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Effect of Deficit Irrigation Strategies and Fertigation Timing on Yield, Water Productivity and Quality of Green Beans Under Dry Sandy Areas

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ABSTRACT

The aim of the research study was to increase productivity, water productivity and crop quality under conditions of irrigation deficit and water scarcity. To achieve this goal, an experimental design was carried out for the seasons 2022 and 2023 to study the effect of irrigation deficit strategies and the most appropriate timing for fertilization on productivity, water productivity and quality of green bean crop under dry sandy soil conditions in the Nubaria region of Egypt. The results of the statistical analysis of the experimental data concluded that: (1) The highest values of green bean crop productivity were achieved when irrigated with 100% or 75% of Full Irrigation (FI) and with fertilization timing 3 hours after irrigation. This may be due to the increase in moisture content and decrease in water stress values with increase in nutrient concentration in the root zone, which led to increase in water and nutrient absorption and consequently increase in green bean crop productivity values compared to other treatments. (2) The highest values of water productivity of green beans were achieved when irrigated with 100% or 75% FI with fertilization timing after 3 hours of irrigation. The reason behind this was achieving the highest values of crop productivity of beans when irrigated with 100% or 75% FI, while the volume of irrigation water added when irrigated with 75% FI was less. As a result, the strategy of irrigation at 75% FI was adopted when irrigating green beans in order to save 25% of fresh irrigation water for planting other areas similar to the same conditions. (3) An improvement and increase in the quality characteristics of green bean pods at 100% and 75% FI and with the best fertilization time, which is 3 hours after irrigation. This may be due to the decrease in moisture stress values and the increase in the concentration of nutrients in the root spread area, which led to an increase in water and nutrients absorption, thus improving the quality characteristics of green bean pods compared to other treatments.

Keywords: Deficit irrigation strategies, fertigation timing, Soil moisture content, Water Productivity, drip irrigation, Green beans.

1. Introduction

Crop productivity is negatively impacted by water scarcity. Drought episodes brought on by climate change exacerbate the scarcity of water (Tesfaye and Nayak, 2022). One of the most important worldwide concerns at the moment is water scarcity, which will only get worse in the future. Irrigated fields provide about 40% of the world's food, and agriculture uses the most water 70% of all freshwater withdrawals of any industry. Increasing food production requires increasing water usage efficiency as the global water constraint gets severe (Bosco *et al*., 2022). There is pressure on agriculture to use freshwater wisely and effectively for irrigation (Abdelraouf *et al*.,

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2020). In arid locations, food production is challenged by water constraint. Water-stressed areas must maximize water use, save irrigation water, and employ cutting-edge technologies (El–Metwally *et al*., 2022). To fulfill the growing demand for food by the rapidly expanding population, it is imperative to improve agricultural production per unit volume of irrigation water (Abdelraouf and Ragab, 2018; Eid and Negm, 2018).

One of the main issues facing Egypt's crop production is water shortage, so innovative technologies that can effectively use this valuable input to their advantage must be developed in order to reduce the amount of water used for irrigation. Due to the limited amount of water resources, applying sophisticated and effective irrigation techniques is a crucial idea that should be adhered to in semi-arid locations like Egypt in order to save some irrigation water (Habbasha *et al*., 2014).

Given the scarcity of water resources in agricultural regions, deficit irrigation is critical to increasing water usage efficiency. However, it's critical to comprehend the times of year when crops are most susceptible as well as the ways in which dry weather impacts crop yields (Bhagyawant *et al*., 2015; Ibba *et al*., 2023). Deficit irrigation, which exposes the farmed crops to varying degrees of water stress for part or all of the growing season, is an effective irrigation method that conserves water. Irrigation that doesn't provide as much water as needed for crop growth is known as deficit irrigation (Geerts and Raes, 2009). When water supplies are scarce or irrigation expenses are high, this approach might be more appropriate than full irrigation. A crop may tolerate a certain amount of water deficit and yield decline when using regulated deficit irrigation (RDI), an optimal technique (Chartzoulakis and Maria, 2015). When weighed against the advantages of using the saved water to irrigate different crops, the yield loss from deficit irrigation is negligible (Zhang, 2003). Introduced in the 1970s, deficit irrigation (DI) is based on applying less water for irrigation (Stewart and Nielsen, 1992). As a result, it can increase water productivity by yielding higher yields per unit of water. According to a review paper cited by Geets and Kirk (2009), DI has been extensively studied as a beneficial and long-term production technique in arid areas. This method tries to maximize water productivity and stable yields rather than maximize them by restricting water applications to the drought-sensitive growth stages. According to research findings, DI can successfully raise water productivity for a variety of crops without significantly reducing yields (Evett and Tolk, 2009). Many crops that can either escape stress by deep roots or are generally resistant to water stress have shown success with deficit irrigation (Kato *et al*., 2006). This allows the crops to access soil moisture that is lower in the soil profile. There may not be a decrease in production in certain situations, and the quality of the crop's final output may even improve (FAO, 2002).

Chemical fertilizer application is essential for crop growth and harvests. The process of fertilization involves adding nutrients with irrigation water. For irrigated agriculture on sandy soils, where huge amounts of fertilizers may be lost to deep percolation into the groundwater if improperly handled, fertilizer management is especially crucial. Crop growth and productivity can be significantly impacted by soil moisture mobility and soil nutrient dynamics (Abdelraouf and Ragab 2018). In addition to influencing soil moisture and nutrient concentration in the rhizosphere (Abalos *et al*., 2014; Zotarelli *et al*., 2009), fertigation frequency also impacts root growth, root to shoot ratio, water and nitrogen uptake efficiency, and yield (Sensoy *et al*., 2007). Segal *et al*. (2006) recommended maintaining a high fertigation frequency in order to keep the root zone's moisture and nutrient levels steady. According to Zegbe *et al*. (2004), a reduction in irrigation and N availability at the same time would result in a decrease in vegetation growth, which would raise the harvest index.

