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RAISING RICE PRODUCTIVITY AND ENHANCING WATER DEFICIT TOLERANCE

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Abstract

Achieving sustainable rice cultivation requires an understanding of the intricate interactions between fertilizer application and water stress. This study looks at how different irrigation schedules, nitrogen fertilization rates, and potassium silicate supplements affect the Sakha 108 rice cultivar's growth characteristics, grain yield, and water usage efficiency. The experiment used a strip plot design with three duplicates. Four different irrigation regimes were used in the vertical plots: continuous flooding (W_1), irrigation at soil depths of 10 cm (W_2), 15 cm (W_3), and 20 cm (W_4) below the surface, and irrigation at a depth of 15 cm (W_3). The horizontal representing fertilization nine treatments were established: control (T_1), 55 kg N/ha (T_2), 55 kg N/ha +Si (T_3), 110 kg N/ha (T_4), 110 kg N/ha +Si (T_5), 165 kg N/ha (T_6), 165 kg N/ha + Si (T_7), 220 kg N/ha (T_8), and 220 kg N/ha +Si (T_9). In contrast to the water-stressed treatment (W_4), the study found a substantial positive association between growth, grain production, and its constituent parts under well-watered circumstances (W_1 and W_2). Furthermore, when compared to the other fertilization treatments, T_7 and T_9 produced better growth and grain yield. Unsurprisingly, W_4 utilized the least amount of irrigation water, whilst W_1 required the most. These results suggest that T_7 fertilization and W_1 irrigation work best together. However, when water was scarce, the best way to achieve the Sakha 108 rice cultivar's ideal growth, yield, grain quality, and water productivity was to apply W_3 irrigation and T_9 fertilization together.

Key words: Rice; Water deficit; Nitrogen fertilizer; Water productivity; Grain yield; Potassium silicate

Introduction

Rice constitutes a vital staple crop in Egypt, holding significant economic and cultural importance (Gaballah *et al*., 2021). It serves as Agriculture constitutes a primary economic activity for a significant segment of the world's population. Notably, rice farming accounts for almost 75% of Egypt's water resources, which is a substantial amount for the country's agricultural sector (Hameed *et al*., 2019). One essential requirement for rice production that is sustainable is the availability of water. Water scarcity and competition for this essential resource have, however, increased alarmingly in recent years (Gaballah *et al*., 2020). Sustainable agriculture is facing a major obstacle as population expansion has clearly surpassed the supply of freshwater resources (Mallareddy *et al*., 2023). Due to the substantial strain that the causes have placed on environmental resources, it is now necessary to investigate alternate water sources for use in agriculture. Adopting sensible water management and conservation techniques is essential to guaranteeing the long-term viability of rice cultivation. These strategies may encompass techniques such as reducing irrigation water application depth, maintaining soil saturation levels, and adopting intermittent irrigation practices (Arora *et al*., 2006). A water management technique called intermittent irrigation alternates periods of field drying with cyclical water supply (Keiser *et al*., 2002). Intermittent irrigation, according to studies, is the regulated delivery of water with the goal of maximizing crop production and water use efficiency (Fonteh *et al*., 2013). Depending on the management strategy used as well as the soil and climate conditions, the duration of dry intervals in intermittent irrigation systems can vary from one to over 10 days. This flexibility raises the possibility that intermittent rice irrigation could be a workable way to alleviate Egypt's water shortage. Although irrigation is still necessary to guarantee enough water for wholesome crop growth, fertilizer serves as a supplement by giving the soil the nutrients it needs to promote the best possible growth (Lu *et al*., 2022).

An essential ingredient for plant growth, nitrogen must be used effectively to produce the best possible crop yields. Therefore, optimizing grain yield in rice agriculture requires improving agronomic nitrogen use efficiency (NUE) (Wang *et al*., 2022). In rice farming, nitrogen has a variety of functions. To begin with, it is an essential component of chlorophyll, the pigment complex that absorbs sunlight and powers photosynthesis. Grain filling requires adequate nitrogen availability as well since it maximizes starch formation and helps produce plump, well-developed grains

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(Bhat *et al*., 2022; Jehangir *et al*., 2022**)**. Moreover, nitrogen is a fundamental component of amino acids, which are the building blocks of proteins. Rice with a higher protein content has better nutritional value in addition to commanding a higher market price (Jiang *et al*., 2023). According to research, the best way to maximize grain yield under continuously watered conditions is to apply nitrogen at a time when there is a moderate water deficit before to blooming. It is possible that a modest water stress period before flowering serves as a "priming" process, making rice plants more receptive to later nitrogen applications. Increased yields could result from this priming effect, which would maximize resource allocation for grain filling. Additionally, applying nitrogen fertilizer while there is a water shortage may reduce any losses due to leaching or volatilization, ensuring that the plants absorb and use it more effectively (Arouna *et al*., 2023). The physiological mechanisms of nitrogen absorption and water uptake are closely related. By encouraging an increase in root hydraulic conductivity, nitrogen application can help plants become more drought resistant. Increased amounts of abscisic acid (ABA) and aquaporin expression most likely cause this action. (Li *et al*., 2022).

