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COMBINED EFFECTS OF IRRIGATION WATER DEPTHS WITH UREA FORMS ON RICE YIELD AND WATER PRODUCTIVITY IN THE SAHEL, BURKINA FASO

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ABSTRACT

This study investigated the impact of urea forms and irrigation levels on paddy rice yields and water use efficiency. An experiment comparing super granular urea (SGU) and prilled urea (PU) under three irrigation levels (5 cm, 7.5 cm, and 10 cm) was established in a split plot design with three replications. The results show that SGU treatments showed better performance in comparison with PU in terms of growth, yield components and yield. The SGU treatment at 5 cm irrigation displayed the highest yield (marginal ≈ 4,845 kg/ha; observed ≈ 4,826 kg/ha) compared to other treatments. Principal component analysis (PCA) revealed that this productivity was strongly correlated to panicle weight and straw yield, placing the SGU treatments on the high-performance. Although the 10 cm irrigation level promoted tillers number (11.5) with SGU, it also increased water consumption without producing a significant yield gain. In contrast, SGU at 5 cm gave the best water saving (≈ 50%). Despite high experimental variability making the linear mixed model statistically not significance at the 5% level, the agronomic trends with growth parameters and PCA confirmed that using SGU combined with controlled 5 cm irrigation is the most promising strategy for optimizing rice yield and water productivity in semi-arid climate.

Keywords: Irrigation; Super granular urea; Prilled urea; Rice; Water productivity

1 INTRODUCTION

Rice is one of the major cereals produced worldwide, ranking third after maize and wheat; the global production volume are indeed substantial, with 2025 seeing record-breaking outputs (FAO, 2026). The global area dedicated to paddy rice for the 2026/27 marketing year is projected at approximately 165 million hectares (FAO, 2026). By 2050, approximately 15 to 20 million hectares of rice fields, representing about 10% of the global total, will face varying degrees of water scarcity while the demand is continuously rising (Zhao et al., 2025). Rice consumption should exceed 905 635 tonnes but, the domestic production meets only 70% of this demand (Zhao et al., 2025).

In Burkina Faso, rice plays an important role in the economy and food security; in years 2018 and 2019, the cultivated area was approximately 161,000 hectares and the country has established a comprehensive second generation of National Rice Development Strategy (SNDR II) from 2021 to 2030 (MAAHA, 2020). The main objective is to reach rice self-sufficiency and create an exportable surplus by the end of the decade.

However, the increase in rice production also entails significant water and fertilizer consumption (He et al., 2026; Zhao et al., 2025). Islam et al. (2023) reported that conventional continuous flooding irrigation is increasingly unsustainable because it consumes between 3,000 and 5,000 liters of water to produce just one kilogram of rice. The worsening lack of water compels adoption of irrigation to secure production particularly in developing countries (Ogbiye et al., 2021). A key tactic is to overcome risk for dry spell that focus on irrigation (Rockström et al., 2010, Fossi et al., 2013, Warwick and Ketema, 2017). Irrigation helps in addressing water shortage and drought in arid and semi-arid areas (Kaboré et al.,2024).

In the actual water scarcity context irrigation water over-supply in agriculture is not viable (Kima et al., 2026). Growing worries emerge over increasing rice yields per water unit to feed fast-expanding populations, especially in dry regions (Kima et al., 2020). Studies conducted by Allen, (1998) and Facon (2000) revealed that inaccurate estimation of crop water requirements leads to waste. Managing water supply to plants is essential for maintaining productivity and ensuring good yields (Hossain et al., 2018; T. Islam et al., 2026).

Also, irrigation alone is insufficient to maintain optimal production (Kima et al., 2025a). Emphasis should be put on considering both irrigation and fertilizer application if yield should be optimized. Islam et al.(2023) mentioned that the excessive and inappropriate use of nitrogen fertilizers is associated with low nitrogen use efficiency, contribute to environmental pollution and land degradation. Furthermore, excessive use of fertilizers such as urea causes soil pollution and reduces agricultural yields (He et al., 2026). The application of urea fertilizer synchronized to suitable amount of water is necessary to achieve high water and rice productivity (Kima et al., 2026). Research conducted by Dumanovic et al. (1996) and Halim et al. (2016) has demonstrated that combining specific irrigation levels with fertilizer application improved yields. Since the reliability and viability of irrigation depend on-farm productivity driven by a water-fertilizer interaction, optimal yield cannot be achieved without synchronizing water and nitrogen because of nutrient-water synergy. Inadequate irrigation water supply may induce deep percolation and nutrient leaching and in turn reduce yield and form profitability.

Past studies (Hossain et al., 2018; Onofrio and Dupuy, 2018) recommended deep placement of urea super granules as a top method over prilled urea in rice cultivation. These investigation emphasized that delayed nitrogen release from granular urea buried 7–10 cm deep enhanced nitrogen uptake efficiency, whereas prilled urea features rapid dissolution and severe loss.

Most of previous studies have focused on irrigation and urea application without much attention on interaction of water levels and the form of urea that affects the nitrogen release and uptake by plant. Plant nitrogen assimilation is governed by fertilizer dissolution rates, which are dictated by urea form and applied water depth. Water level-nitrogen release-nitrogen uptake should be address simultaneously if water and rice productivity should be improved. Fertilizer application should match with suitable water depth (Kima et al, 2025). Exploring various water levels under different form of urea should help pointing out sustainable combination ensuring optimal yield and water use efficiency. Pinpointing best-fit combination will enhance farm gain, water savings and secure production.

