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High Nitrogen Fertilization Modulates Morpho-Physiological Responses, Yield, and Water Productivity of Lowland Rice under Deficit Irrigation

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Abstract: Sustainability of rice production under flooding conditions has been challenged by water shortage and food demand. Applying higher nitrogen fertilization could be a practical solution to alleviate the deleterious effects of water stress on lowland rice (*Oryza sativa* L.) in semi-arid conditions. For this purpose, field experiments were conducted during the summer of 2017 and 2018 seasons. These trials were conducted as split-split based on randomized complete blocks design with soil moisture regimes at three levels (120, 100 and 80% of crop evapotranspiration (ET_c), nitrogen fertilizers at two levels (N₁—165 and N₂—200 kg N ha^{−1}) and three lowland Egyptian rice varieties [V₁ (Giza178), V₂ (Giza177) and V₃ (Sakha104)] using three replications. For all varieties, growth (plant height, tillers No, effective tillers no), water status ((relative water content RWC, and membrane stability index, MSI), physiological responses (chlorophyll fluorescence, Relative chlorophyll content (SPAD), and yield were significantly increased with higher addition of nitrogen fertilizer under all water regimes. Variety V₁ produced the highest grain yield compared to other varieties and the increases were 38% and 15% compared with V₂ and V₃, respectively. Increasing nitrogen up to 200 kg N ha^{−1} (N₂) resulted in an increase in grain and straw yields by 12.7 and 18.2%, respectively, compared with N₁. The highest irrigation water productivity (IWP) was recorded under I₂ (0.89 kg m^{−3}) compared to (0.83 kg m^{−3}) and (0.82 kg m^{−3}) for I₁ and I₃, respectively. Therefore, the new applied agro-management practice (deficit irrigation and higher nitrogen fertilizer) effectively saved irrigation water input by 50–60% when compared with the traditional cultivation method (flooding system). Hence, the new proposed innovative method for rice cultivation could be a promising strategy for enhancing the sustainability of rice production under water shortage conditions.

Keywords: *Oryza sativa*; drought stress; chlorophyll fluorescence; varieties; grain yield and water productivity

1. Introduction

Rice (*Oryza sativa* L.) is a staple food crop for about half of the world's population and ranks 2nd in production after wheat [1,2]. Globally, in 2018, the productivity of rice approximately amounted to 700 million tons, which was produced from 167 million hectares, by an average grain yield of 4.2 tons per hectare [2]. Rice (*Oryza sativa* L.) is being cultivated in various agro-ecosystems: irrigated rice, rainfed lowland rice, upland rice, and flood-prone rice. More than 75% of rice production is supplied by irrigated

lowland rice [3]. Generally, rice has been grown under flooded conditions, maintaining a continuous water depth by 5–10 cm [4]. Under flooded conditions, a large amount of irrigation water supply is required, which is not only used for the growth and development of rice plants but also as a management technique during rice cultivation [5,6]. In a puddled rice field, the consumption of water depends on the rates of evaporation, transpiration, and water losses by percolation, seepage, and surface runoff. The irrigation water demand for rice crops under the traditional flooded system is more than $20,000 \text{ m}^3 \text{ ha}^{-1}$ which is more than 3–4 times that of its biological needs from water, which ranges between $6000\text{--}8000 \text{ m}^3 \text{ ha}^{-1}$ [7].

With increasing water scarcity, rapid population growth, increased urbanization, and the expected potential climate change, the sustainability, food production, and ecosystem services of rice fields are threatened [7–10]. It is estimated that, by 2025, 15–20 million ha of irrigated rice will suffer from some degree of water scarcity. Rice production in the Nile Delta of Egypt consumes about 11 billion m^3 of irrigation water which represents about 20% of the whole quantity of irrigation water used in agriculture ($55.5 \text{ billion}^3/\text{year}$). In addition, many studies conducted in Egypt concluded that the total seasonal water input to rice under continuous flooding ranges between $16,190\text{--}21,428 \text{ m}^3 \text{ ha}^{-1}$ [11]. Therefore, Egypt's policymakers annually reduce the allotted area for rice cultivation, which has decreased by 59% from 745,000 ha to 304,080 ha during the past ten years (2008–2018) [2].

Therefore, good water governance should be adopted to develop socially acceptable, economically viable and environmentally sustainable novel rice-based systems that tend to reduce water losses and enhance crop productivity challenged by high evaporative demand and severe shortages of water supply. Hence, cultivating rice aerobically in non-puddled and non-saturated soils under water-saving irrigation technique as deficit irrigation could be a promising water-saving strategy to cope with water scarcity.

The application of irrigation water below the ET demand is termed deficit irrigation, aiming at optimization in economic output when water is very limited [12]. Plants under deficit irrigation receive a lower amount of irrigation water than their full water requirements either at specific crop growth stages or during the total cultivation period [12]. Consequently, under deficit irrigation technique, plants are subjected to water stress to some extent [13,14].

However, rice is very sensitive to water stress. Water stress negatively affects the growth and productivity of crops [15,16]. Physiological functioning in rice plants [17] viz root length density, root moisture extraction, the rate of apical development, canopy size, leaf elongation rate, leaf rolling, transpiration rate, relative water content, biomass production, spikelet number, spikelet sterility, panicle development, grain size and grain yield [17,18] may be drastically reduced due to water stress, if it occurs during vegetative or reproductive stages of rice, depending upon the stress severity and cultivar tolerance.

