water

MDPI

Article

Optimizing Drip Irrigation and Nitrogen Fertilization for Sustainable Wheat Production in Arid Soils: Water–Nitrogen Use Efficiency

Ahmed A. Abdelrhman [1], Ibrahim M. Abdel-Fattah [2], Mostafa O. Mostafa [3], Mohamed E. Fadl [4,*], Marios Drosos [5] and Antonio Scopa [5,*]

[1] Department of Soils and Water, Faculty of Agriculture, Al-Azhar University, Assiut Branch, Assiut 71524, Egypt; abdelrhmansoil@azhar.edu.eg
[2] Water Requirements and Field Irrigation Research Department, Soils, Water and Environment Research Institute, Agricultural Research Centre (ARC), Giza 12112, Egypt; dr.ibrahim.irri.designed@gmail.com
[3] Wheat Research Department, Field Crops Research Institute, Agricultural Research Centre (ARC), Giza 12619, Egypt; mostafa_8846@yahoo.com
[4] Division of Scientific Training and Continuous Studies, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo 11769, Egypt
[5] Department of Agricultural, Forestry, Food and Environmental Sciences (DAFE), University of Basilicata, Via dell'Ateneo Lucano, 10, 85100 Potenza, Italy; marios.drosos@unibas.it
* Correspondence: madham@narss.sci.eg (M.E.F.); antonio.scopa@unibas.it (A.S.)

Abstract

Water scarcity and inefficient nitrogen (N) use are major constraints on wheat production in arid regions. Drip irrigation offers a precise method for optimizing water and nutrient delivery, but integrated management strategies are needed to maximize yield and resource use efficiency. In Egypt, water shortages and inadequate fertilizer necessitate effective resource management for sustainable agriculture and crop productivity. This study investigates the effects of integrated water and nitrogen fertilizer management under drip irrigation on wheat (*Triticum aestivum* L.) performance in arid zones of Egypt. A two-year field experiment was conducted to evaluate wheat yield, productivity of applied water (PAW), crop water productivity (CWP), and nitrogen use efficiency (NUE) under varying irrigation regimes and nitrogen application rates. This study evaluated two irrigation regimes: 100% (I_1) and 80% (I_2) of crop evapotranspiration (ETc) in combination with three nitrogen application rates: 142.8 kg N ha^{-1} (N_1), 190.4 kg N ha^{-1} (N_2), and 238 kg N ha^{-1} (N_3). Irrigation at 100% of ETc (I_1) significantly enhanced plant height, straw yield, biological output, grain yield, seed index, NUE, and CWP in comparison with the 80% ETc treatment (I_2). However, I_2 demonstrated a higher PAW and grain protein content than I_1. Furthermore, applying nitrogen at a rate of 238 kg N ha^{-1} (N_3) resulted in notable improvements in these parameters relative to the lower rate of 142.8 kg N ha^{-1} (N_1). I_1N_3 and I_1N_2 treatments increased CWP by 29% and 22%, respectively, compared to I_1N_1 across both growing seasons. Principal component analysis (PCA) revealed that the application of 238 kg N ha^{-1} (N_3) may represent the most effective nitrogen management strategy for optimizing winter wheat production under drip irrigation systems. Moreover, PCA suggested that combining deficit irrigation with a high nitrogen application rate (I_2N_3) enhances the productivity of applied water (PAW) and grain quality. In contrast, full irrigation with the lowest nitrogen rate (I_1N_1) appeared to be the most effective strategy for maximizing NUE. These findings highlight the potential of integrated strategies to sustainably boost wheat yields in environments suffering from water shortage.

check for updates

Academic Editors: William Frederick Ritter and Haijun Liu

Received: 6 August 2025
Revised: 9 September 2025
Accepted: 11 September 2025
Published: 13 September 2025

Citation: Abdelrhman, A.A.; Abdel-Fattah, I.M.; Mostafa, M.O.; Fadl, M.E.; Drosos, M.; Scopa, A. Optimizing Drip Irrigation and Nitrogen Fertilization for Sustainable Wheat Production in Arid Soils: Water–Nitrogen Use Efficiency. *Water* **2025**, *17*, 2708. https://doi.org/10.3390/w17182708

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Keywords: wheat; productivity of applied water (PAW); crop water productivity (CWP); nitrogen use efficiency (NUE); nitrogen management

1. Introduction

Wheat is an important cereal crop in the world and the primary food source in Egypt, with implications for national food security [1,2]. Effective water and nitrogen management is essential to sustained wheat production, particularly in arid and semi-arid regions such as Egypt [3,4]. Egypt faces a substantial gap between national production and local consumption levels. Consequently, the cultivation of wheat in sandy soils is increasing in Egypt's agricultural area [5,6]. Effective irrigation scheduling is essential for assisting farmers in increasing crop productivity while conserving water due to restricted availability [7,8]. In Egypt, the agricultural sector is the greatest consumer of freshwater resources, accounting for around 85% of total supply [9–11]. This excessive consumption is mostly due to poor irrigation practices and inappropriate water management methods. Under circumstances of water shortage, these inefficiencies limit farmers' capacity to meet crops' full water requirements, causing physiological water stress in plants. Stress has a negative impact on plant growth and greatly reduces crop yields.

Flood irrigation in the Nile Delta and Valley remains common but has lower water use efficiency (about 60%), which is linked to increasing irrigation water requirements [12]. Therefore, to ensure economic efficiency and effective management, farmers need to adopt water-saving technologies and strategies that enhance irrigation capacity and optimize water use. Drip irrigation is a viable agricultural method, enhancing water use efficiency in arid regions by supplying water directly to the root zone, thereby reducing evaporation and runoff [13]. Integrating it with nitrogen fertilizer augments both water and nitrogen use efficiency, hence improving agricultural yields and mitigating environmental effects.

Deficit irrigation practices present a highly effective approach to enhancing irrigation productivity. Deficit irrigation is a technique of providing crops with less water than their total evapotranspiration requirements [14–16]. While this strategy may result in somewhat lower yields, it can greatly improve the efficiency of water use and minimize total yield losses [17,18]. Several ways may be used to successfully execute deficit irrigation. One such approach is continual deficit irrigation, which applies a consistently low amount of water throughout the growing season [19,20]. To make this technique work, it is vital to understand the crop's water requirements, identify crucial development stages, and evaluate the economic ramifications. Farmers are more likely to adopt this strategy when the projected yield reduction is minimal [21].

Therefore, implementing deficit irrigation strategies presents a potentially effective approach to mitigating water scarcity in Egypt [7,22,23].

Improving nitrogen fertilization practices by evaluating the nitrogen use efficiency (NUE) of mineral nitrogen fertilizers in wheat (*Triticum aestivum* L.), as well as assessing the nitrogen status in both soil and plant tissues, is critical for increasing the yield potential and grain quality in wheat production [24]. Nitrogen plays a crucial role in optimizing plant water use efficiency, particularly under water-limited conditions [25,26]. Its influence extends to various physiological processes, impacting leaf function and overall crop yield [27]. Water use efficiency, defined as the ratio of grain yield to water consumption [28], is enhanced by nitrogen's effects on photosynthetic capacity [29], transpiration rates [30], and root development [31]. Strategic nitrogen management in water-scarce environments can contribute to increased agricultural productivity and improved sustainability.

Current meta-analyses have indicated that combining irrigation and nitrogen fertilizer can boost wheat grain production by up to 17.3% above traditional approaches [32]. These integrated strategies are especially pertinent in Egypt, since wheat production gaps remain considerable [4]. Nevertheless, excessive or poorly managed nitrogen application can result in nitrate leaching, groundwater pollution, and greenhouse gas emissions [33]. As a result, precise water and nitrogen management are required to strike a balance between production and environmental sustainability [34].

Egypt's agriculture relies heavily on irrigation and nitrogen fertilizers for wheat production [3,35]. Excessive nitrogen use causes soil damage, reduces organic matter, and harms beneficial microbes, decreasing fertility and threatening future farming [36]. Healthy soil is crucial for sustained high yields. Most studies examine how appropriate management of irrigation or nitrogen affects the crop yield [3,37–39]. The integrated management of water and nitrogen to improve the water and nitrogen use efficiency (WUE and NUE) in arid and semi-arid environments is still under investigation. Improving water and nitrogen efficiency is crucial for sustainable farming in dry regions like Egypt [40].

This study aims to investigate the effects of integrated water and nitrogen management utilizing drip irrigation on wheat (*Triticum aestivum* L.) yield performance in Egypt's arid regions by evaluating two irrigation regimes (100% and 80% ETc) and three nitrogen rates (142.8, 190.4, and 238 kg N ha^{-1}). This research assesses key agronomic parameters, including yield, crop water productivity (CWP), productivity of applied water (PAW), nitrogen use efficiency (NUE), and grain protein content, to determine optimal resource management strategies. By employing principal component analysis (PCA), this study identifies the most effective combinations of irrigation and nitrogen application for maximizing wheat productivity under water-scarce conditions, providing practical solutions for sustainable agriculture in arid zones.

2. Materials and Methods

2.1. Weather Conditions

At this experimental site, monthly temperature, humidity, and wind conditions fluctuated considerably during both the wheat-growing seasons (Figure 1A), consistent with typical regional trends. Figure 1A shows that air temperatures were lower during the 2022–2023 wheat-growing season than in 2023–2024. Climate data from 2022/23 and 2023/24 show that March and April's temperatures were elevated. Mean maximum temperatures ranged from 32.15 to 33.15 °C in March and 39.05 to 40.40 °C in April. Relative humidity was much lower during the active development period of the 2022/23 season (March–April) than in 2023/24. The monthly average wind speed varied between 8.90 and 14.20 km h^{-1}. Peak wind speeds (14.20 and 13.70km h^{-1}) were recorded in April during both wheat-growing seasons. Reference evapotranspiration (ETo) exhibited substantial variation between the two growth seasons (Figure 1B). ETo was higher during the medium stage to late grain-filling stage in the 2023/24 growing season compared to the 2022/23 season. Total ETo for the 2022/23 season was 23.27 cm, while it was 24.39 cm in the 2023/24 season. As a result, wheat plants experienced significant water stress over the whole 2023/24 growing season.

