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IMPROVING BARLEY PRODUCTION UNDER DEFICIENT IRRIGATION WATER AND MINERAL FERTILIZERS CONDITIONS

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SUMMARY

Scarcity in irrigation water led to a gradual increase in water stress, consequently causing a decrease in dry matter, nitrogen uptake, productivity, and the protein content of barley. During two growing seasons, 2020–2021 and 2021–2022, two field experiments ensued to improve barley production in sandy soil under a deficit of irrigation water. The statistical analysis helped recommend the best factors to achieve maximum benefit with barley production under dry conditions and nitrogen mineral fertilizers. The significant variations occurred when irrigating with 60% full irrigation only, but were nonsignificant when irrigating with 80% full irrigation. Increasing the number of mineral fertilization doses to nine times resulted in higher nitrogen concentrations and availability inside the root-spreading area for the longest possible period without washing outside the root-spreading area by deep percolation than when given with three doses only. Irrigating with 80% full irrigation and nine dosages of mineral fertilization obtained the highest and best yield values. It resulted in a 20% reduction in irrigation water use and increased nitrogen fertilizer effectiveness through repeated application doses, resulting in increased productivity and less groundwater pollution. The simulation model received SALTMED model values with high accuracy for most of the studied traits; the R2 was not less than 0.97; therefore, it can function well under sandy soil conditions, which suffer from water scarcity.

Keywords: Deficit irrigation, fertilization doses, SALTMED model, soil moisture, water stress, water productivity, barley

Key findings: The low productivity of barley crops results in less irrigation water. Saving 20% of irrigation water happened with nonsignificant differences in productivity values when irrigating 100% or 80% of full irrigation occurred. Increasing the frequency of fertilizing doses leads to higher productivity values. Using the SALTMED Model gave high accuracy in simulating actual results.

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INTRODUCTION

Barley (*Hordeum vulgare* L.) is one of the main cereal crops that grow in a wide range of temperate climates in the world, as it ranks fourth among the most important crops globally after wheat, corn, and rice (FAO, 2016). Barley is one of the most significant and tolerant crops because of its ability to withstand harsh and adverse environmental conditions (Singh and Upadhyaya, 2015). Barley adapts well to many different global climates, aided by its distinct genetic development, and is generally grown in temperate and subtropical climates (Kumar *et al*., 2015; Pardo *et al.*, 2022).

The effect of water stress on barley yield correlates with and is conditional on the severity of the water deficit and the stage at which this deficit grows. In general, the results of the various studies confirmed that the lack of irrigation water during the stage of plant development led to a noticeable decrease in the yield due to the reduced potential number of grains per unit of the cultivated area (Cossani *et al.*, 2009; Abrha *et al*., 2012; De-Mezer *et al.,* 2014). Reports also mentioned that the quality of barley grains for the fermentation process gets affected by the lack of added irrigation water, especially during the grain formation stage, where examining the time response and delay of seeds transpires. The harmful effects of water stress resulting from a lack of irrigation water were revealed to be immense, which may also lead to a weak rate of nutrient absorption and distribution of these nutrients within plants (Aspinall *et al.*, 1964; Lodhi *et al*., 2015).

The maximum rate of increase and growth of plants for N requirements is not met by the plants' uptake of N when the concentration and availability of N are low in the soil. Cultivated plants may extend their roots into the soil to reach a larger soil volume and improve and increase the activity of N uptake to reach and obtain all necessary N (Liu et al., 2010). Therefore, it is necessary and fundamental to accurately determine the optimal and appropriate amount of nitrogen to increase and improve the productivity of crops (Azizian and Sepaskhah, 2014). With careful and detailed management of nutrients, one expects that the water use efficiency and water productivity of crops will increase and improve (Abdelraouf *et al.,* 2012; Abdelraouf *et al.,* 2013; Almeida *et al.,* 2015).

Water use efficiency and water productivity concepts also indicate that they are indispensable for understanding, studying, and familiarizing oneself with soil systems and crops; thus designing precise practices to conserve limited water resources, where the impact of water deficit strategies on increasing the productivity and quality of crops becomes greater for the production and cultivation of high yields, whether for crops sensitive to over-irrigation or under-irrigation (Al-Harbi *et al.,* 2008). Most researchers have used the quantitative method to evaluate the response of crop yield to the addition of nitrogen fertilizers and express it in a quantitative manner (Atia *et al.,* 2009).

Sandy soils predominate in most newly cultivated areas. These soils suffer from extreme soil fertility, with very low water holding and nutrient retention capacities. However, using proper barley cultivars with the correct mineral fertilization management might help make its cultivation possible and profitable (Safina, 2010; Mohan *et al*., 2015).

The effect of irrigation water scarcity and shortage is one of the most crucial and dangerous challenges and problems that face the production and cultivation of crops in Egypt, making it necessary to rationalize and reduce water consumption, especially irrigation water, with all new improved and developed innovative technologies that can be effective tools and methods influencing significantly (El-Metwally *et al.,* 2015). The application of the methods and techniques of modern irrigation systems, along with the techniques accompanying these methods, showed that they were very critical to do and apply in the arid and semi-arid regions of Egypt, with the urgent need to provide large volumes and quantities of limited irrigation water (Abdelraouf *et al.,* 2012; Abdelraouf *et al.,* 2013; El-Habbasha *et al.,* 2014).

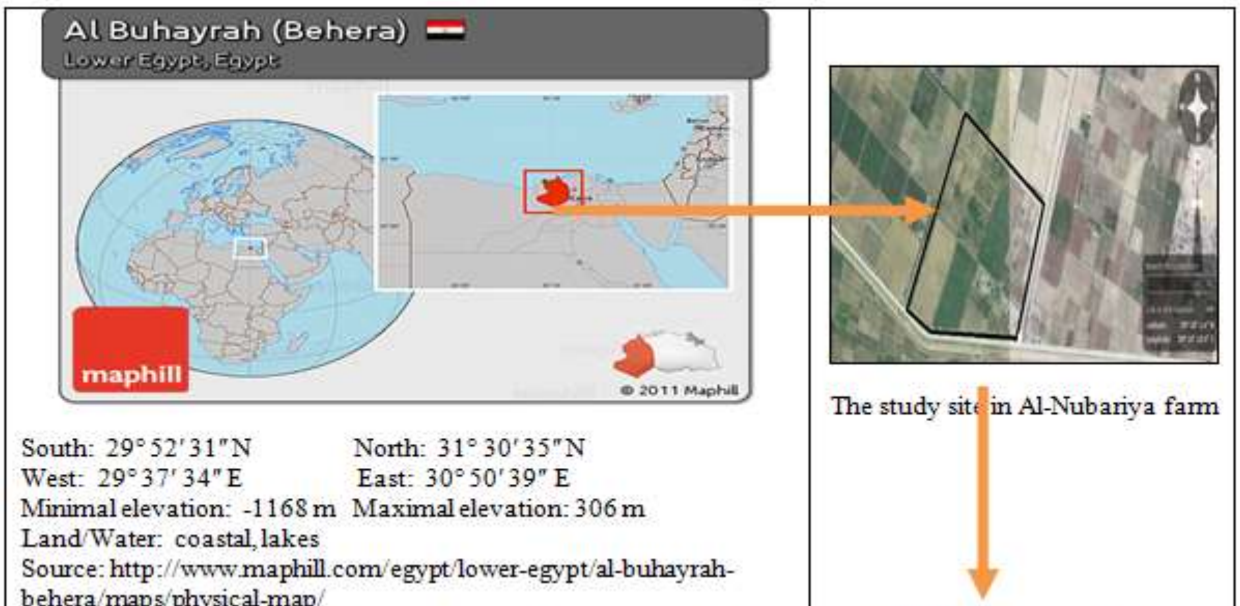
The SALTMED model is one of the most relevant simulation models recently developed, with proven accuracy and the ability to simulate many crop productions under different climatic field areas with various irrigation systems and conventional and non-conventional water sources for irrigation. It also accommodates different irrigation strategies and the many soil types; it can also simulate most of the main crops. It also includes a simulation of agricultural drainage systems. Furthermore, it simulates fertilizer applications and programs, giving good results in simulating drought and salinity conditions with maximum and minimum temperatures. It also replicates irrigation with groundwater (Ragab *et al.,* 2015). One of the advantages of this model, released in 2015, is that it allows the simultaneous simulation of 20 fields and treatments at the same time for different irrigation systems, soils, crops, irrigation strategies, and different types and rates of N fertilizers.

