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Using Desalinated Water from Solar Stills to irrigate Green Beans (*Phaseolus vulgaris* L.) in Different Water Regimes with an Application of ^{15}N Stable Isotope

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A POT EXPERIMENT in the open field was conducted to evaluate the performance of a green bean crop under different irrigation water regimes and two types of solar still (Active and Passive). Irrigation water was applied at regimes of 170, 142, and 114 mm in season, representing T1 (100% WHC), T2 (80% WHC), and T3 (70% WHC) from water holding capacity (WHC), respectively. During the measurement months, the average monthly output of active solar still productivity is 1790 ml m^{-2} with an average overall thermal efficiency (η_{active}) of 5.9%, while in the passive solar still productivity is 1308 ml m^{-2} with an average overall thermal efficiency ($\eta_{passive}$) of 17.6%. The results indicated that desalinated water applied at T1 enhanced growth characteristics, yield, and improved water productivity (WP) and water use efficiency (WUE) compared to T2 and T3 deficit water regimes. Similarly, increasing irrigation water availability to plants improved NPK nutrient uptake by various plant parts. The ^{15}N/^{14}N ratio analysis revealed that under all irrigation water regimes, the absolute values of the N portion derived from fertilizer were higher in pods, followed by shoots, and then roots. In contrast with the nitrogen derived from fertilizer (Ndff), the absolute values of Ndff in pods, shoots, and roots seem significantly higher under T1 than those indicated at either the T2 or T3 regimes. In this respect, the nitrogen use efficiency (NUE) reached nearly 64% and 51% for pods and shoots under the T1 regime, while those for roots were still negligible. These percentages of NUE in pods and shoots tended to decrease gradually with increasing water deficits (T2 and T3).

Keywords: Desalination; Green bean; Stable isotope; Nitrogen; Water deficit.

1. Introduction

Due to a shortage in water sources and the water crisis caused by severe climate change, wastewater, and saline water that has been appropriately treated can be utilized for irrigation (Quist-Jensen *et al.*, 2015). In this regard, desalination's relevance to agriculture, however, becomes more likely when the overall effectiveness of the combined production of water and food, as well as prospects for better soil management, are taken into consideration (Burn *et al.*, 2015). In this respect, (Suwaileh *et al.*, 2020) identified many methods used for the desalination of salt water that differs in quality and energy costs.

In Egypt, green beans are regarded as a significant source of cash income both domestically and abroad due to their high nutritional value and importance as a source of protein (Saleh *et al.*, 2018; Taha *et al.*, 2023). This crop is globally cultivated on about 1,586,086 hectares, production 23,411,172 tons (FAOSTAT, 2021). Water management is crucial to the success of green bean crop cultivation. Plant growth was found to be sensitive to the availability

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of soil moisture. In this respect, deficit irrigation water causes a decrease in total leaf area per plant and leaf number, as well as a reduction in crop growth (Abd El-Mageed *et al.*, 2018). Saleh et al. (2018) investigate two varieties of green beans under three levels of irrigation water: 100%, 80%, and 60% of evapotranspiration (ET), where the pod yield and chemical composition increased under 80% ET; additionally, the WUE increased as water application decreased from 100% to 60% ET, while there were no differences between 80% and 100% ET in most parameters (Saleh et al., 2018). More attention has been paid to WUE, especially with continuous water scarcity due to severe climate change (Bwambale *et al.*, 2022). The irrigation intervals and frequencies greatly impacted the WUE and irrigation water use efficiency (IWUE) values, moreover, exhibited noticeably distinct effects on quality indicators of growth traits, such as; seed number, fresh weight, and 100 pod weight (Sezen *et al.*, 2008). On the other hand, Elhindi et al. (2015) proved that modern irrigation has an effective impact on WUE because it reduces evaporation, runoff, and deep percolation and improves WUE (Elhindi *et al.*, 2015).