The aim of this study was to improve productivity, water productivity and crop quality (green beans as a case study) under conditions of irrigation water scarcity and dry sandy soils by deficit irrigation strategies and determining the best timing for applying the fertigation process with irrigation water.

2. Materials and Methods

2.1. The location of the experiment and the surrounding climate

During the growing seasons of 2022 and 2023, the research was conducted at the National Research Center farm located in EL-Nubaria, EL-Beheira Governorate, Egypt. The research region has an average elevation of 21 meters above sea level and is located between 30° 29' 48.9" N - 30° 29' 46.1" N and 30°18' 49.6" E - 30° 18' 56.0" E (Fig. 1). The region experiences hot summers and mild winters due to its desert climate. During the growing season of green beans (February to April), an on-site weather station gave daily values of the highest and minimum air temperatures, relative air humidity, solar radiation, and wind speed. The annual precipitation total was an exceptionally low 20 mm (Figure 2).

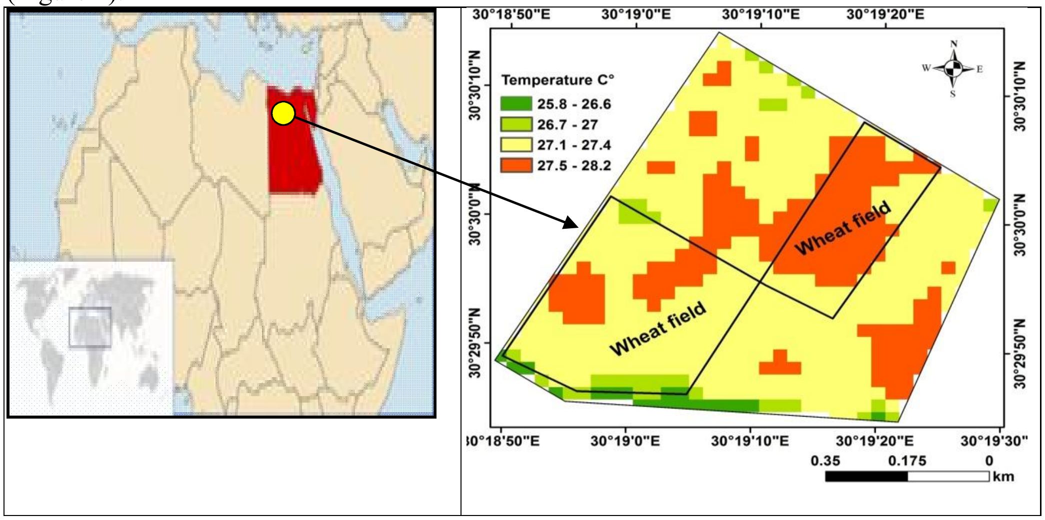

Fig. 1: Meteorological information collected in the green bean growth seasons of 2022 and 2023 at the National Research Center (NRC) research farm in Nubaryia

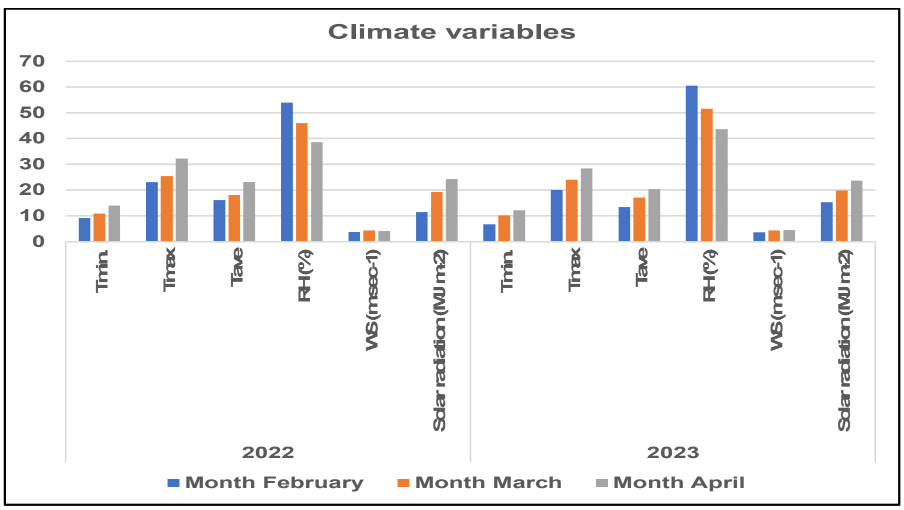

Fig. 2: Climate variable values each month for the two green beans growing seasons.

2.2. Physical characteristics of the irrigation water and soil in the experiment

The soil textural class is sandy soil, including 85.4% sand, 9.5% silt, and 5.1% clay. The pH of the dirt is 7.7. Electric conductivity (EC), which measures soil salinity, was 1.67 dS m^{-1}. In the upper 30 cm of the soil profile, there was 0.41% organic matter content. Extractable levels of Fe, Mn, and Zn were 2.99, 1.75, and 0.67 mg kg^{-1} soil, respectively, whereas available soil N, P, and K values were 17.2, 4.3, and 25 mg kg^{-1} soil. Table (1) displays the irrigation water's chemical composition. At the experimental site, an open irrigation channel provided the irrigation water, which had an average pH of 7.18 and electrical conductivity of 0.43 dS m^{-1} (Table 1).