Despite being abundant in plant waste and the Earth's crust, silicon is typically not regarded as a necessary nutrient for most plant species. However, silicon plays a critical role in rice plant growth and development. Applying silicon to rice has been demonstrated to have several beneficial impacts, including as improved nutrient and water intake, increased grain yield and quality, greater resistance to pests and diseases, and decreased water loss through transpiration. This latter advantage enables rice plants to withstand conditions of water scarcity more effectively (Zargar *et al*., 2019). Additionally, applying potassium silicate strengthens plant cell walls and provides an extra line of defense against water deficit stress (Gomaa *et al*., 2021). By lowering the need for fertilizer, silicon supplementation can further support sustainable rice production. For farmers looking to strike a balance between economic and environmental factors, this makes it a desirable choice to maintain grain yield output and improve agronomic efficiency in the face of harsher abiotic climate conditions, sustainable management techniques must be developed and put into practice (Tayade *et al*., 2022). A viable and sustainable solution to the problem of improving agronomic (NUE). This tactic encourages more effective nitrogen usage, which can result in better cereal development. Research has shown that in abiotic stress-prone conditions, silicon treatment increases crop growth and yield. Because of this property, Si can be used to increase crop yield production in challenging conditions (Barão, 2022). Considering these considerations, the purpose of this study was to evaluate the combined effects of innovative irrigation and nutrient management techniques on water efficiency and rice yield for the Sakha 108 cultivar when water supply is limited.

Materials and Methods

Experimental site: The Experimental farm of Sakha Research Station, Agricultural Research Center, Kafr El-Sheikh, Egypt, hosted a field experiment from May to September in the growing seasons of 2023 and 2024. The study examined how well the Sakha 108 rice cultivar-which takes about 135 days to mature, performed under different irrigation schedules and fertilization treatments that include potassium silicate and nitrogen. Table 1 displays the average weather information for the trial location from May to September. Notably, in every experimental plot, a barley crop (*Hordeum vulgare*) was grown before planting. Three replications per season were used in the strip-plot configuration used in the experiment. The experimental soil's chemical and physical characteristics are shown in Table 1.

There were 4 different irrigation treatments applied to the vertical plots. Among these treatments were: continuous floods (W_1), irrigation upon depletion of soil moisture to a depth of 10 cm (W_2), irrigation upon depletion of soil moisture to a depth of 15 cm (W_3), and irrigation upon depletion of soil moisture to a depth of 20 cm (W_4). A perforated tube inserted at the required depths (10, 15, and 20 cm) was used to apply irrigation water. When the water level in the tube dropped, signaling the need for replenishment, irrigation events started.

In contrast, the horizontal plots comprised nine distinct fertilization treatments, which are detailed as follows: T_1) control (without fertilizer); T_2) 55 kg N/ha; T_3) 55 kg N/ha + Si; T_4) 110 kg N/ha; T_5) 110 kg N/ha + Si; T_6) 165 kg N/ha; T_7) 165 kg N/ha + Si; T_8) 220 kg N/ha and T_9) 220 kg N/ha + Si. A 20 ml/l potassium silicate solution was applied topically 20- and 35-days following transplantation.

Table 1. Mechanical and chemical analysis of the experiments soil.

Soil chemical properties	Season	
	2023	2024
pH (1:2.5)	8.2	8.3
Ec (ds.m-1)	3.2	3.39
Organic matter%	1.22	1.35
Total nitrogen mg/ kg	433	513
Available P, mg/ kg	5.7	6.1
Available K (ppm)	214	238.8
CO3-	--	--
HCO3	5.50	5.6
SO4-	18.32	18.3
Ca++	10.11	11.38
Mg+	5	6.2
Na+	1.88	2
K+	16	15

To create ideal circumstances in the nursery for strong seed germination and seedling development, nursery beds were carefully leveled and tilled before transplanting. Standard nursery management procedures and recommended fertilization were followed. To promote germination, 108 Sakha rice seeds (144 kg ha-1) were imbibitional for 24 hours and then incubated for 48 hours. After that, pre-germinated seeds were dispersed across the flooded nursery. On May 13th and May 15th, respectively, the first and second seasons' seeds were sown in the nursery beds. A basal application of phosphorus fertilizer (35.5 kg P_2O_5 ha-1) was integrated into the soil in the permanent field as part of land preparation efforts. According to the study's design, each experimental plot, which had a total area of 30 m^2 (5 m x 6 m), was given a specific fertilizer treatment. Three to four 30-day-old seedlings were planted in each plot at the transplanting stage, with hills and rows spaced 20 cm apart. To reduce lateral water dispersion and enhance irrigation precision, each primary experimental unit was isolated by two-meter-wide ditches. Upon reaching the heading growth stage, plant samples were to precisely measure the amount of water applied during the experiment, a calibrated water meter was integrated into the water pump system. Plant samples were taken from five randomly chosen hills in each horizontal plot during the heading growth stage to estimate the leaf area index (LAI) and measure the accumulation of dry matter. Plant height and the total number of panicles were measured at harvest maturity from ten randomly chosen hills per plot. To measure panicle length, grain number per panicle, percentage of empty grains, panicle weight, and 1000-grain weight, ten panicles per plot were then harvested. Within each plot, a 16 m^2 randomly chosen region was used to calculate grain yield. Following harvest, the grain was standardized to 14% moisture content and translated to metric tons per hectare.

Determination of enzymatic activities: The antioxidant enzymes peroxidase (POX), catalase (CAT), and superoxide dismutase (SOD) were measured using recognized procedures outlined by Beauchamp & Fridovich (1971) and Kar & Mishra (1976).