This model also simulates ground moisture, crop yield, dry matter, soil salinity, and soil nitrogen dynamics. It also enables the prediction of the requirements of salinity washing and filtration plants, nitrate filtration, and the volume of wastewater. Moreover, it mimics soil temperature, water absorption, evaporation, salinity, and groundwater level. This valuable model and its accuracy and validity were caliberated using many field data sets collected by many researchers worldwide, including Abdelraouf and Ragab (2018). Therefore, this study aimed to improve barley production under conditions of lack of irrigation water and mineral fertilizers on sandy soils in Egypt through a field study and modelling using the SALTMED model.

MATERIALS AND METHODS

Description of the study site and irrigation system

Field experiments proceeded at the experimental farm of the National Research Centre, El-Nubaria, Al-Buhayrah governorate in northern Egypt, during two barley cultivation seasons in 2020–2021 and 2021–2022 (Figure 1). The farm is at a latitude of 30° 30'1.4" N, a longitude of 30° 9' 10.9" E, and a 21-m mean altitude above sea level. The experimental area has a semi-arid climate, mild winters, and hot, dry summers. The data on maximum and minimum temperatures, relative humidity, and wind speed came from the local weather station at El-Nubaria Farm.



Avr. Monthly for 2 seasons	T_{MAX}	T_{MIN}	RH	WIND	RAIN
Nov.	25.25	12.28	59.38	3.43	2.3
Dec.	21.86	11.42	65.61	3.57	5.4
Jan.	18.69	6.98	66.01	3.48	20.6
Feb.	22.12	7.39	61.58	3.65	18.9
Mar.	25.18	11.27	52.64	4.28	7.37
Apr.	28.52	12.63	45.59	4.39	0

T_{MAX}: maximum air temperature (degrees C), T_{MIN}: minimum air temperature (degrees C), RAIN: average precipitation (mm/day), WIND: wind speed (m/s), RH: average relative humidity (%).

Figure 1. Location of the study site, Al-Nubariya Region, Egypt.

Table 1. Chemical characteristics of the irrigation water.

SAR	Cations and anions (meq/l)								EC (dSm-1)	pH
	Anions				Cations					
	SO4--	Cl-	HCO3-	CO3--	K+	Na+	Mg++	Ca++		
2.7	1.45	1.72	1.11	0.73	0.32	2.6	0.66	1.43	0.42	7.15

EC= Electrical Conductivity SAR= Sodium Adsorption Ratio

Irrigation system components

Pumping system, control pressure head, and filtration unit: The irrigation system consisted of a centrifugal pump with a 45-m^3/h discharge rate, a screen filter with a backflow prevention device, a pressure regulator, pressure gauges, control valves, and a flow meter. The main line, a polyvinyl chloride (PVC) pipe with a 110-mm outer diameter (OD), conveyed the water from the source to the main control points in the field. Sub-main lines, connected to the main line, consisted of PVC pipes with a 75-mm OD. Manifold lines, made of polyethylene (PE) pipes of 63-mm OD, were connected to the sub-main line, control valves, and discharge gauges. The sprinkler, 1.905 cm in diameter, has a discharge rate of 1.18 m^3/h, a wetted radius of 12 m, and a working pressure of 250 KPa.

Physical and chemical properties of soil and irrigation water

The soil texture is sandy (85.4% sand, 9.5% silt, and 5.1% clay), with a pH of 7.7. Salinity is expressed as electric conductivity (EC), measured at 1.67 dS m^{-1}, with an organic matter content in the upper 30 cm of the soil at 0.41%. Available soil N, P, and K contents were rated at 17.2, 4.3, and 25 mg/kg soil, respectively, and extractable Fe, Mn, and Zn scored 2.99, 1.75, and 0.67 mg/kg soil, respectively. The chemical characteristics of irrigation water are shown in Table 1.

Experimental design

The study employed an experimental design arrangement of a split plot with three replications. Deficit irrigation strategies included I1 (100% of full irrigation ["FI"]), I2 (80% FI), and I3 (60% of FI)] in main plots, with the number of times the addition of N-fertilizer doses broken down to N-FF1 (three doses per season "control"), N-FF2 (six doses per season), and N-FF3 (nine doses per season) in sub main plots as shown in Figure 2. Each season for 2020–2021 and 2021–2022, 108 kg of nitrogen per hectare was added for barley cultivation . Giza 123 served as the barley variety used in this study, with irrigation scheduled every three days. At nine days of age, the process of applying nitrogen fertilizer is as follows: 1) If fertilizer is added three times per season, it is applied every 21 days; 2) Every nine days, six times the regular dose of fertilizer is applied; and 3) Every six days, nine times the regular dose of fertilizer is applied. The source of the applied nitrogen was ammonia nitrate, with a content of 33.5% nitrogen.

Experimental unit area

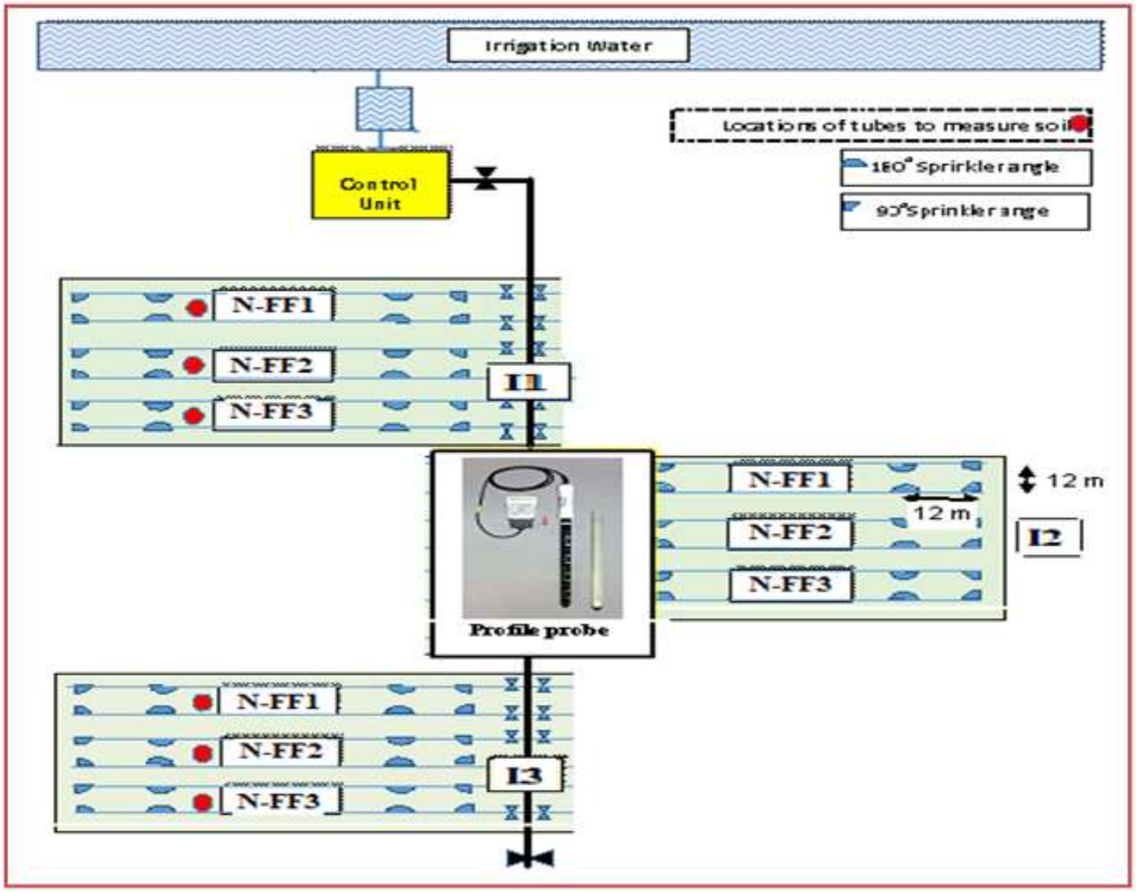
The experiment received an area allocated for growing barley at the National Research Center research farm in the Nubaria region under the sprinkler irrigation system. The total area allocated for implementing the experimental design and the distribution of study factors measured 6480 m^2. Then, dividing the area into three deficit irrigation strategies, the central unit of irrigation treatment amounted to 2160 m^2, which was subdivided further into three experimental units relating to the number of times nitrogen fertilizer application. Hence, the sub-main units comprised 720 m^2, with three spaces taken for three replications, where each replication area was 240 m^2.