2 MATERIAL AND METHODS

2.1 Description of the study area

The study was carried out in Ouagadougou commune, specifically at the Pan-African Institute for the Development of West Africa and the Sahel (IPD/AOS) (**figure 1**). The experimental site is located between 12°23' and 12°32' North latitude and 1°28' and 1°0' West longitude. The study area is influenced by the northern Sudanese climate. It experiences two distinct seasons: a rainy season from May to September and a dry season lasting from October to April. The annual rainfall is 740 mm, exhibiting significant inter-annual variability. The average temperature is 24.2°C, with daily temperature fluctuations that can exceed 13°C. The average relative humidity is 49%. Ouagadougou is located on shallow soil that is deficient in nutrients. The soil is a leached tropical ferruginous, developed on sandy, sandy-clay, or clayey materials. It is rich in iron, manganese oxides and hydroxides. Additionally, the soil is characterized by low levels of potassium and phosphorus, along with a fragile structure that is highly susceptible to erosion.

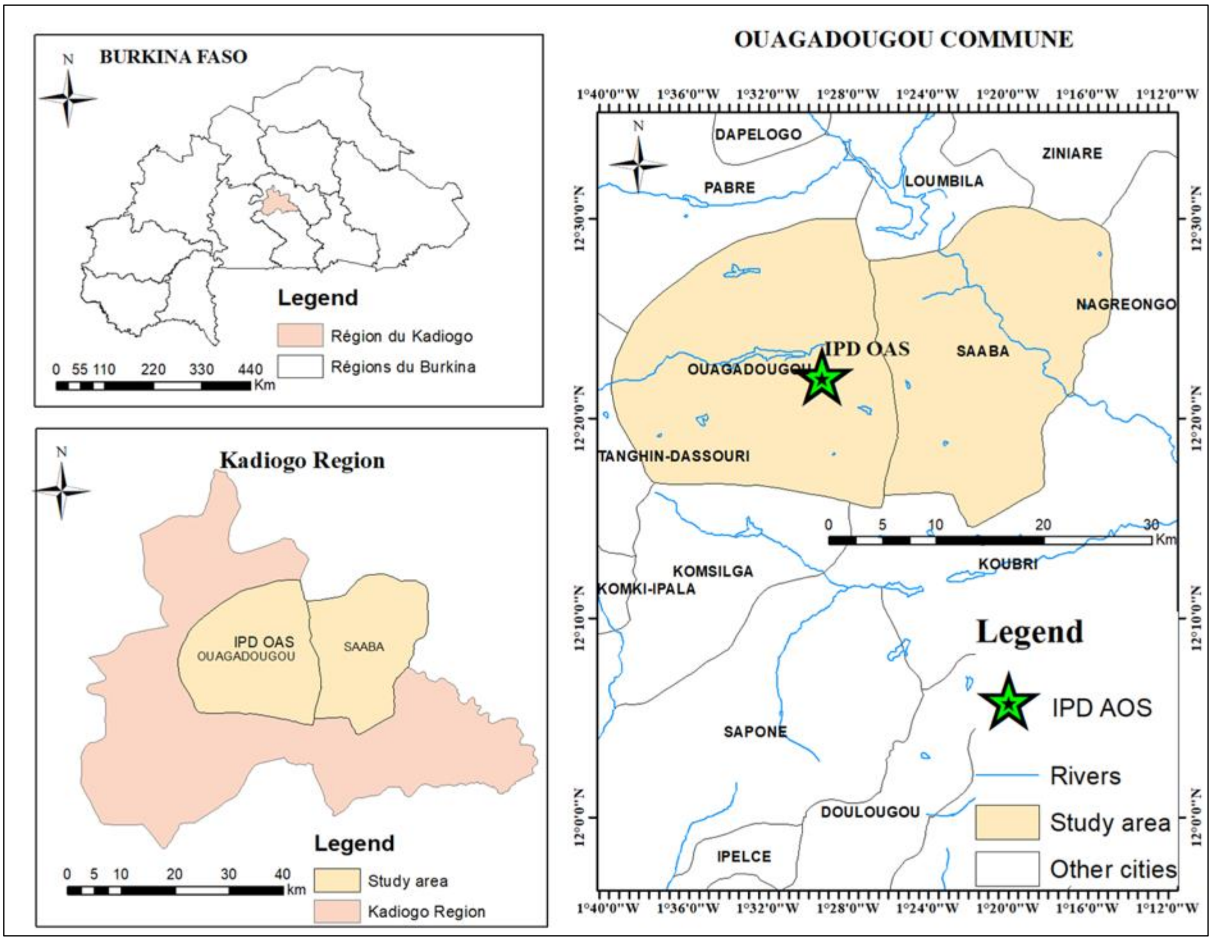


Figure 1: Localisation of the study area

2.2 Experimental design, cultivation and water management

The experiment was conducted from July to October in 2022 through a split-plot design with three replications (**figure 2**). The main plots were constituted by the forms of urea: urea super granulated urea (SGU) and prilled urea (PU). The sub-plots were composed by three irrigation levels (IL) of 10 cm, 7.5 cm, and 5 cm equivalent to the application of to 500 m^3, 750 m^3 and 1000 m^3 of water per hectare respectively. The distance between main plots was 100 cm while the distance between sub-plots was 80 cm. The plots area were 6 m^2. The trial total area was 160.72 m^2. The combination of the two factors resulted in treatments SGU-5cm, SGU-7.5cm, SGU10cm, PU-5cm, PU-7.5cm, and PU-10cm.