Table 1: The irrigation water's chemical composition

S.A.R.	Anion (meq L^{-1})				Cation (meq L^{-1})				EC (dS m^{-1})	pH
	SO_4^{--}	Cl^-	HCO_3^-	CO_3^{--}	K^+	Na^+	Mg^{++}	Ca^{++}		
2.67	1.44	1.75	1.13	0.75	0.34	2.63	0.62	1.48	0.43	7.18

SAR: Sodium Adsorption Ratio

2.3. Irrigation scheduling of green beans

The following equation (1) from Brouwer and Heibloem (1986) was used to determine the gross irrigation need for green beans.

$$IR_g = \left(\frac{ET_O \times K_C \times K_r}{E_i}\right) \quad \ldots\ldots (1)$$

Where, the variables Kc, Ei, ETo, IRg, and Kr stand for gross irrigation requirement (mm day^{-1}), irrigation efficiency (%), crop coefficient (Kc), and ground cover reduction factor (Kr). The values of Kr are determined using the Keller equation (Eq. 2) in the following ways:

$$K_r = GC + 0.15(1 - GC) \quad \ldots\ldots (2)$$

Where: GC is the ground cover (%), and was determined through dividing the shaded area per plant over the whole plant area.

Based on the Penman-Monteith equation (Allen *et al*., 1998), the reference evapotranspiration (ETo) is computed by using daily meteorological parameters that are measured at the experimental location. The ETo was calculated according to the FAO calculator (http://www.fao.org/land-water/databases-and-software/eto-calculator/en/). To estimate the evapotranspiration of green beans, the CLIMWAT 2.0 and CROPWAT 8.0 programs were utilized, with reference to Equation 3. Version of the Modified Penman-Monteith, FAO-56 (Allen *et al.,* 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad \ldots\ldots (3)$$

The reference evapotranspiration (mm day^{-1}) is denoted by ETo (= λ Ep). The bulk surface and aerodynamic resistance (s m^{-1}) are represented by rs and ra. The net radiation (MJ m^{-2} day^{-1}) is denoted by Rn. The soil heat flux density (MJ m^{-2} day^{-1}) is represented by G. The mean daily air temperature at 2 m height is denoted by T. The slope of the saturated vapour pressure curve (kPa $C°^{-1}$), the psychrometric constant (66 Pa $C°^{-1}$), the saturated vapour pressure at air temperature (kPa), the prevailing vapour pressure (kPa), and the wind speed at 2 m height (m s^{-1}) is denoted by U_2.

Table 2: Total volume of irrigation water per feddan added during the two growing seasons of green beans

Deficit irrigation strategies	2022	2023
F1 (100% of full irrigation)	1290	1275
F2 (75% of full irrigation)	968	956
F3 (50% of full irrigation)	645	638

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation

2.4. Recommended Fertilization Rates for Green Beans

On February 1st, 2022 and 2023, three green bean (*Phaseolus vulgaris* L.) seeds were planted next to each emitter. The fertilizers were applied as ammonium sulphate (20.5%), calcium superphosphate (15.5%), potassium sulphate (48%), and nitrogen (50 kg $fed.^{-1}$) in the following quantities: phosphate (20 kg fed^{-1}) and potassium (41.5 kg fed^{-1}). Six equal weekly doses of nitrogen were applied as part of the fertilization cycle; the first dose was applied two weeks after planting. Potassium was added in two equal biweekly dosages starting five weeks after planting, but phosphate was applied in full before planting. After planting, manual harvesting took place about 75 days later.

2.5. Installation of drip irrigation system

In January 2022, the trickling irrigation system was set up under regulated conditions. It included a screen filter, media filter, backflush mechanisms, and a Venturi injector for fertilizer injection. The drip tape (Euro drip GR) was carefully placed in straight lines along the ridges; the tape strips had perforations on the top side of them. The fitted trickling system has drippers with an application rate of 4.0 L h^{-1}, each placed 30 cm apart. Every plot had a gate valve and flow meter installed in order to control the amount of water applied and measure the discharge.

2.6. Experimental design

The experimental design was split plot design with three replicas where the effect of deficit irrigation strategies (F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation;) occupied the main plots, while fertigation timing (C: Control; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process) were applied in the sub plots.

2.7. Evaluation criteria

2.7.1. Soil moisture content and water stress

Measurement of the soil moisture content in the effective root zone prior to irrigation, using the wilting point and field capacity as assessment lines, is thought to be an evaluation parameter for the plants' exposure range to water stress ("WS") (Abdelraouf, 2014). A profile probe instrument was used to measure the moisture content of the soil. Measurements of soil moisture were taken prior to each irrigation event during the whole growing season in order to assess the water stress that crop plants were subjected to in their root zone. Before irrigation, the average moisture content for each treatment was noted. The difference between the soil moisture content before to irrigation and the wilting point was used to calculate the amount of water stress in the rhizosphere.

