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Effect of Irrigation Management and Nitrogen Fertilizer on Water Productivity, Yield Components and Nitrate Pollution Under Maize Crop

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A Filed trial was performed at Sakha Agricultural Research Station, Kafr El-Sheikh Governorate (30°57′N, 31°07′ E) during the 2021 and 2022 summer seasons to investigate the impact of irrigation intervals (day): 10 (I_1), 12 (I_2) and 14 (I_3) and N fertilizer (kg urea fed^{-1}): 193.5 (N_1), 258 (N_2) and 322.5 (N_3) on maize yield, yield attributes, some water relations and NO_3^- pollution. Results showed that the highest average water (4015.7 m³ fed^{-1}) and consumptive use (2498.89 m³ fed^{-1}) were observed under I_1 treatment (mean of all N treatments across both seasons). The highest water productively (WP, 2.51 kg m^{-3}) and productivity of irrigation water (PIW, 1.61 kg m^{-3}) were recorded with I_2 combined with N_2 and I_3 combined with N_3, respectively (mean of both seasons). The highest NO_3^- concentration in soil (68.5 mg kg^{-1}) occurred under the I_3 and N_3 combination after the 1st irrigation, while it was 27.49 mg l^{-1} in water table under I_1 with N_3 treatment after the 2nd irrigation. Conversely, the lowest NO_3^- concentration in soil (7.0 mg kg^{-1}) and water table (6.46 mg l^{-1}) were recorded under I_1 with N_1 at the end of 2nd season. In terms of maize grain yield, The I_2 and N_2 combination produced the highest yield in the first season (26.6 ardab fed^{-1}), while I_2 combined with N_3 achieved the highest yield in the second season (26.4 ardab fed^{-1}). These findings suggest that the I_2 irrigation interval combined with either N_2 or N_3 can be a viable strategy for maximizing maize grain yield, conserving irrigation water, and reducing NO_3^- pollution.

Keywords: Maize crop; irrigation interval; mineral nitrogen fertilizer; water productivity; irrigation water productivity; NO_3^- pollution.

1. Introduction

Maize (*Zea mays* L.) is among the most significant summer crops in Egypt, second only to rice. In 2014, maize was cultivated on approximately 750,000 hectares, yielding 5.8 megatons (FAO, 2014). More than 85% of Egypt's annual Nile water are consumed in agriculture (MWRIE, 2014). Advancing water-saving strategies is critical to achieving an optimal balance between water use and acceptable crop yields (Pereira *et al.* 2002). While, Egypt suffers from relative scarcity of water resources, additional water is essential to reclaim new lands and meet the growing demand for food (Hafez and Gharib, 2016).

In Egypt, water is the most critical factor influencing crop production. Water resources are limited and primarily reliant on the Nile River, which supplies over 95% of the country's freshwater. According to international agreements among Nile Basin countries, Egypt's water share from the Nile is 55.5 billion cubic meters annually. While additional water resources exist, their contributions are comparatively smaller. Currently, Egypt's per capita water share is less than 1,000 m³/year, aligning with the international threshold for water poverty. Irrigation accounts for approximately 85% of the

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country's total renewable water use, making it the largest water-demanding sector at the national level. Consequently, efficient irrigation water management is essential to support Egypt's water rationalization policies. On-farm irrigation management, in particular, is vital for addressing irrigation scarcity and ensuring sustainable water use.

Water productivity (WP) is a crucial indicator for evaluating water management and promoting the sustainable development of agriculture in arid and semi-arid regions. Improvement and development of water management are expected to reduce water consumption and improve water use efficiency (WUE) in many parts of the world, particularly in Egypt (Sepaskhah *et al.*, 2007 and El-Henawy and Elsayed, 2018). Regulating irrigation intervals is important to save water in the clayey soils. Crop productivity negatively affected by water deficiency, as drought conditions trigger various physiological and biochemical responses in plants (Jiang *et al.*, 2020; Sidhu *et al.*, 2021). However, Ghazy *et al.* (2024) highlighted that prolonged irrigation intervals can be an effective strategy for optimizing WUE and conserving water resources. Therefore, water-saving strategies that ensure sustainable crop productivity and enhance WUE must be prioritized (Zain *et al.*, 2023).

Numerous studies have been conducted to examine how irrigation intervals impact maize yield and its attributes. The findings consistently indicate a notable reduction in maize grain yield due to prolonging the irrigation interval or irrigation deficit. Hussein and Pibars (2012) and El-Sobky *et al.* (2017) found that irrigation deficits significantly reduced the growth, yield, and yield attributes of maize. However, ear diameter and length were not significantly affected by extended irrigation intervals, as reported by Sokht-Abandani and Ramezani (2012). Hameedi *et al.* (2015) demonstrated that irrigating every four days resulted in significantly greater plant height and maize grain yield compared to irrigation schedules of every seven and ten days. Koyama *et al.* (2012) reported that optimal rhizosphere drought stress resulted in an 18% reduction in nitrate concentration without negatively affecting lettuce yield.

Aside from water, nitrogen (N) fertilizer is a critical factor influencing crop production (Zhang *et al.*, 2015 and Wang *et al.*, 2015). Nitrogen is particularly critical for cereal crops, as it supports photosynthetic activity, cell development, and protein assimilation (King *et al.*, 2003). Effective management of both N fertilizers and irrigation water is essential to minimize the risk of NO3-N leaching below the root zone in irrigated maize fields (Ferguson *et al.*, 1991). N enhancement the grain yield of maize and its components (George *et al.*, 2016 and El-Sobky and Desoky, 2017). However, excessive use of nitrogen (N) fertilizers to boost food production can lead to nitrate (NO_3^-) pollution of both surface and ground water, contributing to environmental and health issues. Ning *et al.* (2024) reported that high N fertilizer rates increased NO_3^--N concentrations in the 0–100 cm soil layer. However, these concentrations decreased with higher irrigation volumes, as NO_3^--N was leached deeper into the soil profile due to the increased water application. Elevated NO_3^- levels in surface water bodies can promote eutrophication by stimulating algal blooms (Yeomans *et al.*, 1992), reduce nitrogen-use efficiency (Zhang *et al.*, 2018), and trigger a range of environmental problems, including intensified greenhouse gas emissions and groundwater nitrogen contamination (Cui *et al.*, 2018). Prolonged misuse of N fertilizers can also alter soil composition, disrupting the C/N balance, causing soil hardening, acidification, reduced permeability (Wu *et al.*, 2021), and ultimately impairing crop growth and yield (Yan *et al.*, 2015). Additionally, human consumption of water with high NO_3^- concentrations has been associated with methemoglobinemia and other health disorders (Prasad and Power, 1995). Thus, effective nitrogen (N) fertilization and water management are essential for mitigating contamination from mineral N associated with various agricultural practices while sustaining maize crop growth and productivity (Gholamhoseini *et al.*, 2013 and Muhammad *et al.*, 2022). Mosaad *et al.* (2024) concluded that irrigation regularity and nitrogen fertilization significantly affected the groundwater salt content, depth of water table, soil moisture levels, availability of nitrogen in soil and nitrate levels in groundwater.