Estimation of stress tolerance indices: Using the formula established by Bouslama & Schapaugh (1984) the yield stability index (YSI) was computed for each genotype to evaluate genotype-specific stress tolerance: YSI = Ys / Yp

Where:

Yp = Grain yield under continuous flooding (well-watered treatment) or control conditions
Ys = Grain yield under intermittent irrigation treatment

Water management and use efficiency: The water pumping system was equipped with a calibrated water meter to accurately monitor water application during the trial. A metric of water use efficiency called water productivity (WP) was computed as the grain yield per unit amount of water used (kg grains/m^3 water). Furthermore, the following formula was used to calculate water savings:

The percentage of water saved was determined by dividing the total amount of water applied under continuous flooding (Tn) by the total amount of water applied under intermittent irrigation treatments (Ts), then multiplying the result by 100.

Formula: Water saved (%) = [(Tn - Ts) / Tn] x 100

Statistical analysis

Analysis of variance (ANOVA) was used to statistically analyze the gathered data in accordance with the guidelines provided by Gomez & Gomez (1984). Duncan's Multiple Range Test (DMRT) as outlined in Duncan (1957) was used to compare the means of the various treatments. The statistical software package "COSTAT" was employed to execute all statistical analyses.

Results and Discussion

Growth characteristics: In both experimental seasons, Table 2 shows that irrigation regimes had a substantial impact on plant height, dry matter (DM), and leaf area index (LAI). There was no statistically significant difference between the W_1 and W_2 treatments, which showed the highest values. The W4 therapy, on the other hand, produced the lowest results. Furthermore, the combined application of silicon and nitrogen fertilizers led to significantly enhanced growth metrics compared to silicon-deficient plants under water-deficit conditions. Treatments T_7 and T_8, which included both silicon and nitrogen, achieved maximum values without significant variation from each other but surpassing T_1 in both seasons.

There was no significant interaction between irrigation regimes and fertilizer treatments on leaf area index, dry matter, or plant height in both seasons.

Grain yield and its attributes: Irrigation regimes and fertilizer treatments are two important factors significantly impacting yield attributes and grain yield. These include several panicles per hill, number of filled grains, and number of unfilled grains per panicle (Table 3). Results showed that the highest values of these characteristics were recorded with W_1, without any significant difference with W_2. There were no significant differences except the number of unfilled grains per panicle which increased with W_4. Also, this suggests that the combined application of nitrogen and silica can enhance panicle formation, grain filling, and overall yield potential. The impact of silicon and nitrogen fertilizers on panicle number per hill, filled grain count, and unfilled grain count per panicle was examined. Treatments combining potassium silicate and nitrogen resulted in significantly higher panicle numbers per hill and filled grain counts per panicle compared to other treatments in both growing seasons. While no statistically significant difference was found between T9, T8, and T7 for these parameters, a general trend of increased panicle number and filled grain count was observed with higher nitrogen levels and the addition of silica.

Conversely, the number of unfilled grains per panicle was highest in the T1 treatment during both seasons, indicating a negative correlation with increasing nitrogen and silica inputs. A significant interactive effect was observed between treatments on the number of panicles per hill in both growing seasons. Conversely, neither irrigation regimes fertilizer treatments exerted a significant influence on the number of filled or unfilled grains per panicle across both seasons. A significant interactive effect was observed between intermittent irrigation and fertilizer treatments on the number of panicles per hill in both growing seasons (Fig. 1). The combination of W_1 and T_9 yielded the highest number of panicles per hill, with no significant difference observed when compared to T_7. In contrast, the lowest panicle number was recorded under the W_4 and T_1 treatment combination in both seasons.

Fig. 1. Field Perforated tube technique for tracking the recession of water levels to depths of 10, 15, and 20 cm as a signal for irrigation replenishment.

Table 2. Leaf area index (LAI), dry matter at the heading stage, and plant height at harvest of Sakha 108 rice cultivar as affected by irrigation regimes and fertilizer treatments.

Treatment	LAI		Dry matter (g/m^2)		Plant height (cm)	
	2023	2024	2023	2024	2023	2024
Irrigation regime (W)						
W_1	4.71a	5.14a	1128.88a	1147.20a	98.66a	101.09a
W_2	4.32a	4.75a	1115.32a	1133.64a	96.30b	99.73a
W_3	3.41b	4.01b	1004.15b	1013.38b	87.76c	90.63b
W_4	2.88c	3.23c	869.00c	901.29c	82.49d	86.13c
F test	**	**	**	**	**	**
Fertilizer (T)						
T_1	2.73f	3.18f	817.81e	839.20f	88.11h	91.20h
T_2	3.25e	3.70e	893.74d	915.13e	89.69g	92.79g
T_3	3.38de	3.83de	924.80cd	946.19de	90.26f	93.35f
T_4	3.61cde	4.07cde	971.81c	993.20d	90.75e	93.84e
T_5	3.78cd	4.23cd	1059.32b	108071c	92.01d	95.10d
T_6	4.05bc	4.39c	1100.36b	1121.71c	92.32cd	95.41cd
T_7	4.700a	5.27a	1168.87ab	1190.27ab	92.66bc	95.75bc
T_8	4.37ab	4.82b	1119.57ab	1140.96bc	92.84ab	95.93ab
T_9	4.58a	5.04ab	1191.12a	1212.52a	93.11a	96.20a
F test	**	**	**	**	**	**
Interactions						
W × T	NS	NS	NS	NS	NS	NS

