (pH 7.90–8.15) with moderate salinity, as electrical conductivity increased with depth (1.66–2.78 dS m^{-1}). Higher concentrations of Ca^{2+} , Mg^{2+} , Na^{+} , and Cl^{-} were found in deeper layers, especially at 45–60 cm, indicating subsoil salt accumulation. These characteristics suggest moderate water-holding capacity and potential salinity challenges, which are critical for irrigation and crop manageme

Table 1. Mean values of some soil Physical, chemical properties and some water constants of the experimental site before cultivation.

Soil depth (cm)	Particle size distribution, %			Texture class	F.C %	PWP %	Available Water%	Bulk density Mg/m^3	EC dSm^{-1}	pH	Soluble ions (mmolc L^{-1})							
	Sand	Silt	Clay								Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Co^{2-}_3	Hco^-_3	Cl^-	So^{2-}_4
0-15	26.0	28.0	46.0	Clay	47.0	25.3	21.7	1.19	1.5	8.15	0.30	0.10	0.76	0.02	0.0	0.55	0.21	0.42
15-30	29.0	23.0	48.0	Clay	39.0	21.8	17.2	1.16	1.57	8.00	0.31	0.10	0.79	0.02	0.0	0.57	0.22	0.43
30-45	26.5	26.0	47.5	Clay	38.0	21.9	16.1	1.30	1.65	8.00	0.34	0.10	0.89	0.02	0.0	0.65	0.23	0.47
45-60	27.5	25.5	47.0	Clay	38.5	20.8	17.7	1.20	2.78	7.90	0.84	0.27	1.25	0.03	0.0	0.45	0.23	1.71
Mean	27.25	25.63	47.13		40.63	22.45	18.18	1.21	1.88	8.01	0.45	0.14	0.92	0.02		0.56	0.22	0.76

AW = Available Water (%); Bd = Bulk density (Mg m^{-3}); FC = Field capacity (%); PWP = Permanent wilting point (%). CO_3^{2-} was not detected in all soil depths (0.00 mmolc L^{-1}

2.3. Chemical composition of the irrigation water

As outlined by **Estefan et al. (2013),** an analysis was carried out to evaluate the chemical properties of the irrigation water used in the experiment. The results (Table 2) showed that the water was classified as fresh, with an electrical conductivity (ECe) of 0.52 dS m^{-1} and a pH of 8.06, reflecting slightly alkaline conditions. The sodium adsorption ratio (SAR), calculated using the method of **Richards (1954),** was 3.60, indicating a low sodium hazard and confirming that the water is suitable for irrigation in most soil types:

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\mathrm{Ca2} +} + \mathrm{Mg2} +}$$

Cation concentrations were within permissible ranges, with sodium at 3.2 meq L^{-1}, calcium at 0.8 meq L^{-1}, magnesium at 1.0 meq L^{-1}, and potassium at 0.5 meq L^{-1}. The dominant anions were bicarbonates (HCO_3^-) and chlorides (Cl^-), each at 2.5 meq L^{-1}, followed by sulfates (SO_4^{2-}) at 0.5 meq L^{-1}. Carbonates (CO_3^{2-}) were absent. Overall, the chemical profile of the irrigation water indicates good quality for agricultural purposes. With no significant risks of salinity or sodicity, the water can be safely used for crops of moderate salt tolerance without posing threats to soil structure or plant development under the applied management practices.

Table 2. Chemical composition of the irrigation water.

Irrigation water	PH	ECe dS m^{-1}	SAR	Cations and Anions (mmolc L^{-1})							
				Na^+	Ca^{++}	Mg^{++}	K^+	Cl^-	CO_3^-	HCO_3^-	$SO_4^=$
(fresh water)	8.06	0.52	3.60	3.2	0.8	1.0	0.5	2.5	0.0	2.5	0.5

Note: CO_3^{2-} was not detected in the irrigation water (0.00 mmolc L^{-1})

2.4. Experimental Design and Treatments

A split-plot experimental design with three replications was employed to evaluate the effects of transplanting methods and irrigation depths on rice performance. As shown in Fig. 1, the main plots were assigned to three transplanting methods: P_1 : Conventional transplanting on flat soil at a uniform spacing of 20 cm × 20 cm (row × hill). P_2 : Transplanting at the bottom of furrows, each 20 cm high and 35 cm wide, with 60 cm spacing between the midpoints of adjacent furrows. P_3 : Transplanting at the bottom of raised beds, each 20 cm high and 45 cm wide, with 80 cm spacing between the midpoints of adjacent beds. The subplots were allocated to three irrigation depths: D7 (7 cm), D5 (5 cm), and D3 (3 cm). Each subplot covered an area of 52 m². To prevent lateral water movement between plots, 2.5-m-wide ditches were established around each experimental unit. The rice cultivar Giza 178 was used in both growing seasons. Seedlings, 25 days old, were transplanted on 3 June 2023 and 5 June 2024, respectively. At harvest, grains were separated from the straw and weighed. Grain yield was calculated after adjusting the grain moisture content to 14%.