However, optimal application of nitrogen also plays a valuable role in combating drought [19]. Nitrogen (N) is considered a key component of many organic compounds. Nitrogen is one of the most essential nutrient elements for rice growth and metabolic processes [20,21]. Nitrogen represents a vital role in improving yield production and enhancing the photosynthetic activity especially during the grain filling stage of rice crops. Hence, the efficient use and nitrogen management respecting crop production is an urgent case for maximizing crop productivity, environmental safety with increasing economic returns [22,23] also concluded that increasing nitrogen supplying dose up to 144 kg N ha^{-1} improved and significantly affected plant growth, grain yield and yield components. Ref. [24] reported that increasing nitrogen application rates from 120 to 190 kg N ha^{-1} significantly improved plant height, panicle length, filled grains by panicle and grain yields. Ref. [25] reported that the inoculation with *G. diazotrophicus* Pal5 strain was alleviated deleterious effects of drought stress on rice plants, and improved biomass and grain yield. In addition, [26] noted that there were significant increases in plant growth traits, yield parameters and grain yield due to increasing nitrogen supplying rate of 100, 200 and 300 kg N ha^{-1} . Ref. [27] observed an interaction between soil moisture deficit and N supply

rates on the activity of photosynthesis and transpiration processes in rice. Application of N fertilizer resulted in a significant increase in grain yield of rainfed-lowland rice under water deficit, where observed the optimal timing of N application for continuously irrigated rice was when the rice was exposed to moderate water deficit before flowering [28]. The absorption and utilization of water and nitrogen nutrition are two coupled physiological processes [29,30]. Supplying plants with N can increase drought resistance by increasing root hydraulic conductivity (Lpr) through increased abscisic acid (ABA) and aquaporin expression [31–34].

Therefore, the current study hypothesized that exogenous application of N-fertilizer may positively affect the rice performance, irrigation water productivity, chlorophyll fluorescence, water status as well as yield of some drought-stressed lowland rice varieties. Accordingly, the recent investigation was conducted to evaluate the effect of new applied water and nutrition environment on water-saving capacity and productivity of some lowland rice varieties under water-scarce conditions in arid and semi-arid regions.

2. Materials and Methods

2.1. Experimental Design, Treatments, and Cultural Practices

The current investigation was conducted at the experimental station farm of Faculty of Agriculture, Fayoum University, Egypt, (30°56_N latitude, 75°52_ longitude). The site is described by arid climate type, hot in summer. The meteorological data in Table 1 show that the highest mean values of maximum temperature, minimum temperature and relative humidity % by 40.4 °C, 26 °C and 45%, respectively, were recorded during August. The maximum pan evaporation rate (mm day^{−1}) 7.5 occurred in June month and decreased to its lowest value 5.3 in September during the two successive seasons of rice cultivation (2017–2018).

Table 1. Meteorological data recorded at Meteorological observatory of Fayoum governorate, during crop growing seasons of 2017 and 2018.

Month	Year	Temperature °C			Relative Humidity (%)	Wind Speed (m s ^{−1})	Pan Evaporation (mm day ^{−1})
		Max.	Min.	Mean			
May	2017	35.2	20.9	28.1	39.6	4.2	6.5
	2018	37.3	22.6	29.9	41.0	3.9	6.6
June	2017	36.0	21.7	28.9	42.1	5.2	7.3
	2018	40.3	24.4	32.3	38.6	5.0	7.5
July	2017	37.0	21.8	29.4	35.5	4.0	6.9
	2018	39.3	23.9	31.6	37.8	3.7	6.9
August	2017	40.4	26.0	33.2	36.9	1.9	6.2
	2018	36.4	23.0	29.6	45.2	3.7	6.3
September	2017	38.3	13.8	31.0	36.6	2.0	5.5
	2018	35.3	21.0	28.0	44.3	3.5	5.3

Max, and Min are maximum, and minimum temperatures, respectively.

2.2. Soil Characteristics

Table 2 shows that the soil is clay-textured. Soil moisture content % (at 0.33 bar and at 15 bar), available water %, bulk density (g cm^{−3}) and saturated hydraulic conductivity (cm h^{−1}) were determined at the surface soil layer (0–0.25 m) and amounted to 34.33, 14.60, 19.73, 1.40 and 1.2, respectively, and by 32.19, 13.06, 19.13, 1.36 and 0.9, respectively, a subsurface (0.25–0.5 m).

According to the data represented in Table 2, organic matter content was 1.2%, available nitrogen—0.04%, available phosphorus (mg kg^{−1} soil) 5.84 and available potassium 61.9 (mg kg^{−1} soil), ECe, (dS·m^{−1}), pH, CEC (cmol_e kg^{−1}) and CaCO₃ (%) were measured and amounted 2.62, 7.76, 14.10 and 4.81, respectively. Soil physical and chemical properties were determined according to [35,36].

Table 2. Some initial physical and chemical properties of the experimental soil.

Physical Properties									
Layer (cm)	Particle Size Distribution				Bulk Density (g cm ⁻³)	K _{sat} Cm h ⁻¹	FC (%)	WP (%)	AW (%)
	Sand %	Silt %	Clay %	Texture Class					
0–25	10.00	20.00	70.00	Clay	1.40	1.20	34.33	19.73	14.60
25–50	7.00	21.00	72.00	Clay	1.36	0.90	32.19	19.13	13.06
Physical Properties									
	pH	ECe (dS·m ⁻¹)	CEC (cmole kg ⁻¹)	CaCO ₃ (%)	Organic Matter (%)	N (%)	P (mg kg ⁻¹ soil)	K (mg kg ⁻¹ soil)	
0–25	7.76	2.62	14.10	4.81	1.20	0.04	5.8	61.90	
25–50	7.78	2.52	14.00	4.76	1.10	0.04	5.6	60.00	

K_{sat} = Hydraulic conductivity, FC = Field capacity, WP = wilting point, and AW = Available water.