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

Optimal crop growth, development, and yield are significantly impacted by the agronomic practices of irrigation and fertilization. Irrigation and fertilization significantly influenced panicle weight, 1000-grain weight, and grain yield, as indicated in Table 4. Treatments W_1 and W_2 demonstrated comparable efficacy in optimizing these parameters, while treatment W_4 consistently yielded inferior results. Furthermore, fertilizer treatment T_9, when combined with suitable irrigation, maximized grain yields at 10.03 and 10.40 t/ha across both seasons. Conversely, treatment W_4 consistently recorded the lowest grain yield values of 6.95 and 7.41 t/ha. Also reveals that fertilizer treatments T9, T_8, and T_7 consistently excelled in terms of panicle weight, 1000-grain weight, grain yield, and straw yield. In contrast, treatment T_1 consistently exhibited the poorest performance across all measured parameters. It is worth noting that treatments T_9 and T_7 incorporated silicon application, a factor potentially contributing to improved plant resilience. The interaction between grain yields was significant in both seasons. On the other hand, the effects of irrigation regimes and fertilizer treatments on the panicle weight and1000-grain weight were insignificant in both seasons.

The interaction between irrigation regimes and fertilizer treatments was significant for grain yield in both seasons (Fig. 2). The combination of water management practices W_1 and W_2, which exhibited no significant difference, coupled with fertilizer treatment T_9, resulted in the highest grain yield, reaching across both seasons. Conversely, the lowest grain yield values of were observed under water management practice W_4 when paired with fertilizer treatment T_1 during the respective growth seasons.

Table 3. Number of panicles per hill, number of filled grains, and number of unfilled grains per panicle of Sakha 108 rice cultivar as affected by irrigation regimes and fertilizer treatment.

Treatment	No. of panicles/hill		Number of filled grains/ panicles		Unfilled grains percentage	
	2023	2024	2023	2024	2023	2024
W_1	25.1a	26.6a	130.5a	135.1a	5.58d	6.73d
W_2	24.9a	25.7a	126.1a	130.6a	6.18c	7.33c
W_3	20.4b	21.3b	119.5c	124.2b	12.20b	14.57b
W_4	18.8c	19.3d	113.4d	118.2c	18.28a	18.95a
F test	**	**	**	**	**	**
T_1	19.86g	20.68g	101.9g	114.8f	8.10g	9.43g
T_2	20.89f	21.99f	112.5f	118.3ef	9.13f	10.46f
T_3	21.44e	22.54e	117.6ef	121.0ef	9.68e	11.01e
T_4	21.41e	22.51e	120.5de	123.9de	9.65e	10.98e
T_5	22.75d	23.79d	124.6cd	127.9cd	10.99d	12.32d
T_6	23.26c	24.18c	127.6bc	131.0bc	11.49c	12.83c
T_7	23.76ab	24.58ab	132.2ab	135.6ab	12.00ab	13.33ab
T_8	23.52bc	24.32bc	129.0 abc	132.6abc	11.75bc	13.09bc
T_9	24.01a	24.86a	135.1a	138.4a	12.24a	13.58a
F test	**	**	**	**	**	**
Interactions						
W × T	**	**	NS	NS	NS	NS

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

Table 4. Panicle weight, 1000-grain weight, grain and straw yields of Sakha 108 rice cultivar as affected by irrigation regimes and fertilizer treatments.

Treatment	Panicle weight (g)		1000-grain weight (g)		Grain yield (t/ha)		Straw yield (t/ha)	
	2023	2024	2023	2024	2023	2024	2023	2024
Irrigation regime (W)								
W_1	3.97a	4.26a	25.75a	26.01a	10.03a	10.40a	12.97a	13.24a
W_2	3.74a	3.98a	25.40a	25.66a	9.75a	10.14a	12.68a	12.98a
W_3	3.01b	3.33b	20.07b	20.29b	8.63b	8.86b	11.42b	11.70b
W_4	2.44c	2.94b	17.43c	17.65c	6.95c	7.41c	10.48c	10.25c
F test	**	**	**	**	**	**	**	**
Fertilizer (T)								
T_1	2.81e	2.94e	21.25e	21.49e	6.38g	6.61h	8.82e	9.45h
T_2	3.05de	3.17de	21.49de	21.73de	7.41f	7.92g	10.44d	10.76g
T_3	3.16cde	3.28cde	21.57de	21.81de	7.70f	8.22f	11.05c	11.06f
T_4	3.19bcd	3.32bcd	21.84cde	22.08cde	8.18e	8.69e	11.06c	11.53e
T_5	3.27a-d	3.39a-d	21.95cd	22.19cd	9.27d	9.72d	12.55b	12.56d
T_6	3.38a-d	3.51a-d	22.35bc	22.59bc	9.77c	10.11c	12.89ab	12.95c
T_7	3.58ab	3.71ab	23.13a	23.37a	10.28ab	10.51ab	13.40a	13.35ab
T_8	3.53abc	3.66abc	22.83ab	23.07ab	10.03bc	10.25bc	13.37a	13.09bc
T_9	3.63a	3.75a	23.04a	23.28a	10.52a	10.79a	13.43a	13.63a
F test	**	**	**	**	**	**	**	**
Interactions								
W × T	NS	NS	NS	NS	**	**	NS	NS

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

The impact of different water management practices on plant drought tolerance and antioxidant activity. Drought-tolerant plants showed a marked increase in the activity of all three enzymes (CAT, SOD, and POD) (Table 5). The prolonged period from W_1 up to W_4 significantly improves drought tolerance recorded that the highest values of traits gave W_4 as compared with W_1 in both seasons. While effect combination of silicon and nitrogen fertilizers significantly increased compared to those without silica under water deficit. The maximum values that received the combination of silica and nitrogen fertilizers were T_9 without any significant differences with T_8 treatments followed by T_7 as compared with T_1 in both seasons. The interaction between Peroxidase was significant in both seasons. On the other hand, the effects of irrigation regimes and fertilizer treatments on the Catalase and superoxide dismutase were insignificant in both seasons.