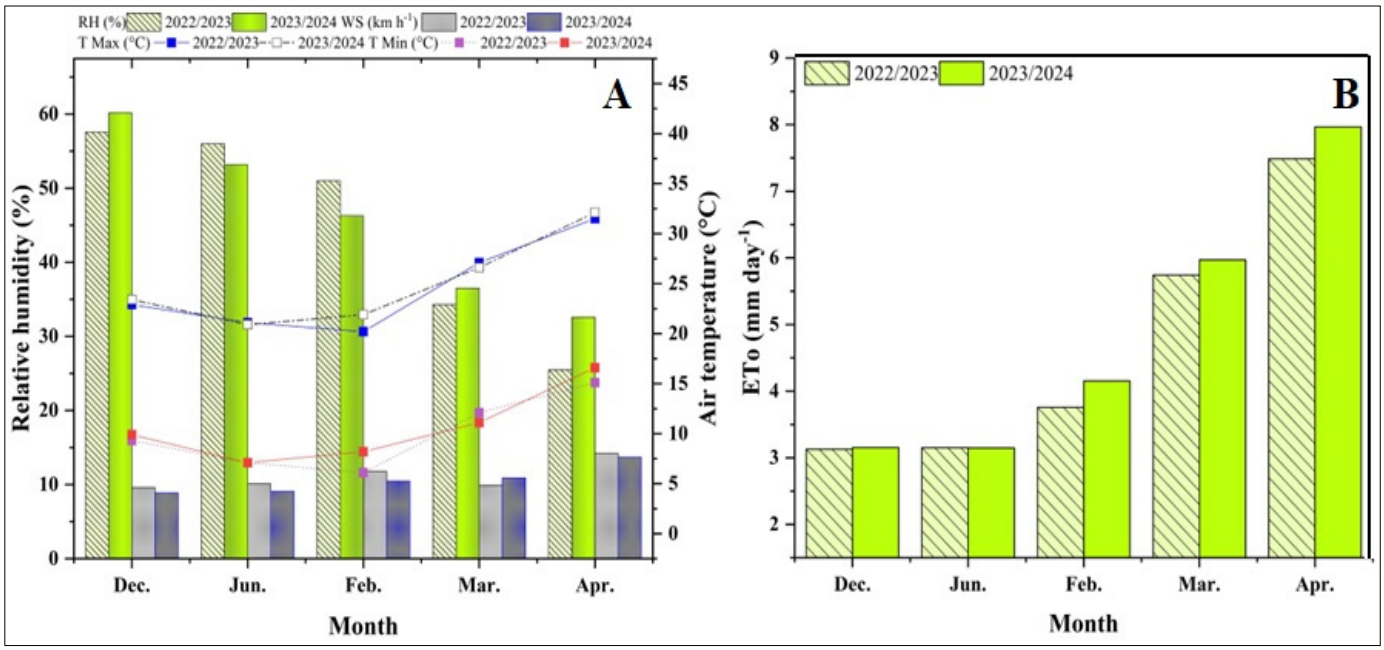


Figure 1. Seasonal variation in meteorological parameters and reference evapotranspiration (ETo) during the 2022/23 and 2023/24 winter growing seasons in Assiut, Egypt: (**A**) monthly averages of maximum/minimum air temperature (lines), relative humidity (RH), and wind speed (WS) (bars); (**B**) monthly reference evapotranspiration (ETo, mm day^{-1}).

2.2. Experimental Site, Design, and Field Management

Field experiments were carried out during the 2022/2023 and 2023/2024 winter seasons at the Arab El-Awammer Research Station Experimental Farm, affiliated with the Agricultural Research Center (ARC), Assiut, Egypt (27°11′ N, 31°06′ E, 71 m above sea level). The primary objective of this study was to evaluate the effects of deficit irrigation based on crop evapotranspiration (ETc) combined with the application of nitrogen fertilizer through drip irrigation in arid sandy calcareous soils. Key physical and chemical properties of the studied soils are summarized in Table 1.

Table 1. Physical and chemical properties for the studied soils.

Property	Unit	Mean Value	Property		Unit	Mean Value
Gravel	%	30.4	Soluble cations	Ca	mmol L^{-1}	1.43
Sand	%	90.9		Mg		1.16
Silt	%	7.1		Na		0.19
Clay	%	3.0		K		0.75
Texture class	-	Sandy	Soluble anions	CO_3 + HCO_3		1.68
Saturation percentage	w%	23.3		Cl		1.47
Field capacity	w%	10.9		SO_4		0.35
Wilting point	w%	4.50	Available N		mg kg^{-1}	32.47
Available water	w%	6.50	Available P			8.31
Bulk density	Mg cm^{-3}	1.62	Available K			37.24
$CaCO_3$	%	30.0	-	-	-	-
Organic matter (OM)	%	0.10	-	-	-	-
pH (1:1)	-	8.37	-	-	-	-
EC (soil past extract)	ds m^{-1}	0.33	-	-	-	-

Note: "w" is weight basis.

The experiment used a split-plot layout within a randomized complete block design (RCBD) and was replicated three times (Figure 2). The main plots were divided into two irrigation treatments: I_1 (100% ETc) and I_2 (80% ETc). Subplots at each irrigation level received varied nitrogen rates: N_1 (142.8 kg N ha^{-1}), N_2 (190.4 kg N ha^{-1}), and N_3 (238.0 kg N ha^{-1}). Six treatments were obtained for each experiment by combining three nitrogen rates of application with two irrigation levels. The study involved 18 plots, each measuring 12.0 m^2 (4 m × 3 m) and containing eight ridges. Plots were spaced 1 m apart, with a 1.5 m gap between blocks. The drip irrigation system made use of 16 mm GR polyethylene tubing with integrated emitters that were spaced by 30 cm. With lateral lines spaced 50 cm apart, water was delivered at a rate of 4 L h^{-1} per emitter at a pressure of 1.5 bars.

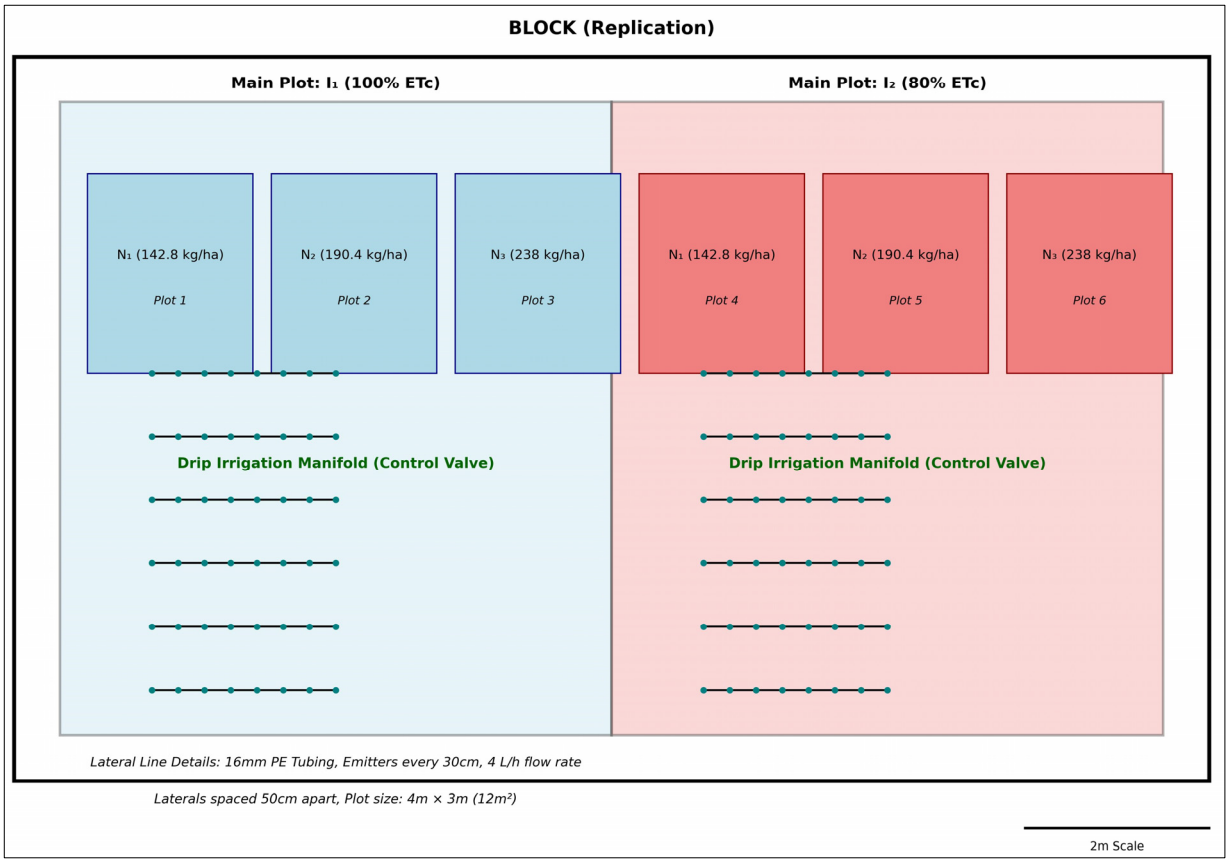


Figure 2. The split-plot layout within a randomized complete block design (RCBD) and drip irrigation system laid in the study experiment.

The wheat cultivar Masr-1 was sown at a seeding rate of 190.5 kg ha^{-1} on 3 and 7 December during the 2022/23 and 2023/24 winter seasons, respectively. Harvesting occurred on 28 April and 5 May in the first and second seasons, approximately 150 days after sowing. All agronomic practices followed the standard recommendations issued by the Egyptian Ministry of Agriculture. Phosphorus and potassium fertilizers were applied at rates of 75 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1}, respectively, and were used as the nutrient sources. Triple superphosphate (46% P_2O_5) was incorporated into the soil in a single dose before planting, while potassium sulfate (50% K_2O) was applied in two equal splits during the growing season. Nitrogen fertilizer was supplied through the irrigation system using ammonium nitrate (33.5% N) for all nitrogen treatments. Note that a rate of 214 kg N ha^{-1} is the recommended dose for wheat under drip irrigation conditions in Egypt. The nitrogen

was applied in six equal fertigation doses for the three application nitrogen rates, starting 15 days after planting and continuing at 10-day intervals.

2.3. Crop Evapotranspiration (ETc)

The CROPWAT model was employed to calculate reference evapotranspiration (ET_0) using the Penman–Monteith approach [41]. Additionally, crop evapotranspiration (ETc) was estimated within the same model framework, applying the Penman–Monteith equation as shown in the following Equation (1) [42]:

$$ET_c = ET_0 \times K_c \quad (1)$$

where ETc is crop evapotranspiration, ET_0 is reference evapotranspiration, and Kc is the wheat winter crop coefficient factor, which equal 0.4 (initial), 1.15 (mid), and 0.25 (end), respectively [42].

2.4. Actual Irrigation Water Applied (AIWA)

The actual volume of irrigation water applied under each treatment was calculated based on the method described by James (1988) [43], using the following Equation (2):

$$AIWA = \frac{ET_c + Lf}{Er} \quad (2)$$

where AIWA is the actual irrigation water applied (mm per interval), ETc is crop evapotranspiration estimated using pan evaporation, Lf is the leaching factor (10%), and Er is the efficiency of the irrigation system.

Plants were hand-harvested into a 1 m^2 section in the middle of each receiving plot and dried naturally. Plant height, straw yield, and biological yield were all determined from each replication. To calculate grain yield, all of the spikes in every plot were cut, sun-dried, and weighed. Finally, the weight of grains in each plot was reduced to kilos per hectare. Wheat grain quality was assessed based on the protein content.