The irrigation and fertilization management could be considered a proper approach to sustain the soil and water resources in particular under arid and semi-arid regions as reported by Amer *et al.* (2019). Consequently, optimizing nitrogen (N) fertilization and irrigation practices is needed to enhance maize crop productivity while ensuring environmental sustainability, as noted by Ma *et al.* (2016). Therefore, this study was designed to investigate the effect of irrigation water interval and fertilizer rate on grain yield, yield attributes, water consumptive use and amount of applied water and water productivity of maize.

2. Materials and Methods

2.1 Experimental site

Two field experiments were conducted during the summer growing seasons of 2021 and 2022 at the Sakha Agricultural Research Station in Kafr El-Sheikh Governorate, Egypt (30^o 56 N latitude and 31^o 05 E longitude) to study the effect of irrigation intervals and nitrogen (N) mineral fertilizer levels on productivity of maize crop (variety hypered 10), water conservation, and environmental nitrate NO_3^- pollution. Some soil chemical and physical properties of the experimental site are presented in Table (1 and 2). Soil properties were determined using the methods outlined by Page *et al.* (1982) and Klute (1986).

TABLE 1. Some soil physical properties of the experimental field.

Soil depth (cm)	Particle size distribution (%)			Texture grade	F.C (%)	P.W.P. (%)	A.W (%)	B.d (mg m^{-3})
	Sand	Silt	Clay					
0-15	15.3	14.5	70.2	Clay	47.8	24.7	23.1	1.17
15-30	17.2	15.3	67.5	Clay	40.6	20.5	20.1	1.21
30-45	16.9	15.7	67.4	Clay	39.5	20.1	19.4	1.25
45-60	15	15.5	69.5	Clay	38.8	19.7	19.1	1.33
Mean	16.1	15.3	68.7	Clay	41.7	21.3	20.4	1.24

Where: F.C: Field capacity, %, P.W.P: Permanent wilting point, %, AW: Available water% and B.d: Soil bulk density, mg m^{-3}.

TABLE 2. Some soil chemical characteristics of the studied site before cultivation.

Soil depth	EC, dS m^{-1}	pH 2.5 soil suspension	Soluble ions, meq l^{-1}							
			Cations, meq l^{-1}				Anions, meq l^{-1}			
			Na^+	K^+	Ca^{++}	Mg^{++}	$CO_3^=$	HCO_3^-	Cl^-	$SO4^=$
0-15	1.69	7.95	7.14	5.17	4.52	0.96	0	5.1	5.03	7.66
15-30	1.72	7.73	7.06	4.63	5.18	0.87	0	5.62	5.51	6.61
30-45	1.77	7.57	6.67	4.25	6.31	0.72	0	5.83	5.97	6.15
45-60	1.8	7.42	6.51	4.1	6.97	0.68	0	6.05	6.25	5.96
Mean	1.75	7.67	6.65	4.54	5.75	0.81	0	5.65	5.69	6.6

2.2 Experimental design and treatments

The experiment was laid out in a split-block design with three replicates. The main plots were designated for the irrigation intervals as follows:

I_1 = 10 days, I_2 = 12 days, I_3= 14 days.

While the sub plots were devoted to three levels of mineral N fertilizer application as follows:

N_1 = application of 75% from the recommended dose (193.5 kg urea fed^{-1}),

N_2 = application of 100% from the recommended dose (258.0 kg urea fed^{-1}),

N_3 = application of 125% from the recommended dose (322.5 kg urea fed^{-1}).

Maize grains, were sown in 16th May 2021 and 2022 in the 1st and 2nd seasons. All plots received a total of 200 kg super phosphate/fed (15.5% P_2O_5) which added with tillage operation. Also, 45 kg K-sulphate/fed (48% K_2O) was added after 30 days from sown. Soil samples were taken to a depth of 0.6 m, before cultivation for analysis. N- fertilizer in the form of urea was added in two doses (before the 1st and the 2nd irrigations). The other agricultural practices were carried out as recommended according to the Egyptian Ministry of Agric. in both growing seasons.

2.3 Water data collection

Irrigation water applied (AW)

Irrigation water application was measured using a submerged flow orifice with fixed dimensions, as described by the following equation (Michael, 1978):

$$Q = CA\sqrt{2gh}$$

Where: Q = water discharge (cm^3 s^{-1}), C = discharge coefficient ranged between 0.6 up to 0.8, A

= Inner cross-section area of the irrigation spiel (cm^2), g = acceleration due to gravity (cms^{-2}) and h= pressure head causing water discharge (cm).

Water consumptive use (CU)

Water consumptive use was determined on a weight basis by taking soil samples before and 48 hours after each irrigation, as well as at harvest, to calculate the actual water consumed, following the method outlined by Hansen *et al.* (1979) as shown below:

$$\mathbf{Cu = SMD = \sum_{i=1}^{i=N} \frac{\theta_2 - \theta_1}{100} * Dbi * Di * A}$$

Where: CU = water consumptive use (cm) in the effective root zone of 60 cm soil depth, SMD = soil moisture depletion (cm), i = number of soil layer (1-4), θ_2 = gravimetric soil moisture %, 48 hrs after irrigation, θ_1 = gravimetric soil moisture %, before irrigation, Dbi = bulk density (kg m^{-3}), Di = soil layer thickness (m) and A = irrigated area (fed).

Consumptive use efficiency (Ecu, %)

Consumptive use efficiency was calculated according to Doornbos and Pruit (1975) as follows:

$$\mathbf{Ecu = ET_c *100/WA}$$

Where: Ecu = consumptive use efficiency (%), ETc = total ET (water consumptive use) (m^3 fed^{-1}) and WA = irrigation water applied (m^3 fed^{-1}).

Water productivity (WP, kg m^{-3})

Water productivity is generally outlined as crop yield per cubic meter of water consumption. It was calculated using the equation described by Ali *et al.* (2007) as follows:

$$\mathbf{WP = Y/ET}$$

Where: WP = water productivity (kg m^{-3}), Y = yield (kg fed^{-1}) and ET = total water consumption through the growing season (m^3 fed^{-1}).

Productivity of irrigation water (PIW)

Productivity of irrigation water (PIW) was calculated according to Ali *et al.* (2007) as follows:

$$\mathbf{PIW= Y/AW}$$

Where: PIW = productivity of irrigation water (kg m^{-3}), Y = yield (kg fed^{-1}) and AW = irrigation water applied (m^3 fed^{-1}).