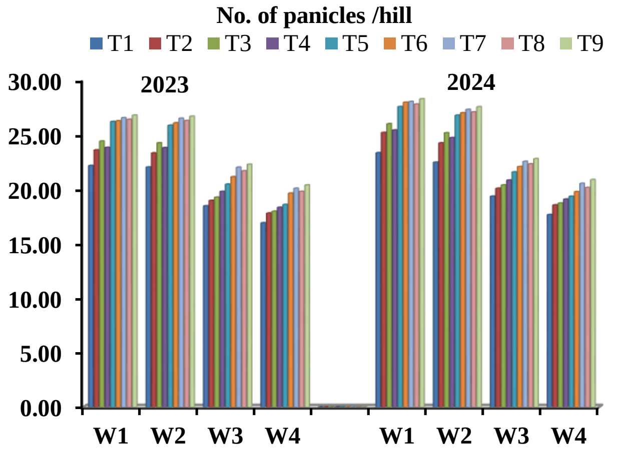

Fig. 1. Number of panicles /hills as affected by the interaction between irrigation regimes and fertilizer treatment.

W_1- continuous flooding, W_2- irrigation at 10 cm depth, W_3- irrigation at 15 cm depth, W_4- irrigation at 20 cm depth, T_1- control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. According to Duncan's multiple range tests, means having the same letter (s) are not significantly different.

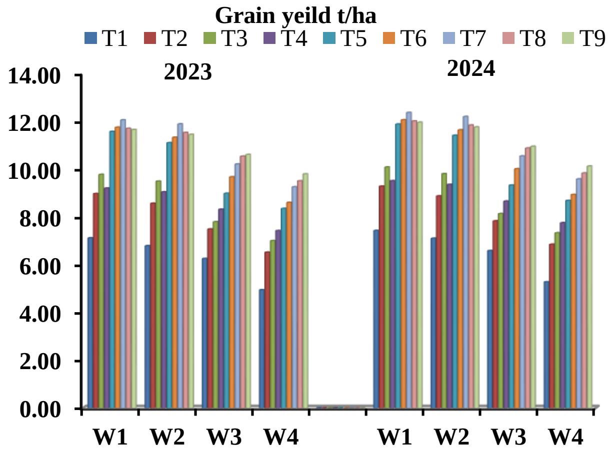

Fig. 2. Grain yield (t/ha) as affected by the interaction between irrigation regimes and fertilizer treatment.

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. According to Duncan's multiple range tests, means having the same letter (s) are not significantly different

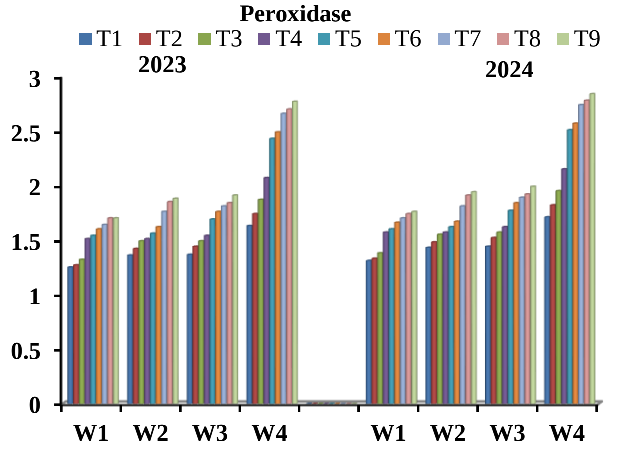

Fig. 3. Peroxidase as affected by the interaction between irrigation regimes and fertilizer treatment.

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si

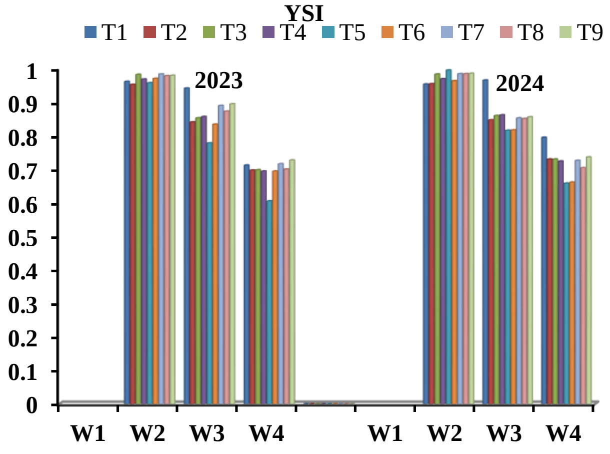

Fig. 4. Stress tolerance indices affected by intermittent irrigation and fertilizer treatment.