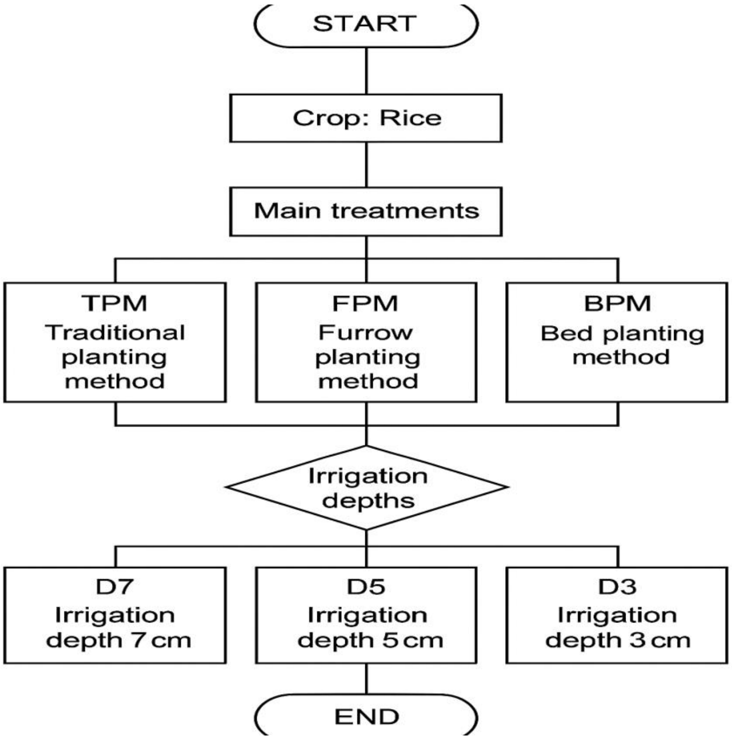

Fig. 1. Flowchart of the experimental layout showing main treatments (planting methods: TPM, FPM, BPM) and sub-treatments (irrigation depths: D7, D5, D3) for rice under surface irrigation.

2.5. Irrigation Water Applied (IWa)

To quantify the irrigation water delivered to each experimental plot, orifice tubes were used. Two spiels each 5 cm as inner diameter and 80 cm in length were installed to facilitate the flow of water from the field ditches into the plots. Throughout irrigation events, the effective water head above the midpoint of the spiel's cross-section was consistently maintained at an average of 10 cm. This consistency was achieved by using fixed sliding gates to regulate water levels in the main canal. Stage gauges were placed within each plot to monitor the water level, ensuring accurate measurement of the water depth conveyed through the spiels. Irrigation continued until the water reached the target submergence depth of 7 cm, and the duration of water application was recorded using a stopwatch According to **Majumdar (2002)**, the formula was used to determine how much water was delivered through the spiel tube

$$q = CA\sqrt{2gh} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where q is the irrigation water discharge (cm^3s^{-1}), C is the discharge coefficient (found by the experiment), A is the irrigation spike's inner cross section area (cm^2), g is the gravity acceleration ($cm\ s^{-2}$), and h is the average effective head (cm).

By changing Q in the following formula, the amount of water given for each plot (6m × 7m = 42 m^2) was determined: spile

$$Q = q \times T \times n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where Q is the water volume per plot (m3), q is the discharge (m3 min^{-1}), T is the total irrigation duration (min), and n is the number of orifice tubes per plot.

2.6. Productivity of irrigation water (PIW)

The following formula was used to determine the productivity of irrigation water in kg grain mm-1 ha-1 in accordance with (**Naroua et al., 2014**)

$$PIW = \frac{\text{Grain yield in kg ha}^{-1}}{\text{Amount of applied water inm3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

2.7. Economic analysis of rice

Economic efficiency was calculated according to the method described by **Hengsdijk and Van Ittersum (2003)**, while economic evaluation (profitability) was assessed using the equations outlined by **Li (2005)** as follows:

1. Gross Revenue = (Grain yield × grain price) + (Straw yield × straw price)
2. Net Return (NR) = Gross revenue − Total cost
3. Benefit-Cost Ratio (BCR) = NR / Total cost

Gross revenue was calculated by multiplying the total yield (kg ha^{-1}) by the respective market prices. The price of a ton of rice was 13,000 L.E. in 2023, increasing to 14,000 L.E. in 2024. The price of a ton of rice straw remained constant at 1,000 L.E. during both years.

The exchange rate was 1 L.E = 0.02 USD in 2023.

2.8. Statistical analyses

The obtained data were statistically analyzed using analysis of variance (ANOVA). As the data from both growing seasons exhibited a similar trend, a combined analysis was conducted according to the method described by Gomez and Gomez (1984). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% significance level, as developed by **Waller and Duncan (1969).** All statistical analyses were performed using the COSTAT software package.

3. Results

3.1. Water applied as affected by planting method

Figure 2 illustrates the total volume of irrigation water applied (m^3 ha^{-1}) under three planting methods—traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM)—during the first and second growing seasons. The results show significant differences among planting methods ($P < 0.05$), with TPM requiring the highest volume of water, followed by FPM, while BPM consistently consumed the least. This trend demonstrates the potential of BPM and FPM as water-saving alternatives compared with the conventional TPM. BPM reduced water applied by approximately 27% .The error bars (± S.E.) reflect the reliability of the data, and the significance letters, based on the least significant difference (LSD) test ($LSD_{0.05}$ = 208.06 in the first season and 43.03 in the second season), confirm the robustness of the observed differences. These findings underscore the importance of planting method choice in optimizing irrigation water use efficiency in rice production systems.