2.4 Yield and yield attributes

Maize harvesting was in 16^{th} Sept. in both seasons. Ten plants were randomly selected from each treatment. The following parameters were measured: plant height (cm), (ear length, height, diameter (cm)), 100-grain weight (g) and grain yield (ardab fed^{-1}). Grain and straw samples of maize were taken and dried at 70°C, grounded with a mill and its N content was determined using Kjeldahl digestion (Cottenie *et al.*, 1982). N-uptake (kg fed^{-1}) was calculated by multiplying dry yield (kg fed^{-1}) by N %.

2.5 Water table depth and NO_3^- (in water table and soil)

Water table depth at midway between the laterals of tile drain during the irrigation interval (10, 12 and 14 days) were recorded through observation wells (19 mm diameter and 1.75 m length) according to Ritzema (1994). The water samples were taken from the observation wells and analyzed for NO_3^- using Kjeldahl method (Cottenie *et al.*, 1982). Disturbed soil samples were taken to a depth of 0.6 m, before cultivation, after the 1st and 2nd irrigations and at the end of the growing seasons. Soil samples were analyzed for NO_3^- according to Cottenie *et al.* (1982).

2.6 Statistical analyses

Analysis of variance (ANOVA) was performed following the method described by Gomez and Gomez (1984). Duncan's Multiple Range Test was used to compare means (Duncan, 1955). Data were analyzed using CoStat software for Windows (version 6.3).

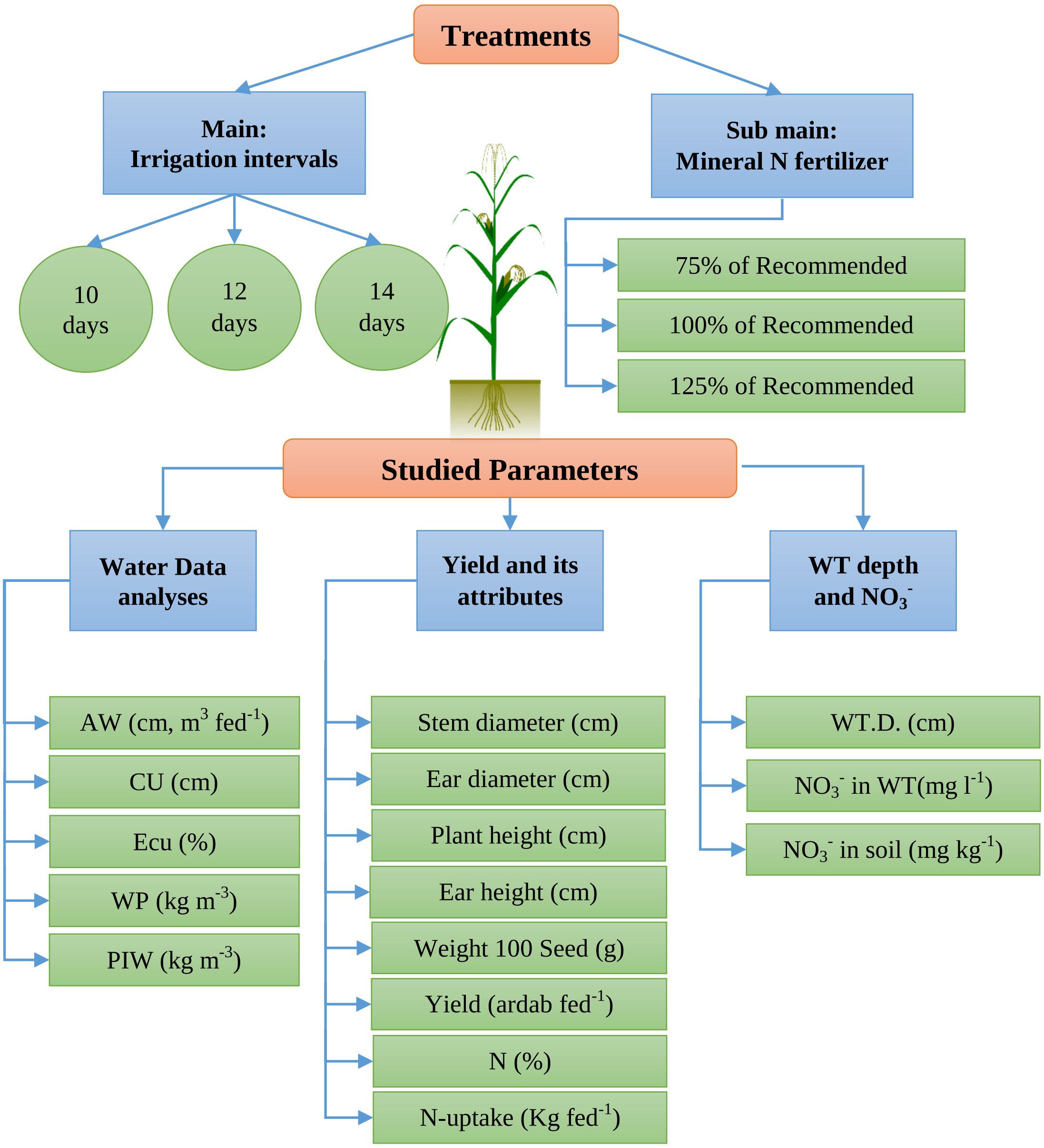

Fig.1. Layout of the experimental treatments, design and studied parameters.

3. Results and Discussion

3.1 Crop water relations

3.1.1 Water applied (cm or m^3 fed^{-1})

Data presented in Table (3) indicate the seasonal irrigation water applied during the two growing seasons. The highest seasonal water applied in the 1st season (94.46 cm or 3988.80 m^3/fed) and in the 2nd season (96.25 cm or 4042.23 m^3 fed^{-1}) were recorded with I_1 (irrigation every 10 days). Conversely, the lowest values were observed with I_3 (irrigation every 14 days) in both growing seasons. The higher values of seasonal water applied in both growing seasons under I_1 compared to I_2 and I_3 can be attributed to the increased number of irrigations under I_1. In contrast, the I_2 and I_3 treatments required fewer irrigations throughout the two growing seasons, leading to reduced seasonal water application. These findings are consistent with the results reported by Abdou *et al.*, (2017), Kassab *et al.*, (2019) and Aiad (2019). Compared to I_1, irrigation water savings of 19.86% and 19.21% were achieved with I_2, while savings of 28.22% and 28.04% were noted with I_3 in the 1st and 2nd seasons, respectively. Additionally, water savings with I_3 compared to I_2 were 10.43% and 10.93% in the 1st and 2nd seasons, respectively.