2.3. Experimental Layout and Treatments

Seeds of the three studied lowland rice varieties [V₁ (Giza-178), V₂ (Giza-177) and V₃ (Sakha-104)] were sown manually on 16 May 2017 and 10 May 2018 in rows with seed rate 130 kg h⁻¹ with rows spaced distance 0.25 m. The characteristics of the tested rice varieties were reported by [37] as follows:

V₁ (Giza-178): Pedigree (Giza175/Milyang 49), Properties (Indica/Japonica type—tolerant to drought—medium maturing—high yield), grain yield (10 t ha⁻¹) growth period (135 days)

V₂ (Giza-177): Pedigree (Giza 171/Yomjo No. 1//PiNo.4,) Japonica type—sensitive to drought—short stature—early duration—,grain yield (9 t ha⁻¹) and the growth period (125 days)

V₃ (Sakha-104): Pedigree (GZ4096-8-1/GZ4100-9-1), Properties (Japonica type—sensitive to drought—), grain yield (10 t ha⁻¹) growth period (135 days)

Each sub-subplot (experimental unit) involved 5 rows. Agronomic practices for crop management viz fertilizers, pesticides and herbicides applications were implemented according to the recommended practices described by [38]. Fertilizers were manually broadcast then incorporated within the basal application (35 kg P and 50 kg K per hectare). The experiments were conducted in a randomized complete block design (Split-split Plot) in three replicates including three factors. Using a surface irrigation system, three different irrigation regimes as follows: I₁ (120% of ETc), I₂ (100% of ETc) and I₃ (80% of ETc) were applied and allocated to the main plots and two N fertilization levels N₁ (100% of recommended dose (RD) by 165 kg N ha⁻¹) and N₂ (125% of RD by 200 kg N ha⁻¹), were broadcasted in three equal splits and added at basal, mid-tillering and panicle initiation of rice developing stages and allocated to the sub main plots, where the three lowland rice varieties seeded and allocated to sub-sub main plots. The total experimental area specified for each year was 1134 m² divided into 54 experimental plots of 21 m² for each. To protect against irrigation and nitrogen fertilizer treatment effects, three meters were utilized to isolate the experimental units.

2.4. Irrigation Water Requirements (IWR)

The IWR was determined according to [39] equation as follows:

$$IWR = \frac{A \times ETc \times Ii}{Ea \times 1000}$$

where, IWR: irrigation water requirements (m³), A: plot area (m²), ETc: water consumptive use (mm day⁻¹), Ii: intervals between irrigation (day), and Ea: application efficiency (%).

To convey water for each plot plastic pipe (spiles) of 2 inch diameter was used, and the amount of water delivered through a plastic pipe was calculated according to [40].

$$Q = CA\sqrt{2gh} \times 10^{-3}$$

where: Q is the discharge of irrigation water (m^3), C is the coefficient of discharge, A is a cross-sectional area of irrigation pipe (cm^2), g is gravity acceleration (cm s^{-2}) and h is the average of the effective head of water (cm) above the pipe.

ETc: Water consumptive use (mm day^{-1})

$$ET_c = ET_0 \times K_c$$

where: ETc: crop water consumption (mm d^{-1}), ET_0 is the reference evapotranspiration (mm d^{-1}), and K_c : crop coefficient.

$$ET_0 = E_{\text{pan}} \times K_p$$

where E_{pan} : is the evaporation from a class A (mm day^{-1}) and K_p : is the pan coefficient.

2.5. Plant Physiological Measurements

2.5.1. Chlorophyll a Fluorescence (F_v/F_m) and Performance Index (PI) Values

Chlorophyll *a* fluorescence was determined by plant efficiency analyzer, Handy PEA (Hansatech Instruments Ltd., Norfolk, UK). From each plot, ten fully expanded flag leaves were randomly selected, the leaf samples were dark-adapted for 15 min before being illuminated with irradiance intensity of $3000 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ [41,42]. While PI was measured as reported by [43].

2.5.2. Relative Water Content (RWC)

Leaf samples for RWC measurement were randomly collected in the morning (8:00 to 9:00 a.m.). RWC was estimated according to the method described by [44].

$$\text{RWC (\%)} = (\text{FW} - \text{DW}) \times 100 / (\text{TW} - \text{DW})$$

where: FW: Fresh weight was measured within two hours after excision of leaves. Turgid weight (TW) was computed by soaking leaves in distilled water and left at room temperature for (16–18 h) then rapidly and carefully blotted dry by tissue paper to determine turgid weight. The small leaf pieces were later oven-dried for 48 h at 70°C to estimate the dry weight (DW).

2.5.3. Relative Chlorophyll Content (SPAD)

The SPAD meter (SPAD502, KONICAMINOLTA. Inc., Tokyo, Japan) was used to estimate the relative chlorophyll content of the rice.

2.5.4. Membrane Stability Index (MSI %)

The (MSI %) was measured by the method described by [45]. The small leaf strips (0.2 g) of equal size were prepared and taken in two sets of test tubes containing 10 mL of distilled water. The test tubes arranged in one set were maintained at 40°C in a water bath for 30 min then the ECe of the water covering the leaf samples was estimated (C_1). While the test tubes of the other set were incubated in a bath of boiling water at 100°C for 15 min then measured ECe (C_2). The MSI was computed: $\text{MSI} = [1 - (C_1/C_2)] \times 100$.

2.6. Growth, Yield and Yield Components Measurements

All the studied three rice varieties were harvested after 135 days from the sowing date. From each plot, ten plants were selected randomly to determine the plant growth and yield components parameters, i.e., tillers and productive tillers number, plant height

(from ground level to the tip of panicle, was measured by meter-scale), length and weight of panicle, number and weight of grains per panicle and 100-grain weight. The grain and straw yield were measured by using digital balance from all plants collected from 1m² sampling area.