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si

Results in Fig. 3 showed that interestingly the irrigation regimes induced a significant effect on rice antioxidants in both seasons. The prolonged period from W_1 to W_4 treatment exposed to water stress in rice plants. The highest values of Peroxidase were obtained by W_4 as compared to W_1 with T_9 without any significant T_7 in both seasons. Drought stress influences physiological functions and biochemical activities that affect plant growth.

Grain quality

Milling characteristics: Table 6 showed that the effect of irrigation treatments on milling characteristics was significant in both seasons. Increasing the prolonged period from W_1 up to W_4 treatment significantly decreases milling characteristics. The highest values of hulling, milling, and head rice percentage values were obtained by W_1 treatment while the lowest value milling characteristics were obtained by W_4 treatment in both seasons. The results presented in Table 6 of milling characters, for potassium silicate + nitrogen rate, were significantly varied in both seasons. The highest hulling, milling, and head rice percentage values were obtained by the T_9 which was on par with T_6 treatment in both seasons. However, the lowest values of all traits were recorded by the T_1 treatment in the two seasons the effect of irrigation intervals and fertilizer treatments on hulling, milling, and head rice percentages were insignificant in both seasons.

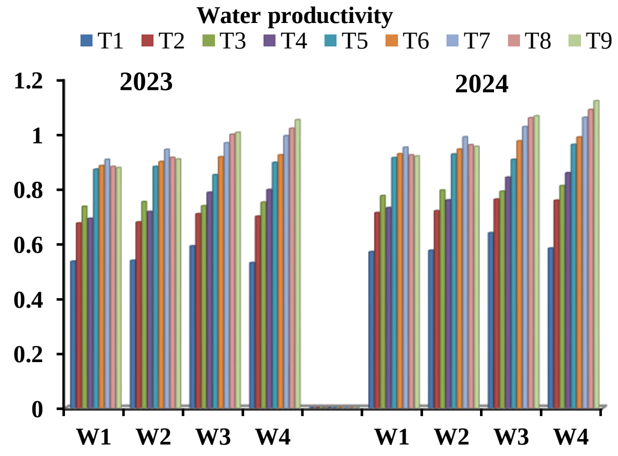

Fig. 5. Water productivity was affected by intermittent irrigation and fertilizer treatment.

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

Assessed drought resistance indexes: The yield stability index is a statistical measure used to evaluate how consistently a crop variety across stress environmental conditions. Figure 4 illustrates the indices of tolerance to intermittent irrigation and fertilizer treatments under low water supply conditions across both seasons. In comparison to W_1, treatments W_2 and W_3 exhibited superior performance in terms of water stress tolerance, with no significant disparities between them. Notably, T_9 excelled in the indices due to its high yield under T_2 conditions, followed by W_3 and subsequently W_4. In both seasons, T_9 under W_2 had the highest yield stability index, while W_3 under T_7 came in second. These results highlight T_9 exceptional performance and stability in W_2 circumstances, suggesting that it is best suited to intermittent fertilization and irrigation techniques in water-limited settings

Water management strategies: Among the many issues facing water management are pollution, population increase, and climate change. It also offers a lot of chances for creativity and cooperation, though. We can guarantee future generations' access to clean water by using sustainable water management techniques. Sustainable development depends on efficient water management as water shortage becomes a more significant worldwide issue.

The combined water consumption, water savings, and water productivity indicators for the two seasons are shown in Table 7. With water application rates of 13,300 and 13,020 m^3/ha in 2023 and 2024, respectively, the W_1 treatment showed the greatest rates. On the other hand, W_4 used the least amount of water, consuming 9,322 and 9,042 m^3/ha over both seasons. In the first and second seasons, W_2 was estimated to save 5.11% and 5.22% of water, respectively. Because of its longer watering interval, W_4 notably saved more water than W_1 in 2023 and 2024, by 29.90% and 30.55%, respectively.

Water productivity was highest for W_3 (0.816 and 0.861 kg/m^3) in seasons one and two, respectively, followed by W_2. The latter treatment was distinguished by its high grain yield coupled with efficient water utilization. Figure 5 showed that among fertilizer treatments, T_9, followed by T_7 and T_1 in terms of water productivity. The superior performance of T_9 was attributed to its higher grain yield. The combination of W_3 and T_9 yielded the maximum water productivity in seasons one and two, respectively. Conversely, W_4 with T_1 demonstrated the lowest water productivity and grain yield across both seasons.

Table 5. Catalase, peroxidase, and superoxide dismutase of Sakha 108 rice cultivar as affected by irrigation regimes and fertilizer treatment.

Treatment	Catalase		Peroxidase		Superoxide dismutase	
	2023	2024	2023	2024	2023	2024
Irrigation regime (W)						
W_1	0.093d	0.103d	1.501d	1.561d	0.224d	0.264d
W_2	0.0968c	0.116c	1.604c	1.661c	0.252c	0.292c
W_3	0.107b	0.127b	1.650b	1.731b	0.284b	0.344b
W_4	0.113a	0.133a	2.262a	2.343a	0.335a	0.415a
F test	**	**	**	**	**	**
Fertilizer (T)						
T_1	0.094f	0.112f	1.403f	1.470f	0.261f	0.316f
T_2	0.095ef	0.113ef	1.465f	1.535f	0.264e	0.319e
T_3	0.096e	0.114e	1.543e	1.613e	0.273d	0.328d
T_4	0.100d	0.117d	1.659d	1.729d	0.276cd	0.329cd
T_5	0.100d	0.118d	1.808c	1.878c	0.276c	0.331bc
T_6	0.101d	0.119d	1.866c	1.937c	0.276bc	0.332bc
T_7	0.107c	0.124c	1.966b	2.037b	0.282a	0.337a
T_8	0.11b	0.127b	2.010ab	2.086ab	0.278b	0.333b
T_9	0.117a	0.134a	2.065a	2.135a	0.282a	0.337a
F test	**	**	**	**	**	**
Interactions						
W × T	NS	NS	**	**	NS	NS