Wetland was manually tilled and 10 cm depth on July 15th and compost was incorporated at recommended rate of 10 t/ha. Bonds were made at 30 cm height and 15 cm width and well compacted; plots were ponded with 5 cm of water and levelled. After land preparation, 20 days old seedlings, obtained from experiment site nursery, were transplanted on July 20th at 25 cm X 25 cm spacing.

After transplanting, 5 cm irrigation water depth was daily applied up to 14 days after transplanting for seedling recovery from transplanting shock. The different water treatments were applied 15 days after transplanting and the fertilizer NPK (14-23-14) was immediately applied at adopted rate of 150 Kg/ha.

PU and SGU were applied at the same rate of 120 kg/ha. PU was applied in two fractions: 1/3 at active tillering and 2/3 at panicle initiation as recommended by Tah et al. (2008). SGU was incorporated at 7-10 cm depth into the soil at active tillering. One granule of 3g was placed between two plants. Specific pesticides were applied on demand for pest control. Hand-weeding was routinely done.

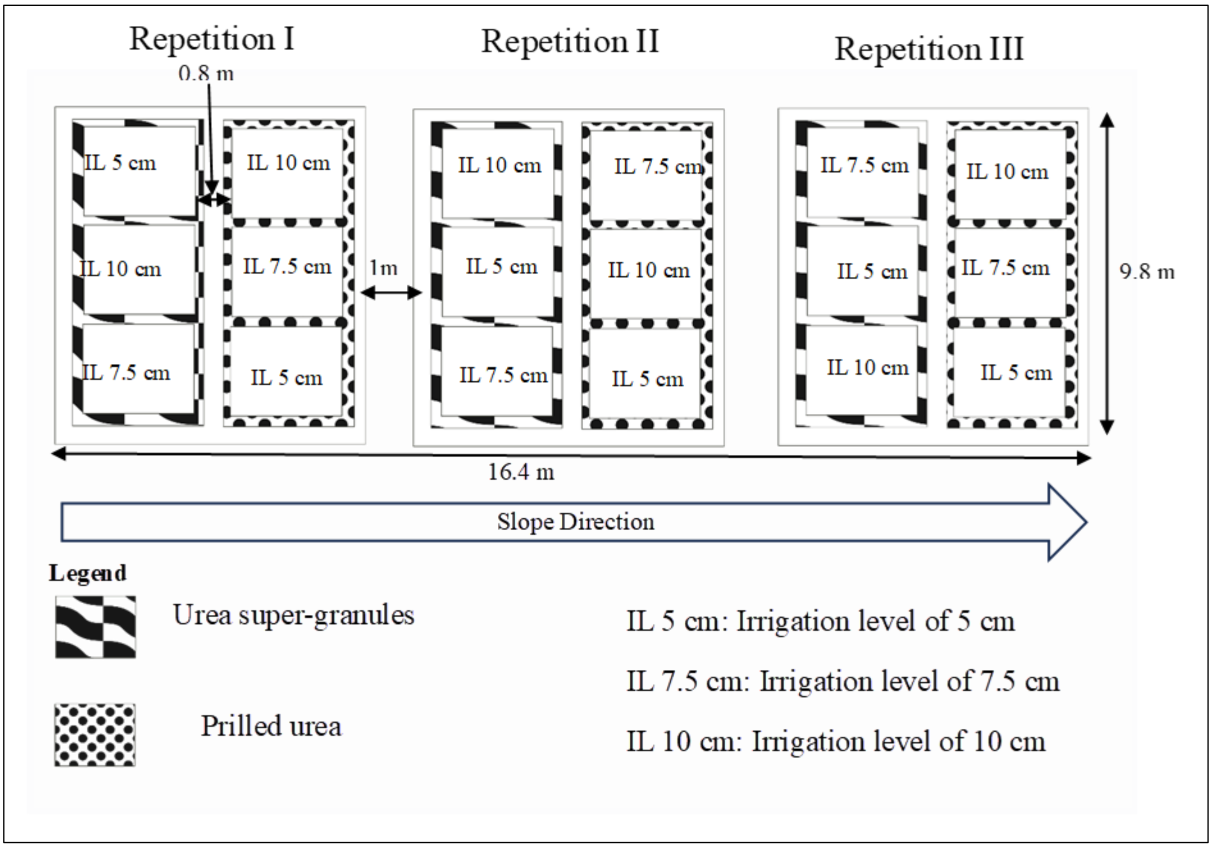


Figure 2: Description of the experimental design

2.3 Data collection procedure

2.3.1 Growth parameters measurement

After transplanting, a quadrat of 1 m^2 was installed in each plot for the assessment of growth parameters such as plant height and tiller number. Totally 16 hills per plot in each replicate were considered. Measurements were done, from each hill, at the vegetative stage, at active tillering and at panicle initiation. Plant height was measured from the base to tip of the highest leave using a ruler. Tiller were manually counted and the number was recorded.