2.7. Grain N Content

Digestion process was performed for the dried grain samples with a mixture consisting of perchloric and nitric acids (at 1:3, *v/v*, respectively). Using the previous digestion solution, an assessment of N content was performed. Determination of N was performed using the micro-Kjeldahl apparatus (Ningbo Medical Instruments Co., Ningbo, China) following [46] methods.

2.8. Irrigation Water Productivity (IWP)

IWP was determined according to [47].

$$\text{IWP (Kg m}^{-3}\text{)} = \frac{\text{grain yield (Kg ha}^{-1}\text{)}}{\text{irrigation water applied (m}^3\text{ ha}^{-1}\text{)}}$$

Crop water productivity (CWP): was computed according to [48].

$$\text{CWP (Kg m}^{-3}\text{)} = \frac{\text{grain yield (Kg ha}^{-1}\text{)}}{\text{water consumptive (m}^3\text{ ha}^{-1}\text{)}}$$

2.9. Statistical Analysis

The obtained data for each variable were subjected to two-way analysis of variance (ANOVA) using GenStat statistical package (12th Ed., VSN International Ltd., Oxford, UK). In case of significant effects, the treatment means were separated using LSD test at $p \leq 0.05$ probability level.

3. Results and Discussion

3.1. Rice Water Status

Results of plant water status (RWC and MSI) in response to irrigation, nitrogen and variety are displayed in Table 3. In both seasons, the highest MSI, RWC values were recorded when rice was subjected to irrigation at 120% of ET_c and received 200 kg N ha⁻¹; on the other hand, the integrative application of irrigation at 80% of ET_c and plants received 165 kg N ha⁻¹ recorded the lowest values over all varieties.

Regarding the effect of varieties, data enumerated in Table 3 revealed that Giza-178 (V₁) recorded the highest MSI, RWC values while Giza-177 (V₂) gave the lowest values in both seasons. Application of 200 kg N ha⁻¹ to drought-stressed plants up to 20% compensated for this shortage of irrigation and recorded similar values to well-irrigated plants (I_{120%}) and received 165 kg N ha⁻¹. RWC and MSI declined remarkably in both I_{100%} and I_{80%} treatment compared with well-watered treatment (I_{120%}) [49,50]. We found that RWC and MSI had positive relationships with IWA irrespective of nitrogen applications. The RWC and MSI values were decreased as drought increased. Interestingly, leaf RWC and MSI in higher N treatment were 3.2 and 5.2% higher than that low N treatment, irrespective of the variety effect. In this investigation, N-supply decreased the detrimental effects of water stress on rice plants and kept their RWC and MSI values at close levels as in well-watered plants (Table 3). In the present study, the adverse changes that occurred in the health of cell membranes under drought stress were assessed. Our results revealed that higher N-application plays an important role in stabilizing membrane integrity and maintaining cell turgor of rice leaves under drought stress. In this respect, increases of tissue RWC and MSI as metabolically available water seems to maintain tissue health and may reflect on the metabolic processes in rice under water stress, which agrees with the results of [34,51], who

stated that, N supply under drought stress improved RWC and MSI as well as enhanced the photosynthetic efficiency with increased grain yield of wheat plants. Our results agree with those of [48,52]. They reported that drought stress severely affected and reduced rice growth, photosynthesis, stomatal conductance. Ref. [53] reported drought adversely affects physiological responses of plants through a reduction in gas exchange especially stomatal conductance, photosynthetic pigments and overall crop water status.

3.2. Leaf Physiological Traits

For all varieties, physiological traits like relative chlorophyll content (SPAD value), chlorophyll fluorescence (F_v/F_m) and performance index (PI) were significantly improved in drought stress-treated rice plants under high N application (Table 3). Drought stress (80% of ETc) reduced the values of SPAD (18.7%), F_v/F_m (5.5%), and PI (46.1%) as compared to plants irrigated at 120% of ETc (Table 3). All physiological traits were significantly decreased under drought [17,54]. However, rice plants that received high N concentrations (200 kg ha^{-1}) significantly increased SPAD (7.3%), F_v/F_m (3.8%), and PI (45.3%), as compared to low N concentration, over all varieties as average for both seasons. Moreover, results in Table 3 showed that the highest SPAD, F_v/F_m , and PI values were recorded in Giza₁₇₈ (V_1), while the lowest values were recorded under Giza₁₇₇ (V_2) for both seasons. The best results of these traits were recorded in Giza₁₇₈ with application of $200 \text{ kg N ha}^{-1} + I_{120}$ of ETc. Our results suggest that the application of high N concentration can mitigate the negative effects of water stress on SPAD, F_v/F_m , and PI and as a result of increasing the photosynthetic efficiency of rice plants. Similar trends were reported by [16,55–58].

3.3. Plant Growth Characteristics

Results presented in Table 4 showed that the applied irrigation regimes, nitrogen fertilization levels and their interaction significantly affected the plant height and the number of effective tillers. Applying water stress level (I 80%) significantly reduced plant height, tillers No, effective tillers no and panicle length by 9.45, 21.54, 21.12 and 10.58% compared by control (I 120%). Increasing the amount of the applied irrigation water and nitrogen dose at ($I_{120} \times N_2$) treatment gave the greatest values of plant height and effective tillers. Tillers number in particular fertile tillers is considered one of the most important components of yield. The observed increase in number of fertile tillers in the current investigation might be related to the higher availability of the nitrogen element that played a vital role in cell division. On the contrary, the lowest estimation for these parameters was observed at ($I_{80} \times N_1$) treatment. Drought stress may cause various structural and functional disruptions in reproductive organs [20]. Among the grown rice varieties (Giza₁₇₈) recorded the maximum plant height (76.14 cm) and effective tillers number (2.75) as compared with other varieties. The increases in both plant height and produced effective tillers under ($I_1 \times N_2$) treatment could be due to the availability of water and nitrogen resulting in better translocation of photosynthesis, higher cell deviation and there by favored highest yield attributes under these treatments. The obtained results were in line with [59] who observed that increasing nitrogen fertilizer resulted in drier matter accumulation. Ref. [60,61] found that the irrigation regime and N application significantly affected rice yield and yield traits. In addition, increasing the N uptake may have beneficial effects on plants grown under drought conditions, where the plant drought resistance increased with increasing N supply resulted in increasing root hydraulic conductivity (Lpr) through increased abscisic acid and aquaporin expression [30,31].