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

Table 6. **Hulling, milling, and head rice (%) of Sakha 108 rice cultivar as affected by irrigation regimes and Fertilizer treatment in both seasons.**

Treatment	Hulling		Milling		Head rice (%)	
	2023	2024	2023	2024	2023	2024
Irrigation regime (W)						
W_1	79.34a	79.92a	74.25a	74.69a	61.10a	61.99a
W_2	78.36b	79.04b	73.52b	74.15b	60.32b	61.21b
W_3	76.10c	76.51c	70.32c	71.25c	58.12c	59.01c
W_4	72.21d	72.70d	68.14d	67.85d	53.77d	54.74d
F test	**	**	**	**	**	**
Fertilizer (T)						
T_1	73.44e	73.98e	68.49e	68.92e	55.26e	56.17e
T_2	75.05d	75.59d	70.10d	70.53d	56.87d	57.78d
T_3	75.66c	76.20c	70.48d	70.91d	57.48c	58.39c
T_4	75.68c	76.22c	70.97c	71.40c	57.50c	58.41c
T_5	77.17b	77.71b	72.22b	72.65b	58.99b	59.90b
T_6	77.50ab	78.04ab	72.56ab	72.99ab	59.33ab	60.24ab
T_7	78.02a	78.56a	73.07a	73.50a	59.84a	60.75a
T_8	77.98a	78.52a	73.04a	73.47a	59.81a	60.72a
T_9	78.06a	78.60a	73.12a	73.54a	59.89a	60.80a
F test	**	**	**	**	**	**
Interactions						
W × T	NS	NS	NS	NS	NS	NS

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, W_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth, T_1- Control, T_2- 55 kg N/ha, T_3- 55 kg N/ha + Si, T_4- 110 kg N/ha, T_5- 110 kg N/ha + Si, T_6- 165 kg N/ha, T_7- 165 kg N/ha + Si, T_8- 220 kg N/ha, T_9- 220 kg N/ha + Si, * = Significant at 0.05 level, ** = Significant at 0.01 level and NS= Not significant. Means having the same letter (s) are not significantly different according to Duncan's multiple range tests

Table7. Response of intermittent irrigation on the total water used, water saved, and water productivity.

Irrigation regimes	Total water applied (m^3/ha)		Grain yield (t/ha)		Water saved (%)		Water productivity	
	2023	2024	2023	2024	2023	2024	2023	2024
W_1	13300	13020	10.03	10.40	-	-	0.754	0.798
W_2	12620	12340	9.75	10.14	5.11	5.22	0.772	0.821
W_3	10566	10286	8.63	8.86	20.55	20.99	0.816	0.861
W_4	9322	9042	6.95	7.41	29.90	30.55	0.745	0.819

W_1- Continuous flooding, W_2- Irrigation at 10 cm depth, w_3- Irrigation at 15 cm depth, W_4- Irrigation at 20 cm depth