2.3.2 Yield components and yield

At harvest, yield components (tiller number, sterile tiller, panicle number, panicle weight and grain weight per panicle) and yield were collected from the one-meter-square sample plot. Measurements were individually done on each hill. The total number of tiller and productive tillers were counted. Sterile tillers were obtained by subtracting productive tiller from total number. Panicles were cut from the base and the straw was separated. The number per plant was then registered.

Panicles per plant were randomly sampled using the class-interval method described by Kima et al. (2014) for panicle weight and grain weight measurement. Three selected panicles were considered. Panicles were first weighted and hand threshed for the determination of grains weight per plant using electric scale.

Grain yield were estimated using the following formula:

$$GY = (GW \times 160{,}000)/1000 \qquad \text{Equation 1}$$

Where GY is grain yield ($kgha^{-1}$), GW is grain weight per plant (g), 160,000 represents the number of hills per hectare and 1000 stands for conversion factor.

Five samples of grain per square were randomly picked to determine the weight of 1000-grains. 1000-grains were counted and weight using CONTADOR grain counting machine.

2.3.3 Water productivity, water savings, and production cost

Water productivity (WP, kg m^{-3}) was calculated as the ratio of grain yield on the volume of irrigation water using equation 2:

$$WP = GY/V \qquad \text{Equation 2}$$

Where WP is the water productivity (kgm^{-3}), GY is grain yield ($kgha^{-1}$) and V is the volume of irrigation water (m^3ha^{-1}).

The irrigation water savings were calculated using the water volume in IL10cm as the reference by applying the following formula:

$$WS = ((VIL10 - Vi)/VIL10) \text{ X } 100 \qquad \text{Equation 3}$$

Where WS is the water savings (%); V_{IL10} is the volume of water (m^3ha^{-1}) applied in IL10 treatment and V_i is the volume of water in treatment i (m^3 ha^{-1}).

The water cost for producing one kilogram of rice was determined based on the formula described by Kima et al. (2025):

$$WC = (1104 \text{ X } Vi) / Y \qquad \text{Equation 2}$$

Where WC is the water cost (F CFA) for one kilogram of rice; 1104 is the cost (F CFA) of 1 m^3 of water from national water office and Y stands for yield (kg ha^{-1}).

3 RESULTS AND DISCUSSION

3.1 Effect of treatments on other growth parameters

The **figure 3** illustrates that all treatments showed an increase in tillers number and plant height from vegetative stage to panicle initiation. The SGU-10 cm treatment achieved the highest tillers number, followed by PU-10 cm and SGU-5 cm. For plant height, SGU-5 cm and SGU-7.5 cm showed the highest height with value ranging from 100 to 101 cm, while PU-7.5 cm exhibited the lowest value of 90 cm. SGU treatments show good performance compared to PU treatments, demonstrating a clear interaction between fertilization and water treatment in favor to SGU. SGU-10 cm enhanced tillers number, while SGU-5 and SGU-7.5 cm positively influence plant elongation. These findings indicate a potential agronomic benefit of the SGU treatment when applied with specific irrigation level. Bhuyan et al. (2016) demonstrated that the application of SGU significantly increased the number of tillers and panicles per square meter compared to conventional prilled urea treatments. Savant and Stangel (1990) attribute this performance to the establishment of a localized "ammonium concentration gradient" in the root zone, which facilitate effective nitrogen absorption and thereby stimulating tillering. The SGU at a 10 cm irrigation level produced more tillers, while lower levels (5-7.5 cm) are associated with plant elongation. The deep placement of urea and the influence of irrigation significantly improved plant growth. Islam et al. (2026) reported that continuous flooding irrigation regimes is linked to more vegetative growth for plant height compared to more water-efficient regimes. Moreover, Hussain et al. (2015) showed that SGU enhances plant height more consistently than prilled urea, as it is less affected to losses through volatilization and runoff. Onofrio and Dupuy (2018) emphasized that the effectiveness of SGU is associated to the management of irrigation level. The use of excessively high irrigation levels can negatively impact the effectiveness of the granules if they are not adequately retained in roots zone. Overall, an irrigation level of 10 cm, combined with the SGU form, optimizes nitrogen availability for tillering, while lower levels are associated with an increase of plant height.