2.5. Nitrogen Fertilizer Use Efficiency (NUE)

The NUE is a critical measure in agriculture that evaluates how effectively crops utilize applied nitrogen (N) to produce a yield, with the goal of minimizing environmental losses such as leaching, volatilization, and greenhouse gas emissions. NUE is influenced by factors like soil properties, crop genetics, fertilizer management, and climatic conditions, and it can be improved through precision agriculture, controlled-release fertilizers, nitrification inhibitors, and optimized crop rotations. NUE was computed using the following Equation (3):

$$NUE = \frac{Grain\ yield\ \left(\mathrm{kg\ ha^{-1}}\right)}{Total\ Nirogen\ Fertilizer\ \left(\mathrm{kg\ ha^{-1}}\right)^0} \quad (3)$$

2.6. Productivity of Applied Water (PAW)

PAW represents the grain yield obtained per unit of irrigation water applied. It serves as a key indicator for assessing how effectively water is utilized in crop production, particularly in areas where water resources are limited. In this study, PAW was determined by dividing the grain yield by the total volume of irrigation water applied. Higher PAW

values reflect more efficient water use, resulting in a greater yield per unit of water. The PAW was calculated using the following Equation (4):

$$PAW = \frac{Total\ grain\ yield\ \left(\text{kg ha}^{-1}\right)}{Irrigation\ Water\ Applied\ \left(\text{m}^3\ \text{ha}^{-1}\right)} \quad (4)$$

2.7. Crop Water Productivity (CWP)

CWP measures the grain yield produced per unit of total water consumed by the crop, which includes both irrigation and evapotranspiration. It is a crucial metric for assessing how effectively water is converted into agricultural output. According to the method outlined by Zwart and Bastiaanssen (2004) [44], CWP is calculated using the following Equation (5):

$$CWP = \frac{Total\ grain\ yield\ \left(\text{kg ha}^{-1}\right)}{Crop\ evapotranspiration\ \left(\text{m}^3\ \text{ha}^{-1}\right)} \quad (5)$$

2.8. Statistical Analysis

Before conducting the main statistical analyses, two key assumptions were verified: normality, assessed using the Shapiro–Wilk test, and homogeneity of variances, evaluated using Levene's test. A two-way analysis of variance (ANOVA) was then performed to examine the effects of two irrigation levels and three nitrogen rates as well as their interactions. Mixed-ANOVA models were employed, treating irrigation and nitrogen factors as fixed effects, while blocks (replications) were considered random effects. The significance threshold was set at $p \leq 0.05$ for all statistical tests. Where significant differences were detected, Duncan's multiple-range post hoc test was applied for pairwise comparisons. All statistical analyses, including the calculation of standard deviations and post hoc comparisons, were conducted using IBM SPSS Statistics version 8.1 (Analytical Software, 2005). Additionally, principal component analysis (PCA) was utilized to identify the best water and nitrogen management treatment and the most influential wheat attributes contributing to water productivity and overall crop yield. Data visualization and PCA plots were generated using OriginPro version 2019b.

3. Results

3.1. Crop Evapotranspiration (ETc) and Actual Irrigation Water Applied (AIWA)

The data in Figure 3 displays crop evapotranspiration (ETc) values derived using the Penman–Monteith equation for the wheat crop during the two successive growing seasons. Additionally, the data showed that the second season's ETc values were generally greater than those of the first season. Actual irrigation water applied (AIWA) was influenced by irrigation deficit treatments (Figure 3A,B). AIWA values were 5729.13 and 4583.30 m^3 ha^{-1} in the first growing season and 5982.39 and 4785.91 m^3 ha^{-1} in the second season, for 100% and 80% ETc, respectively. AIWA was lower in the first season compared to the second season (Figure 3).

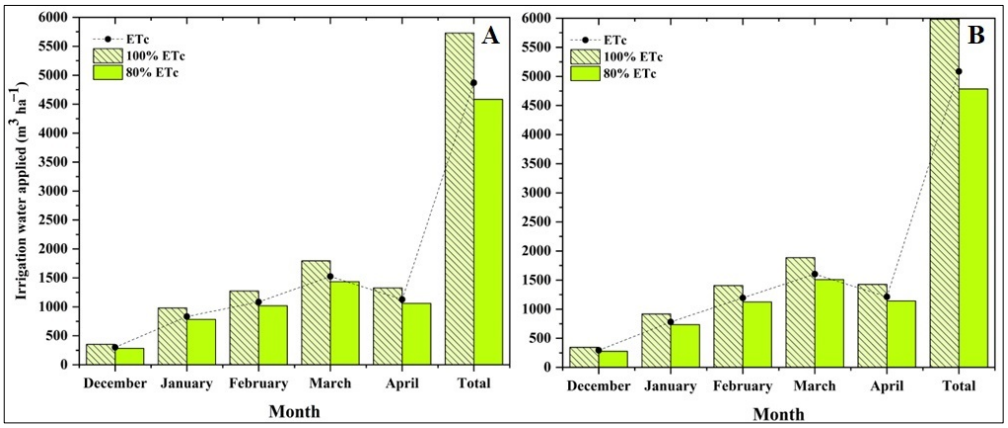


Figure 3. Monthly irrigation applied (bare) and crop evapotranspiration (ETc) (line) during the two winter growing seasons: 2022/23 (**A**) and 2023/24 (**B**).

3.2. Wheat Traits and Yield

Table 2 presents the mean values for plant height, straw yield, and biological yield, considering two water levels and three nitrogen fertilizer rates during the 2022/23 and 2023/24 growing seasons. Irrigation treatments I_1 (100% ETc) and I_2 (80% ETc) differed significantly in plant height, straw yield, and biological yield according to analysis of variance (ANOVA) throughout both growth seasons. I_1 had a much higher plant height, straw yield, and biological yield than I_2. Additionally, the N_3 treatment had the highest mean values in both seasons, indicating that nitrogen fertilizer rates had a very substantial impact on plant height, straw yield, and biological yield across different irrigation water levels.

Plant height was substantially higher in the I_1 (100% ETc) treatment than in the I_2 (80% ETc) treatment across both seasons. Increased nitrogen rates significantly increased plant height, with the N_3 treatment boosting the plants' height ($p < 0.01$) compared to the N_2 and N_1 treatments. The interaction between altered decreased irrigation and nitrogen rates significantly affected plant height ($p \leq 0.05$ in 2022/23 season and $p < 0.001$ in 2023/24 season), indicating that alterations in irrigation amount had a considerable influence on plant height (Table 2). The treatment of 238 kg N ha^{-1} and 100% ETc (I_1N_3) consistently resulted in a higher plant height throughout both seasons. In general, plant height was reduced in the second season compared to the first season (Table 2).

The straw yield exhibited a significant reduction trend with reductions in irrigation amount and nitrogen application rate (Table 2). The lowest straw yield was achieved in both growth seasons with the 142.8 kg N ha^{-1} and 80% ETc (I_2N_1) treatment. The results showed no significant variance in straw yield between the I_2N_1 and 1_1N_1 treatments during the first season. Nitrogen application rates and irrigation water levels had an interaction effect on straw yield that was in line with how they affected plant height in the 2022/23 season. However, the absence of a significant interaction impact between the two variables indicates that the evaluation of irrigation water levels and straw yield was consistent across all three nitrogen application rates in the 2023/24 season. In the first and second seasons, the I_1N_3 treatment raised the straw yield by 23% and 16%, respectively, as compared to the I_1N_1 treatment (Table 2).

Biological yield: Table 2 displays the biological yield data under various water regimes and nitrogen application rates. According to the findings, plant biological yield and water deficit are inversely correlated. Nonetheless, it was shown that applying nitrogen to wheat crops increased their biological yield (Table 2). The interaction between the two variables was statistically significant during both growth seasons, indicating that assessments of irrigation water levels were altered based on nitrogen application rates (ANOVA Table 2). The interaction between nitrogen treatment and water deficit shows that the N_3 rate in

the I_1 treatment produced the maximum biological yield, whereas the N_1 rate in the I_2 treatment produced the lowest. The I_1N_3 treatment resulted in a 28% and 21% increase in biological yield compared to the I_1N_1 treatment in the first and second seasons, respectively. Similarly, the I_2N_3 treatment also demonstrated a 23% and 22% increase in biological yield compared to the I_2N_1 treatment across both seasons.

Table 2. Effect of irrigation water deficit (I), nitrogen fertilizer rates (N), and their interaction on wheat (*Triticum aestivum* L.) average plant height, straw yield, and biological yield (kg ha^{-1}) across the 2022/23 and 2023/24 growing seasons.

	2022–2023			2023–2024		
Treatment	**100% ETc**	**80% ETc**	**Mean**	**100% ETc**	**80% ETc**	**Mean**
			Plant height (cm)			
N_1	89.88 ± 0.31 d	83.93 ± 0.92 e	86.90 ± 1.40 c	88.20 ± 0.07 d	83.40 ± 0.14 f	85.55 ± 1.0756 c
N_2	95.72 ± 0.10 b	92.60 ± 0.32 c	94.16 ± 0.71 b	89.75 ± 0.03 c	85.61 ± 0.06 e	87.55 ± 0.9253 b
N_3	100.72 ± 0.36 a	95.45 ± 0.07 b	98.08 ± 1.19 a	96.34 ± 0.14 a	89.10 ± 0.16 b	92.55 ± 1.6207 a
Mean	95.24 ± 1.57 a	90.24 ± 1.75 b		91.43 ± 1.25 a	86.04 ± 0.83 b	
	F	**P**		**F**	**P**	
IR	128.64	0.008	**	3888.02	0.000	***
N	335.86	0.000	***	3600.73	0.000	***
IR × N	5.71	0.028	*	182.44	0.000	***
			Straw yield (kg ha^{-1})			
N_1	6077.20 ± 25.70 d	6043.89 ± 42.82 d	6060.54 ± 23.54 c	5704.79 ± 11.02 c	5132.16 ± 38.01 d	5418.55 ± 129.26 c
N_2	6710.87 ± 23.82 c	6617.71 ± 28.07 c	6664.29 ± 26.55 b	6087.14 ± 17.69 b	5646.49 ± 35.46 c	5866.55 ± 100.11 b
N_3	7458.89 ± 50.18 a	7057.68 ± 38.93 b	7258.28 ± 94.10 a	6628.91 ± 94.31 a	6086.06 ± 71.57 b	6357.55 ± 132.42 a
Mean	6748.24 ± 200.44 a	6573.24 ± 147.92 a		6140.28 ± 136.91 a	5621.57 ± 140.17 b	
	F	**P**		**F**	**P**	
IR	46.12	0.021	*	137.02	0.007	**
N	528.03	0.000	***	130.90	0.000	***
IR × N	14.34	0.002	**	0.71	0.520	NS
			Biological yield (kg ha^{-1})			
N_1	8880.04 ± 38.06 e	8394.27 ± 17.38 f	8637.15 ± 110.22 c	8316.14 ± 11.19 c	7436.95 ± 29.90 d	7876.55 ± 197.11 c
N_2	9936.65 ± 64.95 c	9376.46 ± 35.17 d	9656.55 ± 129.55 b	9057.23 ± 12.37 b	8251.58 ± 3.37 c	8654.55 ± 180.24 b
N_3	11,385.03 ± 30.03 a	10,370.85 ± 58.05 b	10,877.94 ± 228.65 a	10,059.43 ± 29.33 a	9033.86 ± 57.22 b	9546.55 ± 231.11 a
Mean	10,067.24 ± 363.79 a	9380.24 ± 286.01 b		9144.27 ± 252.75 a	8240.80 ± 231.26 b	
	F	**P**		**F**	**P**	
IR	1434	0.000	***	1559.93	0.000	***
N	1616.66	0.000	***	2177.30	0.000	***
IR × N	26.27	0.000	***	9.76	0.007	**

Note: N_1 = 142.8 kg N ha^{-1}; N_2 = 190.4 kg N ha^{-1}; N_3 = 238 kg N ha^{-1}; 100% ETc = I_1; 80% ETc = I_2. Each value represents the mean of three replicates. Within each column, different letters indicate significant differences ($p < 0.05$). NS, non-significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Table 3 presents the analysis of variance (ANOVA) results for grain yield, seed index, and protein percentage under three nitrogen application rates (142.8, 190.4, and 238 kg N ha^{-1}) and two irrigation water levels (I_1 and I_2) in the 2022/23 and 2023/24 seasons.