Concerning N fertilization as a key factor, (Rouphael *et al.*, 2012) stated that conditions of drought may decrease the mineralization of soil N, hence limiting N availability. Since water is the agent that carries solutes to the soil-root interface, its presence in the soil is necessary for roots to absorb N. Reduced crop transpiration rates during drought diminish N transfer from roots to shoots, decreasing N uptake, also, they mentioned that the water regime is crucial in determining how well potatoes and peppers can absorb the available nitrogen because a crop that has received adequate watering is better able to benefit from the fertilizer that has been applied. In this regard, Incrocci et al. (2017) found that urea is a highly water-soluble molecule that is not absorbable by colloids and freely travels through the soil before turning it into NH_4^+. The length of irrigation and soil properties affect how much urea is distributed in the root zone profile (Incrocci *et al.*, 2017).

The current work is just a pot experiment conducted to examine the possibility of using desalinated seawater from solar distillers and mixed water to irrigate a green bean crop grown in virgin sandy soil that lacks all nutrients and under natural weather conditions.

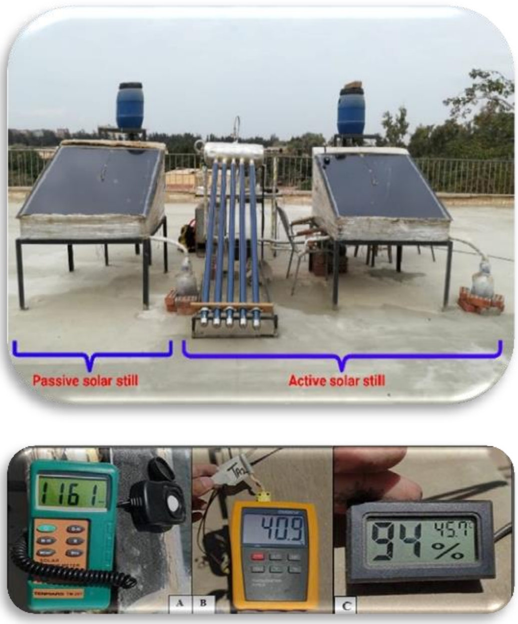
2. Materials and Methods

A pot experiment was carried out using green bean (*Phaseolus vulgaris* L.) cv. Bronco as a tested crop moderately saline tolerant. The dimension of the experimental pot is 23 cm (inner diameter) and a height of 20 cm. Each pot was filled with 9.6 kg of dry virgin sandy soil from the farm of the Soil and Water Research Department, Nuclear Research Center, located at Inshas, Atomic Energy Authority, Egypt, with the latitude and longitude of the experimental site 30° 24` N, 31° 35` E, respectively, while the altitude is 20 m above sea level. Table 1 explains some chemical and physical characteristics of soil samples subjected to physical and chemical analysis, according to (Carter and Gregorich, 2007). About 10 seeds per pot were planted at a depth of 1-2 cm and then thinned to three plants per pot. Seeds of *Phaseolus vulgaris* were cultivated in the middle of October 2021 and harvested at the end of December 2021. The plants were irrigated with desalinated saline water, which was produced by using two solar stills (Active Solar Still and Passive Solar Still) were built with identical dimensions, specifications, and materials to work together simultaneously. One is a conventional still, and the other is related to an evacuated tube collector (ETC). The ETC consists of five evacuated tubes with a length of 1.8 meters, where the outer diameter of the evacuated tube is 58 mm, and an inner tube with a diameter of 47 mm. The outer tube is made of transparent glass (borosilicate glass) to allow sunlight to evacuate the gap between the two tubes. The borosilicate glass is a unique selective material that transfers heat from the heat pipe to the cylindrical tank and the closed circle inside the solar basin. The basins used are made of galvanized iron (GI sheets), with a thickness of 0.8 mm and dimensions 1 m x 1 m, and covered by glass (6mm thickness) with a slope of 30°, nearly identical to Egypt's latitude, the hot water naturally rises to the top, while cold water condenses at the bottom as the hot water replaces it (Fig. 1).

Table 1. Some physical and chemical characteristics of tested soil.