Barley irrigation requirements

Seasonal irrigation requirements for barley crops were calculated for seasons 2020–2021 and 2021–2022. The seasonal irrigation water applied, obtained from Equation 1, measures 2620 m^3/ha/season for 2020–2021 and 2600 m^3/ha/season for 2021–2022.

$$IRg = [ET_O \times Kc] / Ei - R + LR \quad ……(1)$$

Where IRg = gross irrigation requirements, mm/day; ET_O = reference evapotranspiration, mm/day (estimated from the Central Laboratory for Climate - Agricultural Research Center Egyptian Ministry of Agriculture at El-Nubaryia farm and according to Penman-Monteith equation); Kc = crop factor (Allen *et al.,*1998); Kr = ground



Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and N-Fertigation Frequency: N-FF1 (3 times per season "control"), N-FF2 (6 times per season), and N-FF3 (9 times per season).

Figure 2. The layout of experimental design.

cover reduction factor; Ei = irrigation efficiency (%); R = water received by the plant from sources other than irrigation, i.e., rainfall (mm); and LR = amount of water required for the leaching of salts (mm).

Data recorded

Soil moisture and water stress inside the roots zone

Soil moisture measurement ensued in the effective roots zone before irrigation, considering the field capacity and wilting point as evaluation parameters for the exposure range of the plants to water stress "WS" (Abdelraouf *et al.,* 2020a). Measurements started at soil depths at the mid-growth stage, with soil moisture measured by a profile probe device.

Dry matter

The dry matter and grain yield measurements of barley proceeded at harvest time, examining random samples from a sample area of 20 m^2 from each plot to estimate dry matter and grain yields in kg/ha for the entire area of the experimental unit, then converted to yield per ton per ha.

Grain yield of barley

Each plot had a random area of 5 m × 4 m harvested, determining the grain, straw, and biological yields which were then converted to yield per hectare. The harvest index calculated as grain yield/biological yield had the grain yield of barley expressed in ton per hectare.

Nitrogen uptake

Calculating nitrogen uptake consisted of multiplying the biomass by its N concentration.

Protein content

Some of the most frequently used methods for food protein determination use the analysis of the total nitrogen content in the samples. Examples of such methods come from Dumas (1831) and Kjeldahl (1883). Measuring the total nitrogen (TN) of barley using Kjeldahl's formula, and determining the total crude protein (TCP) consisted of multiplying the TN content of grains by 6.25, as follows:

Protein content, % = N-content * 6.25 …… (3)

Water productivity of barley

"WP_{Barley}": The water productivity of barley calculation, according to James (1988) proceeded as follows:

$$WP_{Barley} = Ey/Ir \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where;
WP_{Barley} is water productivity ($kg_{Barley}\ m^{-3}{}_{water}$),
Ey is the economical yield (kg_{Barley} /ha), and
Ir is the amount of applied irrigation water ($m^3{}_{water}$/ha/season).

The SALTMED model

The SALTMED model is freely downloadable from the Water4Crops EU-funded project website: http://www.water4crops.org/saltmed-2015-integrated-management-tool-water-crop-soil-and-fertilizers and from the website of the International Commission on Irrigation and Drainage, ICID, web site: http://www.icid.org/res_tools.html# saltmed_2015 (Ragab *et al.*, 2015). During the model calibration, relevant SALTMED model parameters underwent fine-tuning against the observed data (O) for soil moisture, dry matter, grain yield, N-uptake, protein content, and water productivity. For calibration, (I1) + (N-FF1) for season 2020–21 was selected. Adjusting various soil parameters, such as the hydraulic properties of sandy soils, took place until a very close match was achieved between the actual and simulated (S) soil moisture values, with the parameters of the cultivated crop under study also adjusted (Table 2). After achieving a good fit for sandy soil moisture, precise control over the photosynthetic efficiency of dry matter barley and the actual yield was all that was required. The appropriate evaluation criteria used were the coefficient of determination (R^2), root means square error (RMSE), and residual mass factor (CRM). Calculations for the RMSE, R^2, and CRM values used the following equations (4), (5), and (6), respectively:

$$RMSE = \sqrt{\frac{\sum (y_o - y_s)^2}{N}}$$

Where y_o= predicted value, y_s = observed value, and N = total number of observations. The R^2 statistics demonstrate the ratio between the scatter of simulated values to the average value of measurements:

$$R^2 = \left\{ \frac{1}{N} \frac{\sum (y_o - \bar{y_o})(y_s - \bar{y_s})}{\sigma y_o - \sigma y_s} \right\}$$

Where y_o= averaged observed value, y_s = averaged simulated value, N = observed data standard deviation, and σ = simulated data standard deviation. The coefficient of residual mass (CRM) is defined in Equation (6):

$$CRM = \frac{(\sum y_o - \sum y_s)}{\sum y_o}$$

Whenever these evaluation criteria are related to the following values, it indicates the high ability of this model to simulate the actual values. As for the full compatibility between the observed data and the simulation, the RMSE, CRM, and R^2 values should equal 0.0, 0.0, and 1.0, respectively.

Statistical analysis

The recorded data underwent statistical analysis to clarify the discrepancy between the different treatments under study, as described by Snedecor and Cochran (1982). Conducting a joint statistical analysis of the results for both seasons followed the method adopted by Steel and Torrie (1980), where the average values of the recorded data comparison used the least significant differences (LSD with significance at <0.05).

Table 2. The primary input parameters for barley for calibrating I1 and N-FF1 (2020–2021), Egypt.

Barley	Growth Stage	Parameter
20 November.		The sowing date of the barley plant
145		Number of days to harvest
20	Initial	Age stages of barley plants
32	Development	
56	Middle	
37	Late	
0.35	Initial	Crop coefficient, Kc
1.15	Middle	
0.28	End	
0.69	Initial	Leaf area index, LAI
3.53	Middle	
3.15	End	
0.00		Mini. Root depth, m
0.50		Maxi. root depth, m
3.78		Un-stressed crop yield, t ha^{-1}
0.84	Initial	Water uptake threshold
0. 44	Middle	
0.71	End	
0.34		Harvest index
0.15		Field capacity, m^3 m^{-3}
0.25		Saturated soil moisture content, m^3m^{-3}
0.04		Wilting point, m^3 m^{-3}
0.31		Root width factor
0.00		Residual water content, m^3 m^{-3}
0.21		Lambda pore size
11.10		Bubbling pressure, cm
50.00		Max. depth for evaporation, mm

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season); O is observed and S is simulated.

RESULTS AND DISCUSSION

The detailed results of the studied effect of deficit irrigation and N-fertilizer doses on the water stress inside the root zone, dry matter, nitrogen uptake, grain yield, water productivity, and protein content of barley under sandy soil conditions are as follows:

Soil moisture and water stress inside the root zone of barley

The current results describe the effect of the irrigation deficit and nitrogen fertilizer timing during the two growing seasons of barley and their impact on the moisture content of the root zone and the water stress condition to which the roots of barley plants are exposed (Figures 3, 4, and Table 3). An effect is evident on both studied factors on the values of the moisture content of the root zone (Figure 3). The results showed that a decrease in the added irrigation water volume also decreased the average moisture content values before and after irrigation, which meant an increase in water stress on the roots of barley plants exposed during the two growing seasons. The presented results also showed the effect of the number of times the addition of fertilizer doses during one season on the moisture content values within the root zone before and after the irrigation process. It revealed that by increasing the number of fertilizer doses, the moisture content values increased, indicating a decrease in the percentage of water stress within the root spreading area. In general, and when considering the interaction effect of both parameters, one discovered that attaining the highest water stress resulted from irrigating 60% of the total irrigation and applying nitrogen fertilizers in only three doses over both growing seasons.