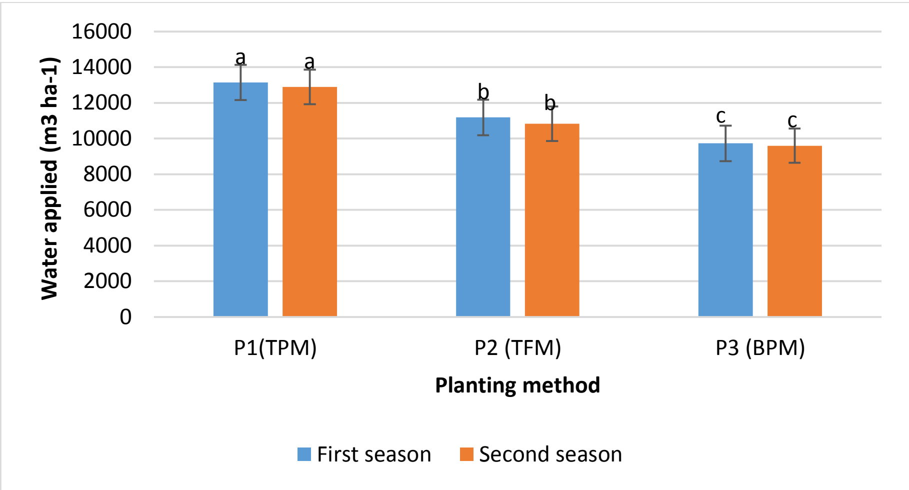

Fig. 2. Water Applied (m^3ha^{-1}) under different planting Methods during the during the first and second seasons. Traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM).

Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level). LSD 0.05 = 208.062 in the first season and LSD 0.05 = 43.0281057592 in the second season

3.2. Water applied as affected by irrigation depth

Figure 3 presents the total volume of irrigation water applied (m^3 ha^{-1}) under three irrigation depths: 7 cm (D7), 5 cm (D5), and 3 cm (D3), during two successive growing seasons. The data reveal a statistically significant reduction in irrigation water applied as depth decreased ($P < 0.05$). The highest water volume was consistently recorded at the 7 cm depth (D7), averaging approximately 12,595 m^3 ha^{-1}, followed by the 5 cm depth (D5) with about 11,199 m^3 ha^{-1}, while the lowest application was observed at 3 cm (D3), with around 9,890 m^3 ha^{-1}. These trends were consistent across both seasons, demonstrating a strong positive relationship between irrigation depth and the total volume of water applied. The error bars (± S.E.) confirm the reliability of the measurements, and the statistical grouping letters indicate significant differences among treatments ($P < 0.05$). Overall, the results highlight that reducing irrigation depth can substantially decrease water input, underscoring the potential of moderate deficit irrigation as a practical water-saving strategy in rice production systems.

3.3. Grain yield as affected by planting method

Figure 4 illustrates the grain yield (kg ha^{-1}) under three planting methods: traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM), evaluated over two consecutive growing seasons. The results show significant differences in yield among the planting methods ($p < 0.05$), while year-to-year variations within each method were not statistically significant. Both TPM and FPM achieved the highest yields, ranging from approximately 11,579 to 11,523 kg ha^{-1}, with no significant difference between them. In contrast, BPM consistently produced lower yields, averaging around 11,019 kg ha^{-1} across both seasons representing a 6 % reduction compared to TPM.

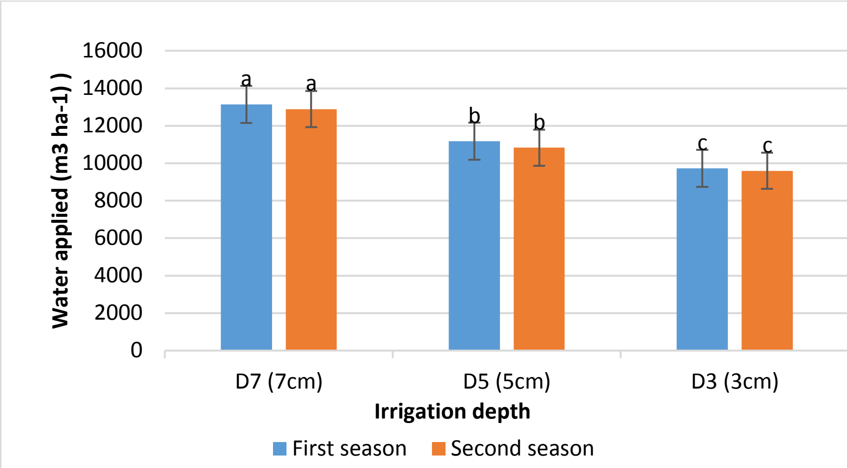

Fig. 3. Water applied as affected by irrigation depth during the first and second seasons.