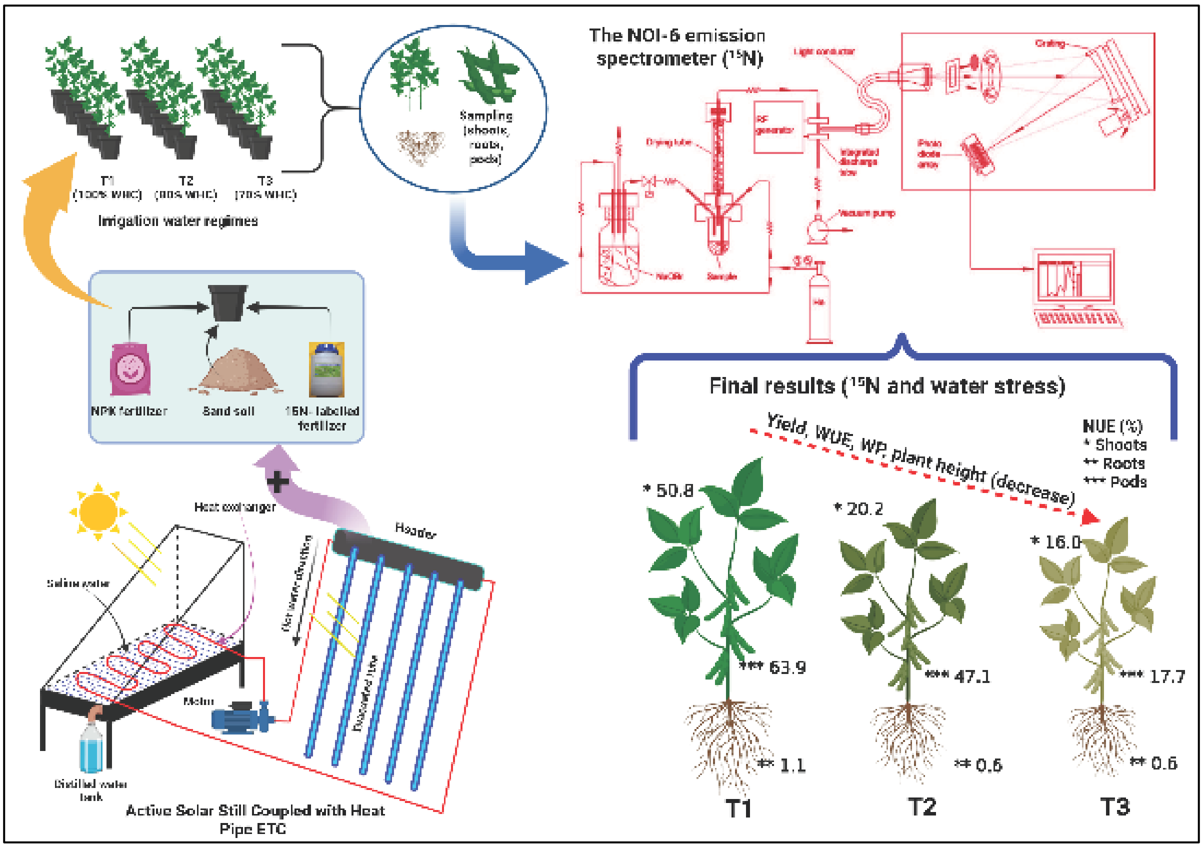
Physical characteristics		
Particle size distribution (%)	Sand	89.5
	Silt	4.9
	Clay	5.6
	Soil texture	Sand
Bulk density (g cm^{-3})	ρ	1.3
Porosity (%)	φ	50.9
Moisture content by volume (%)	FC	21.6
	PWP	8.1
	AW	13.5
Chemical characteristics of soil		
Sample analysis time	**Before cultivation**	**After cultivation**
pH (1:2.5)	7.8	6.9
EC_e (dS m^{-1})	0.3	0.9
OM (%)	0.3	0.3
$CaCO_3$ (%)	4.5	4.2
Soluble anions (cmol$_c$ kg^{-1})		
Cl^-	1.8	5.8
HCO_3^-	0.5	1.7
CO_3^-	--	--
SO_4^{2-}	0.5	1.5
Soluble cations (cmol$_c$ kg^{-1})		
Ca^{2+}	0.5	1.8
Mg^{2+}	0.4	1.4
Na^+	1.7	5.2
K^+	0.2	0.6
SAR (-)	2.5	4.1

Note: *FC is the field capacity, PWP is the permanent wilting point, AW is the available water, OM is the organic matter, and* SAR is the sodium adsorption ratio.