Grain yield: was shown to vary significantly between irrigation treatments I_1 and I_2, with I_1 showing higher mean values in both seasons, according to analysis of variance (ANOVA; Table 3). In both I_1 and I_2, grain production significantly declined when nitrogen treatment rates decreased.

The N_3 treatment resulted in the most grain (238 kg N ha^{-1}), whereas the N_1 treatment produced the least (142.8 kg N ha^{-1}). As a result, the grain yield from the I_1N_3 treatment was 40 to 31% greater than that from the I_1N_1 treatment, during both growing seasons, respectively. Significant variations were found in all nitrogen application rates and irrigation water levels during both growing seasons, according to Duncan's post hoc analysis. The absence of significance in the interaction between the two factors across both growing seasons suggests that the response to different nitrogen application rates was unaffected by water irrigation levels.

Table 3. Effect of irrigation water deficit (I), nitrogen fertilizer rates (N), and their interaction on wheat (*Triticum aestivum* L.) average grain yield (kg ha^{-1}), seed index, and protein content (%) across the 2022–2023 and 2023–2024 growing seasons.

	2022–2023			2023–2024		
Treatment	**100% ETc**	**80% ETc$_1$**	**Mean**	**100% ETc$_2$**	**80% ETc$_3$**	**Mean**
			Grain yield (kg ha^{-1})			
N_1	2802.84 ± 38.36 c	2350.38 ± 25.52 d	2576.61 ± 103.25 c	2611.36 ± 8.65 c	2304.80 ± 46.78 d	2458.55 ± 71.77 c
N_2	3225.78 ± 41.96 b	2758.74 ± 26.70 c	2992.26 ± 106.77 b	2970.09 ± 29.91 b	2605.09 ± 32.10 c	2787.55 ± 83.94 b
N_3	3926.14 ± 50.12 a	3313.17 ± 19.12 b	3619.66 ± 139.15 a	3430.52 ± 69.82 a	2947.80 ± 52.80 b	3189.55 ± 114.81 a
Mean	3318.24 ± 165.23 a	2807.24 ± 140.01 b		3003.99 ± 120.58 a	2619.23 ± 95.53 b	
	F	**P**		**F**	**P**	
IR	1957.47	0.000	***	174.04	0.006	**
N	357.20	0.000	***	120.13	0.000	***
IR × N	2.55	0.139	NS	1.80	0.226	NS
			Seed index (%)			
N_1	45.23 ± 0.29 c	44.07 ± 0.25 d	44.65 ± 0.31 c	42.28 ± 0.34 c	40.58 ± 0.34 d	41.55 ± 0.44 c
N_2	47.28 ± 0.12 b	45.88 ± 0.18 c	46.58 ± 0.33 b	44.70 ± 0.47 b	43.16 ± 0.28 c	43.55 ± 0.42 b
N_3	48.55 ± 0.24 a	47.70 ± 0.21 b	48.12 ± 0.24 a	47.84 ± 0.38 a	45.26 ± 0.36 b	46.55 ± 0.62 a
Mean	47.24 ± 0.50 a	45.24 ± 0.53 b		44.94 ± 0.83 a	43.00 ± 0.70 b	
	F	**P**		**F**	**P**	
IR	62.12	0.015	*	130.67	0.008	**
N	107.42	0.000	***	91.55	0.000	***
IR × N	0.66	0.54	NS	1.09	0.381	NS
			Protein content (%)			
N_1	10.77 ± 0.08 e	12.09 ± 0.10 d	11.43 ± 0.30 c	11.42 ± 0.08 e	12.85 ± 0.14 d	12.55 ± 0.33 c
N_2	12.25 ± 0.02 d	13.01 ± 0.03 c	12.63 ± 0.17 b	13.05 ± 0.03 d	13.76 ± 0.06 c	13.55 ± 0.16 b
N_3	14.28 ± 0.08 b	14.97 ± 0.07 a	14.63 ± 0.16 a	15.04 ± 0.17 b	15.78 ± 0.06 a	15.55 ± 0.18 a
Mean	12.24 ± 0.51 b	13.24 ± 0.43 a		13.17 ± 0.53 b	14.13 ± 0.44 a	
	F	**P**		**F**	**P**	
IR	698.86	0.001	**	969.20	0.001	**
N	748.16	0.000	***	386.08	0.000	***
IR × N	8.28	0.011	*	5.86	0.027	*

Note: N_1 = 142.8 kg N ha^{-1}; N_2 = 190.4 kg N ha^{-1}; N_3 = 238 kg N ha^{-1}; 100% ETc = I_1; 80% ETc = I_2. Each value represents the mean of three replicates. Within each column, different letters indicate significant differences ($p < 0.05$). NS, non-significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Seed index: A significant difference in the seed index between the I_1 and I_2 irrigation treatments was found by statistical analysis (ANOVA, Table 3). In the first and second seasons, the I_1 treatment increased the seed index by approximately 4% and 4.5%, respectively, in comparison with the I_2 treatment. A highly significant difference was seen in the nitrogen application rates; the N_3 treatment showed the highest mean values (48.12% and 46.55% for both seasons, respectively) in comparison to the N_1 treatment (44.65% and 41.55% for both seasons, respectively). Duncan's post hoc analysis revealed considerable differences in nitrogen application and irrigation levels across both growing seasons. During the first season, the I_1N_3 treatment increased the seed index by 7% compared to the I_1N_1 treatment. The second season saw a larger increase of 13% with the same comparison. Similarly, the I_2N_3 treatment also showed an improved seed index, with an 8% increase in the first season and a 12% increase in the second season when compared to the I_2N_1 treatment. As was shown with grain yield, the two variables' interaction had no noticeable effect on the seed index during both growing seasons.

Grain protein content was significantly affected by both water deficit and nitrogen rates according to statistical analysis (ANOVA). The grain protein content rose specifically when the amount of applied water irrigation was reduced (Table 3). Compared to a normal water irrigation level (I_1), the water deficit (I_2) increased the protein percentage by 8% and 7% in the two growth seasons, respectively. The application rate of nitrogen fertilizer significantly impacted grain quality. Specifically, using a high rate of nitrogen (N_3) increased the grain protein content, while using a low rate (N_1) decreased that content. This was observed with both watering levels across the 2022/23 and 2023/24 growth seasons (Table 3). The protein content was significantly affected by the interaction between irrigation water levels and nitrogen application rates ($p \leq 0.05$ in the 2022/23 and 2023/24 seasons),

suggesting that a water deficit substantially influenced the protein content (Table 3). The I_2N_3 treatment (238 kg N ha^{-1} and 80% ETc) consistently yielded a higher protein content across both seasons. Overall, the protein content increased in the second season compared to the first season (Table 3).

3.3. Water and Nitrogen Efficiency

Figure 4 displays the mean nitrogen use efficiency (NUE) for each water irrigation level and nitrogen application rate, while Table 4 presents the results of an ANOVA. The ANOVA results (Table 4) show that both factors examined in this study had a significant effect on wheat nitrogen use efficiency (NUE). Wheat showed a greater NUE under normal water irrigation (I_1) than under deficient water irrigation (I_2). A water deficit at 80% ETc (I_2) decreased NUE by 18% and 14%, respectively, across two wheat-growing seasons compared to water irrigation at 100% ETc (I_1). Duncan's post hoc analysis revealed significant differences among the three nitrogen application rates. In the first season, the nitrogen application rate of 142.8 kg N ha^{-1} (N_1) resulted in a 29% and 42% increase in nitrogen use efficiency (NUE) compared to the N_2 and N_3 treatments, respectively. Similarly, in the second season, N_1 increased NUE by 32% and 54% compared to the N_2 and N_3 treatments, respectively.

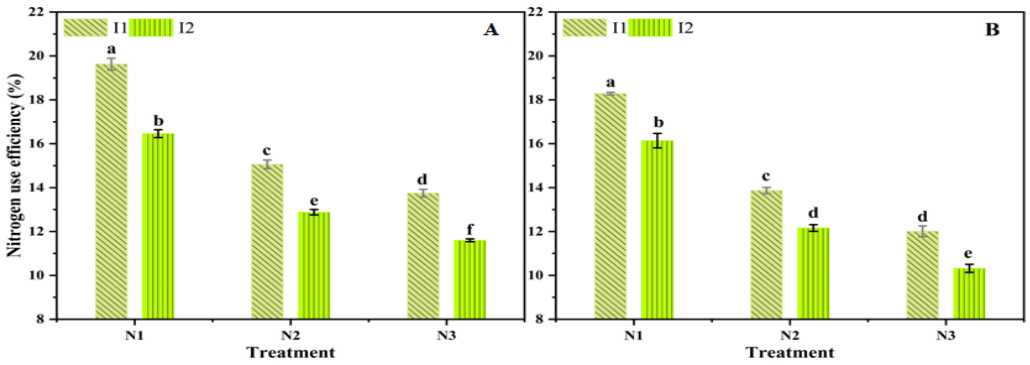


Figure 4. Effect of irrigation levels and nitrogen rates on nitrogen use efficiency (NUE) during two winter seasons: (**A**) 2022/23 and (**B**) 2023/24. Data are presented as means; line bars indicate ± standard errors. Within each column, different letters indicate significant differences ($p < 0.05$).

Table 4. Analysis of variance (ANOVA) for nitrogen use efficiency (NUE), productivity of applied water (PAW), and crop water productivity (CWP) across two growing seasons.

Treatment	2022–2023			2023–2024		
	Nitrogen Use Efficiency (NUE%)					
	F	**P**		**F**	**P**	
IR	31.41	0.031	*	128.10	0.008	**
N	6526.45	0.000	***	445.39	0.000	***
IR × N	4.59	0.047	*	0.80	0.482	NS
	Productivity of Applied Water (PAW kg ha^{-1})					
	F	**P**		**F**	**P**	
IR	64.69	0.015	*	67.24	0.015	*
N	491.61	0.000	***	102.32	0.000	***
IR × N	1.35	0.313	Ns	0.15	0.864	NS
	Crop Water Productivity (CWP kg ha^{-1})					
	F	**P**		**F**	**P**	
IR	1289.29	0.000	***	165.14	0.006	**
N	420.30	0.000	***	125.21	0.000	***
IR × N	2.98	0.11	NS	2.13	0.181	NS

Note: NS, non-significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Because of the significant interaction between irrigation water levels and nitrogen application rates, the impact of irrigation water levels on NUE varies with nitrogen applica-

tion rate during the 2022/23 season. The absence of a significant interaction effect indicates that the impact of irrigation water levels on nitrogen use efficiency (NUE) remained consistent across all nitrogen application rates during the 2023/24 season. In the first season, the I_1N_1 treatment enhanced NUE by 30% and 43% compared to the I_1N_2 and I_1N_3 treatments, respectively (Figure 4). A comparable pattern was observed in the second season, where I_1N_1 led to a 32% and 52% increase in NUE relative to I_1N_2 and I_1N_3, respectively.