3.1.2 Water consumptive use (cm, m^3 fed^{-1})

Consumptive water use (CU) refers to water removed from available supplies without return to a water resource. Seasonal CU for maize was clearly influenced by both irrigation intervals and N application treatments in both growing seasons as shown in Table (4). Concerning the irrigation intervals treatments, the highest CU value (59.50 cm) was recorded under I_1, in comparison to I_2 and I_3, while the lowest value (43.39 cm) was observed by I_3. The increased CU in treatment I_1, which received a higher number of irrigations than the other treatments, can be attributed to the greater volume of applied water, leading to higher soil moisture content. These findings are consistent with those of Amer *et al.* (2020), who reported that CU declines with reduced soil water availability. Similarly, Ouda *et al.* (2010) and Kassab *et al.* (2019) documented comparable trends, highlighting the strong relationship between irrigation frequency and CU.

TABLE 3. Seasonal amount of applied water (cm, m^3 fed^{-1}) for maize crop as effected by irrigation treatment and nitrogen fertilization doses in two seasons.

Irrigation treatment	Nitrogen fertilization rate (N)	1st growing season 2021		2nd growing season 2022		Overall mean values through the two growing seasons	
		cm	m^3 fed^{-1}	cm	m^3 fed^{-1}	cm	m^3 fed^{-1}
I_1	N_1	94.46	3988.80	96.25	4042.53	95.61	4015.67
	N_2	94.46	3988.80	96.25	4042.53	95.61	4015.67
	N_3	94.46	3988.80	96.25	4042.53	95.61	4015.67
Mean		94.46	3988.80	96.25	4042.53	95.61	4015.67
I_2	N_1	76.10	3196.39	77.76	3265.95	76.93	3231.17
	N_2	76.10	3196.39	77.76	3265.95	76.93	3231.17
	N_3	76.10	3196.39	77.76	3265.95	76.93	3231.17
Mean		76.10	3196.39	77.76	3265.95	76.93	3231.17
I_3	N_1	68.17	2863.08	69.26	2908.95	68.72	2886..02
	N_2	68.17	2863.08	69.26	2908.95	68.72	2886..02
	N_3	68.17	2863.08	69.26	2908.95	68.72	2886..02
Mean		68.17	2863.08	69.26	2908.95	68.72	2886..02

TABLE 4. Irrigation treatment and nitrogen fertilization rates effects on seasonal amount of consumptive use (cm, m^3 fed^{-1}) for maize crop in the two growing seasons.

Irrigation treatment	Nitrogen fertilization rate (N)	1st growing season 2021		2nd growing season 2022		Overall mean values through the two growing seasons	
		cm	m^3 fed^{-1}	cm	m^3 fed^{-1}	cm	m^3 fed^{-1}
I_1	N_1	56.25	2383.62	57.01	2394.24	56.88	2388.73
	N_2	59.24	2488.28	57.43	2495.94	59.34	2492.11
	N_3	62.21	2612.94	62.34	2618.34	62.28	2615.64
Mean		59.40	2494.95	59.39	2302.84	59.50	2498.89
I_2	N_1	44.44	1866.55	44.56	1871.59	44.50	1869.07
	N_2	49.09	1977.83	48.21	2024.89	47.65	2001.36
	N_3	51.09	2145.69	51.32	2155.53	51.21	2150.61
Mean		47.54	1996.69	48.03	2017.34	47.79	2007.01
I_3	N_1	39.98	1658.10	41.43	1739.96	40.46	1699.03
	N_2	42.74	1803.55	44.71	1877.85	43.83	1840.70
	N_3	45.71	1919.91	46.03	1933.37	45.87	1926.64
Mean		42.71	1793.85	44.06	1850.39	43.39	1822.12

On the other hand, application of 125% recommended N (N_3) effects on CU and it was the most efficient application rate under all irrigation treatments in both seasons with overall mean values of 62.28, 51.21 and 45.87 cm for I_1, I_2 and I_3 respectively. Nitrogen (N) deficiency reduces yield per unit of evapotranspiration (ET) by negatively affecting all yield components, particularly biomass production per unit of transpiration. The primary mechanism behind this reduction is the impairment of photosynthesis, which consequently lowers biomass production per unit of transpiration.

3.1.3 Consumptive use efficiency (Ecu, %)

Consumptive use efficiency (Ecu) reflects the plant's ability to effectively utilize soil moisture within the root zone. The highest overall mean Ecu (63.13%) was recorded under I_3 as shown in Table 5. Additionally, Ecu increased with higher nitrogen (N) application rates in both seasons, with the highest values (65.14%, 66.57%, and 66.76%) observed under the N_3 treatment for I_1, I_2, and I_3, respectively. This indicates that reducing the volume of applied water allows plants to utilize irrigation water more efficiently, thereby minimizing water losses.

TABLE 5. Effect of irrigation treatments and N fertilization doses on consumptive use efficiency (Ecu, %) for maize crop in the both seasons.

Irrigation treatment	Nitrogen fertilization	1st growing season 2021	2nd growing season 2022	Overall mean values through two growing seasons
I_1	N1	59.76	59.23	59.50
	N2	63.38	61.74	62.06
	N3	65.51	64.77	65.14
Mean		62.55	61.91	62.23
I_2	N1	58.40	57.31	57.86
	N2	61.88	62.00	61.94
	N3	67.13	66.00	66.57
Mean		62.47	61.77	62.12
I_3	N1	57.91	59.81	58.86
	N2	62.99	64.55	63.77
	N3	67.06	66.46	66.76
Mean		62.65	63.61	63.13

3.1.4 Water productivity (WP) and productivity of irrigation water (PIW, kg m^{-3})

Water productivity (WP) is a critical physiological characteristic that reflects a crop's ability to cope with water stress, defined as the biomass produced per unit of evapotranspiration (ET). As shown in Table 6, WP increased under extended irrigation intervals (water stress conditions) compared to I_1, with the highest value (2.40 kg m^{-3}) recorded under the I_2 treatment in both growing seasons. This increase in WP under I_2 and I_3 relative to I_1 is could be attributed to reduced water consumption and lower amounts of applied water in these treatments. These findings align with those of Aliabadi *et al.* (2008), who reported that reduced irrigation enhanced water use efficiency (WUE) in coriander, with the highest WUE observed under water scarcity stress. Regarding N fertilizer application, the maximum WP values (2.55 and 2.47 kg m^{-3}) were achieved with 100% of the recommended N dose (N_2) under I_2 in the 1st and 2nd seasons, respectively. Conversely, applying 125% of the recommended N dose (N_3) under I_1 resulted in the lowest WP values in both seasons (1.82 kg m^{-3}).

The highest WP values achieved with 100% of the recommended nitrogen dose highlight the importance of optimal fertilization in maximizing crop productivity under varying irrigation conditions. Conversely, the lower WP values associated with the 125% of recommended nitrogen application under more frequent irrigation suggest that excessive nitrogen may lead to inefficient water use, potentially due to increased biomass production without a proportional improvement in water uptake efficiency.