Table 3. Effect of deficit irrigation, nitrogen fertilizer varieties, and their interaction on plant water status (RWC% and MSI %), chlorophyll florescence (Fv/Fm and PI), and leaf chlorophyll content (SPAD) of rice plants in 2017 (S_I) and 2018 (S_{II}) seasons.

Source of Variation	RWC%		MSI%		SPAD		Fv/Fm		PI	
	S _I	S _{II}	S _I	S _{II}	S _I	S _{II}	S _I	S _{II}	S _I	S _{II}
Irrigation (I)	**	**	**	**	**	**	**	**	**	**
I _{120%}	70.20 ± 1.1a	70.41 ± 1.2a	65.70 ± 1.6a	65.65 ± 1.5a	44.64 ± 0.63a	44.60 ± 0.46a	0.82 ± 0.00a	0.83 ± 0.00a	5.50 ± 0.30a	5.60 ± 0.28a
I _{100%}	68.91 ± 1.7b	69.22 ± 1.6b	68.94 ± 2.1a	67.64 ± 1.8a	42.14 ± 0.60b	42.80 ± 0.56b	0.80 ± 0.00b	0.81 ± 0.01b	4.04 ± 0.26b	3.93 ± 0.23b
I _{80%}	61.65 ± 1.4c	62.14 ± 1.3c	61.00 ± 1.6b	60.50 ± 1.7b	36.35 ± 0.82c	36.20 ± 0.72c	0.78 ± 0.01c	0.78 ± 0.01c	2.94 ± 0.35c	3.04 ± 0.32c
Nitrogen (N)	**	**	**	**	**	**	**	**	**	**
N ₁₆₅	65.44 ± 1.2b	66.20 ± 1.1b	62.52 ± 1.4b	63.00 ± 1.3b	39.82 ± 0.69b	39.64 ± 0.72b	0.78 ± 0.00b	0.79 ± 0.00b	3.44 ± 0.27b	3.40 ± 0.26b
N ₂₀₀	68.40 ± 1.1a	68.34 ± 1.0a	66.54 ± 1.4a	66.24 ± 1.6a	42.34 ± 0.59a	42.92 ± 0.65a	0.81 ± 0.00a	0.82 ± 0.01a	4.94 ± 0.25a	5.00 ± 0.30a
Variety (V)	**	**	**	NS	**	NS	NS	NS	**	**
V ₁	69.11 ± 1.0a	69.42 ± 1.1a	66.00 ± 1.9a	65.14 ± 1.6a	42.13 ± 0.68a	41.74 ± 0.74a	0.81 ± 0.01a	0.81 ± 0.01a	4.34 ± 0.38a	4.34 ± 0.36a
V ₂	66.14 ± 1.2b	66.73 ± 1.3b	65.50 ± 1.8a	65.24 ± 1.4a	40.84 ± 0.88b	41.07 ± 0.95a	0.81 ± 0.00a	0.81 ± 0.01a	4.45 ± 0.39a	4.50 ± 0.33a
V ₃	65.50 ± 1.4b	65.64 ± 1.3c	62.14 ± 1.5b	63.40 ± 1.3a	40.20 ± 0.72b	41.15 ± 0.63a	0.80 ± 0.00a	0.80 ± 0.01a	3.80 ± 0.27b	3.81 ± 0.31b
I × N	**	**	NS	NS	**	**	**	**	**	**
I × V	**	**	NS	*	NS	**	**	**	**	NS
V × N	**	**	*	NS	**	**	NS	NS	NS	**
I × N × V	NS	**	*	**	NS	NS	NS	**	**	**

** and * refer to the significant difference at $p \leq 0.01$ and $p \leq 0.05$, respectively; and “ns” refers to no significant difference. Different letters next to mean values in each column indicate significant differences according to the LSD test ($p < 0.05$).

Table 4. Effect of deficit irrigation, nitrogen fertilizers varieties, and their interaction on growth characteristics of rice plants in 2017 (S_I) and 2018 (S_{II}) seasons.