Three irrigation depths D7 (7cm), D5 (5cm) and D3 (3cm) Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

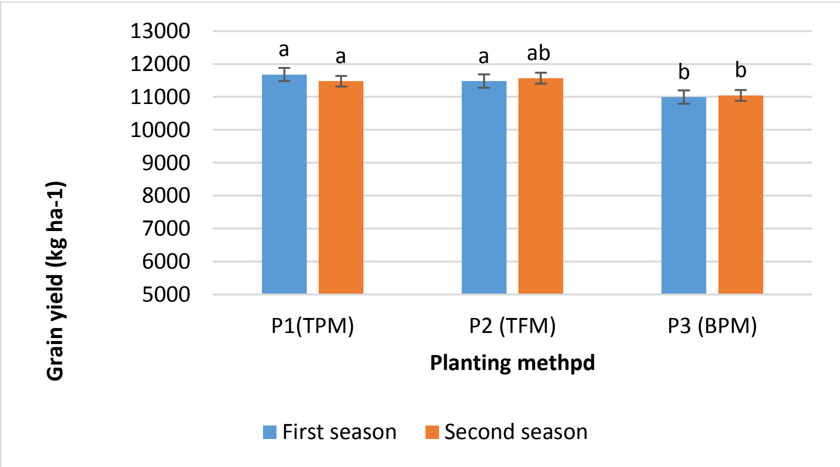

Fig. 4. Grain yield kg ha^{-1} as affected by planting method during the first and second seasons.

Traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM)
Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

3.4. Grain yield as affected by irrigation depth

Figure 5 presents the effect of irrigation depth on rice grain yield (kg ha^{-1}) during the first and second growing seasons. Grain yield was significantly influenced by irrigation depth ($P < 0.05$), with the 7 cm depth (D7) consistently producing the highest yields across both seasons, followed by the 5 cm depth (D5), while the 3 cm depth (D3) resulted in the lowest yields. The error bars (± S.E.) indicate the consistency of the results, and the statistical grouping letters confirm significant differences among treatments. These findings highlight that while reducing irrigation depth can save water, excessive reduction (D3) compromises yield performance, whereas moderate irrigation depth (D5) provides a balance between water savings and stable grain yield.

3.5. Productivity of irrigation water (PIW)as affected by planting method

Figure 6 displays PIW (kg m^{-3}) under different planting methods. TPM (P_1) had the lowest PIW values (~0.89 kg m^{-3}) in both seasons. FPM (P_2) achieved moderate PIW (1.03 kg m^{-3} and 1.06 kg m^{-3} in the first and second seasons, respectively). The highest PIW was recorded with BPM (P_3), exceeding 1.12 kg m^{-3} in the first season and increasing to 1.15 kg m^{-3} in the second. This upward trend reflects improved water use efficiency with advanced planting techniques.

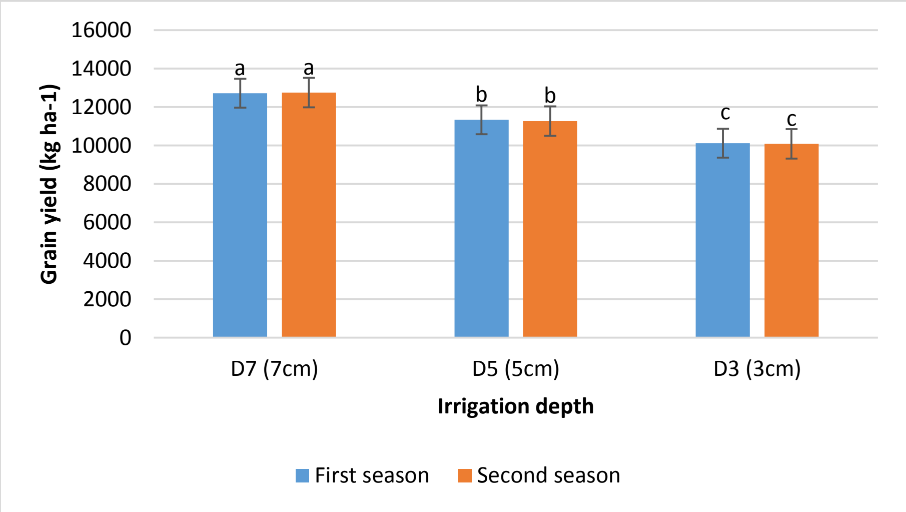

Fig. 5. Grain yield (kg ha^{-1}) as affected by irrigation depth during the during the first and second seasons.

Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

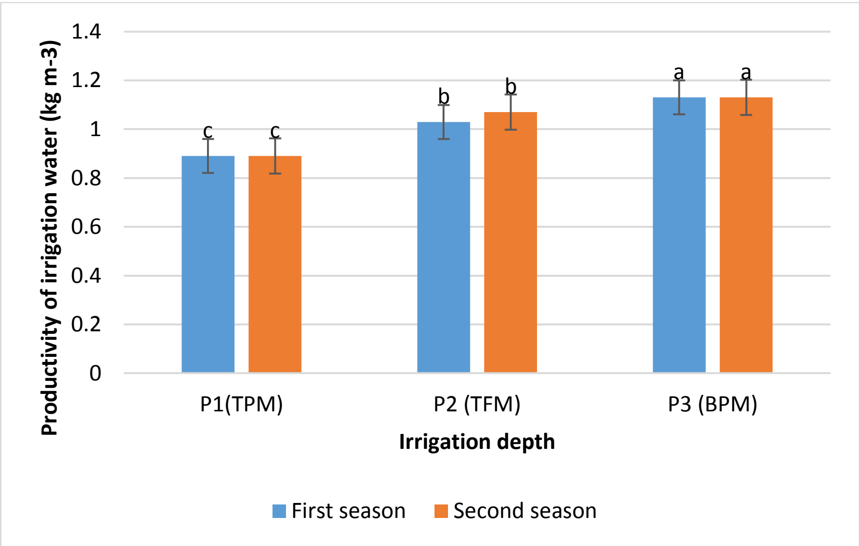

Fig. 6. Productivity of irrigation water (kg m^{-3}) as affected by planting method during the 2023 and 2024 growing seasons.

Traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM). Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

3.6. Productivity of irrigation water (PIW) as affected by irrigation depth

As illustrated in Figure 7, PIW improved significantly as irrigation depth decreased. The lowest PIW values were observed under D_7 (1.00 kg m⁻ ³ in 2023 and 1.02 kg m⁻ ³ in 2024), while D_5 resulted in moderate improvements (~1.03 kg m⁻ ³). The highest PIW values were achieved under D_3 , with 1.01 kg m⁻ ³ in 2023 and up to 1.03 kg m⁻ ³ in 2024. These findings confirm that shallower irrigation depths contribute to enhanced water productivity without substantial yield penalties.

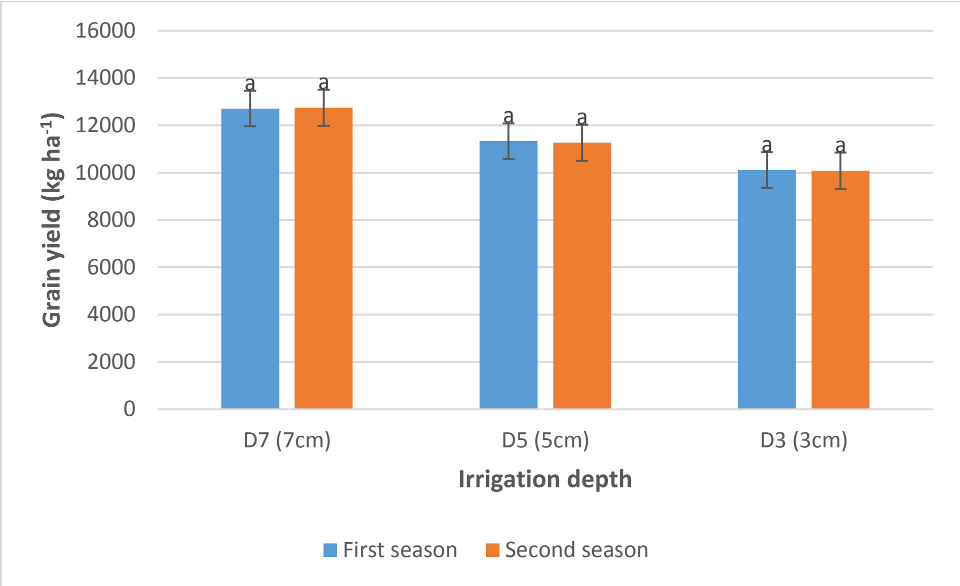

Fig. 7. Productivity of irrigation water(PIW) as affected by irrigation depths during the 2023 and 2024 growing season.

Three irrigation depths D7 (7cm), D5 (5cm) and D3 (3cm). Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

3.7. Interaction Effects of Planting Method and Irrigation Depth on Rice Yield and Water Productivity

Table 3 presents the interaction effects of planting method and irrigation depth on water applied, grain yield, and productivity of irrigation water (PIW) for rice during the 2023 and 2024 seasons. The results clearly demonstrate significant trade-offs between yield maximization and water use efficiency across the tested treatments. In both seasons, the traditional planting method (TPM) with 7 cm irrigation depth (P1×D7) achieved the highest grain yield (13.0 and 12.95 t ha⁻ ¹ in 2023 and 2024, respectively); however, this treatment consumed the largest volume of irrigation water (>14,500 m³ ha⁻ ¹) and produced the lowest PIW (0.88–0.89 kg m⁻ ³). Conversely, the bed planting method (BPM) combined with 3 cm irrigation depth (P3×D3) consistently recorded the lowest water application (8,604 and 8,473 m³ ha⁻ ¹ in 2023 and 2024, respectively) and the highest PIW (1.14–1.18 kg m⁻ ³), though grain yields were comparatively lower (9.79–10.02 t ha⁻ ¹). The furrow planting method (FPM), particularly under 7 cm irrigation depth (P2×D7), represented a compromise between high yield and water use efficiency, producing grain yields close to those of TPM at 7 cm, but with substantially lower water requirements and higher PIW values (1.03–1.08 kg m⁻ ³). Overall, the findings indicate that while TPM under high irrigation depth maximizes yield, BPM under reduced irrigation depth optimizes water productivity. FPM at moderate to high irrigation depths offers a balanced option, achieving competitive yields while improving irrigation efficiency. These outcomes highlight the potential of integrating furrow or bed planting with water-saving irrigation strategies to enhance rice water productivity in water-scarce environments.

Table 3. Planting method and irrigation depth interaction on water applied, grain yield, and productivity of irrigation water (PIW) for rice during the 2023 and 2024 seasons.