The ratio of yield to applied irrigation water is the productivity of irrigation water (PIW), which calculated to assess the treatments that optimized yield per unit of water applied. Regarding irrigation intervals, the highest PIW (1.49 kg m^{-3}) was observed under I_2 in both growing seasons as shown in table 6, while the lowest values (1.15 kg m^{-3}) was recorded under I_1. These findings align with those of Bandyopadhyay and Mallick (2003), who found that PIW was increased with increasing irrigation intervals. Similarly, Abd El-Hay (2008) and Kassab *et al.* (2019) found comparable trends, emphasizing the role of reduced irrigation in enhancing PIW. Abdel-Fattah *et al.* (2020) also concluded that reducing the amount of applied water leads to higher PIW values, whereas excessive water application results in decreased PIW.

On the other hand, PIW increased with higher nitrogen (N) fertilizer application rates across all irrigation treatments. The highest PIW values (1.63 and 1.59 kg m^{-3}) were achieved with the N_3 treatment under I_3 in the 1st and 2nd seasons, respectively, resulting in an overall mean of 1.61 kg m^{-3}. In contrast, the lowest PIW (1.10 kg m^{-3}) was recorded with the N_1 treatment under I_1 in both seasons.

3.2 Water table depth and NO_3^- (in water table and soil)

3.2.1 Water table depth (WT.D) (cm)

The WT.D, as influenced by nitrogen (N) fertilizers and irrigation intervals, is presented in Table 7. In general, following irrigation, the water table rose rapidly toward the soil surface and then gradually receded. Slight effect of N fertilizers on WT.D was observed in either growing season. However, regarding the impact of irrigation intervals, the data indicated that WT.D increased with longer intervals between irrigations in both seasons. The deepest WT (90.25 cm) was recorded with a 14-day irrigation interval combined with 125% of the recommended N dose, whereas the shallowest WT (72.4 cm) was observed with a 10-day interval combined with 75% of the recommended N dose. This may be due to exacerbated drought effects. As well, greater nitrogen fertilization heightens plant growth and water consumption, additional rising the WT.D (Mosaad *et al.*, 2024). Nguyen and Walker, (2005) showed that the time interval between flood irrigation events has a more significant impact on WT.D, where the shorter irrigation interval the greater the rise in water table level.

TABLE 6. Irrigation treatment and nitrogen fertilization rates effects on water productivity (WP, Kg m^{-3}) and productivity of irrigation water (PIW), Kg m^{-3}) for maize crop.

Irrigation treatment	Nitrogen fertilization rate (N)	1st growing season 2021		2nd growing season 2022		Overall mean values through both seasons	
		WP (kg m^{-3})	PIW (kg m^{-3})	WP (kg m^{-3})	PIW (kg m^{-3})	WP (kg m^{-3})	PIW (kg m^{-3})
I_1	N_1	1.82 d	1.09 e	1.88	1.11 d	1.85	1.10
	N_2	1.81 d	1.13 de	1.89	1.17 cd	1.85	1.15
	N_3	1.78 d	1.17 de	1.86	1.21 c	1.82	1.19
Mean		1.80	1.13	1.88	1.16	1.84	1.15
I_2	N_1	2.26 bc	1.32 c	2.34	1.34 b	2.30	1.33
	N_2	2.55 a	1.58 a	2.47	1.53 a	2.51	1.56
	N_3	2.38 b	1.59 a	2.39	1.57 a	2.39	1.58
Mean		2.40	1.50	2.40	1.48	2.40	1.49
I_3	N_1	2.13 c	1.23 cd	2.24	1.34 b	2.19	1.29
	N_2	2.30 bc	1.45 b	2.35	1.52 a	2.33	1.49
	N_3	2.44 ab	1.63 a	2.39	1.59 a	2.42	1.61
Mean		2.29	1.44	2.33	1.48	2.31	1.46
F-Test		*	**	Ns	*		
LSD 0.05		0.162	0.099	0.116	0.071		

3.2.2 NO_3^- level in water table, WT (mg l^{-1})

In general, there was clear effect of different N doses on NO_3^- concentration in WT (Table, 7). Where, NO_3^- concentrations in WT increased with higher N-fertilizer rates. The highest NO_3^- concentration in WT (24.59 mg l^{-1}) was recorded with N_3 treatment after the 2nd irrigation. These findings are in harmony with previous research that found a relation between N-fertilizer rates and nitrate escaping into groundwater (Minikaev *et al.*, 2021 and Mosaad *et al.*, 2024). Before fertilization, NO_3^- concentrations in the WT were relatively low (8.6 mg l^{-1}) but increased after N fertilization (following the first and second irrigations), ranging from 16.96 to 24.59 mg l^{-1}. Concentrations then decreased at the end of both seasons (7.02-9.06 mg l^{-1}).

The increase in NO_3^- concentrations in WT after the 1st and 2nd irrigations may be explicated on the origin of the supplement of N-fertilizer before the 1st and 2nd irrigations., The drop in NO_3^- in WT with wholly fertilizer treatments at the end of season could be attributed either to the drop of N concentration in the soil solution and/or to the rising N demand for maize plant during this growing period. Comparable results were reported by El-Hawary (2012) and Antar, (2013). Greater irrigations intervals lower nitrate concentration in WT. Where, the highest nitrate concentrations (20.4 and 22.89 mg l^{-1}) at I_1 and the lowest value (18.37 and 19.88 mg l^{-1}) at I_3 irrigation interval after first and second irrigation, respectively. This is accordance with previous research shown that lengthening irrigation intervals decreases nitrate concentrations in groundwater (Abbasi and Sepaskhah, 2023 and Mosaad *et al.*, 2024).

TABLE 7. Average water table depth (cm) and nitrate concentrations (mg l^{-1}) in water table with all treatments in both seasons.