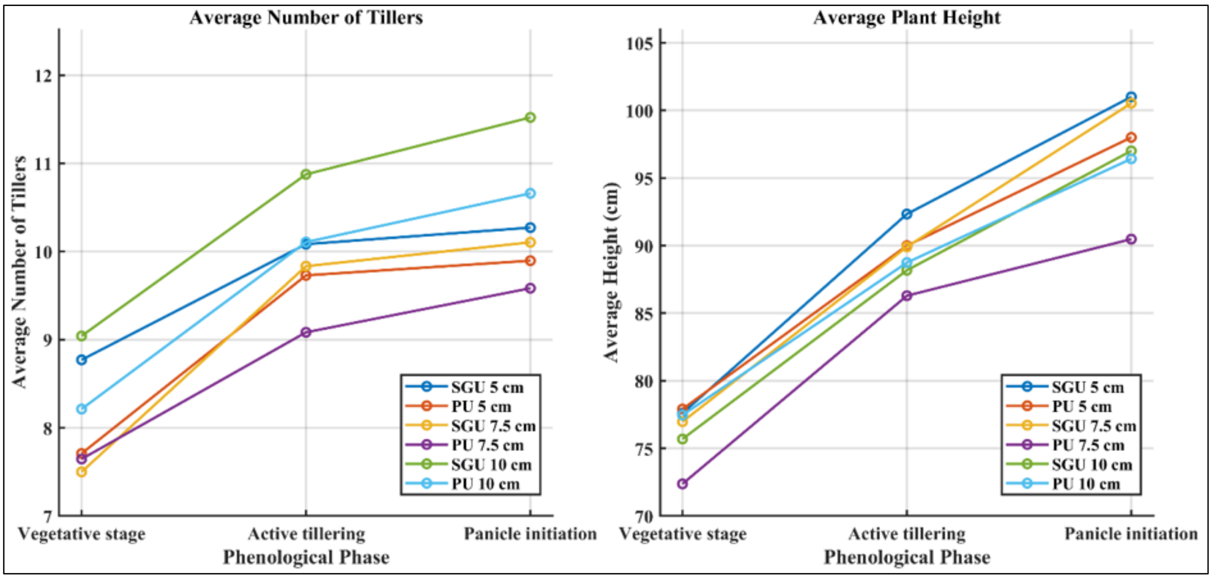


Figure 3: Average number of tillers and average plant heights during different phenological stages

3.2 Effect of treatments on some yield components

The **table 1** shows that growth parameters such as tiller number, panicle number and the percentage of sterile tiller were not significantly different in all treatments. However, the trend of average values of these parameters showed that the SGU-5cm had a near-zero sterility rate (0.19%), markedly lower than PU-10cm and SGU-7.5cm; tiller number and panicle number tended to be had higher values under SGU-10cm (10.85 and 10.58, respectively) compared with the other treatments indicating that treatments with greater vegetative growth did not necessarily conduct to yield establishing. The results concerning tiller and panicle numbers which were not statistically significant at the 5% level, despite numerical variations, was reported by Hossain et al. (2018) who similarly sowed that nitrogen applied PU or SGU can have the same effect on growth parameters with similar results observed across different treatments. Bhuyan et al. (2016) showed that SGU application significantly increases the number of tillers and panicles per unit area compared to conventional PU broadcasting, as the localized ammonium source provides a steady nutrient supply throughout the vegetative phase. However, according to the results obtained from this study, these higher vegetative values do not always lead to improved yield components. Islam et al. (2026) report that while excessive amount of irrigation water can support important vegetative growth while in the same time the effect on yield is marginal. Regarding sterility, the SGU-5cm show best efficient nitrogen and optimized water management. Islam et al. (2026) sustain that a thin water layer of 3 to 5 cm maximize irrigation water productivity without sacrificing biomass or yield. Moreover, Zhao et al. (2025) explain that when nitrogen or water supply is excessive, crops tend to prioritize the growth of stems and leaves over grain production.

Table 1: Growth parameters by treatment

Treatments	Tillers numbers	Panicles number	Sterile tillers (%)
SGU-5cm	9.27 ± 0.69	9.25 ± 0.68	**0.19 ± 1.62**
PU-5cm	10.12 ± 0.69	9.58 ± 0.68	4.90 ± 1.62
SGU-7.5cm	9.47 ± 0.69	8.98 ± 0.68	5.62 ± 1.62
PU-7.5cm	8.78 ± 0.69	8.49 ± 0.68	2.96 ± 1.62
SGU-10cm	**10.85 ± 0.69**	**10.58 ± 0.68**	1.96 ± 1.62
PU-10cm	9.89 ± 0.69	9.30 ± 0.68	5.62 ± 1.62
F	1.11	1.02	2.37
P	0.414	0.452	0.114
Significance	ns	ns	ns

Values are means ± SE. No significant (ns) differences were detected among treatments for any parameter ($p > 0.05$, Tukey/Šidák), so no grouping letters are shown. Bold indicates the numerically best-performing treatment for each parameter.

3.3 Effect of treatments on water productivity

The analysis of the four water-related agronomic parameters assessed in **table 2** shows that only the water saving was significantly affected by treatments. The Water savings with p < 0.001 separated treatments into three groups. SGU-5cm and PU-5cm treatments achieved the highest water savings (44–50%); SGU-7.5cm and PU-7.5cm treatments gave intermediate values (25–27%) while SGU-10cm and PU-10cm treatments showed no savings (0%) serving as the reference depth. However, fertilizer type did not show significant difference among treatments within a given irrigation depth. The water volume applied, water productivity of supplementary irrigation, and production cost did not significantly different among treatments. The significant effect at 5 cm irrigation level achieved water savings of 44 - 50% was reported Atwill (2021) reported that alternate wetting and drying (AWD) irrigation corresponding to the 5 cm irrigation level reduced the amount of water applied by 50% to 53% compared to a continuous flood. Similarly, Bhuyan et al. (2016) showed that using SGU in raised bed planting achieved water savings of 47.58% over conventional methods. The results showed that fertilizer type (SGU vs. PU) did not show significant differences within a given irrigation depth aligns with observations by Hossain et al. (2018). In their rice trials, they noted that application of nitrogen as either PU or SGU through applicators had the same effect on various growth and yield parameters, and they explicitly stated that all nitrogen treatments produced statistically similar grain yields in some instances.