Further discoveries in the study showed that the least amount of water stress on the roots of barley plants occurred when irrigating with 100% and 80% of complete irrigation with nine doses as the number of times adding fertilizer in both growing seasons. These findings are consistent with other studies that show increasing water volume and the number of times adding N-fertilizer doses reduce water stress and improve soil fertility by increasing nitrogen availability for the extended duration during the effective period of fertilizer (Cossani *et al.,* 2009; Domínguez *et al.,* 2011; Abrha *et al.,* 2012;

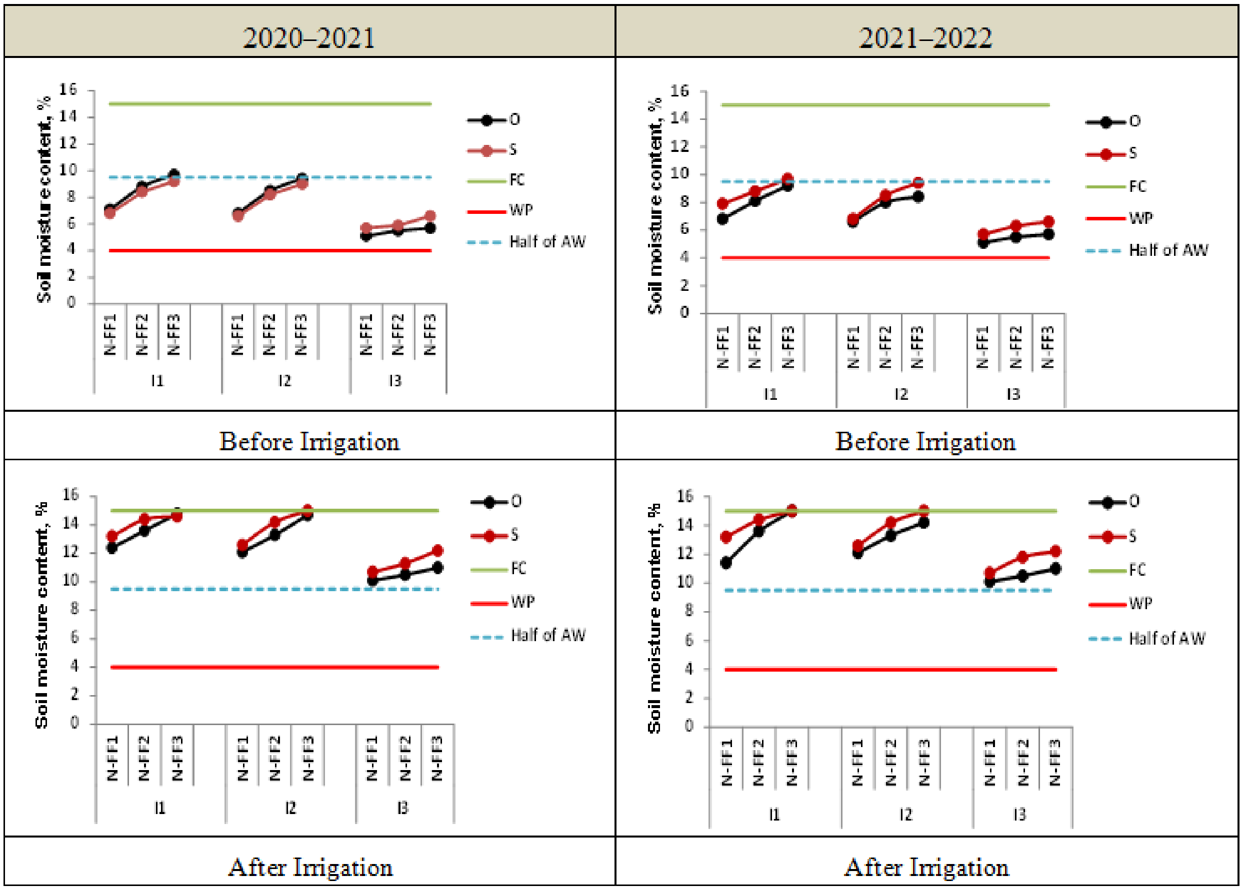


Figure 3. Effect of deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) and the number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season) on the soil moisture content during two growing seasons compared with the simulated soil moisture content.

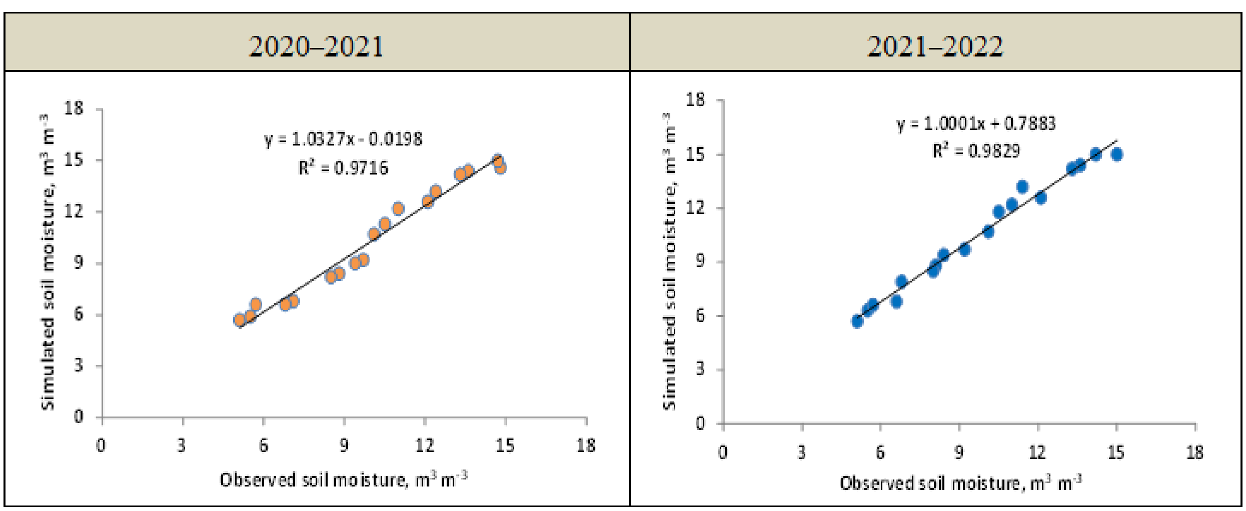


Figure 4. Observed and simulated soil moisture at a depth of 0–30 cm, during two seasons for overall validation treatments.

Table 3. Coefficient of determination (R^2), root mean square error (RMSE), and residual mass factor (CRM) coefficients for soil moisture in one-layer depth (0–30 cm) for all irrigation treatments.

Date	C.P.	I1			I2			I3			Overall R2
		N-FF1	N-FF2	N-FF3	N-FF1	N-FF2	N-FF3	N-FF1	N-FF2	N-FF3	
2020–21	R2	0.950	0.970	0.980	0.970	0.960	0.980	0.960	0.970	0.970	0.97
	RMSE	0.001	0.002	0.001	0.000	0.001	0.003	0.002	0,001	0.004	
	RCM	0.011	0.012	0.014	0.015	0.000	0.016	0.005	0.013	0.014	
2021–22	R2	0.970	0.970	0.980	0.990	0.970	0.980	0.980	0.970	0.980	0.98
	RMSE	0.002	0.003	-0.001	0.005	0.004	0.003	0.001	0.000	0.003	
	RCM	0.007	0.023	0.019	0.016	0.021	0.014	0.003	0.011	0.012	

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season), C.P.: Correlation Parameter.

De-Mezer *et al.,* 2014; Chai *et al.,* 2016).

Results showed the high ability of the SALTMED simulation model to simulate the change in moisture content within the root spreading zone during both growing seasons of barley plants (Figure 4). The correlation coefficient values were 0.972 and 0.993 for the two seasons, 2020–2021 and 2021–2022, respectively. The detailed results of all scores for the evaluation criteria for the simulation program SALTMED Model in Table 3 confirmed the high accuracy in simulating the change in moisture content within the root spreading area for each treatment separately.

Dry matter

The results showed the effect of different strategies for the irrigation deficit on the number of times applying nitrogen fertilizer doses during the two growing seasons and their influence on the dry matter of barley plants (Figures 5, 6, and Table 4). There was a direct effect of both study factors on the values of the dry matter of barley plants. The results illustrated that with a decrease in the added irrigation water volume, the dry matter of barley plants decreased (Figure 5 and Table 4). It may be due to the decrease in volume of the

Table 4. Effect of deficit irrigation strategies and N-fertilizer doses on the dry matter of barley.

Deficit irrigation	N-Fertigation Frequency	Dry matter, ton/ha				Straw yield, ton/ha	
		2020–2021		2021–2022			
		O	S	O	S	2020/2021	2020/2022
I1		12.29	12.09	12.39	12.65	8.29	8.37
I2		12.35	12.31	12.45	12.61	8.52	8.59
I3		10.42	10.49	10.5	10.62	7.86	7.92
$LSD_{0.05}$		0.23		0.23		0.17	0.17
	N-FF1	11.34	11.48	11.43	11.54	8.04	7.97
	N-FF2	11.69	11.67	11.78	12.00	8.26	8.32
	N-FF3	12.03	11.73	12.13	12.34	8.36	8.58
$LSD_{0.05}$		0.18		0.18		0.13	0.13
I1	N-FF1	11.98	11.62	12.07	12.08	8.2	7.85
	N-FF2	12.33	12.60	12.42	12.72	8.31	8.37
	N-FF3	12.57	12.04	12.67	13.15	8.37	8.86
I2	N-FF1	12.15	12.81	12.25	12.44	8.52	8.59
	N-FF2	12.36	12.11	12.46	12.19	8.65	8.72
	N-FF3	12.55	12.01	12.65	13.21	8.38	8.44
I3	N-FF1	9.89	10.02	9.96	10.11	7.4	7.45
	N-FF2	10.38	10.31	10.46	11.09	7.81	7.87
	N-FF3	10.98	11.14	11.07	10.65	8.35	8.42
$LSD_{0.05}$		0.30		0.31		0.22	0.23

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season); O is observed and S is simulated.