Treatments		Before Fertilization	After fertilization				
			After 1st irrigation		After 2nd irrigation		End of both season
		NO_3^- WT (mg l^{-1})	WT.D. (cm)	NO_3^- WT (mg l^{-1})	WT.D. (cm)	NO_3^- WT (mg l^{-1})	NO_3^- WT (mg l^{-1})
I_1		8.6	73.95 c	20.40 a	73.21 c	22.89 a	7.23 c
I_2		8.6	82.39 b	19.80 b	84.71 b	20.97 b	8.32 b
I_3		8.6	88.62 a	18.37 c	89.94 a	19.88 c	8.68 a
F-Test		Ns	***	***	***	***	**
LSD 0.05			0.44	0.198	0.47	0.72	0.33
N_1		8.6	81.63 a	16.96 a	82.37	18.12 c	7.02 c
N_2		8.6	81.56 a	19.74 b	82.67	21.05 b	8.16 b
N_3		8.6	81.77 a	22.20 c	82.82	24.59 a	9.06 a
F-Test		Ns	Ns	**	Ns	***	***
LSD 0.05				0.52		0.46	0.37
I_1	N_1	8.6	73.85 d	17.38 e	72.4 f	18.64 e	6.46
	N_2	8.6	74.0 d	20.44 c	72.73 e	22.55 c	7.16
	N_3	8.6	74.0 d	24.09 a	73.51 e	27.49 a	8.07
I_2	N_1	8.6	82.12 c	17.19 ef	85.16 c	18.28 e	7.26
	N_2	8.6	82.98 c	20.42 c	84.47 d	20.39 d	8.45
	N_3	8.6	82.08 c	22.08 b	84.50 d	24.25 b	9.24
I_3	N_1	8.6	88.90 a	16.33 f	89.50 b	17.43 f	7.32
	N_2	8.6	87.71 b	18.36 d	90.25 a	20.19 d	8.88
	N_3	8.6	89.24 a	20.44 c	90.02 ab	22.04 c	9.85
F-Test		Ns	*	**	**	**	Ns
LSD 0.05			0.99	0.91	0.62	0.8	

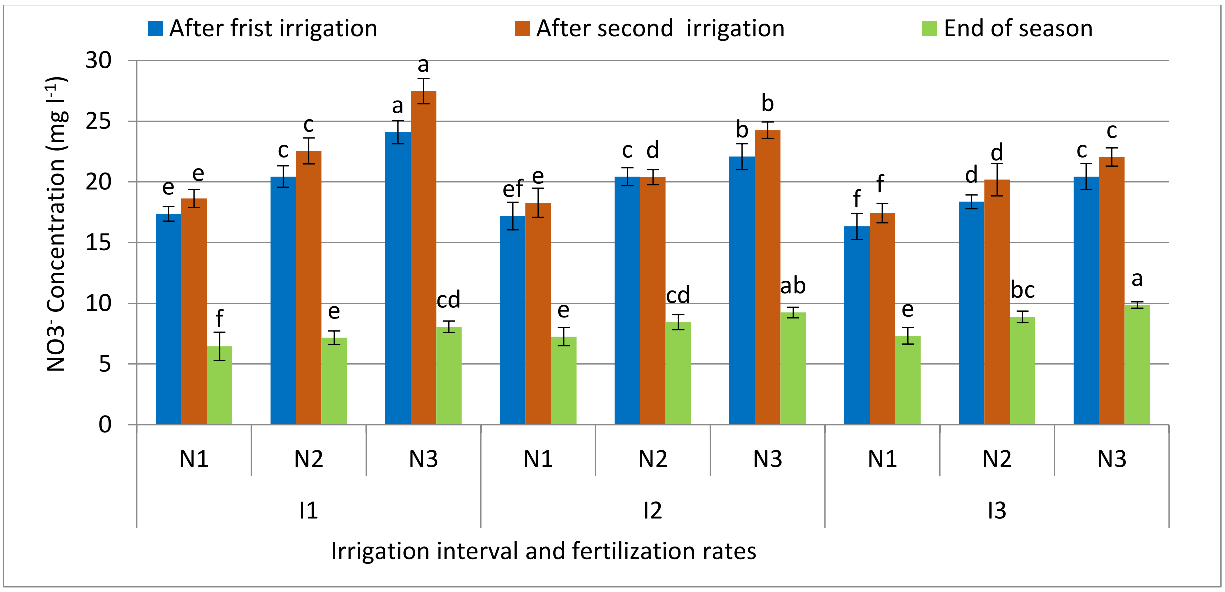

Fig 2. Average concentrations of NO_3^- (mg l^{-1}) in WT after irrigation for the treatments of study through both seasons.

Data illustrated in Fig. (2) also showed that high NO_3^- concentrations in WT were recorded under I_1 with N_3. The highest main concentrations of NO_3^- (18.64, 22.55 and 27.49 mg l^{-1}) in WT were recorded after the 2nd irrigation with I_1 irrigation interval under N_1, N_2 and N_3, while, the lowest main concentrations (16.33, 18.36 and 20.44 mg l^{-1}) were recorded after the 1st irrigation with I_3 under the three N-fertilizer rates, respectively. The low NO_3^- concentration in WT was more pronounced at the end of both seasons (6.46 - 9.85 mg l^{-1}). These results align with Tarkalson *et al.* (2006), who reported that proper irrigation scheduling minimizes the deep seepage of water and NO_3 -N. Thus, governing N dosages is crucial for controlling NO_3^- concentrations in WT, as shorter irrigation intervals significantly increase

NO_3^- leaching. The opposite trend was observed with the increasing of irrigation interval and decreasing N doses (Khan *et al.*, 2018). Adequate management of irrigation intervals and nitrogen fertilization levels can help lower nitrate seeping into water table (Mosaad *et al.*, 2024).

3.2.3 NO_3^- in soil

The soil NO_3^- content decreased significantly with soil depth during both growing seasons, as shown in Table (8). This trend can be attributed to the surface application of mineral N fertilizers and the relatively high organic matter (OM) content near the soil surface, which diminishes with depth. Before cultivation, NO_3^- content in the soil ranged from 14.3 to 26.5 mg kg^{-1}. The highest contents of NO_3^- (68.5 and 25.3 mg kg^{-1}) were found after fertilization (after the 1st and 2nd irrigations, respectively). However, by the end of the growing seasons, NO_3^- levels dropped to 7.0–9.1 mg kg^{-1}, likely due to rapid nitrogen uptake by plants immediately after irrigation when soil water tension was minimal. These findings are consistent with those reported by Antar, (2013) and Khafagy *et al.*, (2018). Additionally, NO_3^- content after fertilizer application was higher under the I_3 irrigation interval (15.1 - 68.5 mg kg^{-1}) compared to the I1 interval (13.0 - 55.5 mg kg^{-1}). This can be explained by the longer irrigation intervals reducing drainage water losses, thereby concentrating nutrients in the soil solution. Moreover, higher rates of N fertilization resulted in greater levels of NO_3^- in the soil solution (Elmi *et al.*, 2002).

TABLE 8. Average NO_3^- concentration (mg kg^{-1}) in two seasons at different soil depths before cultivation, after the 1st and 2nd irrigations and at the end for all treatments.