Table 2: Water productivity parameters by treatment

Treatment	Water Volume (m^3/ha)	Irrigation water productivity	Water Savings (%)	Production Cost (FCFA/ha)
SGU-5cm	3,000 ± 1076.1 ^{a}	**1.03 ± 0.17 ^{a}**	**50.00 ± 2.68 ^{a}**	**1499.4 ± 489.6 ^{a}**
PU-5cm	3,000 ± 1076.1 ^{a}	0.80 ± 0.17 ^{a}	**50.00 ± 2.68 ^{a}**	1765.3 ± 489.6 ^{a}
SGU-7.5cm	4,500 ± 1076.1 ^{a}	0.70 ± 0.17 ^{a}	25 ± 2.68 ^{b}	2133.4 ± 489.6 ^{a}
PU-7.5cm	4,500 ± 1076.1 ^{a}	0.63 ± 0.17 ^{a}	25 ± 2.68 ^{b}	2352.4 ± 489.6 ^{a}
SGU-10cm	6,000 ± 1076.1 ^{a}	0.75 ± 0.17 ^{a}	0.00 ± 2.68 ^{c}	1916.7 ± 489.6 ^{a}
PU-10cm	6,000 ± 1076.1 ^{a}	0.66 ± 0.17 ^{a}	0.00 ± 2.68 ^{c}	2012.6 ± 489.6 ^{a}
F	0.27	0.74	61.93	0.44
P	0.919	0.609	<0.00001	0.810
Significance	ns	ns	***	ns

Means followed by the same letter within a column are not significantly different (Tukey/Šidák test, α = 0.05). ns = not significantly different at p < 0.05 ; ***: highly different (p < 0.001). Bold indicates the numerically best-performing treatment for each parameter.

3.4 Analysis of yield components and yield from various treatments

3.4.1 Mixed model analysis of panicle weight, 1000-grain weight and yield

The table 3 showed the results of mixed-model analysis of the effect of treatments on panicle weight, 1000-grain weight and yield. Panicle weight (F = 1.13, *p* = 0.40), 1000-grain weight (F = 1.47, *p* = 0.28) and paddy yield (F = 3.25, *p* = 0.053) showed no statistically significant difference among treatments. The SGU-5cm ranked highest on panicle weight (35.63 g, essentially tied with SGU-10cm at 35.40 g), 1000-grain weight (30.28 g), and paddy yield (4844.9 kg/ha). The yield gradient was substantial from 4844.9 kg/ha (SGU-5cm) down to 3266.7 kg/ha (PU-7.5cm). Moreover, SGU treatments outperformed PU treatment at every irrigation depth (SGU-5cm > PU-5cm; SGU-7.5cm > PU-7.5cm; SGU-10cm > PU-10cm), suggesting the fertilizer placement/type itself (SGU vs. PU) may be a more consistent driver of yield than irrigation depth alone. The yield ranking directly supports the results of SGU-5cm which showed the lowest spikelet sterility (0.19%) with the highest yield, despite having fewer tillers and panicles than SGU-10cm. This is consistent with the percentage of sterile spikelet which is a stronger yield determinant than raw panicle number in rice, and reinforces that SGU-10cm's greater vegetative growth did not conduct into a yield advantage. Since paddy yield narrowly missed significance (*p* = 0.053) and the two yield components were clearly non-significant, frame these results as a *trend* rather than a proven treatment effect. The performance of SGU over PU is supported by Savant and Stangel (1990), who confirm that the deep placement of SGU prevent nitrogen from significant loss mechanisms such as ammonia volatilization and denitrification, in comparison of PU application. Moreover Onofrio and Dupuy (2018) corroborate this finding by reporting yield increases of up to 23% with SGU relative to PU, showing the SGU fertilizer has a greater impact than the conventional manual application of PU. Furthermore, Bhuyan et al. (2016) also demonstrated that the application of SGU improve rice yield by 12.32% compared to conventional PU. Although, the SGU show interesting performance, the variability observed, particularly with SGU shows the necessity of controlling other factors such water management. Islam et al. (2026) confirm that water management is a critical factor, with irrigated rice responding to intensified nitrogen application. Furthermore, Savant and Stangel (1990) mention that the effectiveness SGU is based on the proper closure of holes post-application because if the holes remain open, nitrogen dissolves in the submergence water, rendering SGU as ineffective as PU.

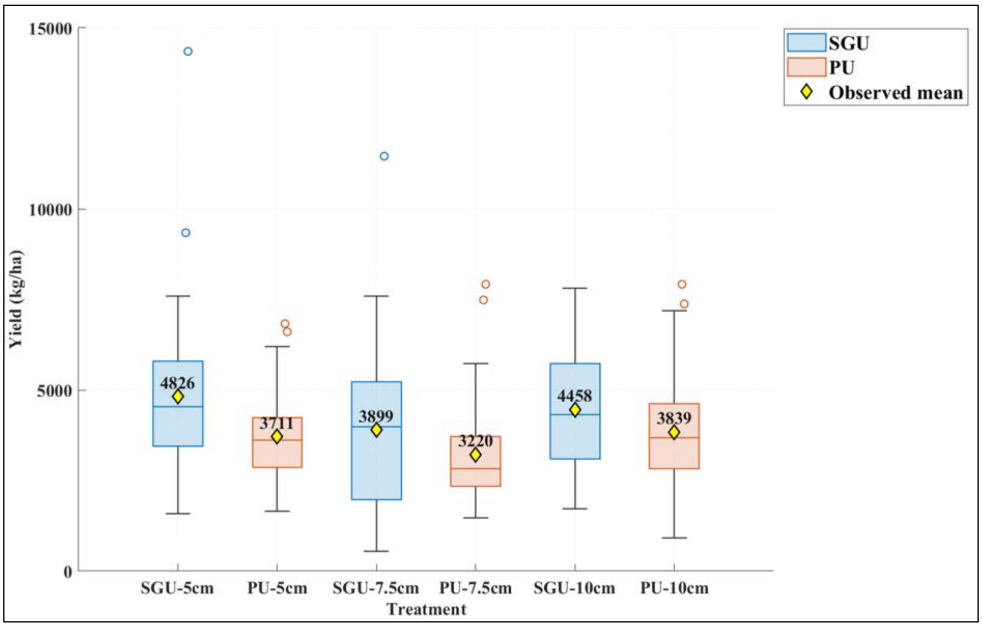
Table 3: Panicle weight, 1000-grain weight and yield by treatment