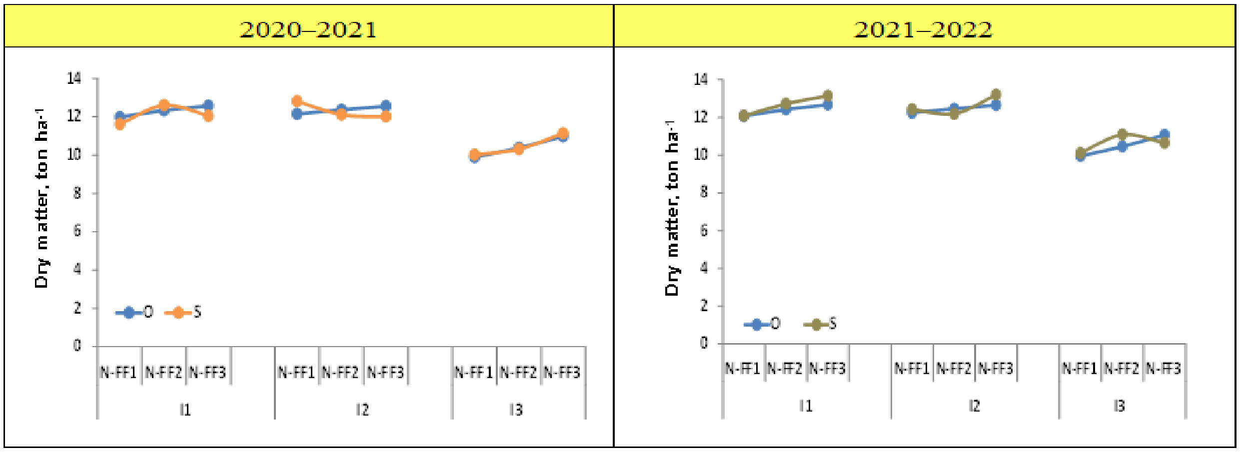


Figure 5. Effect of deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) and the number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season) on the dry matter during two growing seasons compared with the simulated dry matter.

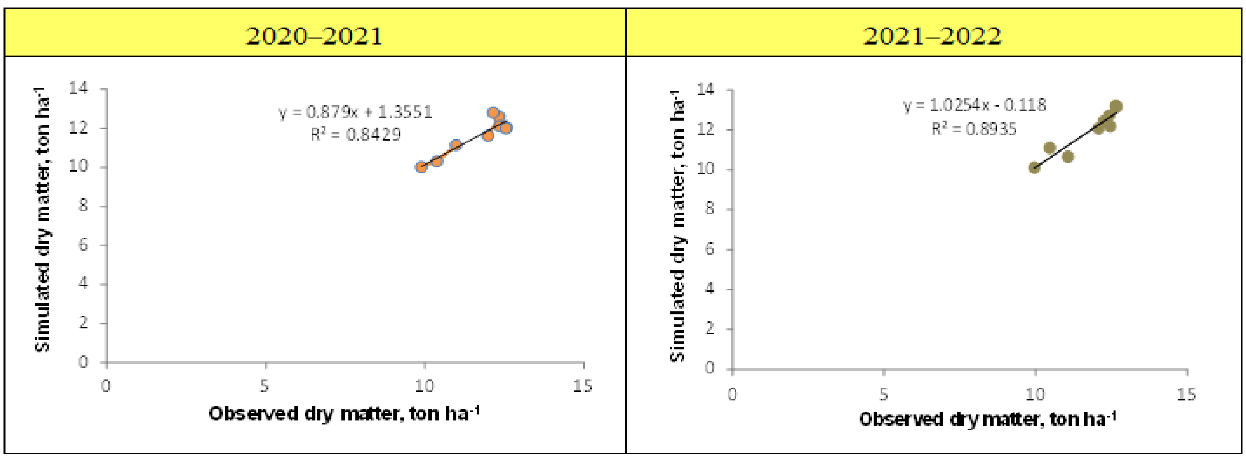


Figure 6. The observed and simulated dry matter at harvesting time and during two seasons for overall validation treatments.

added irrigation water and the increased amount of water stress on the roots of barley plants, which negatively affected the absorption of water and nutrients, thus resulting in a decrease in the dry matter amount for barley plants, especially when irrigating only with 60% full irrigation. No significant difference in dry matter values occurred when irrigating with 80% or 100% full irrigation, but highly significant differences appeared when irrigating with 60% full irrigation. It may be because the percentage of moisture stress when irrigating at 80% did not affect the rate of absorption of water and nutrients in the soil but rather stimulated the simple water stress, increasing the size of the roots, which facilitate and expand the size of the area of the spread of roots, thereby increasing nutrient absorption stores and water absorption.

The presented results also indicated the effect of the number of times the addition of fertilizer doses occurred during the two seasons on the dry matter content. Observations found that increasing the number of fertilizer doses increased the values of dry matter, which means that increasing the number of fertilizer doses during the growing season increases the availability and concentration of fertilizer elements for as long as possible within the area of sandy root spread. The highest amounts of dry matter emerged in barley when nitrogen was applied nine times per season, whereas the lowest values occurred when nitrogen was applied in only three doses; a substantial amount of fertilizer given by washing was lost by deep seepage far from the root spreading area. Figure 6 shows the high ability of the SALTMED simulation model to simulate the change in dry matter values during both growing seasons of barley plants. The correlation coefficient values were 0.843 and 0.894 for the two seasons of 2020–2021 and 2021–2022, respectively.

Nitrogen uptake

The present results also revealed the effects of different irrigation deficits on the number of times adding nitrogen fertilizer doses during the two growing seasons of barley and their influence on nitrogen uptake (Figures 7, 8, and Table 5). Figure 7 shows the apparent effect of the studied factors on the nitrogen uptake values of barley plants. The data showed that as the volume of irrigation water added decreased, so did the nitrogen uptake rate. Probably, the decrease in the added irrigation water volume and the increase in the water stress on barley plant roots negatively affected the rate of nutrient absorption, leading to a lesser nitrogen absorption amount in barley plants, especially when irrigating at 60% full irrigation. No significant difference existed between the values of nitrogen absorption rate when irrigating at 80% or 100% of the full irrigation, but significant differences surfaced at 60% of the full irrigation. The water stress at 80% full irrigation may not have affected the rate of nutrient uptake in the soil, but instead stimulated the minor water stress at 80% watering to increase the volume. It facilitated and increased the root's area of spread, increasing nutrient absorption and storage.

Table 5. Effect of deficit irrigation strategies and N-Fertilizer doses on the Nitrogen uptake compared with the simulated Nitrogen uptake.

Deficit irrigation	N-Fertigation Frequency	Nitrogen Uptake, (gN/m^2)			
		2020–2021		2021–2022	
		O	S	O	S
	N-FF1	6.53	6.64	7.54	7.62
I1	N-FF2	7.32	7.21	7.77	7.79
	N-FF3	7.85	8.11	7.86	7.91
	N-FF1	6.46	6.71	6.92	7.36
I2	N-FF2	7.12	7.23	7.57	7.61
	N-FF3	8.21	8.17	8.76	8.71
	N-FF1	3.79	4.11	4.09	4.02
I3	N-FF2	4.05	4.45	4.35	4.52
	N-FF3	4.29	4.63	4.61	4.57

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season); O is observed and S is simulated.