Treatments	Season 2023			Season 2024		
	Water applied m^3ha^{-1}	Grain yield kg ha^{-1}	Productivity of irrigation water	Water applied m^3ha^{-1}	Grain yield kg ha^{-1}	Productivity of irrigation water
P1(TPM)×D7	14689 a	13000 a	0.88 c	14566 a	12947 b	0.89 c
P1(TPM) ×D5	13145 b	12200 a	0.89 c	12971 b	11495 d	0.89 c
P1(TPM) ×D3	11595 d	12200 b	0.89 c	11138 d	9996 f	0.90 c
P2(FPM) ×D7	12512 c	11700 c	1.03 b	12138 c	13090 a	1.08 b
P2(FPM) ×D5	11138 e	11300 d	1.01 b	10710 e	11376 e	1.06 b
P2(FPM) ×D3	9887 e	11000 e	1.03 b	10781 e	10234 g	1.06 b
P3(BPM) ×D7	10886 f	10334 f	1.12 a	9639 f	12186 c	1.13 a
P3(BPM) ×D5	9691 f	10201 g	1.14 a	9544 g	10924 f	1.14 a
P3(BPM) ×D3	8604 g	9789 h	1.14 a	8473 h	10017 h	1.18 a

TPM= Traditional planting method, FPM=Furrow planting method, and BPM= Bed planting , D7 irrigation depth 7 cm, D5 irrigation depth 5cm,and D3irrigation depth 3cm , Values within the same column followed by different letters are significantly different according to Duncan's Multiple Range Test (DMRT) at the 0.05 probability level. Similar letters indicate no significant difference.

4. Economic evaluation

4.1. Comparative Analysis of Production Costs for Different Rice Planting Methods Over Two Seasons

Table 4 presents the breakdown of production costs per hectare of rice cultivated using the traditional planting method (TPM), furrow planting method (FPM), and bed planting method (BPM) across two consecutive seasons. Total costs increased from the first to the second season for all planting methods, reflecting higher input prices and rising operational expenses. Among the cost components, land preparation, irrigation, and rent constituted the largest shares of total expenditure, while pest control, transportation, and other expenses contributed relatively little. FPM and BPM incurred higher costs than TPM, largely due to additional land preparation and irrigation requirements. Specifically, the adoption of FPM and BPM led to an additional cost of 2,380 L.E. per hectare in the first season and 2,856 L.E. in the second season, attributable to the preparation of beds and furrows. Notably, the escalation of rent and irrigation costs between seasons was the primary driver of the overall increase in production costs. These findings highlight the need for cost-efficient resource management, particularly in irrigation and land preparation, to sustain the economic viability of rice production under different planting methods.

Table 4. Production costs per hectare of rice under different planting methods during the first and second growing seasons.

Coasts	First season			Second season		
	TPM	FPM	BPM	TPM	FPM	BPM
Land Preparation	2380	4760	4760	2856	5712	5712
Seedling and planting	5474	5474	5474	6568	6568	6568
irrigation	6806	7140	7140	8168	8568	8568
Fertilization	3689	3689	3689	4426	4426	4426
Weeding	1785	1785	1785	2142	2142	2142
Pest Control	2023	2023	2023	2427	2427	2427
Harvesting	3927	3927	3927	4712	4712	4712
Transportation	2618	2618	2618	3141	3141	3141
Other Expenses	2856	2856	2856	3427	3427	3427
Rent	14280	14280	14280	17136	17136	17136
Total	**46172**	**48552**	**48552**	**55406**	**58262**	**58262**

TPM= Traditional planting method, FPM=Furrow planting method, and BPM= Bed planting , D7 irrigation depth 7 cm, D5 irrigation depth 5cm,and D3irrigation depth 3cm , The crop Rice, surface irrigation

4.2. Economic Evaluation of Planting Methods and Irrigation Depths in Rice Cultivation Across Two Seasons

Table 5 illustrates the economic performance of rice cultivation as affected by planting method and irrigation depth over two successive seasons. The results highlight clear variations in yield, revenue, and profitability depending on the interaction of treatments. In both seasons, the traditional planting method (TPM) combined with an irrigation depth of 7 cm (P1×D7) consistently achieved the highest net returns and benefit–cost ratio (BCR), reaching 138,948 L.E. (BCR = 3.01) in the first season and 142,734 L.E. (BCR = 2.58) in the second season. Similarly, the TPM × 5 cm treatment (P1×D5) performed competitively, particularly in the second season where it recorded the highest net return (154,144 L.E.) and BCR (2.78). By contrast, the bed planting method (BPM) generally resulted in the lowest economic outcomes, particularly under shallow irrigation (3 cm), where both net returns and BCR were markedly reduced (91,145 L.E., BCR = 1.88 in the first season; 95,006 L.E., BCR = 1.63 in the second season). This suggests that although BPM may contribute to water-saving objectives, it is less favorable in terms of profitability under the tested conditions. Overall, the findings indicate that adopting TPM with moderate irrigation depths (5–7 cm) optimizes both productivity and profitability. These results emphasize the need to balance water-saving practices with economic viability, particularly in regions where irrigation water is becoming increasingly scarce.

Table 5. Grain and straw yields, revenues, production costs, net returns, and benefit–cost ratio of rice under different planting methods and irrigation depths across two seasons.