Treatment	Panicle Weight (g)	1000-Grain Weight (g)	Paddy Yield (kg/ha)
SGU-5cm	**35.63 ± 4.68**	**30.28 ± 3.75**	**4,844.9 ± 434.9**
SGU-7.5cm	31.33 ± 4.68	24.68 ± 3.75	4,816.3 ± 434.9
SGU-10cm	35.40 ± 4.68	27.86 ± 3.75	4,458.0 ± 434.9
PU-10cm	30.11 ± 4.68	23.90 ± 3.75	3,823.9 ± 434.9
PU-5cm	30.83 ± 4.68	23.90 ± 3.75	3,823.4 ± 434.9
PU-7.5cm	26.77 ± 4.68	20.42 ± 3.75	3,266.7 ± 434.9
F	1.13	1.47	3.25
P	0.405	0.282	0.053
Significance	ns	ns	ns

Values are means ± SE. ns: no significant difference at p > 0.5. Bold indicates the numerically best-performing treatment across all three components.

3.4.2 Observed yield distribution by treatment

This boxplot from **figure 4** supports the result obtained from mixed-model results and provides visual confirmation of yield ranking. Observed yield closely track the estimated marginal yield exhibiting highest value in SGU-5cm followed by SGU-7.5cm and SGU-10cm. SGU treatments visually outperforming PU treatments. This tendency across all three irrigation depths confirms that fertilizer type is the more an important yield driver. The large standard errors observed in the mixed model implied that the SGU-5cm and SGU-7.5cm treatments contain one or two high-value outliers (up to 14,300 kg/ha for SGU-5cm and 11,500 kg/ha for SGU-7.5cm) higher than the bulk of their respective distributions. These outliers pull the treatment means upward relative to their medians and they contribute to the wide confidence intervals seen in the mixed-model output (e.g., SGU-5cm: 95% CI 3309–6381 kg/ha) and to the yield effect narrowly missing the conventional 0.05 significance threshold despite a clear mean separation between the highest (SGU-5cm, 4845 kg/ha) and lowest (PU-7.5cm, 3267 kg/ha) treatments.



Yellow diamonds = observed (raw) treatment means. Model-based estimated marginal means (accounting for block effects) are reported in the text and Table 3.

Figure 4: Yield responses to the combination of different of Fertilizer (urea) and water treatment

3.4.3 Multivariate relationships on yield components, yield and water use efficiency

Principal Component Analysis (PCA) was implemented on yield components, yields and water utilization to investigate the relationships among these parameters and to identify the profiles of the different treatments. The analysis (**figure 5)** showed that, except the percentage of sterile tiller, all variables are well represented and can be reliably discussed. The first two principal components account for 64.5% of the total variance (PC1: 43.6%; PC2: 20.9%). The first axis, PC1, with a value of 43.6%, represents the productivity gradient. It is strongly and positively correlated with the weight of panicles, the weight of grains per panicle and grain yield. Thus, it shows the overall productive capacity of the rice in this trial. The second axis, PC2, with a value of 20.9%, is associated with the parameters related to water consumption (water volume, number of tillers and panicle number per plant) with those linked with water savings. It is revealed that, based on the type of urea used (SGU and PU), treatments were clearly separated. Loadings and contribution values from tables 4 and 5 confirmed that panicle weight (19.1%), grain weight per panicle (18.5%), and water productivity (17.4%) were the strongest contributors to PC1, while irrigation water volume (24.0%) and tiller number (21.0%) were the main contributors of PC2. In contrast, the percentage of sterile spikelet contributed marginally to both axes (<3%), indicating that, despite its apparent treatment-level trend, it was not a major source of variance across the dataset as a whole. Treatments based on SGU predominantly occupy the right side of the graph with high productivity. Among these, the SGU-5 cm combination shows the most effective by combining a high level of productivity and good water management. However, treatments based on PU are grouped on the left side of the graph, indicating significantly lower productivity. Increasing the irrigation depth from 5 to 10 cm tends to relocate the treatments upward on the graph, indicating an increase in water consumption and a rise in the percentage of infertile tillers without a proportional gain in yield. The results of the PCA confirm a strong interaction between the type of urea and the irrigation level. SGU at 5 cm was able to produce high yields while improving water efficiency. The fact that SGU treatments show the high productivity capacity, associated with panicle weight and straw yield is well-documented. The positioning of the SGU-5 cm combination as the most effective aligns with recommendations Islam et al. (2026) , who highlight that irrigation water level from 3 to 5 cm maximize water productivity without sacrificing biomass. However, the increasing of irrigation level to 10 cm leads to more infertile tillers without potential yield gains is explained by Zhao et al. (2025) who pointed out excessive water and nitrogen often promote exuberant vegetative growth at the expense of photosynthate translocation to the grains. While your PCA shows a clear separation; the linear mixed-model showed no significant differences at the 5% level. Hossain et al. (2018) reported trials where no significant yield differences were detected despite numerical variations, often due to high experimental variability linked to soil conditions. The PCA, by capturing nearly 65% of the total variance, successfully reveals a data structure that standard mean comparison tests may have struggled to isolate from experimental errors.