2.7.2. Vegetative growth of green bean plants

By keeping track of the number of days from seed sowing until 50% of the plants in a plot begin to produce flowers, the flowering initiation time was determined. Days to maturity were calculated as the amount of time that elapsed from the time of sowing until 50% of the plants in the plot were considered ready to be harvested. Mature pods are defined by their hard, meaty texture and contain tiny, immature green seeds. Four separate intervals were used to measure the mean value of different vegetative features of green bean plants: the planting date, followed by 20, 30, 40, and 50 days after planting. The following measurements were made: fresh weight (g), plant height (cm), leaf surface area (cm^2), and total chlorophyll content (mg L^{-1}). With the use of a Minolta Chlorophyll Meter, SPAD-502, and Spectrum Technologies10, the total chlorophyl concentration was determined. The dried plant weight (g) and mean shoot dry weight (g) of each plant were measured after a random selection of specific plants from each watering treatment was made. The plants were oven dried for 24 hours at 65°C to achieve this. A leaf area meter (Model CI 202, Germany) was used to measure the total leaf area (cm^2) of all four plants in each section. Four plants were measured for pod length, and the results were averaged.

2.7.3. Yield of green beans

The fully grown pods were removed from the center of each plot's three rows when the green beans were ready for harvest. Every green bean's biomass was computed for every watering plan. 50 days after planting, there was a 25 days window for harvest. Kilograms per feddan (kg $fed.^{-1}$) were used to calculate the total productivity of green beans. Visual inspection was used to sort the entire harvested pod crop; marketable pods were those that were homogenous in color, had no visible curvature, and were free of disease and insect damage. The kilos per hectare was then calculated based on the marketable yield per plot.

2.7.4. Water productivity of green beans " $WP_{\text{green beans}}$ "

$WP_{\text{green beans}}$ is an indicator of effectiveness use of irrigation water for crop production. $WP_{\text{green beans}}$ was calculated according to James (1988) as follows:

$$WP_{\text{green beans}} = Ey/Ir$$

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Where: $WP_{green\ beans}$ is the water productivity of flax seed ($kg_{green\ beans}.\ m^{-3}{}_{irrigation\ water}$), Ey is the economical yield (kg $_{green\ beans}$ $fed.^{-1}$) and Ir is the amount of applied irrigation water ($m^{-3}{}_{irrigation\ water}$ $fed.^{-1}season^{-1}$).

2.7.5. Quality traits of green beans

The percentage of protein in the pods was determined using Bradford's technique (Bradford, 1976). To ascertain the protein content, 0.3 g of the dry powder was used in a wet digestion procedure with oxygen peroxide and salicylic acid after the pods were pulverized and dried at 50°C for 48 hours. After that, each sample received 2.5 mL of sulfuric acid, and it was incubated at 280 °C for an hour. The percentage of protein was calculated by multiplying the readings by 6.25. Pod fiber % was computed using (Rai and Mudgal, 1988).

2.8. Statistical analyses

Snedecor and Cochran's (1980) analysis of variance method was used to statistically examine all the data collected throughout the two combined seasons of the study. Nonetheless, the Duncan's multiple range test allowed for the distinction of means (Duncan, 1955).

3. Results and Discussion

3.1. Soil moisture content and water stress

The data presented in fig. (2) showed the significant effect of deficit irrigation strategies and different timings of fertilization on the moisture content level in the root zone.

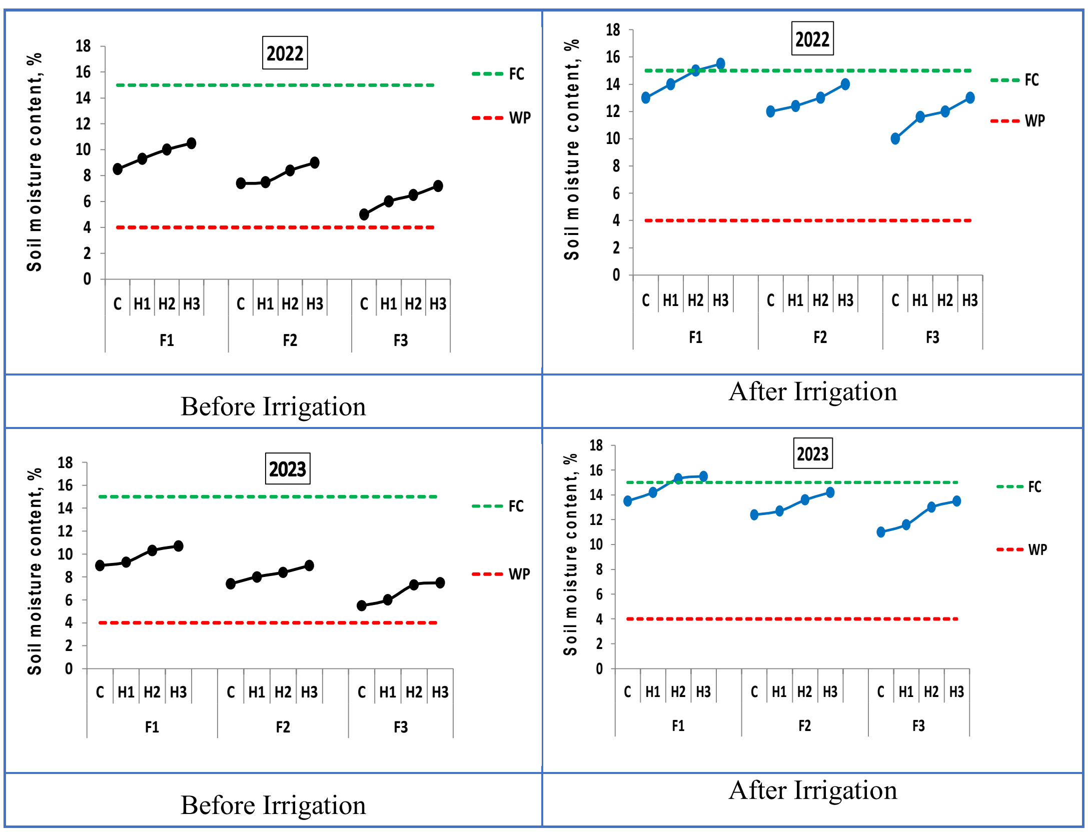

Fig. 2: Effect of deficit irrigation strategies and fertigation timing on the soil moisture content

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process)

With the decrease in the volume of irrigation water added in application of the deficit irrigation strategy, it was found that the moisture content in the root zone decreased, which resulted in high water stress with water volumes less than 100% of the total volume.