3.4. Productivity of Applied Water (PAW) and Crop Water Productivity (CWP)

Under different irrigation levels and nitrogen application rates, as illustrated in Figure 5, the ANOVA results (Table 4) show that irrigation levels had a statistically significant effect on PAW; additionally, nitrogen application rates exhibited highly significant differences. However, no significant interaction effects were observed between irrigation and nitrogen treatments. Duncan's post hoc test revealed that treatments I_1N_1 and I_2N_1 exhibited the lowest PAW, with values of 0.49 and 0.51 kg ha^{-1}, respectively. Intermediate PAW values were observed under I_1N_2 (0.56 kg ha^{-1}) and I_2N_2 (0.60 kg ha^{-1}), while the highest efficiencies were recorded for I_1N_3 and I_2N_3, reaching 0.69 and 0.72 kg ha^{-1}, respectively (Figure 5A,B), in the first season. A comparable trend was noted during the second season. When comparing irrigation levels, a slightly higher PAW was achieved under I_2 (80% ETc), ranging from 0.61 to 0.57 kg ha^{-1} across the two growing seasons, compared to I_1 (100% ETc), which ranged from 0.57 to 0.50 kg ha^{-1}. Regarding nitrogen application rates, mean PAW values across both seasons were 0.50–0.46 kg ha^{-1} for N_1 (142.80 kg N ha^{-1}), 0.58–0.52 kg ha^{-1} for N_2 (190.40 kg N ha^{-1}), and 0.70–0.59 kg ha^{-1} for N_3 (238.00 kg N ha^{-1}).

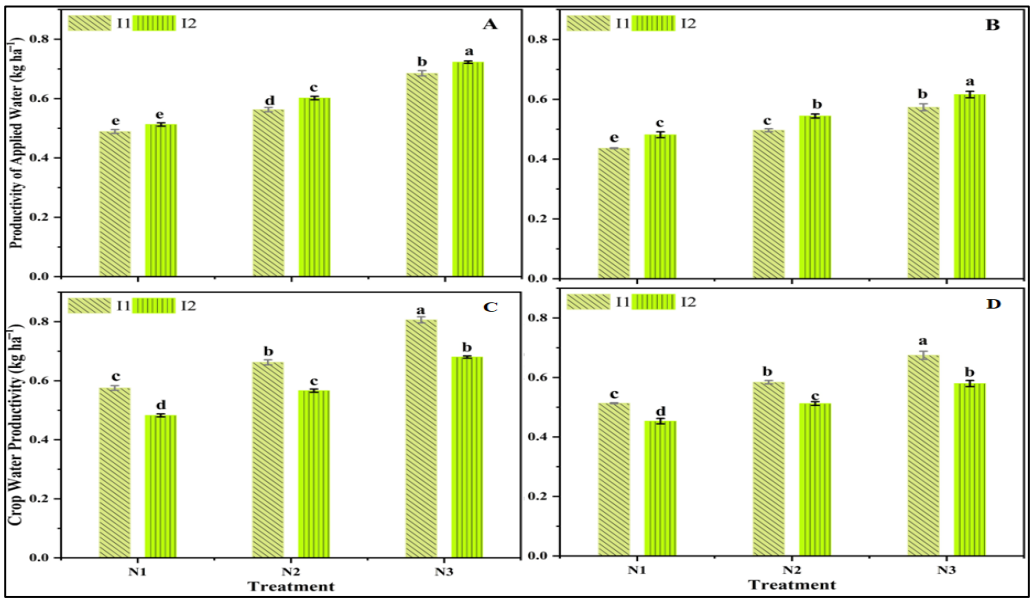


Figure 5. Effect of irrigation levels and nitrogen rates on productivity of applied water (PAW) and crop water productivity (CWP) for two winter seasons: (**A**,**C**) 2022/23 and (**B**,**D**) 2023/24. Data are presented as means; line bars indicate ± standard errors. Within each column, different letters indicate significant differences ($p < 0.05$).

3.5. Optimizing Crop Water Productivity

Analysis of variance (ANOVA) revealed highly significant effects of both irrigation levels and nitrogen application rates on crop water productivity (CWP) during both growing seasons (Table 4). The application of irrigation water at 100% of actual crop evapotranspiration (ETc) (I_1) resulted in a significant increase in crop water productivity (CWP) compared to the 80% ETc treatment (I_2). Specifically, I_1 resulted in a 17% rise in CWP during the first season and a 14% increase during the second season compared to I_2.

Among the nitrogen treatments, N_3 and N_2 have a substantial impact on CWP compared to N_1 across both growing seasons. N_3 exhibited a 42% to 31% rise in CWP over N_1 and a 19% to 15% increase over N_2 during both growth seasons. The ANOVA revealed no statistically significant interaction between the factors under investigation. Treatments I_1N_3 and I_1N_2 significantly increased crop water productivity (CWP), as confirmed by Duncan's post hoc test. Specifically, I_1N_3 led to a 16–42% increase in CWP across both growing seasons compared to the I_1N_1 treatment. Similarly, I_1N_2 resulted in a 13–31% increase in CWP relative to I_1N_1 (Figure 5C,D). A similar trend was observed in the 80% ETc treatment (I_2). These findings indicate that increasing nitrogen fertilizer rates had a substantial positive impact on CWP, regardless of the irrigation level applied.

3.6. Principal Component Analysis (PCA)

Principal component analysis (PCA) was conducted to investigate the relationships between key wheat traits and efficiency indicators under both full and deficit drip irrigation. The analysis evaluated plant height, straw yield, biological yield, grain yield, seed index, protein content, productivity of applied water (PAW), crop water productivity (CWP), and nitrogen use efficiency (NUE).

As shown in Figure 6, treatments I_1N_2, I_1N_3, and I_2N_3 were strongly associated with higher values of yield-related traits, quality parameters, PAW, and CWP across two consecutive seasons. These associations highlight the effectiveness of moderate to high nitrogen levels under full irrigation in enhancing both yield and water productivity. In contrast, treatment I_1N_1 exhibited a strong association with NUE, indicating its potential for enhancing nitrogen efficiency under reduced input conditions. These findings provide valuable insights for optimizing water and nitrogen management strategies in wheat cultivation.

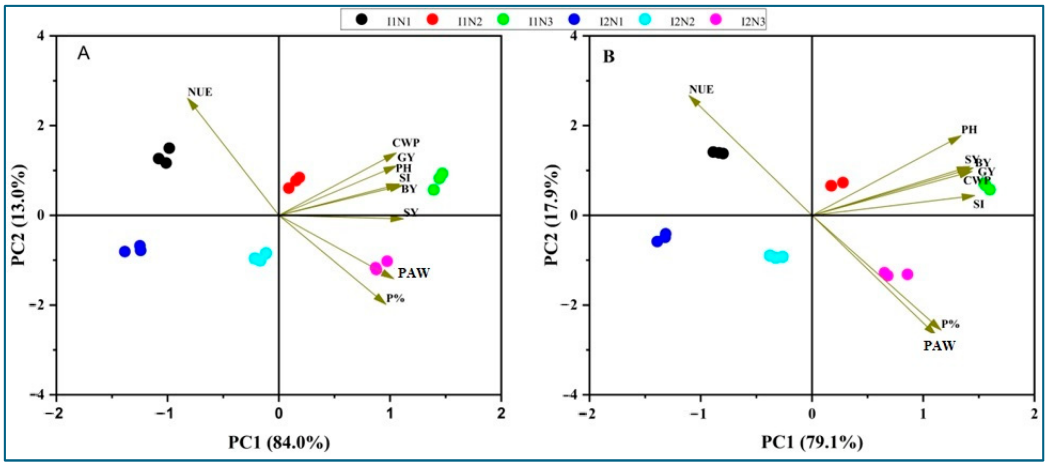


Figure 6. Principal component analysis (PCA) of the effects of irrigation water levels and nitrogen application rates on major plant growth: yield attributes during the first season (2022/23) (**A**), and the second season (2023/24) (**B**).

The patterns observed in the relationships among PAW, CWP, NUE, and wheat traits during the 2022/23 season were consistent with those recorded in 2023/24 (Figure 6B). A negative correlation was identified between NUE and both PAW and protein content across both seasons, suggesting that a greater nitrogen use efficiency may reduce the efficiency of water and grain quality. In contrast, CWP exhibited a strong positive association with various wheat characteristics (Figure 6A,B). These findings indicate that improvements in biomass and grain production are closely linked to enhanced water productivity. Among these, biological yield and grain yield emerged as the most influential contributors to enhanced CWP, whereas protein content and NUE appeared to be the primary factors

influencing PAW. Notably, protein content surfaced as the principal characteristic linked to PAW, suggesting a trade-off between grain quality and water use efficiency.

4. Discussion

Wheat yield in arid and semi-arid areas is highly influenced by variations in the air temperature, wind speed, and relative humidity [45,46]. The results showed that reduced average temperatures during the anthesis period (early February) of the 2022–2023 growing season enhanced wheat growth and production. Also, higher April temperatures in the 2023–2024 season than in the 2022–2023 season resulted in reduced grain weight. Air temperature markedly influences reference evapotranspiration (ETo) in arid areas, consistent with the conclusions of Eslamian et al. (2011) [47], who ascribed inter-seasonal fluctuations in total ETo mostly to alterations in the surrounding air temperature and relative humidity.

In this study, the peak crop evapotranspiration (ETc) under full drip irrigation (I_1) reached 5982.39 m^3 ha^{-1}, which is lower than typical values reported for surface irrigation methods in similar arid regions, suggesting that drip irrigation may contribute to water conservation [48,49]. Crop evapotranspiration (ETc) and actual irrigation water applied (AIWA) were lower in 2022/23 than in 2023/24. The observed decreases can be primarily attributed to inter-annual climatic variability. These variations likely influenced seasonal irrigation volumes and overall water availability, resulting in increased drought stress [50]. Consequently, the increased water requirement of wheat in the 2023/24 season led to higher irrigation water applied. Throughout the two growing seasons, the actual irrigation water applied (AIWA) varied from month to month (Figure 3). Our data show that variations in actual irrigation water applied (AIWA) were minimal during the early growing season, consistent with limited canopy development and dominant soil evaporation processes [13]. Water consumption gradually increases as the plant develops, peaking during a mid-growth stage when irrigation needs are highest [46].

The execution of a comprehensive management strategy is crucial due to the intricate interrelations among soil, water, and nitrogen in arid and semi-arid regions. The fundamental purpose of this investigation is to improve the resistance of wheat crops to drought circumstances. In sandy soils of Egypt, drip irrigation improves the agronomic performance of wheat by integrating water and nitrogen management. Plant height, straw and biological yields, grain yield, seed index, and grain protein content were all significantly influenced by irrigation water levels and nitrogen application rates. Wheat traits were slightly higher in the 2022/23 season than in the 2023/24 season (Table 1). This difference is probably due to the weather, specifically lower average temperatures and humidity in the 2022/23 season than in the 2023/24 season. These results corroborate the outcomes of Tari (2016) [51] and Vashisth et al. (2020) [52], who indicated that grain yield, irrigation water demand, evapotranspiration, and water productivity of wheat differed with climatic conditions.