Source of Variation	Plant Height (cm)		Tillers No		Effective Tillers No		Panicle Length (cm)	
	S _I	S _{II}	S _I	S _{II}	S _I	S _{II}	S _I	S _{II}
Irrigation (I)	**	**	**	*	*	*	**	**
I ₁₂₀	74.73 ± 0.87a	75.30 ± 0.67a	3.11 ± 0.08a	3.14 ± 0.09a	2.95 ± 0.09a	2.78 ± 0.08a	20.46 ± 0.21a	20.58 ± 0.18a
I ₁₀₀	71.87 ± 0.65b	72.26 ± 0.62b	2.56 ± 0.09b	2.79 ± 0.08b	2.45 ± 0.09b	2.54 ± 0.08b	19.41 ± 0.24b	19.38 ± 0.21b
I ₈₀	67.84 ± 0.67c	68.00 ± 0.63c	2.44 ± 0.08c	2.46 ± 0.08c	2.35 ± 0.09b	2.17 ± 0.09c	18.36 ± 0.23c	18.34 ± 0.20c
Nitrogen (N)	**	**	**	NS	**	NS	**	**
N ₁₆₅	69.92 ± 0.67b	70.01 ± 0.55a	2.54 ± 0.08b	2.81 ± 0.08a	2.44 ± 0.08b	2.49 ± 0.09a	18.87 ± 0.23b	18.89 ± 0.22b
N ₂₀₀	73.04 ± 0.70a	73.69 ± 0.59a	2.85 ± 0.08a	2.80 ± 0.09a	2.72 ± 0.08a	2.51 ± 0.07a	19.95 ± 0.19a	19.97 ± 0.17a
Variety (V)	**	**	NS	NS	NS	*	**	**
V ₁	75.79 ± 0.77a	76.49 ± 0.73a	2.86 ± 0.09a	3.01 ± 0.09a	2.70 ± 0.08a	2.80 ± 0.06a	20.57 ± 0.21a	20.56 ± 0.19a
V ₂	67.31 ± 0.57c	67.47 ± 0.65b	2.65 ± 0.09b	2.76 ± 0.09b	2.59 ± 0.10b	2.44 ± 0.06b	18.54 ± 0.23c	18.57 ± 0.24c
V ₃	71.34 ± 0.57b	71.59 ± 0.59b	2.59 ± 0.10b	2.64 ± 0.09b	2.44 ± 0.09c	2.26 ± 0.07b	19.11 ± 0.20b	19.14 ± 0.22b
I×N	**	**	**	**	*	*	**	**
I×V	**	**	**	*	**	**	**	**
V×N	**	**	NS	*	*	*	**	**
I×N×V	NS	NS	*	*	NS	NS	*	*

** and * refer to the significant difference at $p \leq 0.01$ and $p \leq 0.05$, respectively; and “ns” refers to no significant difference. Different letters next to mean values in each column indicate significant differences according to the LSD test ($p < 0.05$).

3.4. Yield Components

Yield components of, i.e., panicle length (cm), grains number per panicle, panicle weight, weight of grain per panicle (g) and weight of 100 grain (g), were significantly affected by irrigation and nitrogen nutrition treatments. Results in Table 5 showed that rice variety Giza₁₇₈ yielded the highest values of these traits under irrigation and nutrition level (I₁₂₀ × N₂), while the lowest values were yielded by Giza₁₇₇ under (I₈₀ × N₁). Among irrigation regimes (I₁₂₀) produced the highest averages of these traits, that gradually reduced by increasing drought level. The reduction percent amounted to 5.48, 7.78, 13.63, 18.41 and 11.07% respectively, as compared with those obtained at moderate stress level (I₁₀₀) and by 10.57, 17.83, 29.66 32.61 and 18.38% respectively compared to (I₈₀). The obtained results were in line with those reported by [52] who found that yield components of rice crop (panicle number, panicle length, 100-grain weight and grain yield) decreased with increasing water stress especially if it occurred at the stage of panicle initiation. Ref. [17,62] noted that depending upon the stress severity the plant physiological responses, the apical development rate, biomass production, panicle development, spikelet number, and grain yield were decreased.

However, applying nitrogen fertilization at N₂ resulted in an increase in panicle length (cm), grains number per panicle, panicle weight, weight of grain per panicle (g) and weight of 100 grain (g) by 5.72, 10.81, 12.85, 11.91 and 5.21% as compared to N₁. Inter varietal comparison showed that, yield component traits were significantly differed in both seasons. Results are in agreement with those revealed by [63,64] who noted that the application of N fertilizers significantly increased the yield and yield components of rice.

3.5. Grain, Straw and Biological Yield

Results presented in Table 6 show that, grain, straw, biological yield and grains N content were varied significantly among the grown rice varieties as affected by both irrigation and nitrogen nutrition management. As average (2017–2018) rice variety Giza₁₇₈ gave the highest grain, straw and biological yield 7.97, 12.23 and 20.19 t ha^{−1} respectively, while Giza₁₇₇ recorded the lowest yields (5.78, 8.84 and 14.61 t ha^{−1} respectively). As presented above in (Tables 3–5) the higher application of irrigation water (I₁₂₀) improved the plant water status, enhanced growth and development of rice plants that contributed to achieve the maximum values for grain yield (8.11 t ha^{−1}), straw yield (11.89 t ha^{−1}) and biological yield (20.00 t ha^{−1}). Furthermore, comparing with irrigation treatment (I₁₂₀),

moderate irrigation regime (I_{100}) reduced the grain, straw and biological yield of grown lowland rice varieties. The reductions were by 10.98, 5.55 and 7.75%, respectively, and by 34.18, 26.53 and 29.63%, respectively, under the application of deficit irrigation treatment (I_{80}). A similar trend was observed by [62,65–67].

Table 5. Effect of deficit irrigation, nitrogen fertilizer varieties, and their interaction on yield component of rice in 2017 (S_I) and 2018 (S_{II}) seasons.