Treatments	Grain Yield (T ha^{-1})	Straw Yield (T ha^{-1})	Grain revenue (LE) ha^{-1}	Straw revenue (LE) ha^{-1}	Total Revenue (TR) (LE) ha^{-1}	Total cost (LE)	Net Return (LE) ha^{-1}	Benefit-Cost Ratio (BCR)
First season								
P1 (TPM)	11.678	14.48	151814	14480	166294	46172	120122	2.60
P2 (FPM)	11.478	14.24	149214	14240	163454	48552	114902	2.37
P3 (BPM)	10.996	13.64	142948	13640	156588	48552	108036	2.23
D7 (7cm)	12.711	15.76	165243	15760	181003	46172	134831	2.92
D5 (5cm)	11.333	14.85	147329	14850	162179	46172	116007	2.51
D3 (3cm)	10.108	12.54	131404	12540	143944	46172	97772	2.12
P1×D7	13	16.12	169000	16120	185120	46172	138948	3.01
P1×D5	12.933	14.81	168129	14810	182939	46172	136767	2.96
P1×D3	12.2	12.81	158600	12810	171410	46172	125238	2.71
P2×D7	11.7	16.03	152100	16030	168130	48552	119578	2.46
P2×D5	11.3	14.41	146900	14410	161310	48552	112758	2.32
P2×D3	11	12.65	143000	12650	155650	48552	107098	2.21
P3×D7	10.334	15.13	134342	15130	149472	48552	100920	2.08
P3×D5	10.201	13.64	132613	13640	146253	48552	97701	2.01
P3×D3	9.789	12.44	127257	12440	139697	48552	91145	1.88
Second season								
P1 (TPM)	11.479	14.92	160706	14920	175626	55406	120220	2.17
P2 (FPM)	11.567	15.204	161938	15204	177142	58262	118880	2.04
P3 (BPM)	11.043	14.06	154602	14060	168662	58262	110400	1.89
D7 (7cm)	12.74	16.56	178360	16560	194920	55406	139514	2.52
D5 (5cm)	11.265	14.64	157710	14640	172350	55406	116944	2.11
D3 (3cm)	10.082	13.51	141148	13510	154658	55406	99252	1.79
P1×D7	12.95	16.84	181300	16840	198140	55406	142734	2.58
P1×D5	13.9	14.95	194600	14950	209550	55406	154144	2.78
P1×D3	12.186	13.4	170604	13400	184004	55406	128598	2.32
P2×D7	11.495	17.02	160930	17020	177950	58262	119688	2.05
P2×D5	11.376	14.79	159264	14790	174054	58262	115792	1.99
P2×D3	10.924	13.3	152936	13300	166236	58262	107974	1.85
P3×D7	9.996	15.85	139944	15850	155794	58262	97532	1.67
P3×D5	10.234	14.2	143276	14200	157476	58262	99214	1.70
P3×D3	10.017	13.03	140238	13030	153268	58262	95006	1.63

TPM = traditional planting method, FPM = furrow planting method, and BPM = bed planting method. The price of a ton of rice was 13,000 L.E. in 2023, increasing to 14,000 L.E. in 2024. The price of a ton of rice straw remained constant at 1,000 L.E. during both years.

5. Discussion

5.1. Water applied as affected by planting method

The consistently greater water requirement observed under the Traditional Planting Method (TPM) can be attributed to the inefficiencies of conventional surface irrigation, which often result in higher surface evaporation, uneven water distribution, and increased percolation losses. These findings align with those reported by **Yao et al. (2021),** who documented significant water losses with traditional surface irrigation systems due to their lack of precision and uniformity. **Rathore et al. (2017)** also highlighted that traditional systems tend to offer poor soil moisture retention, necessitating more frequent irrigation. In contrast, the bed planting method (BPM) demonstrated the highest water-saving potential. The use of furrow irrigation and raised beds helps to concentrate water near the root zone, reduce the wetted soil surface, and limit both evaporation and runoff. **Yao et al. (2021)** further emphasized the benefits of structured irrigation techniques such as furrow or bed systems in enhancing water distribution efficiency. While the furrow planting method (FPM) showed improved water efficiency compared to TPM, it did not match the water-saving capabilities of BPM. FPM promotes more uniform water application than TPM but lacks the structural advantages necessary for effective moisture retention.

5.2. Water applied as affected by irrigation depth

The higher water applied observed under the 7 cm depth (D7) can be explained by the excessive volume delivered per irrigation event. This approach often results in inefficient water use due to increased surface runoff, deep percolation losses beyond the crop root zone, and elevated evaporation. **Yao et al. (2021)** In the United States, furrow irrigated rice production has increased from less than 1% in 2015 to 10% in 2019 due to the ease of crop rotations and the reduction in time and expenses when compared to flood irrigated rice production, as demonstrated by **Hardke and Chlapecka(2021**) . **Stevens et al. (2018)** claim that the furrow irrigation technique reduces the amount of arsenic in irrigated rice grain and is superior to traditional flood irrigation for growing rice with less water and labor. According to other research, rice grown under furrow irrigation had a low yield component and yield, while rice grown under flood irrigation had a significant content of arsenic **Aide(2018) and Vories et al(2002).**

5.3. Grain yield as affected by planting method

The higher grain yield observed under the TPM method, despite greater water usage, is likely attributed to the continuous availability of moisture throughout the plant root zone, upporting steady vegetative and reproductive development. This aligns with findings by **Rathore et al. (2017),** who noted that traditional irrigation practices, though often inefficient, can buffer crops against temporary water shortages and thereby help stabilize yields. Similarly, the FPM treatment achieved yields nearly equivalent to those of TPM, indicating that moderate reductions in irrigation volume may not necessarily compromise productivity as long as soil moisture remains within favorable levels. Comparable results were reported by **Zhang et al. (2021),** who highlighted that furrow planting, when paired with appropriate irrigation management and good agronomic practices, can maintain high yield performance. In contrast, BPM, although effective in conserving water, led to significantly lower yields.