Regardless of the rate of nitrogen supplied, wheat growth and yield improved with increased irrigation water, as was hypothesized (Table 1). The decreased grain yield and biomass observed at I_2 (80% ETc irrigation level) across all nitrogen treatments are consistent with the effects of moisture stress when compared to I_1 (100% ETc full irrigation). Grain yield and biomass may decline as a result of stress, which likely impaired photosynthesis and other vital biological functions, thereby harming the photosystem's reaction center [3,21,46].

Eissa et al. (2018) [22] and Asmamaw et al. (2023) [21] observed a reduction in wheat grain production and biomass associated with increased moisture deficit in deficit irrigation field experiments.

Irrespective of the irrigation water deficit, nitrogen fertilizer rates had a significant impact on plant height, straw, and biological yield, highlighting the crucial role of nitrogen in stimulating wheat vegetative growth and biomass production. The observed rise in plant height with increasing nitrogen rates is likely attributed to enhanced cell division and elongation facilitated by greater nitrogen availability [53]. Likewise, enhanced straw and biological yields indicate that nitrogen plays an important role in boosting plant structure and metabolism [54]. Also, nitrogen is essential for root development, facilitating elongation, branching, and biomass accumulation, hence improving water and nutrient absorption [55]. So, the improved root system likely enhanced wheat vegetation and yield in this study [29,38].

Plant height, straw yield, and total biological yield all increased significantly during both growing seasons when 238 kg N ha^{-1} nitrogen fertilizer (N_3) was applied in combination with I_1 (full irrigation at 100% ETc). These results suggest that better water and nitrogen supply promote biomass accumulation and vegetative development, which is key for soil health and fertility in sustainable agriculture. Farouk et al. (2024) [49] found similar results, indicating that drip irrigation boosted straw production and biomass in wheat when compared to sprinkler irrigation. Ashmawy and Abo-Warda (2002) [56] found that a combination of irrigation and nitrogen treatments boosted wheat straw production in sandy soils. The results are consistent with those of Cui et al. (2024) [32], who discovered that integrated fertigation procedures increase total biomass production in wheat.

Wheat grain yield was greatly influenced by irrigation deficiency (Table 2). The data show that full irrigation was usually linked to increased grain production. This suggests that the amount of water available is a key factor in determining how well a crop performs.

This is consistent with the findings of Cui et al. (2024) [32], who discovered that when irrigation and nitrogen fertilizer were combined, wheat grain production rose by 17.3% in comparison to controls. The higher yields under full irrigation (I_1) align with improved physiological performance, which is supported in the literature by enhanced rates of photosynthesis, nutrient uptake, and biomass accumulation under sufficient soil moisture [13,29,38]. Conversely, deficit irrigation likely induced water stress, leading to stomatal closure, reduced carbon assimilation, and ultimately, a lower grain yield [57]. Nitrogen fertilizer rates significantly affected grain yield, demonstrating the importance of wheat productivity. In dry conditions, studies show that the level of nitrogen applied directly affects the number of grains per spike, the weight of the grains, and the final grain yield [58]. The improved grain yield may be attributed to nitrogen application, which enhances the photosynthetic rate, leaf area, nitrogen use efficiency, and radiation use efficiency [59]. Increased nitrogen applied rates under deficit irrigation resulted in considerably higher grain productivity. Numerous studies show that adding nitrogen (N) mitigates the detrimental consequences of water shortage [37,39,59]. Consistent with previous findings (e.g., Abid et al. (2016)) [60], our results indicate that nitrogen application under deficit irrigation (I_2) helped maintain physiological functions, as evidenced by improved yield components and water productivity compared to low-nitrogen treatments.

The boost in seed index with irrigation at 100% ETc emphasizes how crucial it is to satisfy all crop evapotranspiration requirements in order to maximize seed development. Especially during the grain-filling stage, optimal watering techniques improve photosynthetic efficiency and nutrient absorption [7,24]. The seed index rises dramatically when the rate of nitrogen treatment is increased, underscoring the significance of nitrogen in promoting seed development through enhanced vegetative growth and assimilating partitioning. Chlorophyll production and enzyme activity, which have a direct impact on seed development, are mostly driven by nitrogen [61]. Zeng et al. (2016) [62] established that nitrogen fertilizer, when applied under appropriate irrigation conditions, markedly

enhances nitrogen transformation and absorption, thus increasing crop yields. Also, a meta-analysis by Cui et al. (2024) [32] revealed that whole irrigation coupled with fertilization led to enhanced grain yields in maize and wheat, with wheat showing yield increases of up to 17.32%.

Many studies have provided strong support for the current results, which demonstrate that water deficiencies raise the protein ratios in wheat grains [51,63,64]. Wheat plants usually undergo a physiological change in response to drought or water shortages, which raises the grain's protein content; this phenomenon can be explained by a reduction in carbohydrate accumulation under water deficit, which, coupled with a maintained nitrogen uptake, increases the relative protein concentration in the grain [54].

The findings of this study show that the nitrogen (N) fertilizer application rate has a considerable impact on grain quality, specifically the grain protein content. This discovery is consistent with prior research showing that nitrogen is an essential ingredient for protein synthesis in cereal crops like wheat and maize [65]. This is in line with the findings of Shi et al. (2007) [65], who found that increasing nitrogen rates enhanced nitrogen absorption and translocation efficiency, resulting in greater grain nitrogen accumulation and protein content in wheat. Nitrogen is essential for amino acid and protein production, and having it available throughout the grain-filling stage is critical for reaching high protein levels [66]. The combination of irrigation water levels and nitrogen application rates had a significant influence on protein content, demonstrating that the water deficit significantly affected protein levels. Combining high nitrogen application rates with a water deficit reduced grain yield losses and increased grain protein accumulation [59]. Even with a watering deficit, this twofold advantage can be related to increased metabolic activity and higher nitrogen intake under moderate N supplies [67]. Furthermore, under drought circumstances, moderate N levels can promote grain filling and protein deposition by promoting root development and increasing water use efficiency [68]. In order to improve grain protein accumulation, a crucial factor in determining the quality of baked goods, Ali and Akmal (2022) [59] emphasized the significance of satisfying the higher nitrogen needs of wheat under water-deficient situations. In order to maintain production and quality in dry agroecosystems, our findings highlight the significance of integrated water and nutrient management techniques.

With a 100% ETc irrigation level, wheat exhibited a higher nitrogen utilization efficiency (NUE) than with deficit irrigation (80% ETc), suggesting that enough water is essential for nitrogen absorption and assimilation. Sufficient irrigation encourages microbial activity and root growth, both of which are essential for the transformation and absorption of nitrogen. This is consistent with Wallace et al. (2020) [69], who discovered that in semi-arid wheat, optimal irrigation enhances nitrogen recovery and lowers losses. Nitrogen use efficiency (NUE) was higher with lower nitrogen delivery than with medium and high treatments. This adverse association supports the findings of Cai et al. (2021) [70], who discovered that NUE is reduced when nitrogen levels are higher than recommended. They promote sustainable wheat production by implying that great yields may be achieved without proportionately increasing nitrogen. The combination of a lower nitrogen application rate with full irrigation at 100% ETc resulted in a significantly higher nitrogen use efficiency (NUE) in wheat. This outcome underscores the importance of synchronizing water and nitrogen management to optimize nutrient uptake and minimize losses [55].

According to Thorburn et al. (2024) [71], NUE is highly sensitive to environmental conditions, and full irrigation can mitigate nitrogen losses through volatilization and leaching, especially under lower nitrogen input scenarios. Sutton et al. (2020) [72] suggest applying "just enough nitrogen" to match crop demand, improving nitrogen use efficiency

(NUE) and lowering environmental risks, as excessive nitrogen is inefficient, especially with limited water.

Improving water use efficiency and crop water productivity requires an integrated approach that includes deficit irrigation, the adoption of advanced irrigation technologies, precise irrigation scheduling, and the implementation of agronomic practices that enhance yield potential [51,59]. These strategies contribute to sustainable agricultural water management. The results of our study demonstrate that PAW was significantly higher under the deficit irrigation treatment (80% ETc) compared to the full irrigation treatment (100% ETc). This finding suggests that reducing irrigation volumes can enhance the productivity of applied water. Our observations are consistent with those reported by Tari (2016) [51], who found that water use efficiency tends to decrease as irrigation amounts increase. The higher CWP under full irrigation corresponded with significantly greater crop yields (as shown in Table 3). In such conditions, optimal soil moisture can encourage root development, potentially leading to a higher root length density and improved resource acquisition, which supports higher yield formation. Chai et al. (2016) [19] stated that full irrigation promotes superior physiological and morphological responses in crops, such as enhanced root-to-shoot ratios and nutrient recovery, both of which are essential for increasing water use efficiency. Furthermore, Howell (2003) [73] underlined that irrigation efficiency, which includes consistent water delivery and timing, has a direct impact on crop response and production. While controlled deficit irrigation can enhance water use effectiveness in some situations, it could compromise production and CWP if not properly managed.

In our investigation, the application of nitrogen enhanced PAW and CWP at both irrigation water levels. The use of nitrogen in this study resulted in a higher PAW and CWP, which may be related to an improvement in wheat components. The findings of the present study are consistent with those of Si et al. (2020) [38], who demonstrated that deficit irrigation combined with nitrogen fertilization significantly improved wheat yield and water use efficiency under drip irrigation. These results are further corroborated by recent research by Sandhu et al. (2019) [17], which highlights the effectiveness of drip irrigation in maximizing water and nutrient use efficiency in wheat cultivation.

5. Conclusions

The irrigation water level and the weather have a bigger impact on total water use than how much nitrogen fertilizer was used. The evaluated parameters, such as crop water productivity (CWP), plant growth, and grain yield, were primarily influenced by irrigation levels and nitrogen application rates. Deficit irrigation at 80% ETc reduced water availability, which in turn limited photosynthetic activity and nutrient uptake, ultimately diminishing yield components like the grain number. In this study, higher nitrogen rates (N_2 and N_3) under deficit irrigation (I_2) significantly improved straw yield, biological yield, and PAW, suggesting that nitrogen management can mitigate the negative impacts of water stress and enhance yield stability in arid conditions. Additionally, climatic variability—particularly elevated temperatures during April of the 2023–2024 season—further intensified evapotranspiration, leading to a reduction in grain weight. Despite these climatic influences, water stress remained the dominant limiting factor. Consequently, the combination of full irrigation (100% ETc) with the highest nitrogen rate (N_3) was identified as the most effective strategy for balancing water conservation and yield optimization in arid environments. These results highlight the importance of optimizing irrigation strategies to maximize the productivity of applied water and sustain wheat productivity, particularly in arid and semi-arid regions where water resources are scarce. Future studies could explore the integration of deficit irrigation techniques or the use of drought-tolerant wheat cultivars to further enhance resilience under water-limited conditions.