Increasing the fertilization time after irrigation led to an increase in the moisture content in the root zone. This was due to the fact that the water added with fertilizers is completely stored inside the root zone and nothing is lost through deep infiltration.

The highest moisture content in the root zone was with irrigation at 100% and 75% of full irrigation and with fertilization timing after 3 hours of irrigation. This resulted in lower moisture stress values in the root zone compared to other treatments.

3.2. Vegetative growth of green beans

The data presented in both tables (3,4) showed the significant effect of deficit irrigation strategies and different timings of fertilization on all vegetative growth characteristics of green bean plants (plant height, plant Fresh weight, plant dry weight, Leaves area and Chlorophyll content).

Table 3: Effect of deficit irrigation strategies and fertigation timing on the plant height, plant fresh weight and plant dry weight of green beans

	Plant height, cm		Plant Fresh weight, gm		Plant dry weight, gm	
Season / Treatments	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
F1 (100%FI)	32.8 a	43.26 a	206.59 a	210.61 a	29.48 a	31.38 a
F2 (75%FI)	32.1 b	42.85 b	201.92 b	205.99 b	28.82 b	30.67 b
F3 (50%FI)	20.6 c	32.98 c	129.44 c	134.12 c	18.47 c	19.96 c
L.S.D at α 0.05	0.134	0.062	0.681	1.825	0.119	0.566
C (Control)	24.5 d	37.62 d	154.40 d	162.14 d	22.00 d	24.14 d
H1 (1Hr)	26.5 c	38.44 c	166.80 c	168.31 c	23.82 c	25.07 c
H2 (2Hr)	29.2 b	40.07 b	183.87 b	186.97 b	26.22 b	27.79 b
H3 (3Hr)	33.7a	42.64 a	212.19 a	216.87 a	30.30 a	32.29 a
L.S.D at α 0.05	0.532	0.070	3.315	4.115	0.479	0.805
F1x C	27.9 e	40.53 f	175.77 e	187.37 de	25.03 e	27.90 de
F1x H1	30.3 d	41.47 d	190.87 d	193.07 d	27.23 d	28.77 d
F1x H2	34.4 c	43.90 b	216.49 c	217.60 c	30.90 c	32.43 c
F1x H3	38.6 a	47.13 a	243.23 a	244.40 a	34.73 a	36.40 a
F2x C	27.7e	40.167 g	174.57 e	181.53 e	24.90 e	27.07 ef
F2x H1	30.2 d	41.33 e	189.70 d	190.83 d	27.10 d	28.40 de
F2x H2	34.0 c	42.86 c	214.13 c	218.80 c	30.53 c	32.57 c
F2x H3	36.5 b	47.03 a	229.27 b	232.80 b	32.73 b	34.63 b
F3x C	17.9 h	32.17 k	112.87 h	117.53 g	16.07 h	17.47 g
F3x H1	19.0 g	32.53 j	119.83 g	121.03 g	17.13 g	18.03 g
F3x H2	19.2 g	33.47 i	121.00 g	124.50 g	17.23 g	18.37 g
F3x H3	26.1 f	33.77 h	164.07 f	173.40 f	23.43 f	25.83 f
L.S.D at α 0.05	0.922	0.121	5.742	7.127	0.830	1.394

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process

Table 4: Effect of deficit irrigation strategies and fertigation timing on the leaves area and Chlorophyll of green beans

	Leaves area (cm^2)		Chlorophyll	
Season / Treatments	2022	2023	2022	2023
F1 (100%FI)	62.25 a	62.32 a	0.296 a	0.300 a
F2 (75%FI)	61.68 a	62.53 a	0.288 a	0.286 b
F3 (50%FI)	40.74 b	41.08 b	0.234 b	0.256 c
L.S.D at α 0.05	0.794	0.362	0.036	0.011
C (Control)	49.56 d	50.23 d	0.247 c	0.257 d
H1 (1Hr)	54.41 c	54.39 c	0.269 b	0.274 c
H2 (2Hr)	55.30 b	55.97 b	0.274 b	0.288 b
H3 (3Hr)	60.30 a	60.64 a	0.300 a	0.303 a
L.S.D at α 0.05	0.258	0.487	0.010	0.010
F1x C	56.50 f	56.83 d	0.270	0.280
F1x H1	61.30 e	61.30 c	0.293	0.290
F1x H2	63.10 c	63.40 b	0.300	0.310
F1x H3	68.10 a	67.73 a	0.320	0.320
F2x C	56.07 f	56.70 d	0.260	0.260
F2x H1	61.27 e	61.50 c	0.283	0.280
F2x H2	61.90 d	63.50 b	0.290	0.290
F2x H3	67.50 b	68.40 a	0.317	0.313
F3x C	36.10 i	37.17 g	0.210	0.230
F3x H1	40.67 h	40.37 f	0.230	0.253
F3x H2	40.90 h	41.00 f	0.233	0.263
F3x H3	45.30 g	45.80 e	0.263	0.277
L.S.D at α 0.05	0.447	0.844	N.S	N.S

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process

With the decrease in the volume of irrigation water added in application of deficit irrigation strategy, the vegetative growth characteristics of beans were negatively affected. This may be due to the decrease in moisture content in the root zone, which resulted in high water stress with water volumes less than 100% of the total volume, which resulted in a decrease in the water absorption rate.