Irrigation	Soil depth	Before fertilization	After fertilization								
			After 1st irrigation			After 2nd irrigation			End of season		
			NO_3^- 75%	NO_3^- 100%	NO_3^- 125%	NO_3^- 75%	NO_3^- 100%	NO_3^- 125%	NO_3^- 75%	NO_3^- 100%	NO_3^- 125%
I_1	0-15	26.5	50.0	52.0	55.5	16.1	18.0	20.0	7.0	7.3	8.0
	15-30	23.0	40.0	43.5	43.5	15.5	15.5	17.5			
	30-60	14.5	35.5	40.5	40.5	13.0	14.0	13.5			
I_2	0-15	26.5	53.5	55.0	60.1	18.5	20.0	23.0	8.0	8.3	8.8
	15-30	23.0	40.5	48.0	52.0	17.0	18.5	20.1			
	30-60	14.3	36.5	40.5	45.5	14.0	14.5	15.5			
I_3	0-15	26.5	60.0	63.0	68.5	20.5	22.5	25.3	8.1	8.8	9.1
	15-30	23.0	51.3	53.5	58.5	17.3	20.5	21.5			
	30-60	14.5	40.0	45.5	50.0	15.1	15.5	16.5			

Also, data in Table (8) revealed that soil NO_3^- content was increased with the increasing N-fertilizer rate (75, 100 and 125 % of the recommended N) across irrigation intervals (10, 12 and 14-day interval) in both growing seasons. The average NO_3^- contents in the soil across both seasons were 28.35, 30.58, and 31.75 mg kg^{-1} under I_1; 30.0, 32.75, and 36.03 mg kg^{-1} under I_2; and 34.03, 36.75, and 40.05 mg kg^{-1} under I_3, corresponding to N_1, N_2, and N_3, respectively. The highest dosages of N (125%) resulted in higher soil NO_3^- content under I_3 irrigation interval. These findings align with those of Wu *et al.* (2019), who observed that soil nutrient content is influenced by irrigation practices and nitrogen fertilization levels. Excessive irrigation water can lead to increased nutrient leaching, thereby reducing soil nutrient content. At the end of the growing season, the mean values of soil NO_3^- content were 7.0, 7.3 and 8.0 mg kg^{-1} with I_1, 8.0, 8.3 and 8.8 mg kg^{-1} with I_2 and 8.1, 8.8 and 9.1 mg kg^{-1} with I_3 under the N-fertilizer treatments of N_1, N_2 and N_3, respectively. This pattern may be attributed to shorter irrigation intervals, which result in increased NO_3^- leaching and enhanced plant N uptake, leading to diminished NO_3^- accumulation at the harvest stage compared to the sowing or soil preparation stage (Wang *et al.*, 2012). Furthermore, the NO_3^- concentrations in WT were found to closely correspond to the soil NO_3^- content throughout both seasons.

3.3 Nitrogen (%) and N-uptake of maize seed

Data in Table 9 indicate significant differences in nitrogen content (N%) and nitrogen uptake (kg fed^{-1}) in maize seeds across varying irrigation intervals and N-fertilizer rates. Among the treatments, N_3 resulted in the highest N% and N-uptake, followed by N_2 and N_1. As fertilization rate increases, the N% and N-uptake in maize seed were increased. Specifically, N_3 led to a 0.012% higher N% and a 17.25 kg fed^{-1} greater N-uptake compared to N_1. These findings are consistent with those of El-Dissoky and Gahwash (2018), who reported that the uptake of essential nutrients such as N, P, K, S, Ca, Fe, Mn, and Zn by plants significantly increased with higher rates of mineral nitrogen fertilization. Also, in the same Table (9) irrigation interval I_2 caused more increase of N (%) and N-uptake by maize grain than I_1 (by 0.02 %, 6.83 Kg fed^{-1}) and I_3 by 0.002 %. 14.42 Kg fed^{-1}, respectively. These findings may be attributed to the extended irrigation intervals, which likely promoted more extensive root growth, thereby enhancing nutrient uptake. This aligns with El-Dissoky and Gahwash's (2018), who reported a positive correlation between irrigation intervals and improvements in soil fertility, plant growth, and nutrient uptake after 110 days.

The interaction between irrigation intervals and fertilization rates had a highly significant influence on N contents and N-uptake in both seasons. The highest N content and N-uptake in seed (2.145 % and 109.33 kg fed^{-1}, respectively) were achieved due to the combination of I_2 with N_3. These findings are consistent with those of Al-Kaisi *et al.* (2003) and Wang *et al.* (2012), who reported significant positive effects of irrigation levels and N rates on corn grain yield. Additionally, Ati *et al.* (2013) demonstrated that the irrigation can enhance the efficiency of fertilization.

TABLE 9. Through both seasons of study, average N-uptake in grain for all treatments.

Treatments	N (%)	N-uptake Kg fed^{-1}	Treatments		N (%)	N-uptake Kg fed^{-1}
Irrigation interval (I)			Interactions between irrigation interval and fertilization			
I_1	2.128 c	95.67 b	I1	N_1	2.118 e	92.03 f
I_2	2.140 a	102.5 a		N_2	2.131 d	95.48 e
I_3	2.138 b	88.08 c		N_3	2.134 c	99.5 d
F-Test	***	***	I_2	N_1	2.136 c	90.06 g
LSD 0.05	0.002	0.079		N_2	2.14 b	108.11 b
Fertilization rates (N)				N_3	2.145 a	109.33 a
N_1	2.129 c	85.82 c	I_3	N_1	2.135 c	75.37 i
N_2	2.135 b	97.36 b		N_2	2.135 c	88.50 h
N_3	2.141 a	103.07 a		N_3	2.145 a	100.37 c
F-Test	***	***	F-Test		***	***
LSD 0.05	0.0012	0.056	LSD 0.05		0.002	0.097

3.4 Yield and yield attributes

Irrigation intervals significantly influenced maize yield and various yield components, including ear diameter (cm), ear length (cm), and seed yield (Table 10). The highest values of ear diameter (14.6 and 14.8 cm), ear length (16.2 and 16.6 cm) and seeds yield (24.8 and 24.8 ardabfed^{-1}) were obtained at irrigation every 12 days in the 1st and 2nd seasons, respectively. The rank of irrigation intervals impacts on the yield and yield components are as follows: I_2 >I_1 >I_3. Statistical analysis exposed greatly significantly variances between I_2 and other treatments in two growing seasons. These results may be ascribed to the fewer or close irrigation intervals as related to other irrigation ones. The increasing of yield and yield component by I_2 could be due to the ideal plant- water relationship, which resulted by this irrigation treatment and as a result enhancing deep and diffusion of roots, plant growth, nutrients uptake and then yield. On the conflicting, other irrigation treatments recorded the lower values of these parameters. These results are within conformity with those stated by Bhat *et al.* (2017) and El-Henawy and Elsayed (2018), who noticed that slightly water stress caused a slightly significant constituent.