Discussion

Since water is necessary for healthy agricultural development, water scarcity, and inadequate management have a detrimental impact on crop output. This decrease in LAI, DM, and plant height can be attributed to a lack of water, hurting plant growth and reduction in the number of the tiller, total leaf area, and death of the lower leaves. These results agree with those obtained by (Toscano & Romano, 2021). The observed increase in panicle number may be attributed to the pronounced influence of water on cellular division and elongation. Additionally, when water availability increased, improved nitrogen intake, dry matter buildup, and vegetative growth were probably facilitated by improved root development and higher nitrogen mobility in the soil solution. These results are consistent with earlier studies by Bhattacharya (2021). There was no discernible difference between treatments T_7 and T_8, which showed the highest values for plant growth metrics. Silica treatment prevented lower leaves from self-shading by producing plants with upright growth tendencies. Increased leaf area index, dry matter accumulation, and plant height are indicators of improved light interception, photosynthetic efficiency, and overall plant growth. These results support the findings of Olagunju *et al*., (2022). Additionally, nitrogen plays a crucial role in increasing yield and photosynthetic capacity, especially in improving cellular elongation, dry matter accumulation, and leaf area, all of which contribute to a taller plant (Abdou *et al*., 2021). Fertilizer treatments and irrigation schedules have a major influence on grain output and yield characteristics. These include panicle length, panicle weight, 1000-grain weight, number of panicles per hill, number of full and unfilled grains within each panicle, and grain and straw yield. Within the plant, water serves as a solvent and a medium for the movement of minerals and nutrients. Higher soil moisture content translates to better absorption and transportation of these essential elements, which encourages strong root growth and function. Development, promotes cell division and elongation in shoots, fueling vital processes like photosynthesis and enzyme, and leads to more tillers and panicles, water facilitates the movement of sugars and other photosynthates from leaves to panicles the necessary resources for proper growth and the number of panicles, number of filling grains. Similar findings have been reported by Umair *et al*., (2020). Also, sufficient moisture ensures efficient translocation of these resources through the phloem to developing panicles, fueling their growth and ultimately contributing to higher grain weight and grain filling for higher grain yield. Similar findings have been reported by Godoy *et al*., (2021). Water deficiency impairs the functioning of roots and limits the uptake of water and nutrients. The decreased osmotic pressure within cells causes' stomata closure, further hindering the intake of CO_2 for photosynthesis and the movement of nutrients through transpiration. Under water stress, the production of free radicals and oxidizing agents increases due to impaired metabolic processes. These free radicals damage plant cells and tissues, leading to premature aging and reduced yield. Similar findings have been reported by Yang *et al*., (2020). Also, data showed that the increasing nitrogen levels along with the addition of silica improved the above-mentioned traits, except for the number of unfilled grains per panicle. Nitrogen is crucial for cell division and elongation and essential metabolic processes for grain development leading to more tillers, higher grain weight and grain filling for higher grain yield. Similar findings have been reported by Luo *et al*., (2020). While silicon can mitigate stress and protect developing grains from diseases and pests. Silicon strengthens rice stems, making them less susceptible to lodging and breaking under strong winds. When applying silica through spraying, the silica particles combine with essential plant components, leading to a reduction in the dimensions and diameter of the stomata apertures, this decreases the transpiration process, minimizing water loss and aiding in the maintenance of optimal water levels within the plant. Similar findings have been reported by Barbosa *et al*., (2023). The interaction between irrigation depth and nitrogen fertilizer application is an interesting aspect of your findings. Investigating silica's possible contribution to raising rice yield is necessary for this. Both approaches may give the rice plants in the root zone enough access to water and nutrients, producing yields that are comparable. Deeper flooding may result in reduced soil oxygen levels, which could affect root growth and nutrient uptake, ultimately lowering yields. Additionally, the anoxic conditions at greater soil depths may result in larger nitrogen losses through denitrification. By increasing cell wall stiffness and membrane integrity, Si can help reduce abiotic stresses including drought, salinity, and high temperatures. It can also increase the amount of chlorophyll in leaves and the efficiency of light capture, which will increase photosynthetic rates and biomass output. Plant nitrogen uptake may be impacted by silica, although the impact is complicated and contingent on several variables: Benefits: silica can increase root growth, boost the effectiveness of nutrient utilization, and lessen nitrogen loss brought on by stress, which may result in higher nitrogen absorption. Negative effects: Excessive silica levels may cause decreased nitrogen absorption by competing with nitrogen for absorption sites and obstructing nitrogen transport throughout the plant. There have been similar findings reported by Raza *et al*., (2023). Higher plant height and the quantity of tillers per hill were the main variables associated with the highest possible output of straw. Abiotic and biotic stress tolerance was enhanced, and lodging was reduced in plant sections with silicon accumulation. All these factors could have ultimately resulted in a higher straw yield. These results align with the study carried out by (Patil *et al*., 2017; Shankar *et al*., 2021). The effects of various water management techniques on the antioxidant activity and drought tolerance of plants. All three enzymes' (CAT, SOD, and POD) activity was significantly higher in drought-tolerant plants. It's possible that persistently flooded plants have lesser antioxidant activity because they don't need as many defensive systems in a consistently saturated environment. On the other hand, when encountering water constraints, drought-tolerant plants use their antioxidant defense mechanism to scavenge toxic reactive oxygen species (ROS) produced under stress. Silicon can also lessen water loss by controlling transpiration. By triggering antioxidant enzymes like peroxidase and catalase, which scavenge dangerous reactive oxygen species (ROS) and free radicals, silica plays a critical role in plants' ability to withstand stress. This stops premature aging and preserves cellularity by shielding plant cells from oxidative damage and allowing them to continue performing vital tasks even in the face of constraints. The research by Laxa *et al*., (2019) is in line with these findings. Nitrogen and silicon play complementary functions in rice cultivation optimization. The metabolic mechanisms that support grain production depend on nitrogen, although silicon increases the plant's ability to tolerate stress. By offering structural support and defense mechanisms during the vegetative and reproductive growth stages, silicon plays a critical role in enhancing plants' resistance to stress. Plants usually close their stomata in response to drought to reduce transportational water loss. The depletion of internal carbon dioxide is accelerated by the greater diffusion barrier caused by ongoing photosynthetic activity under these circumstances. Peroxisomes produce photorespiratory hydrogen peroxide because of the ribulose-1,5-bisphosphate oxygenation process being triggered by this CO_2 constraint. These findings are in line with those of Prathap *et al*., (2019). New irrigation technology, such smart irrigation that makes use of sensors and the Internet of Things, should be taught to farmers.

Conclusion

The simultaneous application of silica and nitrogen exhibits potential for enhancing plant growth, development, and grain yield. Under conditions of restricted water availability, findings indicate that an irrigation depth of 15 cm combined with a nitrogen application rate of 165 kg N/ha, supplemented with silica, could optimize grain yield and water productivity for the Sakha 108 rice cultivar.

Statements and Declarations

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Author's Contribution: H. Ghazy conceptualized and designed the study. H. Ghazy, I. El-Refaee, O.Elshayb, A. Okasha, Hanan A. Taha, A. Gharieb, and W. Sorour carried out the field experiments and data collection at the Sakha Agricultural Research Station. A. Mohammed, M. Helal, and F. Alzuaibr contributed to the formal analysis and software validation. H. Ghazy performed the statistical analysis and wrote the original draft of the manuscript. A. MOHAMMED managed the project administration and performed the final review and editing. All authors read and approved the final manuscript.

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