Increasing the fertilization time after irrigation led to an increase in the vegetative characteristics of green bean plants. This was due to the addition of water with fertilizers to increase their storage completely within the root zone and nothing is lost through deep infiltration, which resulted in an increase in the concentration of fertilizers in the root zone, which resulted in an increase in the water and fertilizer absorption rate and thus an improvement and increase in the vegetative characteristics.

The data presented in Tables (3,4) showed an improvement and increase in the vegetative characteristics of green bean plants at 100% and 75% of full irrigation and with fertilization timing 3 hours after irrigation. This may be due to the decrease in moisture stress values and the increase in the concentration of nutrients in the root zone, which led to an increase in water and nutrient absorption and thus an improvement in vegetative characteristics compared to other treatments.

3.3. Yield of green beans

The data presented in both Figure (4) and Table (5) showed the significant effect of deficit irrigation strategies and different timings of fertilization on green bean productivity.

With the decrease in the volume of added irrigation water, the productivity values of green beans were negatively affected. This may be due to the decrease in moisture content in the root zone, which resulted in high water stress with water volumes less than 100% of the total volume, which resulted in a decrease in the water absorption rate and a decrease in productivity values.

Increasing the fertilization time after irrigation led to an increase in the productivity values of green beans. This was due to the addition of water with fertilizers to increase their storage completely within the root zone and nothing is lost through deep infiltration, which resulted in an increase in the concentration of fertilizers in the root zone, which resulted in an increase in the rate of water and fertilizer absorption and thus an increase in the crop productivity values per acre of green beans.

The highest values of green bean crop productivity were achieved when irrigated with 100% or 75% of full irrigation and with fertilization timing 3 hours after irrigation. This may be due to the increase in moisture content and decrease in water stress values with increase in nutrient concentration in the root zone, which led to increase in water and nutrient absorption and consequently increase in green bean crop productivity values compared to other treatments.

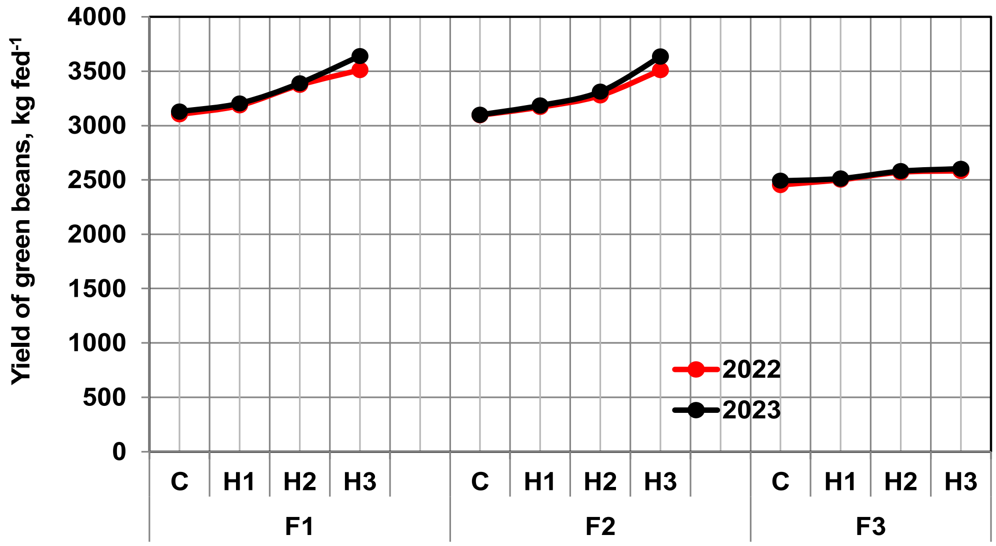

Fig. 4: Effect of deficit irrigation strategies and fertigation timing on the yield of green beans
F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process**)**

3.4. Water productivity of green beans

Before starting to discuss the results of water productivity for any crop, we must remind you that water productivity values are the quotient of the crop productivity values divided by the total irrigation water volume values added to the soil throughout the crop growing season from planting to harvest. This means that water productivity values are affected by changes in both crop productivity values and different volumes of added irrigation water.

The data in Figure (5) and Table (5) showed the significant impact of deficit irrigation strategies and different fertilization dates on the water productivity of green beans.

With the decrease in the volume of added irrigation water, the water productivity values of green beans increased. This may be due to the significant decrease in the volume of added irrigation water and the insignificant increase in the crop productivity values of green beans. In addition, increasing the fertilization time after irrigation led to an increase in the water productivity values of green beans due to the increase in the crop productivity values per acre of green beans as a result of the increase in the concentration of nutrients resulting from the storage of all added fertilizers in the root spread area and the difficulty of their escape, especially through deep infiltration.