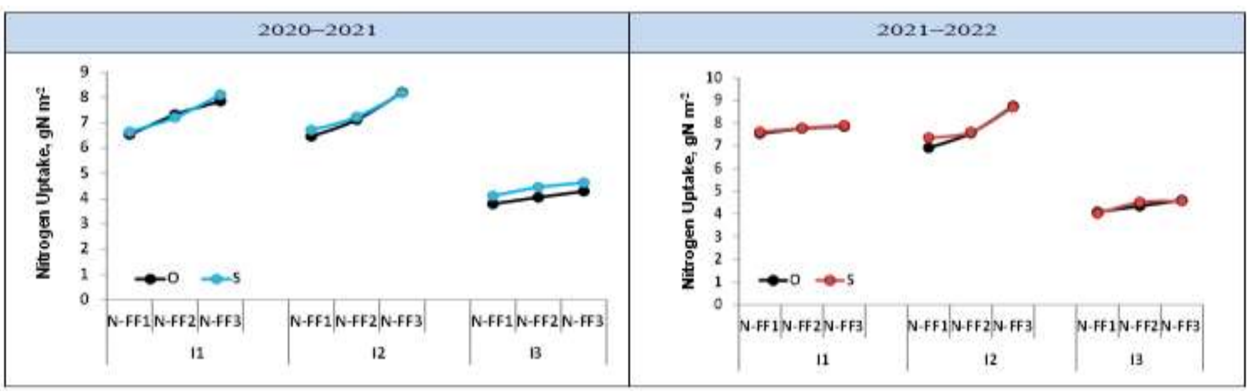
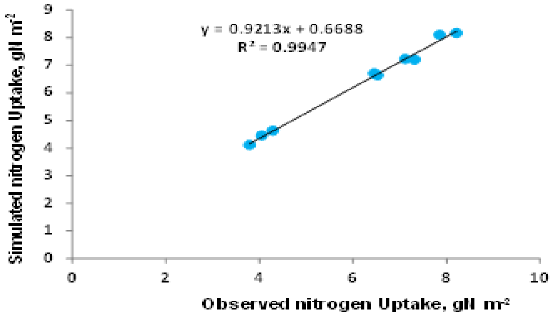


Figure 7. Effect of deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) and the number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season) on the Nitrogen uptake during two growing seasons compared with the simulated Nitrogen uptake.

2020–2021



2021–2022

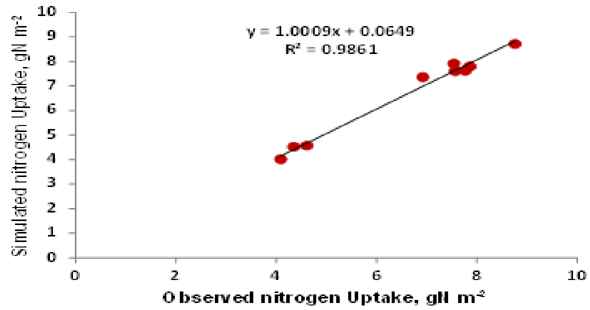


Figure 8. Observed and simulated Nitrogen uptake at harvesting time and during two seasons for overall validation treatments.

The presented results also indicated the effect of the number of times the addition of nitrogen fertilizer doses for barley during the two growing seasons on the nitrogen absorption rate values. Notably, increasing the number of fertilizer doses causes an increase in the nitrogen absorption rate values, which means that by increasing the number of fertilizer doses during the growing seasons, the availability and concentration of fertilizer elements increase for the longest possible period within the region of sandy root spread. The highest values of barley's nitrogen absorption showed when fertilizing with nitrogen in nine doses per season, with the lowest rate showing with fertilizer application in only three doses. It caused a loss of a large amount of the mineral fertilizer added by washing and seeping away from the root spreading area. The findings align with other studies also showing an increase in water volume and the number of times the addition of N-fertilizer applications causes a positive effect on barley N-uptake by reducing water stress and improving soil fertility due to sustained nitrogen availability for the longest duration during the effective period of fertilizer (Birch *et al.,* 1997; Liu *et al.,* 2010). Figure 8 shows the high ability of the SALTMED simulation model to simulate the change in nitrogen uptake values during both growing seasons of barley plants. The correlation coefficient were rated at 0.995 and 0.986 for the two seasons of 2020–2021 and 2021–2022, respectively.

Yield components of barley

There was an effect of both study factors on the values of the studied yield components of barley (Table 6). The results showed that with a decrease in the added irrigation water volume, the yield components of barley decreased, such as plant height, spike length, and the number of spikes/m^2. Probably the decrease in the added irrigation water volume increased the water stress exposure of the barley plant roots, negatively affecting the absorption of water and nutrients, which resulted in a decrease in the values of the yield components of barley, especially when rinsing with 60% FI. The probable reason explains the percentage of moisture stress when irrigation at 80% FI did not affect the absorption rate of water and nutrients in the soil. Instead, it stimulated the simple water stress with the 80% FI to increase the size of the roots, which facilitated and expanded the size of the area of the spread of roots, then increasing nutrient absorption stores and water absorption. The findings also showed the effect of the number of times the addition of fertilizer doses occurred during the two seasons on the yield components of barley (plant height, spike length, and the number of spikes/m^2). Increasing the number of fertilizer doses caused the barley yield components to increase, which means increasing the number of fertilizer doses during the growing season maintained the availability and concentration of fertilizer elements for as long as possible within

Table 6. Effect of deficit irrigation strategies and N-Fertilizer doses on some of the yield components of barley.

Deficit irrigation,%	N-Fertilizer doses	Plant height, cm		Spike length, cm		No. of spikes/m^2	
		2020–2021	2021–2022	2020–2021	2021–2022	2020–2021	2021–2022
I1		86.6	87.2	10.8	11.0	358.3	361.5
I2		83.5	84.1	10.7	11.0	355.2	358.4
I3		60.4	60.4	6.8	7.0	256.0	258.0
$LSD_{0.05}$		2.0	2.2	0.3	0.5	3.1	3.5
	N-FF1	72.2	72.2	8.9	9.1	319.0	321.9
	N-FF2	76.8	77.4	9.4	9.6	323.4	326.4
	N-FF3	81.5	82.1	10.0	10.3	327.1	329.7
$LSD_{0.05}$		1.0	1.2	0.3	0.3	2.1	2.3
	N-FF1	83.0	83.4	10.2	10.4	354.7	358.0
I1	N-FF2	86.9	87.5	10.8	11.0	358.3	361.7
	N-FF3	89.8	90.6	11.4	11.7	362.1	364.7
	N-FF1	77.7	78.4	10.2	10.4	348.5	351.8
I2	N-FF2	82.9	83.6	10.8	11.0	356.7	360.0
	N-FF3	89.8	90.3	11.2	11.5	360.4	363.5
	N-FF1	55.8	55.0	6.2	6.4	253.7	255.9
I3	N-FF2	60.6	61.1	6.7	6.9	255.3	257.4
	N-FF3	64.7	65.3	7.5	7.6	258.8	260.9
$LSD_{0.05}$		1.8	2.1	N.S	N.S	N.S	N.S

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season).

Table 7. Effect of deficit irrigation strategies and N-Fertilizer doses on the grain yield and water productivity of barley.

Deficit irrigation	N-Fertigation Frequency	Grain yield, ton ha^{-1}				Water productivity, kg/m^3			
		2020–2021		2021–2022		2020–2021		2021–2022	
		O	S	O	S	O	S	O	S
I1		4	4.07	4.03	4.11	1.52	1.57	1.55	1.58
I2		3.84	3.87	3.87	4.21	1.83	2.01	1.86	2.02
I3		2.57	2.63	2.58	2.63	1.63	1.67	1.65	1.69
$LSD_{0.05}$		0.06		0.06					
	N-FF1	3.3	3.43	3.46	3.69	1.58	1.65	1.61	1.67
	N-FF2	3.44	3.39	3.46	3.64	1.65	1.62	1.67	1.81
	N-FF3	3.67	3.75	3.56	3.63	1.75	1.8	1.78	1.82
$LSD_{0.05}$		0.05		0.05					
	N-FF1	3.78	3.91	3.81	3.93	1.44	1.49	1.47	1.51
I1	N-FF2	4.02	4	4.05	4	1.53	1.53	1.56	1.54
	N-FF3	4.2	4.31	4.22	4.41	1.6	1.65	1.62	1.7
	N-FF1	3.63	3.75	3.66	4	1.73	1.79	1.76	1.92
I2	N-FF2	3.71	3.65	3.73	4.21	1.77	1.74	1.79	2.02
	N-FF3	4.17	4.21	4.21	4.41	1.99	2.01	2.02	2.12
	N-FF1	2.49	2.64	2.51	2.45	1.58	1.68	1.61	1.57
I3	N-FF2	2.58	2.51	2.59	2.91	1.64	1.6	1.66	1.87
	N-FF3	2.63	2.73	2.65	2.54	1.67	1.74	1.7	1.63
$LSD_{0.05}$		0.08		0.09		Y = 0.934× + 0.1407 R^2=0.913		y = 1.2639× - 0.3687 R^2= 0.80	

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI)] in main plots and number of times addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season); O is observed and S is simulated.

the area of sandy root spread. The highest values of yield components of barley occurred when applied with nine times nitrogen fertilizers per season, whereas the lowest occurred when given with only three times fertilizers doses, during which time a large amount of fertilizer was lost by washing with the deep seepage far from the root spreading area. These results also agree with the previously reported ones (Samarah *et al.,* 2009; Albrizio *et al*., 2010; Rajala *et al.,* 2011).