While this study lacks a formal economic analysis, it provides farmers with crucial, actionable strategies for optimizing wheat production under water scarcity by clearly demonstrating how to synchronize drip irrigation levels and nitrogen fertilization to achieve specific goals, whether maximizing yield, conserving water, improving grain quality, or reducing fertilizer input, enabling them to make more informed decisions based on robust agronomic evidence until localized cost–benefit data becomes available.

Author Contributions: Conceptualization, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; methodology, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; software, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; validation, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; formal analysis, A.A.A., I.M.A.-F., M.O.M. and M.E.F.; investigation, A.A.A., I.M.A.-F., M.O.M. and M.E.F.; resources, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; data curation, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; writing—original draft preparation, A.A.A., I.M.A.-F., M.O.M. and M.E.F.; writing—review and editing, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; visualization, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; supervision, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; project administration, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S.; funding acquisition, A.A.A., I.M.A.-F., M.O.M., M.E.F., M.D. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This manuscript presented is a scientific collaboration between scientific institutions in two countries (Egypt and Italy). The authors would like to thank Al-Azhar University, the Agricultural Research Centre (ARC), the National Authority for Remote Sensing and Space Science (NARSS), and the Department of Agricultural, Forestry, Food and Environmental Sciences (DAFE), University of Basilicata, for their support during the field survey and data analysis.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Shehata, G.; Zahran, H.; Srour, A. Egyptian food security of wheat in light of new challenges. *Proc. Syst. Dyn. Innov. Food Netw.* **2023**, 158–173. [CrossRef]
2. Fadl, M.E.; AbdelRahman, M.A.E.; El-Desoky, A.I.; Sayed, Y.A. Assessing soil productivity potential in arid region using remote sensing vegetation indices. *J. Arid Environ.* **2024**, *222*, 105166. [CrossRef]
3. Awaad, M.S.; Deshesh, T.H. Wheat growth and nitrogen use efficiency under drip irrigation on semi-arid region. *Eurasian J. Soil Sci.* **2019**, *8*, 229–236. [CrossRef]
4. Elsayed, M.L.; Elkot, A.F.; Noreldin, T.; Richard, B.; Qi, A.; Shabana, Y.M.; Saleh, S.M.; Fitt, B.D.; Kheir, A.M. Optimizing wheat yield and water productivity under water scarcity: A modeling approach for irrigation and cultivar selection across different agro-climatic zones of Egypt. *Agric. Water Manag.* **2025**, *317*, 109668. [CrossRef]
5. Noreldin, T.; Ouda, S.; Mounzer, O.; Abdelhamid, M.T. CropSyst model for wheat under deficit irrigation using sprinkler and drip irrigation in sandy soil. *J. Water Land Dev.* **2015**, *26*, 57–64. [CrossRef]
6. Abdalla, A.; Becker, M.; Stellmacher, T. The contribution of agronomic management to sustainably intensify Egypt's wheat production. *Agriculture* **2023**, *13*, 978. [CrossRef]
7. Ouda, S.; Noreldin, T.; Alarcón, J.J.; Ragab, R.; Caruso, G.; Sekara, A.; Abdelhamid, M.T. Response of spring wheat (*Triticum aestivum*) to deficit irrigation management under the semi-arid environment of egypt: Field and modeling study. *Agriculture* **2021**, *11*, 90. [CrossRef]
8. Fadl, M.E.; Sayed, Y.A.; El-Desoky, A.I.; Shams, E.M.; Zekari, M.; Abdelsamie, E.A.; Drosos, M.; Scopa, A. Irrigation practices and their effects on soil quality and soil characteristics in arid lands: A comprehensive geomatic analysis. *Soil Syst.* **2024**, *8*, 52. [CrossRef]
9. Mekonnen, M.M.; Hoekstra, A.Y. Water footprint benchmarks for crop production: A first global assessment. *Ecol. Indic.* **2014**, *46*, 214–223. [CrossRef]
10. Nikiel, C.A.; Eltahir, E.A.B. Past and future trends of Egypt's water consumption and its sources. *Nat. Commun.* **2021**, *12*, 4508. [CrossRef]

11. Sayed, Y.A.; Fadl, M.E. Agricultural sustainability evaluation of the new reclaimed soils at Dairut Area, Assiut, Egypt using GIS modeling. *Egypt. J. Remote Sens. Sp. Sci.* **2021**, *24*, 707–719. [CrossRef]
12. Gabr, M.E.S. Management of irrigation requirements using FAO-CROPWAT 8.0 model: A case study of Egypt. *Model. Earth Syst. Environ.* **2022**, *8*, 3127–3142. [CrossRef]
13. Yang, M.-D.; Leghari, S.J.; Guan, X.-K.; Ma, S.-C.; Ding, C.-M.; Mei, F.-J.; Wei, L.; Wang, T.-C. Deficit Subsurface Drip Irrigation Improves Water Use Efficiency and Stabilizes Yield by Enhancing Subsoil Water Extraction in Winter Wheat. *Front. Plant Sci.* **2020**, *11*, 508. [CrossRef]
14. El-Aty, M.A.; Gad, K.; Hefny, Y.; Shehata, M. Performance of some wheat (*Triticum aestivum* L.) genotypes and their drought tolerance indices under normal and water stress. *Egypt. J. Soil Sci.* **2024**, *64*, 19–30. [CrossRef]
15. Shehzad, M.A. Impact of nitrogen nutrition and moisture deficits on growth, yield and radiation use efficiency of wheat (*Triticum aestivum* L.). *Afr. J. Biotechnol.* **2012**, *11*, 13980–13987. [CrossRef]
16. Saad, A.M.; Elhabbak, A.K.; Mohamed, I.; AbdelRahman, M.A.; Scopa, A.; Bassouny, M.A. Can deficit irrigations be an optimum solution for increasing water productivity under arid conditions? A case study on wheat plants. *Saudi J. Biol. Sci.* **2023**, *30*, 103537. [CrossRef]
17. Sandhu, O.; Gupta, R.; Thind, H.; Jat, M.; Sidhu, H.; Singh, Y. Yadvinder-Singh Drip irrigation and nitrogen management for improving crop yields, nitrogen use efficiency and water productivity of maize-wheat system on permanent beds in north-west India. *Agric. Water Manag.* **2019**, *219*, 19–26. [CrossRef]
18. Mekonen, B.M.; Moges, M.F.; Gelagl, D.B. Innovative irrigation water-saving strategies to improve water and yield productivity of onions. *Int. J. Res. Agric. Sci.* **2022**, *9*, 37–2022.
19. Chai, Q.; Gan, Y.; Zhao, C.; Xu, H.-L.; Waskom, R.M.; Niu, Y.; Siddique, K.H. Regulated deficit irrigation for crop production under drought stress. A review. *Agron. Sustain. Dev.* **2016**, *36*, 3. [CrossRef]
20. Yang, B.; Fu, P.; Lu, J.; Ma, F.; Sun, X.; Fang, Y. Regulated deficit irrigation: An effective way to solve the shortage of agricultural water for horticulture. *Stress Biol.* **2022**, *2*, 28. [CrossRef] [PubMed]
21. Asmamaw, D.K.; Janssens, P.; Dessie, M.; Tilahun, S.A.; Adgo, E.; Nyssen, J.; Walraevens, K.; Assaye, H.; Yenehun, A.; Nigate, F.; et al. Effect of deficit irrigation and soil fertility management on wheat production and water productivity in the Upper Blue Nile Basin, Ethiopia. *Agric. Water Manag.* **2023**, *277*, 108077. [CrossRef]
22. Eissa, M.A.; Rekaby, S.A.; Hegab, S.A.; Ragheb, H.M. Effect of deficit irrigation on drip-irrigated wheat grown in semi-arid conditions of Upper Egypt. *J. Plant Nutr.* **2018**, *41*, 1576–1586. [CrossRef]
23. Fadl, M.E.; ElFadl, D.M.A.; Hussien, E.A.A.; Zekari, M.; Shams, E.M.; Drosos, M.; Scopa, A.; Megahed, H.A. Irrigation Water Quality Assessment in Egyptian Arid Lands, Utilizing Irrigation Water Quality Index and Geo-Spatial Techniques. *Sustainability* **2024**, *16*, 6259. [CrossRef]
24. Zhang, X.; Zhang, J.; Li, L.; Liu, Y.; Zhen, W.; Wang, G. Interaction Effects of Water and Nitrogen Practices on Wheat Yield, Water and Nitrogen Productivity under Drip Fertigation in Northern China. *Agriculture* **2024**, *14*, 1496. [CrossRef]
25. Chawla, R.; Balasaheb, K.S. Optimizing water use efficiency and yield of wheat crops through integrated irrigation and nitrogen management: A comprehensive review. *Int. J. Environ. Clim. Change* **2023**, *13*, 4059–4067. [CrossRef]
26. Hamani, A.K.M.; Abubakar, S.A.; Fu, Y.; Kpalari, D.F.; Wang, G.; Duan, A.; Gao, Y.; Ju, X. The coupled effects of various irrigation scheduling and split nitrogen fertilization modes on post-anthesis grain weight variation, yield, and grain quality of drip-irrigated winter wheat (*Triticum aestivum* L.) in the North China Plain. *J. Integr. Agric.* **2024**, *24*, 2123–2137. [CrossRef]
27. Drobnitch, S.T.; Donovan, T.C.; Wenz, J.A.; Flynn, N.E.; Schipanski, M.E.; Comas, L.H. Can nitrogen availability impact plant performance under water stress? A review of traits, mechanisms, and whole plant effects. *Plant Soil* **2024**, *511*, 45–67. [CrossRef]
28. Bwambale, E.; Abagale, F.K.; Anornu, G.K. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agric. Water Manag.* **2022**, *260*, 107324. [CrossRef]
29. Tahir, M.; Arshad, M.A.; Akbar, B.A.; Bibi, A.; Ain, Q.U.; Bilal, A.; Arqam, S.M.; Asif, M.; Ishtiaq, M.H.; Rasheed, H.U.; et al. Integrated nitrogen and irrigation management strategies for sustainable wheat production: Enhancing yield and environmental efficiency. *J. Pharmacogn. Phytochem.* **2024**, *13*, 209–222. [CrossRef]
30. Hütsch, B.W.; Schubert, S. Maize harvest index and water use efficiency can be improved by inhibition of gibberellin biosynthesis. *J. Agron. Crop Sci.* **2018**, *204*, 209–218. [CrossRef]
31. Yan, M.; Lian, H.; Zhang, C.; Chen, Y.; Cai, H.; Zhang, S. The role of root size and root efficiency in grain production, and water-and nitrogen-use efficiency in wheat. *J. Sci. Food Agric.* **2023**, *103*, 7083–7094. [CrossRef]
32. Cui, J.; Mak-Mensah, E.; Wang, J.; Li, Q.; Huang, L.; Song, S.; Zhi, K.; Zhang, J. Interactive effects of drip irrigation and nitrogen fertilization on wheat and maize yield: A meta-analysis. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 1547–1559. [CrossRef]
33. Pan, Y.; She, D.; Ding, J.; Abulaiti, A.; Zhao, J.; Wang, Y.; Liu, R.; Wang, F.; Shan, J.; Xia, Y. Coping with groundwater pollution in high-nitrate leaching areas: The efficacy of denitrification. *Environ. Res.* **2024**, *250*, 118484. [CrossRef] [PubMed]