Instruments	Measuring Function	Accuracy	Range
Solar power meter TM-207	Solar radiation	±10W/m^2 or ±5%	0~1999 W/m^2
Temperature Humidity meter	Steam temp. Inside humidity	±1°C (-30°C~+40°C)	R_t= -50°C~+70°C R_m= 0%~99%
Digital thermometer	All temps.	±(0.2%+1°C)	-50°C~199.9°C
Thermocouples K type	Probe	±1.5°C	-50°C~250°C
Waterproof EC/TDS Testers AD32	Total dissolved solids	±0.5°C ±2%f.s. (TDS/EC)	0~20 ms/cm 0~10 ppt
Calibrated flask	Output productivity	±5 mL	0~1000 mL
Manometer	Water pressure inside serpentine	±0.5 bar	0~20 bar
Water flow meter MetroTech EGYPT	Water flow inside serpentine	0.0001 m^3	0~1.6 m^3/h

Fig. 1. The experimental design and placement of sensors arrangements of active and passive solar still.



Graphical abstract

The two systems were operated continuously for two days in October, November, and December 2020 and May, June, July, and August 2021. The temperatures were recorded every fifteen minutes from 9:00 am to 2:00 pm (Eldehn, 2022; Eldehn *et al.*, 2022) for both active solar still and passive solar still. (Dwivedi and Tiwari, 2010; Manokar *et al.*, 2018) described the overall thermal efficiency of passive ($\eta_{passive}$) and active (η_{active}) solar still by the following equations:

$$\eta_{passive} = \frac{m_{ew} \times \lambda}{I(t)_s \times A_s \times 3600} \times 100\% \tag{1}$$

$$\eta_{active} = \frac{m_{ew} \times \lambda}{\left[(I(t)_c \times A_c) + (I(t)_s \times A_s) \right] \times 3600} \times 100\% \tag{2}$$

Where:

m_{ew} : Total daily yield from solar still (kg m^{-2} day^{-1}),
λ : Latent heat of vaporization (J kg^{-1}),
$I(t)_c$: Intensity of solar radiation over the inclined surface of the solar collector (W m^{-2}),
$I(t)_s$: Intensity of solar radiation over the inclined surface of the solar still (W m^{-2}),
A_c : Area of solar collector (m^2), and
A_s : Area of basin in solar still (m^2).

The distilled water produced by the solar distiller was mixed with saline water of 5000 ppm to produce water with 300 ppm to irrigate the green bean crop, which is considered sensitive to salinity (Ayers and Westcot, 1985). Saline water, distilled water, and applied water used in this study were chemically analyzed for pH, electrical conductivity (EC_w), TDS, and other factors as shown in Table 2.

The three different water regimes, T1 (100% WHC), T2 (80% WHC), and T3 (70% WHC), were replicated five times, with the total irrigation water used during the growing season being 170, 142, and 114 mm, respectively, Fig 2 illustrates the distribution of irrigation water requirements for the initial (15 days), development (25 days), midseason (25 days), and late stage (10 days) growth stages, as well as for the T1, T2, and T3 irrigation regimes. The greatest quantity of irrigation water used was recorded at the mid-season stage, followed by those at the development stage, and then those applied in the late season. On the other hand, the smallest quantities were applied at the initial growth stage. The water holding capacity (WHC) in the pots was calculated according to soil water content (SWC), bulk density (ρ), and the field capacity (θ_{FC}) in the pots was measured using the weighing method described by Ding et al. (2018) and Mulidzi et al. (2016) (Ding *et al.*, 2018; Mulidzi *et al.*, 2016).

Table 2. Some chemical characteristics of saline water, distillate water, and applied water.

Chemical characteristics	Saline water	Distillate water	Applied water
pH	7.8	6.1	6.6
EC_w (dS m^{-1})	6.6	0.06	0.47
Soluble anions (meq l^{-1})			
Cl^-	44.4	0.33	3.24
HCO_3^-	11.8	0.19	1.04
CO_3^-	--	--	--
SO_4^{2-}	9.8	0.08	0.42
Soluble cations (meq l^{-1})			
Ca^{2+}	18.8	0.18	0.62
Mg^{2+}	14.0	0.11	0.47
Na^+	30.3	0.28	3.41
K^+	2.9	0.03	0.20
SAR (-)	7.6	0.7	4.6