Grain yield

The outcomes also exhibited the effects of different irrigation deficits on the number of times the addition of nitrogen fertilizer doses during the two growing seasons of barley and their influence on the grain yield (Figures 9, 10, and Table 7). A clear impact emerged from both studied factors on the values of the grain yield of barley (Figure 9). The results showed that with a decrease in the added irrigation water volume, the grain yield of barley plants also decreased. Perhaps this was due to the decrease in the added irrigation water volume and the increase in the water stress on the roots of barley plants, which negatively affected the absorption of water and nutrients, resulting in a decrease in the amount of barley grain yield, especially when irrigating with 60% FI. The nonsignificant difference in grain yield rates appeared when given 80% or 100% FI, but highly significant differences surfaced with 60% FI. Probably because the percentage of moisture stress when irrigating at 80% FI did not affect the absorption rate of water and nutrients in the soil, but instead stimulated the simple water stress when watering at 80% FI to increase the size of the roots. It then facilitated and expanded the size of the area covered by the spread of roots, increasing nutrient storageand water absorption.

Similarly, the study's findings revealed that the number of times the addition of fertilizer treatment affects the grain yield

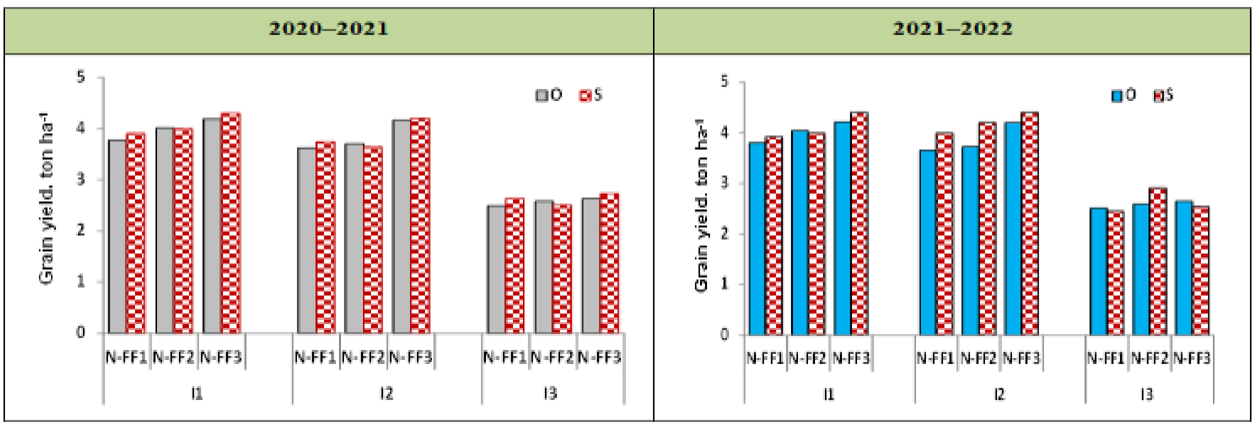


Figure 9. Effect of deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) and the number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season) on the grain yield during two growing seasons compared with the simulated grain yield.

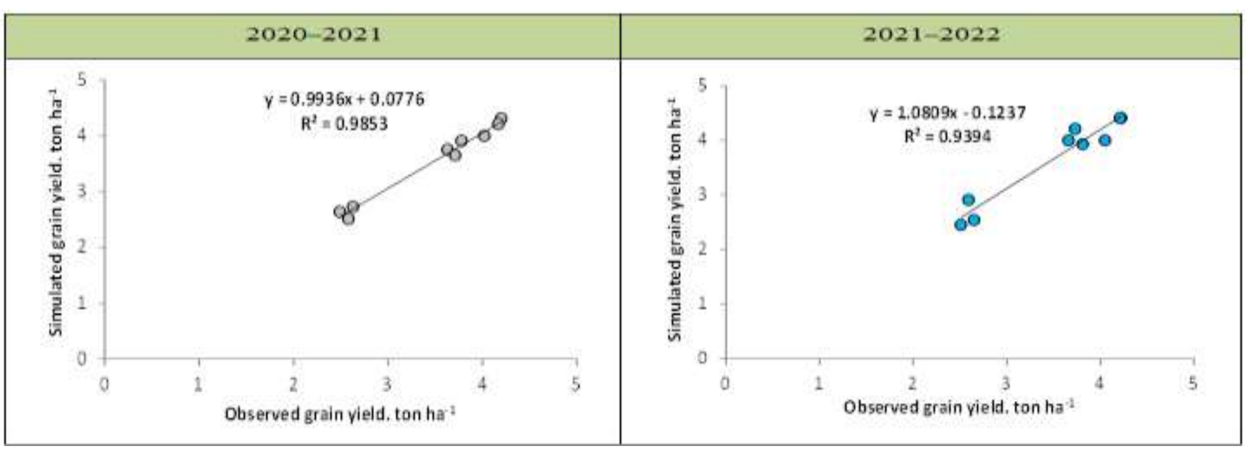


Figure 10. Observed and simulated grain yield at harvesting time and during two seasons for overall validation treatments.

values during the two seasons. Notably, increasing the number of fertilizer doses increased the grain yield amounts. Hence, increasing the number of fertilizer doses during the growing season caused na increase in the availability and concentration of fertilizer elements for as long as possible within the area of sandy root spread. The highest values of barley grain yield showed with nine times nitrogen fertilizer applications per season, whereas the lowest values showed with only three doses of fertilizer applications per season, during which time a large amount of added fertilizer was lost by washing due to deep percolation far from the root spreading area.

Data showed that the lowest yield values were rated at 2.49 and 2.51 t ha^{-1} for both seasons of 2020–2021 and 2021–2022, respectively. The highest yield values came at 4.2 and 4.17 t ha^{-1} when irrigating at 100% and 80% FI, respectively, with the number of times applying mineral nitrogen fertilizer at nine doses during the effective period of barley plants needing the N-fertilizer (at the maximum tillering stage) for the season of 2020–2021. Meanwhile, the highest values of yield for season of 2021–2022 scored at 4.22 t/ha, with 4.21 t/ha when watered at 100% and 80% FI, respectively, combined with the number of times mineral nitrogen fertilizer at nine doses during the effective period of barley plants needing the N-fertilizer (at the maximum tillering stage).

These findings are consistent withother studies that show an increase in the additional water volume and increasing the number of times adding N-fertilizer certainly influenced the grain yield because of the reduction of water stress and improving soil fertility with the increased availability of nitrogen for the extended duration during the effective period of fertilizer (Atia *et al.,* 2009; Samarah *et al.,* 2009; Albrizio *et al*., 2010; Rajala *et al.,* 2011; Azizian and Sepaskhah, 2014). Figure 10 shows the high ability of the SALTMED simulation model to simulate the change in grain yield values during both growing seasons of barley plants. The correlation coefficients were rated at 0.985 and 0.933 for the two seasons of 2020–2021 and 2021–2022, respectively.

Water productivity

The recorded data showed the effects of different deficit irrigation methods and the number of times the addition of nitrogen fertilizer doses during the two growing seasons of barley and their impact on the water productivity of barley (Table 7). As detailed in Table 7, a noticeable effect of both studied factors occurred on the values of the water productivity of barley. The results showed that with a decrease in the added irrigation water volume, the water productivity of barley decreased. It probably resulted in a reduction in barley productivity values caused by a decrease in irrigation water volume added. The presented results also disclosed the effect of the number of times the addition of nitrogen fertilizer doses during two seasons on the water productivity of barley. It is attributable to an increase in barley productivity values as a result of increasing the number of times applying nitrogen fertilizer throughout the effective period of fertilizer application to nine doses rather than three doses during the barley growing season.

The water productivity of barley was highest when nitrogen fertilizer was applied in nine doses per season, and lowest when nitrogen fertilizer was applied in only three doses per season. The highest value of water productivity of barley was measured at 1.99 and 2.02 kg m^{-3} when watered by 80% FI for the seasons of 2020–2021 and 2021–2022, respectively, given the number of times the addition of mineral nitrogen fertilizer in nine doses occurred during the effective period of fertilizer in the barley plant's life cycle. These findings are consistent with other studies that show that increasing the addition of water volume and the number of times applying the addition of N-fertilizer has a progressive effect on barley water productivity due to reduced water stress and improved soil fertility by increasing nitrogen availability for the prolonged duration during the effective period of fertilizer (Abdelraouf *et al.,* 2012; Almeida *et al.,* 2015; Eid and Negm, 2019). Table 7 also shows the high ability of the SALTMED simulation model to simulate the change in water productivity values during both growing seasons of barley plants. The correlation coefficients were 0.913 and 0.80 for the two growing seasons of 2020–2021 and 20210–2022, respectively.