34. Lakhiar, I.A.; Yan, H.; Zhang, C.; Wang, G.; He, B.; Hao, B.; Han, Y.; Wang, B.; Bao, R.; Syed, T.N.; et al. A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture* **2024**, *14*, 1141. [CrossRef]
35. EL-Sayed, M.M.; Khalifa, Y.A.M.; Elglaly, A.M.M. Effect of Water Irrigation Management and Nitrogen Fertilizer Sources on Water Productivity and Quality of Some Egyptian Cotton Cultivar. *Misr J. Agric. Eng.* **2020**, *37*, 297–312. [CrossRef]
36. Yanardağ, A.B. *Damage to Soil and Environment Caused by Excessive Fertilizer Use*; Agriculture, Forestry and Aquaculture Sciences; Serüven Publishing: Ankara, Turkey, 2024; p. 203.
37. Akram, M.; Iqbal, R.M.; Jamil, M. The response of wheat (*Triticum aestivum* L.) to integrating effects of drought stress and nitrogen management. *Bulg. J. Agric. Sci.* **2014**, *20*, 275–286.
38. Si, Z.; Zain, M.; Mehmood, F.; Wang, G.; Gao, Y.; Duan, A. Effects of nitrogen application rate and irrigation regime on growth, yield, and water-nitrogen use efficiency of drip-irrigated winter wheat in the North China Plain. *Agric. Water Manag.* **2020**, *231*, 106002. [CrossRef]
39. Li, Y.; Huang, G.; Chen, Z.; Xiong, Y.; Huang, Q.; Xu, X.; Huo, Z. Effects of irrigation and fertilization on grain yield, water and nitrogen dynamics and their use efficiency of spring wheat farmland in an arid agricultural watershed of Northwest China. *Agric. Water Manag.* **2022**, *260*, 107277. [CrossRef]
40. Alharbi, S.; Felemban, A.; Abdelrahim, A.; Al-Dakhil, M. Agricultural and Technology-based strategies to improve water-use efficiency in Arid and Semiarid areas. *Water* **2024**, *16*, 1842. [CrossRef]
41. Smith, N. *CROPWAT Model for ETo Calculation Using Penman Monteith Method*; FAO: Rome, Italy, 1991; pp. 112–140.
42. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998; Volume 300, p. D05109.
43. James, L.G. *Principles of Farm Irrigation Systems Design*; John Willey & Sons. Inc.: Hoboken, NJ, USA, 1988.
44. Zwart, S.J.; Bastiaanssen, W.G.M. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manag.* **2004**, *69*, 115–133. [CrossRef]
45. Faghih, H.; Behmanesh, J.; Rezaie, H.; Khalili, K. Climate and rainfed wheat yield. *Theor. Appl. Climatol.* **2021**, *144*, 13–24. [CrossRef]
46. Duvnjak, J.; Katanic, Z.; Sarcevic, H.; Spanic, V. Analysis of the Photosynthetic Parameters, Grain Yield, and Quality of Different Winter Wheat Varieties over a Two-Year Period. *Agronomy* **2024**, *14*, 478. [CrossRef]
47. Eslamian, S.; Khordadi, M.J.; Abedi-Koupai, J. Effects of variations in climatic parameters on evapotranspiration in the arid and semi-arid regions. *Glob. Planet. Change* **2011**, *78*, 188–194. [CrossRef]
48. Sugita, M.; Matsuno, A.; El-Kilani, R.M.M.; Abdel-Fattah, A.; Mahmoud, M.A. Crop evapotranspiration in the Nile Delta under different irrigation methods. *Hydrol. Sci. J.* **2017**, *62*, 1618–1635. [CrossRef]
49. Farouk, A.S.; Abdelghany, A.M.; Shehab, A.A.; Alwakel, S.E.; Makled, K.M.; Naif, E.; Ren, H.; Lamlom, S.F. Optimizing wheat productivity through integrated management of irrigation, nutrition, and organic amendments. *BMC Plant Biol.* **2024**, *24*, 548. [CrossRef]
50. Djaman, K.; O'neill, M.; Owen, C.; Smeal, D.; West, M.; Begay, D.; Allen, S.; Koudahe, K.; Irmak, S.; Lombard, K. Long-term winter wheat (*Triticum aestivum* L.) seasonal irrigation amount, evapotranspiration, yield, and water productivity under semiarid climate. *Agronomy* **2018**, *8*, 96. [CrossRef]
51. Tari, A.F. The effects of different deficit irrigation strategies on yield, quality, and water-use efficiencies of wheat under semi-arid conditions. *Agric. Water Manag.* **2016**, *167*, 1–10. [CrossRef]
52. Vashisth, A.; Goyal, A.; Krishanan, P. Effect of weather variability on growth and yield of wheat crop under semi-arid region of india. *J. Agrometeorol.* **2020**, *22*, 124–131. [CrossRef]
53. Faloye, O.T.; Ajayi, A.E.; Oguntunde, P.G.; Kamchoom, V.; Fasina, A. Modeling and Optimization of Maize Yield and Water Use Efficiency under Biochar, Inorganic Fertilizer and Irrigation Using Principal Component Analysis. *Agriculture* **2024**, *14*, 1813. [CrossRef]
54. Liu, J.; Zhang, J.; Zhu, G.; Zhu, D.; Yan, Y. Effects of water deficit and high N fertilization on wheat storage protein synthesis, gluten secondary structure, and breadmaking quality. *Crop J.* **2022**, *10*, 216–223. [CrossRef]
55. Li, G.; Niu, W.; Sun, J.; Zhang, W.; Zhang, E.; Wang, J. Soil moisture and nitrogen content influence wheat yield through their effects on the root system and soil bacterial diversity under drip irrigation. *Land Degrad. Dev.* **2021**, *32*, 3062–3076. [CrossRef]
56. Ashmawy, F.; Abo-Warda, A.M.A. Response of some wheat cultivars to different seeding rates and nitrogen fertilization levels in sandy soil. *Egypt. J. Appl. Sci.* **2002**, *17*, 136–157.
57. Pouri, K.; Mardeh, A.S.-S.; Sohrabi, Y.; Soltani, A. Crop phenotyping for wheat yield and yield components against drought stress. *Cereal Res. Commun.* **2019**, *47*, 383–393. [CrossRef]
58. Ghafoor, I.; Habib-Ur-Rahman, M.; Ali, M.; Afzal, M.; Ahmed, W.; Gaiser, T.; Ghaffar, A. Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 43528–43543. [CrossRef]

59. Ali, N.; Akmal, M. Wheat Growth, Yield, and Quality Under Water Deficit and Reduced Nitrogen Supply. A Review. *Gesunde Pflanz.* **2022**, *74*, 371–383. [CrossRef]
60. Abid, M.; Tian, Z.; Ata-Ul-Karim, S.T.; Cui, Y.; Liu, Y.; Zahoor, R.; Jiang, D.; Dai, T. Nitrogen nutrition improves the potential of wheat (*Triticum aestivum* L.) to alleviate the effects of drought stress during vegetative growth periods. *Front. Plant Sci.* **2016**, *7*, 981. [CrossRef]
61. Muhammad, I.; Yang, L.; Ahmad, S.; Farooq, S.; Al-Ghamdi, A.A.; Khan, A.; Zeeshan, M.; Elshikh, M.S.; Abbasi, A.M.; Zhou, X.-B. Nitrogen fertilizer modulates plant growth, chlorophyll pigments and enzymatic activities under different irrigation regimes. *Agronomy* **2022**, *12*, 845. [CrossRef]
62. Zeng, W.-Z.; Ma, T.; Huang, J.-S.; Wu, J.-W. Nitrogen transportation and transformation under different soil water and salinity conditions. *Ecol. Chem. Eng.* **2016**, *23*, 677–693. [CrossRef]
63. Khan, S.; Anwar, S.; Shaobo, Y.; Gao, Z.; Sun, M.; Ashraf, M.Y.; Ren, A.; Yang, Z. Soil water consumption, water use efficiency and winter wheat production in response to nitrogen fertilizer and tillage. *PeerJ* **2020**, *8*, e8892. [CrossRef] [PubMed]
64. Bashir, Z.; Hussain, K.; Iqbal, I.; Nawaz, K.; Siddiqui, E.H.; Javeria, M.; Nazeer, A.; Ali, S.S. Improvements of crop productivity in wheat (*Triticum aestivum* L.) by the applications of phytohormones. *Pak. J. Bot.* **2021**, *53*, 585–595. [CrossRef]
65. Shi, Y.; Yu, Z.; Wang, D.; Li, Y.; Wang, X. Effects of nitrogen rate and ratio of base fertilizer and topdressing on uptake, translocation of nitrogen and yield in wheat. *Front. Agric. China* **2007**, *1*, 142–148. [CrossRef]
66. Ochieng', I.O.; Gitari, H.I.; Mochoge, B.; Rezaei-Chiyaneh, E.; Gweyi-Onyango, J.P. Optimizing Maize Yield, Nitrogen Efficacy and Grain Protein Content under Different N Forms and Rates. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 1867–1880. [CrossRef]
67. Gonzalez-Dugo, V.; Durand, J.-L.; Gastal, F. Water deficit and nitrogen nutrition of crops. A review. *Agron. Sustain. Dev.* **2010**, *30*, 529–544. [CrossRef]
68. Wang, L.; Palta, J.A.; Chen, W.; Chen, Y.; Deng, X. Nitrogen fertilization improved water-use efficiency of winter wheat through increasing water use during vegetative rather than grain filling. *Agric. Water Manag.* **2018**, *197*, 41–53. [CrossRef]
69. Wallace, A.J.; Armstrong, R.D.; Grace, P.R.; Scheer, C.; Partington, D.L. Nitrogen use efficiency of 15N urea applied to wheat based on fertiliser timing and use of inhibitors. *Nutr. Cycl. Agroecosystems* **2020**, *116*, 41–56. [CrossRef]
70. Cai, T.; Chen, Y.; Pan, J.; Ye, Y.; Miao, Q.; Zhang, H.; Cui, Z. Improved crop management achieved high wheat yield and nitrogen use efficiency. *Int. J. Plant Prod.* **2021**, *15*, 317–324. [CrossRef]
71. Thorburn, P.J.; Biggs, J.S.; Puntel, L.A.; Sawyer, J.E.; Everingham, Y.L.; Archontoulis, S.V. The nitrogen fertilizer conundrum: Why is yield a poor determinant of crops' nitrogen fertilizer requirements? *Agron. Sustain. Dev.* **2024**, *44*, 18. [CrossRef]
72. Sutton, M.A.; Mason, K.E.; Bleeker, A.; Hicks, W.K.; Masso, C.; Raghuram, N.; Reis, S.; Bekunda, M. Just enough nitrogen: Summary and synthesis of outcomes. In *Just Enough Nitrogen: Perspectives on How to Get There for Regions with Too Much and Too Little Nitrogen*; Springer Nature: Berlin/Heidelberg, Germany, 2020; pp. 1–25.
73. Howell, T.A. Irrigation efficiency. *Encycl. Water Sci.* **2003**, *467*, 500.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.