Source of Variation	Grains No/Panicle		Panicle Weight		Weight of Grains/Panicle		W of 100 g	
	S_I	S_{II}	S_I	S_{II}	S_I	S_{II}	S_I	S_{II}
Irrigation (I)	**	**	**	**	**	**	**	**
I_{120}	93.56 ± 1.7a	94.45 ± 1.6a	2.50 ± 0.03a	2.49 ± 0.09a	2.24 ± 0.03a	2.27 ± 0.13a	2.39 ± 0.29a	2.40 ± 0.28a
I_{100}	86.34 ± 1.9b	87.05 ± 1.8b	2.15 ± 0.06b	2.16 ± 0.10b	1.80 ± 0.06b	1.88 ± 0.16b	2.10 ± 0.47b	2.16 ± 0.36b
I_{80}	77.16 ± 1.5c	78.18 ± 1.6c	1.75 ± 0.07c	1.76 ± 0.06c	1.46 ± 0.06c	1.58 ± 0.09c	1.89 ± 0.49c	2.02 ± 0.45c
Nitrogen (N)	**	**	**	**	**	**	**	**
N_{165}	82.99 ± 1.6b	83.63 ± 1.5b	1.98 ± 0.06b	2.00 ± 0.06b	1.72 ± 0.06b	1.81 ± 0.10b	2.07 ± 0.45b	2.16 ± 0.39b
N_{200}	88.39 ± 1.6a	89.47 ± 1.7a	2.27 ± 0.06a	2.27 ± 0.12a	1.93 ± 0.06a	2.02 ± 0.16a	2.19 ± 0.49a	2.26 ± 0.38a
Variety (V)	**	**	**	**	**	**	**	**
V_1	97.20 ± 1.6a	95.85 ± 1.8a	2.46 ± 0.04a	2.48 ± 0.11a	2.20 ± 0.04a	2.25 ± 0.08a	2.27 ± 0.26a	2.34 ± 0.36a
V_2	77.00 ± 1.2c	79.01 ± 1.3c	1.81 ± 0.07c	1.80 ± 0.09c	1.41 ± 0.07c	1.54 ± 0.11c	1.84 ± 0.65c	1.95 ± 0.54c
V_3	82.87 ± 1.3b	84.80 ± 1.3b	2.11 ± 0.07b	2.13 ± 0.08b	1.88 ± 0.12b	1.94 ± 0.09b	2.27 ± 0.67b	2.29 ± 0.57b
$I \times N$	**	**	**	*	*	**	NS	**
$I \times V$	**	**	**	**	**	**	**	**
$V \times N$	**	**	NS	**	**	*	NS	**
$I \times N \times V$	NS	NS	**	**	*	**	*	**

** and * refer to the significant difference at $p \leq 0.01$ and $p \leq 0.05$, respectively; and “ns” refers to no significant difference. Different letters next to mean values in each column indicate significant differences according to the LSD test ($p < 0.05$).

However, nitrogen application gave an apposite effect and improved the productivity of all grown rice varieties. Data in Table 6 showed that increasing the nitrogen fertilization dose from N_1 to N_2 resulted in an increase in grain, straw and biological yield by 12.66, 18.20 and 15.99%, respectively. Nitrogen application could produce promoted root growth, enhanced water and nitrogen extraction from soil, resulting in better crop growth and higher yield productivity. Similar trend was noted by [68] who observed an increase in grain yield with the increasing of nitrogen application levels. The combined effect of ($I \times N$) on grain and straw was found to be significant during both seasons except their effect on straw yield in the second year was non-significant. The effect of ($V \times N$) during two seasons was non-significant. Meanwhile, the effect of ($I \times V \times N$) was significant.

3.6. Irrigation Water Applied and Water Productivity

Results in Table 7 show that total water applied was varied between the applied irrigation treatments. The lowest amount of irrigation water (646 mm ha^{-1}) required was at (I_{80}), while the highest (970 mm ha^{-1}) was needed for (I_{120}). According to the grain yield obtained under each watering treatment, the applied irrigation water and crop water consumption, irrigation water productivity (IWP) and crop water productivity (CWP) were significantly differed ($p \leq 0.05$) in both growing seasons. Among irrigation treatments watering at (I_{100}) gave the highest values of IWP and CWP by 0.89 and $1.28 \text{ (kg m}^{-3}\text{)}$, respectively, when comparing with other irrigation treatments. In addition, increasing nitrogen application dose up to N_2 resulted in higher IWP and CWP by 12.50 and 12.17%, respectively, than N_1 (as average for both seasons). Between rice varieties, Giza₁₇₉ corresponding to its high grain productivity which resulted in the highest value as averages of IWP (0.99 Kg m^{-3}) and CWP (1.41 kg m^{-3}) meanwhile, the lowest IWP and CWP amounted 0.71 and 1.02 kg m^{-3} , respectively, noted for Giza₁₇₇.

Table 6. Effect of deficit irrigation, nitrogen fertilizers varieties, and their interaction on grain yield, straw yield, biological yield, and grains N content of rice plants in 2017 (S_I) and 2018 (S_{II}) seasons.

Source of Variation	Grain Yield (t ha^{-1})		Straw Yield (t ha^{-1})		Biological Yield (t ha^{-1})		N (%)	
	S_I	S_{II}	S_I	S_{II}	S_I	S_{II}	S_I	S_{II}

Table 7. Effect of deficit irrigation, nitrogen fertilizer varieties, and their interaction on grain yield, straw yield, biological yield, irrigation water productivity and crop water productivity of rice plants in 2017 (S_I) and 2018 (S_{II}) seasons.

Source of Variation	Irrigation Water Applied ($m^3 ha^{-1}$)		Irrigation Water Productivity ($kg m^{-3}$)		Crop Water Productivity ($kg m^{-3}$)	
	S_I	S_{II}	S_I	S_{II}	S_I	S_{II}
Irrigation (I)			**	**	**	**
$I_{120\%}$	9661	9733	$0.83 \pm 0.01b$	$0.84 \pm 0.01b$	$1.19 \pm 0.09b$	$1.20 \pm 0.12b$
$I_{100\%}$	8051	8111	$0.89 \pm 0.02a$	$0.90 \pm 0.02a$	$1.27 \pm 0.08a$	$1.29 \pm 0.09a$
$I_{80\%}$	6441	6489	$0.82 \pm 0.01b$	$0.83 \pm 0.01b$	$1.17 \pm 0.11c$	$1.19 \pm 0.08b$
Nitrogen (N)			**	**	**	**
N_{165}	8051	8111	$0.79 \pm 0.01b$	$0.81 \pm 0.01b$	$1.13 \pm 0.09c$	$1.16 \pm 0.08c$
N_{200}	8051	8111	$0.90 \pm 0.02a$	$0.90 \pm 0.02a$	$1.29 \pm 0.06a$	$1.29 \pm 0.07a$
Variety (V)			**	**	**	**
V1	8051	8111	$0.98 \pm 0.02a$	$0.99 \pm 0.02a$	$1.40 \pm 0.11a$	$1.42 \pm 0.09a$
V2	8051	8111	$0.72 \pm 0.00c$	$0.71 \pm 0.01c$	$1.03 \pm 0.09c$	$1.02 \pm 0.0c$
V3	8051	8111	$0.84 \pm 0.01b$	$0.87 \pm 0.02b$	$1.20 \pm 0.08b$	$1.24 \pm 0.10b$
$I \times N$			**	**	**	**
$I \times V$			**	**	**	**
$V \times N$			NS	NS	*	**
$I \times N \times V$			NS	NS	NS	NS