Protein content

The effects of different irrigation deficit conditions on the number of times the addition of nitrogen fertilizer doses occurred during the two growing seasons of barley, as well as their influence on the average moisture and protein contents of grain barley, appear in Figures 11, 12, and Table 8. The distinct effects of both

Table 8. Effect of deficit irrigation strategies and N-Fertilizer doses on the nitrogen and protein content of barley.

Deficit irrigation	N-Fertigation Frequency	Nitrogen content, %				Protein content, %			
		2020–2021		2021–2022		2020–2021		2021–2022	
		O	S	O	S	O	S	O	S
I1	N-FF1	1.73	1.70	1.84	1.73	10.8	10.63	11.5	10.81
	N-FF2	1.82	1.80	1.94	1.95	11.4	11.25	12.1	12.19
	N-FF3	1.87	1.88	1.98	2.01	11.7	11.75	12.4	12.56
I2	N-FF1	1.78	1.79	1.89	1.73	11.1	11.19	11.8	10.81
	N-FF2	1.92	1.98	2.03	1.90	12.0	12.38	12.7	11.88
	N-FF3	1.97	1.94	2.08	1.98	12.3	12.13	13.0	12.38
I3	N-FF1	1.52	1.56	1.63	1.64	9.5	9.75	10.2	10.25
	N-FF2	1.57	1.77	1.68	1.55	9.8	11.06	10.5	9.69
	N-FF3	1.63	1.70	1.74	1.80	10.2	10.63	10.9	11.25
		$Y = 0.7395\times + 0.492$ $R^2 = 0.791$		$Y = 0.8773\times + 0.1713$ $R^2 = 0.742$					

Deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) in main plots and number of times addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season); O is observed and S is simulated.

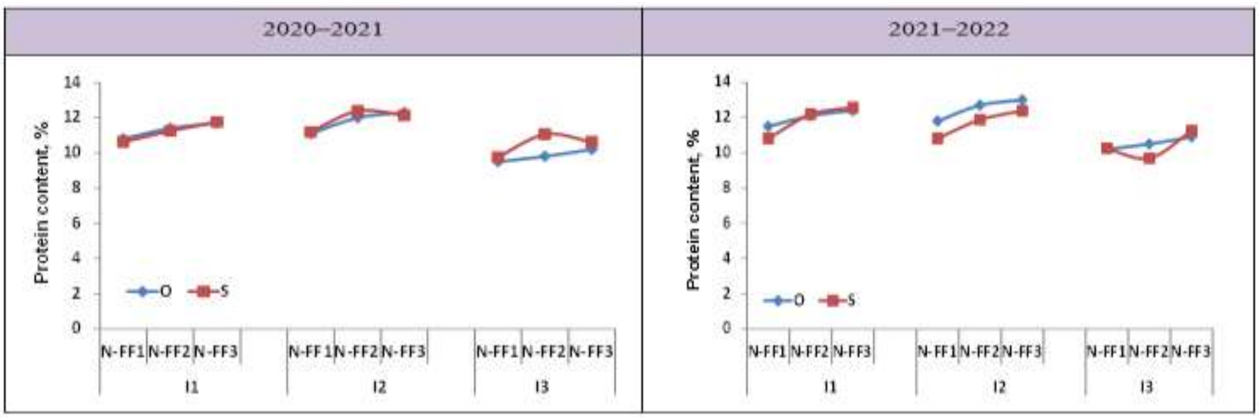


Figure 11. Effect of deficit irrigation strategies: I1 (100% Full Irrigation "FI"), I2 (80% FI), and I3 (60% FI) and number of times the addition of N-Fertilizer doses: N-FF1 (3 doses per season "control"), N-FF2 (6 doses per season), and N-FF3 (9 doses per season) on the protein content during two growing seasons compared with the simulated protein content.

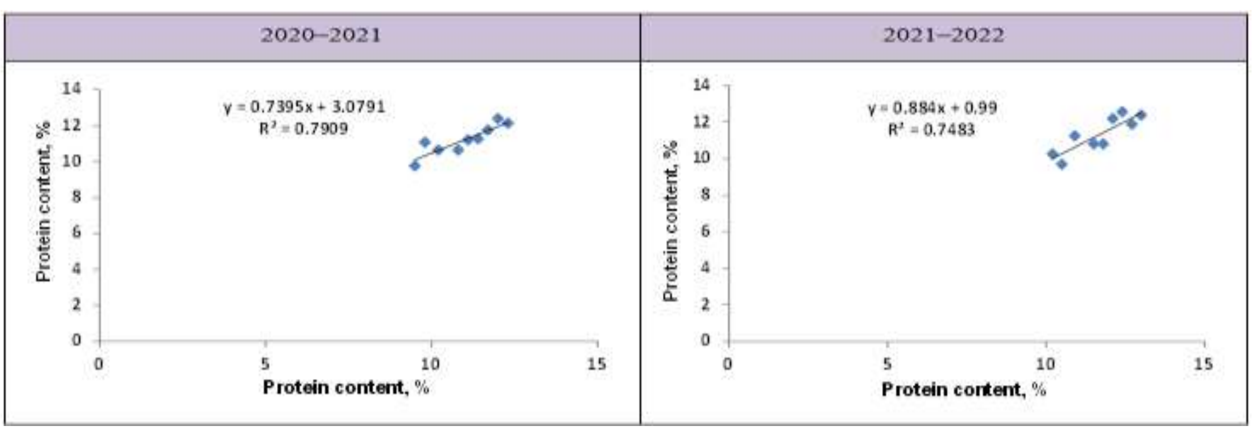


Figure 12. Observed and simulated protein content at harvesting time and during two seasons for overall validation treatments.

studied factors resulted in different values for the protein content of barley (Figure 11). The results showed that with a decrease in the added irrigation water volume, the protein content of barley decreased. It could be due to the fact that the decrease in the added irrigation water volume increased the water stress on the roots of barley plants, negatively affecting the absorption of nutrients, which resulted in a decrease in the values of the protein content of barley, especially when watered with 60% FI. No significant effect appeared among the values of the protein content of barley when given with 80% or 100% FI, but highly significant differences occurred when irrigated with 60% FI. It could be due to the high percentage of moisture stress when irrigating at 80% FI not affecting the rate of absorption of nutrients in the soil. Instead, when watered by 80%, it stimulated the simple water stress to increase the size of the roots, which facilitated and expanded the size of the zone of the spread of roots, increasing nutrient absorption stores and water absorption.

The presented results also showed the effect of the number of times the addition of fertilizer doses during the two growing seasons on the protein content of barley. The study found that by increasing the number of fertilizer doses, the amount of the protein content of barley increased, which means that by increasing the number of fertilizer doses during the growing season, the availability and concentration of fertilizer elements increased sustainably within the zone of sandy root spread. The highest values of the protein content of barley appeared with the application of nine doses of nitrogen fertilizer per season. Conversely, the lowest amount occurred when only three doses of fertilizer were applied per season, due to the loss of a large amount of fertilizer added with the washing to deep seepage far from the root spreading zone. The study findings agreed with other reports stating that increasing the water volume and the number of times adding N-fertilizer has a positive effect on the protein content of barley, resulting in water stress reduction and soil fertility improvement, thus increasing the availability of nitrogen sustainably during the effective fertilizer period throughout the plant life cycle (Cossani *et al.,* 2009; Abrha *et al.,* 2012; De Mezer *et al.,* 2014; Cozzolino *et al.,* 2021; Pardo *et al.,* 2022). Figure 12 shows the high ability of the SALTMED simulation model to simulate the change in the protein content values during both growing seasons of barley plants. The correlation coefficients scored 0.791 and 0.748 for the two growing seasons of 2020–2021 and 2021–2022, respectively.

CONCLUSIONS

For various variables, full irrigation at 60% and 80% revealed significant and nonsignificant differences. Increasing the number of times addition of nitrogen fertilizer doses revealed nine doses led to an increase in the concentration and availability of nitrogen for the longest possible period inside the root-spreading zone of barley plants without washing outside the root-spreading zone by deep percolation as compared with the application of only three doses during the growing season. The highest and best values emerged when irrigating 80% of the full irrigation and adding nitrogen fertilizer in nine doses during the effective period of the applied process. It led to a 20% reduction in irrigation water use, in addition to increasing the effectiveness of the use of nitrogen fertilizers by increasing the number of times additional doses were administered, leading to an increase in productivity and a reduction in groundwater pollution. The simulation model, given SALTMED model values, showed high accuracy for most of the studied traits, with a correlation coefficient higher than 0.97.
The findings were highly recommended for use in Egyptian lands with sandy soils and limited water resources.

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