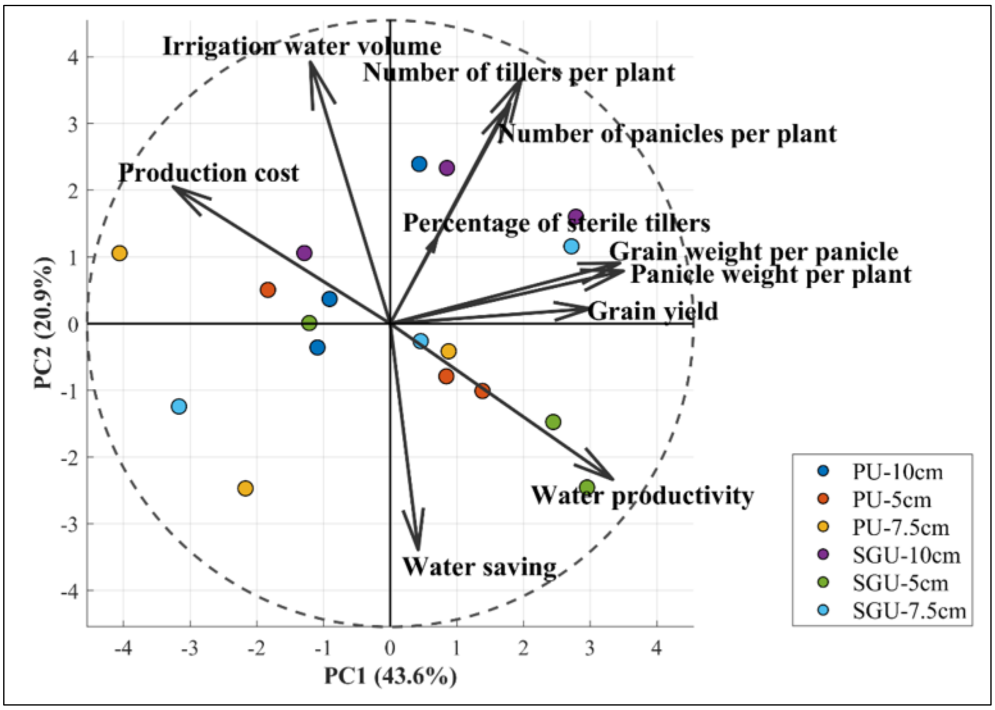


Figure 5: Principal Component Analysis with plants agronomic parameters

Table 4: Eigenvalues and variance explained by the principal components

Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	4.356	43.56	43.56
PC2	2.092	20.92	64.48
PC3	1.494	14.94	79.42
PC4	0.954	9.54	88.96
PC5	0.679	6.79	95.74
PC6	0.335	3.35	99.1
PC7–PC10	<0.07 each	<1.0 each	100

Only PC1 and PC2, jointly explaining 64.5% of total variance, were retained for interpretation.

Table 5: Loadings and contributions (%) of variables to PC1 and PC2

Variable	Loading PC1	Loading PC2	Contribution PC1 (%)	Contribution PC2 (%)
Panicle weight per plant	0.437	0.099	19.11	0.97
Grain weight per panicle	0.43	0.113	18.51	1.29
Water productivity	0.417	−0.292	17.38	8.53
Production cost	−0.407	0.257	16.58	6.58
Grain yield	0.375	0.028	14.04	0.08
Number of tillers per plant	0.246	0.459	6.05	21.04
Number of panicles per plant	0.224	0.412	5.04	16.97
Irrigation water volume	−0.150	0.49	2.24	24.01
Percentage of sterile tillers	0.088	0.161	0.77	2.59
Water saving	0.052	−0.424	0.27	17.95

grain yield, weight, and water productivity variables are the main contributors to PC1; irrigation water volume, tiller/panicle number, and water saving are the main contributors to PC2. Loadings are Pearson correlations between each variable and the component (data standardized prior to PCA); contribution (%) reflects each variable's relative importance to that axis.

4 CONCLUSION

This study shows that optimizing rice grain yields requires a synchronized management of water and urea supply. SGU performed better than prilled urea by improving tillering, plant growth, and nutrient use efficiency. A water depth of 5 cm was sufficient to achieve the best yield performance when combined with SGU, whereas 10 cm irrigation increased water use and vegetative growth without improving grain yield. Multivariate analysis also indicated a strong combination of SGU and moderate irrigation level, identifying the SGU–5 cm combination as the most promising option. Although the linear mixed model did not detect significant differences at the 5% level, the yields average means and PCA patterns support this treatment as the most efficient strategy. Overall, the results suggest that precision rice management using SGU and controlled irrigation water of 5 cm depth can improve productivity while saving water and nitrogen resources.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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