** and * refer to the significant difference at $p \leq 0.01$ and $p \leq 0.05$, respectively; and “ns” refers to no significant difference. Different letters next to mean values in each column indicate significant difference according to the LSD test ($p < 0.05$).

Many studies have been summarized that rice cultivation under flooded condition consumes approximately $20,000 m^3 ha^{-1}$ [7]. In North Delta, Egypt [69] estimated water requirements for flooded-rice by $19,000 m^3 ha^{-1}$ and water utilization efficiency by 48%. Similar results reported by [70] who found that rice normally needs under traditional methods in Egypt a water application of about $20,000 m^3 ha^{-1}$. Studies conducted by [11] concluded that the water requirement of paddy fields in Egypt is about $1800\text{--}2200 mm ha^{-1}$. Therefore, compared with previous studies, the current investigation aimed to create new environmental cultivation conditions to grow lowland rice varieties (aerobically) in non-puddled fields under non-flooded conditions and maintain a profitable grain yield could save irrigation water by 60%. Moreover, results concluded that lowland rice variety Giza₁₇₈ was observed to be more tolerant than other varieties, Giza₁₇₇ and Sakha₁₀₄, while v. Giza₁₇₇ was much affected by deficiency of irrigation water. A similar trend was reported by [3].

3.7. Correlation Analysis

Results in Tables 8 and 9 illustrated the correlation coefficients between rice grain yield and the other yield components. This type of examination could be used as an appropriate instrument to indicate which one of them is positive and greatly associated with the obtained yield of grains.

Table 8. A matrix of simple correlation coefficients between grain yield and other important traits estimated for 2017 and 2018 seasons.

Parameter	Season	1	2	3	4	5	6	7	8	9	10
1 Grain yield	2017	1									
	2018	1									
2 Plant height	2017	0.920 **	1								
	2018	0.921 **	1								
3 Branch No	2017	0.486 **	0.469 **	1							
	2018	0.361 **	0.308 **	1							
4 No spike	2017	0.405 **	0.396 **	0.712 **	1						
	2018	0.377 **	0.313 **	0.568 **	1						
5 Spike length	2017	0.827 **	0.815 **	0.535 **	0.455 **	1					
	2018	0.819 **	0.775 **	0.306 **	0.349 **	1					
6 Grain No	2017	0.903 **	0.879 **	0.430 **	0.380 **	0.844 **	1				
	2018	0.894 **	0.849 **	0.268 *	0.294 **	0.736 **	1				
7 Spike weight	2017	0.915 **	0.866 **	0.541 **	0.454 **	0.841 **	0.872 **	1			
	2018	0.809 **	0.854 **	0.393 **	0.376 **	0.781 **	0.812 **	1			

Table 9. Correlation coefficient (r), coefficient of determination (R^2) and standard error of the estimates (SEE) for predicting grain yield for S_I (2017) and S_{II} (2018) seasons.

Season	r	R^2	SEE	Significance	Fitted Equation
2017	0.961	0.924	0.33	***	Grain yield = $-4.1 + 0.09$ plant height + 1.69 spike weight + 0.179 skillets no $- 0.074$ weight of 1000 grain
2018	0.961	0.924	0.33	***	Grain yield = $-6.18 + 0.08$ plant height + 0.72 spike weight + 0.031 grain no + 0.104 spike length

*** indicate correlation is significant at the 0.01 level.

It was observed that grain yield was positive and strongly correlated with plant height, spike length, grain no/spike then followed by spike weight, which validates their economic importance.

Data in Table 9 show that plant height and spike weight in both seasons were significantly ($p \leq 0.01$) contributed to variations in rice grain yield.

4. Conclusions

Cultivating rice aerobically under deficit irrigation has been observed to be used as an effective and efficient approach in saving irrigation water and improving IWP compared with the flooding system. Additionally, improving nitrogen supply enhanced rice crop productivity under deficit irrigation conditions. The combined effect of ($I_{120} \times N_2$) treatment achieved the greatest values of all agronomic and physiological traits, grain and straw yield of rice. Applying of irrigation water at (I_2) produced the maximum (IWP) and (CWP) by 0.89 and 1.28 kg m⁻³, respectively, compared with other irrigation schedules. Rice variety (Giza₁₇₈, V1), gave the highest CWP and grain yield which amounted to 1.41 and 7.97, respectively. Consequently, it could be a suitable genotype for improving rice productivity under drought conditions as compared with other tested rice varieties. Thus, based on the results of the current study the incorporating deficit irrigation technique at level (100 of ETc) with nitrogen application at 120% of recommended dose could be a valuable agro-management strategy for maintaining relatively high yields of some sensitive-drought Egyptian rice varieties and saving irrigation water supply by 50–60% compared to the conventional rice cultivation method.

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