The highest values of water productivity of green beans were achieved when irrigated with 100% or 75% of full irrigation with fertilization timing after 3 hours of irrigation. The reason behind this was achieving the highest values of crop productivity of beans when irrigated with 100% or 75% of full irrigation, while the volume of irrigation water added when irrigated with 75% of full irrigation was less. As a result, the strategy of irrigation at 75% of full irrigation was adopted when irrigating green beans in order to save 25% of fresh irrigation water for planting other areas similar to the same conditions.

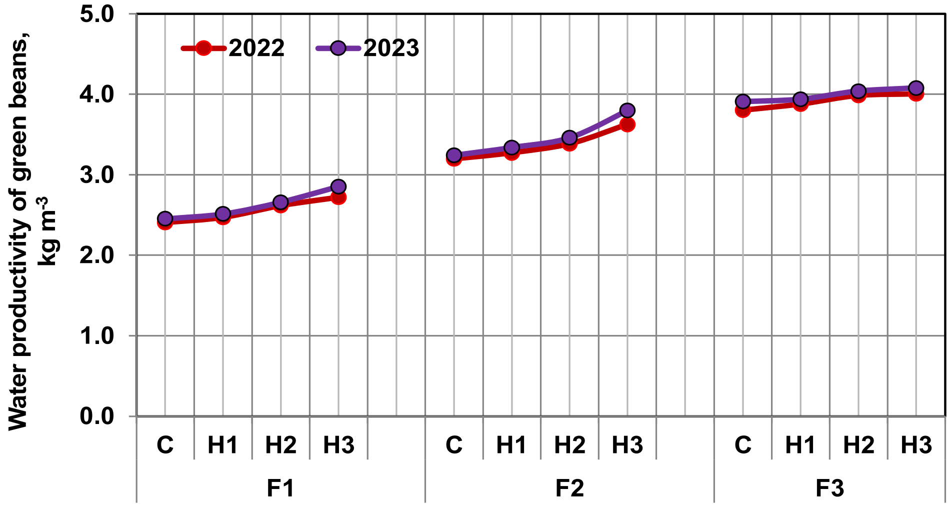

Fig. 5: Effect of deficit irrigation strategies and fertigation timing on the water productivity of green beans

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process**)**

Table 5: Effect of deficit irrigation strategies and fertigation timing on the yield and water productivity of green beans

	Yield of green beans (kg fed^{-1})		**WP $_{green\ beans}$ (kg m^{-3})**	
Season / Treatments	**2022**	**2023**	**2022**	**2023**
F1 (100%FI)	3293.83 a	3340.65 a	2.6	2.6
F2 (75%FI)	3263.28 b	3307.31 b	3.4	3.5
F3 (50%FI)	2527.49 c	2547.48 c	3.9	4.0
L.S.D at α 0.05	1.266	2.449		
C (Control)	2884.48 d	2907.20 d	3.1	3.2
H1 (1Hr)	2952.63 c	2967.32 c	3.2	3.3
H2 (2Hr)	3073.95 b	3093.94 b	3.3	3.4
H3 (3Hr)	3201.74 a	3292.12 a	3.5	3.6
L.S.D at α 0.05	3.225	3.115		
F1x C	3103.33 f	3129.07 g	2.4	2.5
F1x H1	3186.20 d	3204.13 e	2.5	2.5
F1x H2	3374.50 b	3389.53 c	2.6	2.7
F1x H3	3511.30 a	3639.87 a	2.7	2.9
F2x C	3096.40 g	3099.67 h	3.2	3.2
F2x H1	3169.83 e	3185.00 f	3.3	3.3
F2x H2	3276.87 c	3311.20 d	3.4	3.5
F2x H3	3510.00 a	3633.37 b	3.6	3.8
F3x C	2453.70 k	2492.87 l	3.8	3.9
F3x H1	2501.87 j	2512.83 k	3.9	3.9

F3x H2	2570.47 i	2581.10 j	4.0	4.0
F3x H3	2583.93 h	2603.13 i	4.0	4.1
L.S.D at α 0.05	5.586	5.396		

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process.

3.5. Quality characteristics of green beans

The data in Tables (6) showed the significant effect of deficit irrigation strategies and different fertilization dates on all values of some quality traits of green bean pods (pod weight, pod length, protein content and fiber content).

Table 6: Effect of deficit irrigation strategies and fertigation timing on the quality of green beans