5.4. Grain yield as affected by irrigation depth

Additionally, **Singh et al. (2019)** observed that water stress reduces vegetative growth and tillering, directly affecting yield. Their study supports the observed reduction in yield at the D3 level. The statistical similarity between D7 and D5 in this figure highlights a potential for water-saving without compromising Productivity of irrigation water crucial for regions with limited water availability. According to **Afifah et al. (2015)**, flooding a field to a depth of 1 cm resulted in significant improvements in WUE and a 45% reduction in water usage when compared to flooding at a depth of 5 cm. However, equal rice yields were produced by flooding at depths of 5 cm and 1 to 3 cm, which was higher than the rice yield produced under AWD.

5.5. Effect of planting method on Productivity of Irrigation Water (PIW)

Modern planting methods significantly improve the productivity of irrigation water compared to traditional practices. Bed planting (P3) proved most effective by enhancing soil moisture retention, drainage, and aeration, thereby maximizing water use efficiency, consistent with Yao et al. (2021). Furrow planting (P2) also improved efficiency by directing water to the root zone and reducing evaporative losses, supporting the findings of **Singh et al. (2019)**. Overall, bed planting offers the highest gains in water productivity, followed by furrow planting, while the traditional method remains least efficient..

5.6. Effect of Irrigation Depth on Productivity of Irrigation Water (PIW)

The results indicate that reducing irrigation depth improves the productivity of irrigation water, reflecting more efficient use when smaller amounts are applied. The highest productivity was recorded at the 3 cm depth (D3), most likely because the applied water was utilized more effectively, with limited losses from deep percolation or evaporation. These findings align with **Yao et al. (2021),** who noted that shallow, well-managed irrigation can substantially increase water use efficiency. The 5 cm depth (D5) also outperformed the conventional 7 cm level (D7), as the water supplied was closer to the crop's actual requirements, helping to avoid unnecessary losses. Nonetheless, this balance must be managed with caution, as **Singh et al. (2019)** emphasized the need to weigh water conservation against yield stability. Overall, the figure highlights a steady improvement in irrigation water productivity as depth decreases from 7 cm to 3 cm, with maximum efficiency at 3 cm, though long-term sustainability depends on carefully aligning efficiency with crop yield.

5.7. Interaction of Planting Method and Irrigation Depth on Water Productivity

The results show a clear balance between grain yield and the productivity of irrigation water (PIW) under different planting methods and irrigation depths. While deeper irrigation (7 cm) produced higher grain yields, particularly with the traditional planting method (TPM), it lowered PIW because of inefficient water use through percolation and evaporation on flat surfaces. Similar patterns were reported by **Zhang et al. (2022),** who found comparable inefficiencies with conventional flood irrigation in rice. On the other hand, reducing irrigation depth to 3 cm greatly improved PIW, with the strongest gains observed under the bed planting method (BPM). These findings suggest that combining shallower irrigation with improved planting systems such as BPM can increase water use efficiency. Still, the slight yield decline under minimal irrigation underscores the importance of carefully balancing efficiency and productivity to ensure sustainable water management.

5.8. Economic Performance of Rice as Influenced by Planting Methods and Irrigation Depths (2023–2024)

These findings are consistent with previous studies. **Singh et al. (2019)** demonstrated that higher irrigation depths significantly improved rice yield and profitability under traditional planting, albeit with increased water use. Similarly, **Rathore et al. (2017)** confirmed that conventional systems combined with sufficient irrigation achieved the highest productivity and economic returns. **Yao et al. (2021)** highlighted that alternative planting geometries, such as bed and furrow systems, improve water distribution efficiency but often result in lower grain yields compared to traditional methods under full irrigation.

Conclusion

This study highlights the significant influence of planting methods and irrigation depth on rice yield, irrigation water productivity (PIW), and economic feasibility in the North Nile Delta. The results indicate that using the furrow planting method (FPM) with a 5 cm irrigation depth (P2×D5) can achieve nearly the same grain yield as the 7 cm depth (D7), while saving about 15% of irrigation water compared to traditional practices. Although bed planting (BPM) reduced water application by around 27%, it led to a 19% decrease in yield compared to the traditional method (TPM); however, when combined with moderate to shallow irrigation depths, it demonstrated a notable improvement in water productivity, offering a promising approach for sustainable rice cultivation under water-limited conditions. These findings emphasize the need for further research to refine and validate such practices to optimize rice yield while conserving irrigation water in line with the principle of "**more crop per drop**."

Declarations

Ethics approval and consent to participate

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