Conversely, irrigation times did not significantly affect certain yield components, such as stem diameter (cm) in all seasons, as well as plant height (cm), ear height (cm), and 100-seed weight (g) in the first season only, as indicated in Table 10. In contrast, fertilization demonstrated significant positive effects on yield and yield attributes across all growing seasons. The maximum values for stem diameter (7.59 and 7.62 cm), ear diameter (14.6 and 14.8 cm), ear height (98.0 and 97.9 cm), ear length (16.7 and 16.6 cm), plant height (202.5 and 202.7 cm), 100-seed weight (31.36 and 32.0 g) and seeds yield (24.9 and 25.0 ardab fed^{-1}) were achieved with N_3 in the 1st and 2nd seasons, respectively. In contrast, the lowest yield and yield attributes were recorded with N_1 in both seasons. These might be due to the rising of available N content in the root zone. These results are in concord with those achieved by Zhang *et al.* (2018) and She *et al.* (2022) 98.7 who recovered that higher N fertilizer applications contributed to an increase in spike number per area, 1000-grain weight, and grain number per ear.

TABLE 10. Effects of irrigation and N fertilization treatments on yield and yield attributes of maize (Zea maize).

Treatments		Stem diameter (cm)	Ear diameter (cm)	Plant height (cm)	Ear height (cm)	Weight 100 Seed(g)	Seeds yield (ardabfed^{-1})	Ear length (cm)
First season 2021								
I_1		7.10	14.4 b	198.1	94.8	30.70	23.7 a	15.8 ab
I_2		7.17	14.6 a	198.3	97.8	31.03	24.8 a	16.2 a
I_3		6.97	14.2 c	195.8	93.2	29.42	21.7 b	15.3 b
F-Test		Ns	**	Ns	Ns	Ns	**	*
LSD 0.05			0.16				1.21	0.65
N_1		6.74 b	14.1 b	193.4 b	91.4 b	29.96	21.2 b	15.1 b
N_2		7.02 b	14.5 a	196.3 b	96.5 a	30.44	24.0 a	15.5 b
N_3		7.59 a	14.6 a	202.5 a	98.0 a	31.36	24.9 a	16.7 a
F-Test		***	**	*	***	Ns	***	***
LSD 0.05		0.33	0.24	6.31	1.79		1.0	0.66
I_1	N_1	6.8	14.3	195.7	90.3 c	29.80	22.9 cd	14.6
	N_2	7.2	14.4	196.4	96.3 ab	30.14	23.6 cd	15.2e
	N_3	7.7	14.5	202.3	97.6 ab	31.30	24.5 b	17.6
I_2	N_1	6.8	14.2	195.9	96.5 ab	28.90	22.2 d	15.9
	N_2	7.1	14.7	198.5	98.3 a	32.20	26.6 a	16.1
	N_3	7.6	14.9	200.6	98.7 a	32.98	25.7 ab	16.6
I_3	N_1	6.7	13.9	188.7	87.3 c	29.50	18.6 e	14.8
	N_2	6.8	14.3	193.9	94.8 b	29.80	21.8 d	15.2
	N_3	7.4	14.4	204.7	97.6 ab	30.60	24.6 bc	16.0
F-Test		Ns	Ns	Ns	*	Ns	**	Ns
LSD 0.05					3.11		1.75	
Second season 2022								
I_1		7.26	14.7 a	198.7 a	95.1 b	31.6 b	24.1 a	15.9 b
I_2		7.26	14.8 a	198.9 a	98.3 a	32.7 a	24.8 a	16.6 a
I_3		7.04	14.2 b	196.3 b	93.4 c	30.6 c	22.1 b	15.5 c
F-Test		Ns	**	**	**	**	**	***
LSD 0.05			0.18	0.78	1.25	0.67	1.2	0.07
N_1		6.83 b	14.2 c	194.3 b	92.3 c	31.4 b	21.9 c	15.4 c
N_2		7.10 b	14.6 b	197.0 b	96.6 b	31.5 b	24.2 b	16.1 b
N_3		7.62 a	14.8 a	202.7 a	97.9 a	32.0 a	25.0 a	16.6 a
F-Test		**	***	*	***	***	***	***
LSD 0.05		0.35	0.14	5.05	0.92	0.14	0.68	0.13
I_1	N_1	6.9	14.4	196.2	91.2 e	31.4	23.1	15.1 e
	N_2	7.1	14.8	198.3	96.5 cd	31.6	24.2	15.9 c
	N_3	7.7	14.9	201.7	97.7 bc	31.9	25.1	16.7 b
I_2	N_1	6.8	14.4	196.3	96.8 bc	32.5	22.5	16.1 c
	N_2	7.3	14.9	197.5	98.4 ab	32.6	25.7	16.7 b
	N_3	7.7	15.1	203.1	99.8 a	33.1	26.4	17.0 a
I_3	N_1	6.7	13.9	190.4	88.9 f	30.2	20.0	14.8 f
	N_2	6.9	14.3	195.3	95.0 d	30.4	22.6	15.6 d
	N_3	7.5	14.5	203.3	96.4 cd	31.1	23.7	16.1 c
F-Test		Ns	Ns	Ns	**	Ns	Ns	**
LSD 0.05					1.59			0.23

The interaction of N fertilizer dose with irrigation times presented insignificant impact on stem diameter, ear diameter, plant height and weight 100 grain of maize plant in both seasons. But it seemed to be highly significant on ear height (98.7 and 99.8 cm) during both seasons, respectively and on seeds yield (26.6 ardab fed^{-1}) in the 1st season and ear length (17.0 cm) in the 2nd season. This influence may be exposed to soil moisture which is essential to activate microorganisms under field irrigated every 10, 12 and 14 days. Also, this effect refers to a complementally positive role between fertilization and water supply of maize plants. Ati *et al.* (2013) and El-Sobky and Desoky, (2017) showed that the irrigation improves the efficiency of fertilization. These results are a like to Al-Kaisi *et al.* (2003) who mentioned significant and positive effects of irrigation levels on maize grain yield and its responses to N doses.

4. Conclusion and recommendations

Under the circumstances of water shortage in Egypt, it is more necessary now than ever to make proper management of the on-farm irrigation. Also, NO_3^--N concentrations in water table always surpass the maximum contaminant level of 10 mg l^{-1} (U.S. Environmental Protection Agency, 1991) except at the end of the season. Therefore, this study is to discuss the influence of irrigation intervals and N-fertilizer rate on environment, maize crop and its components. The obtained results showed that:

- The highest mean values of water productively (WP) were recorded under I_2 treatment (irrigation every 12 days) with N_3 (100% of N fertilizer). Whilst, the highest mean values of productivity of irrigation water (PIW) were recorded under I_3 treatment (irrigation every 14 days) with N_3 (125% of N fertilizer).
- For maize crop; grain yield, plant height, 100-grain weight and other yield components gave the highest values under irrigation treatment of I_2 with N_3 treatment.
- Application of N-fertilizer rate more than the recommended leads to high NO_3^--N pollution with negligible increase in maize yield.
- It is recommended that 12-day irrigation interval with 100% of N fertilizer can be used as a guide means to obtain a promising maize grain yield, saving water and reducing NO_3^- losses through leaching and consequentially improving surface and groundwater quality.

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