	Pod weight, g		**Pod length, cm**		**Protein content (%)**		**Fiber content, %**	
Season / Treatments	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
F1 (100%FI)	4.60 a	4.73 a	13.29 a	13.63 a	12.77 a	13.22 a	9.98 a	10.43 a
F2 (75%FI)	4.53 a	4.80 a	13.18 a	13.53 a	10.97 b	11.19 b	8.06 b	8.41 b
F3 (50%FI)	2.77 b	3.08 b	10.18 b	10.35 b	11.58 b	11.91 b	7.02 c	7.37 c
L.S.D at α 0.05	0.143	0.227	0.119	0.124	1.108	0.988	0.072	0.168
C (Control)	3.48 d	3.69 d	11.64 d	11.91 d	11.58 b	11.82 a	6.99 d	7.32 d
H1 (1Hr)	3.73 c	4.00 c	11.89 c	12.22 c	10.79 c	11.01 c	8.04 c	8.42 c
H2 (2Hr)	4.14 b	4.47 b	12.39 b	12.69 b	12.07 ab	12.62 a	8.79 b	9.11 b
H3 (3Hr)	4.50 a	4.66 a	12.93 a	13.20 a	12.64 a	12.97 a	9.58 a	10.09 a
L.S.D at α 0.05	0.177	0.174	0.083	0.083	0.761	0.753	0.063	0.129
F1x C	4.30 cd	4.37 c	12.53 e	12.87 e	12.63	12.7	9.00 d	9.43 c
F1x H1	4.50 cd	4.63 bc	12.83 d	13.23 d	11.80	11.9	9.20 c	9.60 c
F1x H2	4.60 bc	4.80 ab	13.57 b	13.90 b	12.57	13.9	10.50 b	10.87 b
F1x H3	5.00 a	5.10 a	14.23 a	14.53 a	14.07	14.3	11.20 a	11.83 a
F2x C	4.20 d	4.40 c	12.47 e	12.80 e	10.10	10.4	7.23 h	7.50 g
F2x H1	4.40 cd	4.87 ab	12.70 d	13.10 d	10.23	10.5	7.87 g	8.20 ef
F2x H2	4.60 bc	4.90 ab	13.27 c	13.63 c	11.73	11.9	8.03 f	8.37 e
F2x H3	4.90 ab	5.03 a	14.27 a	14.57 a	11.80	11.9	9.10 cd	9.57 c
F3x C	1.93 h	2.30 e	9.93 h	10.07 h	12.00	12.3	4.73 j	5.03 h
F3x H1	2.30 g	2.50 e	10.13 g	10.33 g	10.33	10.6	7.07 i	7.47 g
F3x H2	3.23 f	3.70 d	10.33 f	10.53 f	11.90	12.1	7.83 g	8.10 f
F3x H3	3.60 e	3.83 d	10.30 f	10.50 f	12.07	12.6	8.43 e	8.87 d
L.S.D at α 0.05	0.307	0.302	0.144	0.144	N.S	N.S	0.109	0.224

F1: 100% of full irrigation; F2: 75% of full irrigation; F3: 50% of full irrigation; FI: full irrigation; C (Control): fertigation with irrigation process; H1: The fertigation time was one hour after the irrigation process; H2: The fertigation time was two hours after the irrigation process; H3: The fertigation time was three hours after the irrigation process

With the decrease in the volume of irrigation water added when applying deficit irrigation technique, the quality traits of green bean pods decreased. This may be due to the decrease in moisture content in the root zone, which led to increased water stress with the decrease in water volume below 100% of the total volume, which led to a decrease in the water absorption rate and also a decrease in the absorption rate of nutrients, the deficiency of which inevitably negatively affects the decrease in quality traits. Sometimes the values of the traits obtained when irrigated with 100% of full irrigation and at 75% of full irrigation are not affected, as the reason behind this may be that the effect of water stress is not significant and does not affect the absorption rate of nutrients, but rather the concentration of nutrients may increase when irrigated with 75% of full irrigation, which may lead to an improvement in the values of quality traits as a result of the increase in the absorption rate of nutrients when irrigated with 75% of full irrigation.

Increasing the fertilization time after irrigation also led to an increase in the quality characteristics of green bean pods as a result of adding water with fertilizers to increase their full storage inside the root zone and not losing anything through deep infiltration, which led to an increase in the concentration of these fertilizers in the root spread area, which led to an increase in the rate of water and fertilizer absorption, thus improving and increasing the quality characteristics of green bean pods.

The data shown in Tables (6) showed an improvement and increase in the quality characteristics of green bean pods at 100% and 75% of full irrigation and with the best fertilization time, which is 3 hours after irrigation. This may be due to the decrease in moisture stress values and the increase in the concentration of nutrients in the root spread area, which led to an increase in water and nutrients absorption, thus improving the quality characteristics of green bean pods compared to other treatments.

4. Conclusion

The results of the study on the effect of deficit irrigation strategies and the most appropriate timing for fertilization on both soil moisture content and water stress, vegetative growth of green beans, yield of green beans, water productivity of green beans and quality characteristics of green beans concluded that there were significant differences in most of the studied traits.

The highest moisture content in the root zone was with irrigation at 100% and 75% of full irrigation and with fertilization timing after 3 hours of irrigation. This resulted in lower moisture stress values in the root zone compared to other treatments.

An improvement and increase in the vegetative characteristics of green bean plants at 100% and 75% of full irrigation and with fertilization timing 3 hours after irrigation. This may be due to the decrease in moisture stress values and the increase in the concentration of nutrients in the root zone, which led to an increase in water and nutrient absorption and thus an improvement in vegetative characteristics compared to other treatments.

The highest values of green bean crop productivity were achieved when irrigated with 100% or 75% of full irrigation and with fertilization timing 3 hours after irrigation. This may be due to the increase in moisture content and decrease in water stress values with increase in nutrient concentration in the root zone, which led to increase in water and nutrient absorption and consequently increase in green bean crop productivity values compared to other treatments.

The highest values of water productivity of green beans were achieved when irrigated with 100% or 75% of full irrigation with fertilization timing after 3 hours of irrigation. The reason behind this was achieving the highest values of crop productivity of beans when irrigated with 100% or 75% of full irrigation, while the volume of irrigation water added when irrigated with 75% of full irrigation was less. As a result, the strategy of irrigation at 75% of full irrigation was adopted when irrigating green beans in order to save 25% of fresh irrigation water for planting other areas similar to the same conditions.

An improvement and increase in the quality characteristics of green bean pods at 100% and 75% of full irrigation and with the best fertilization time, which is 3 hours after irrigation. This may be due to the decrease in moisture stress values and the increase in the concentration of nutrients in the root spread area, which led to an increase in water and nutrients absorption, thus improving the quality characteristics of green bean pods compared to other treatments.

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