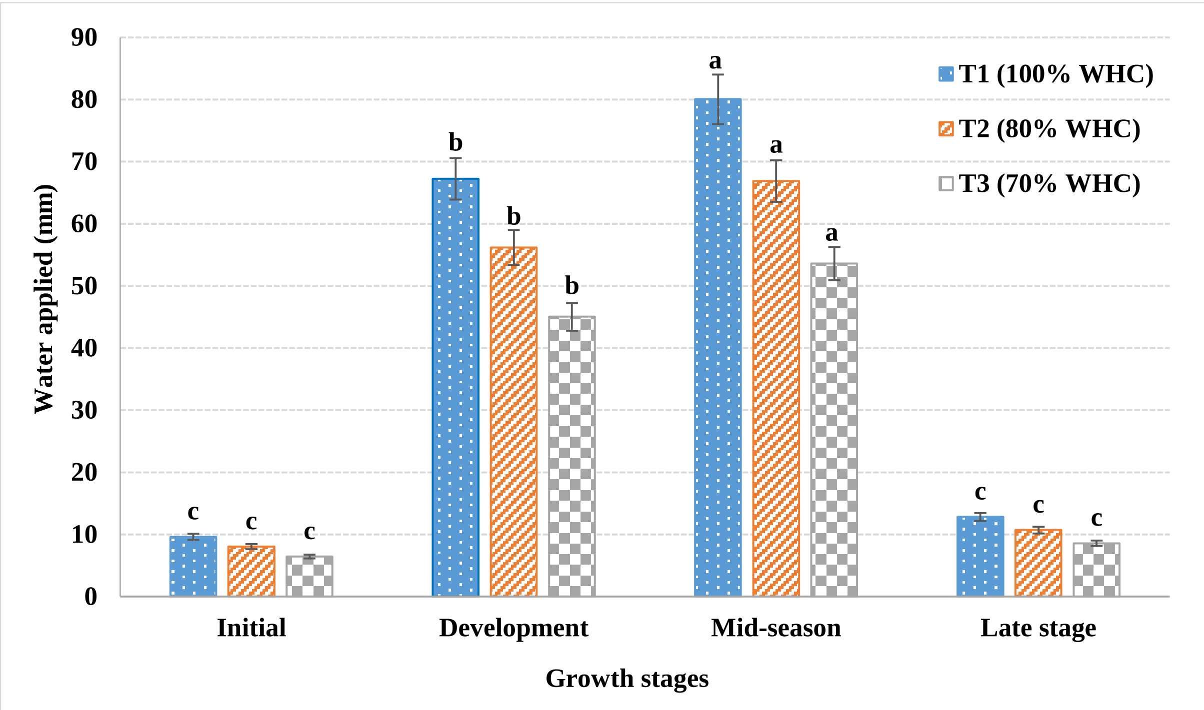


Fig. 2. Distribution of water quantities used by green beans along the different growth stages.

All agronomic practices were done according to the recommendations of the Ministry of Agriculture and Land Reclamation, Egypt. Chemical fertilizers (NPK) were added to the experiment at appropriate times during the growing season, where the nitrogen (N) rate in the form of urea fertilizer (46% N) was 114 kg N ha^{-1}; this nitrogen form was labeled with ^{15}N at a 10% atom excess. Thus, the recommended phosphorus (P) fertilizer was added at the rate of 115 kg P ha^{-1} in the form of single superphosphate (15% P_2O_5) and the potassium (K) fertilizer at a rate of 72 kg K ha^{-1} in the form of potassium sulfate (48% K_2O).

Plants were harvested 75 days after sowing and separated into roots, shoots, and pods. Each organ's fresh plant weight was demarcated. Then, the plant samples were dried in an oven for 24 hours at 70 °C until their dry weights were constant. According to the established procedures outlined by Estefan et al. (2013), chemical analysis was performed on homogeneous plant samples to estimate the N, P, and K contents of different plant organs (Estefan *et al.*, 2013). The $^{14}N/^{15}N$ ratio analysis was determined using the emission spectrometer model NOI-6PC Fischer. The portions of nitrogen derived from fertilizer (% Ndff) and nitrogen use efficiency (% NUE) were estimated using the following Equations 3-7 (Hamed *et al.*, 2019; IAEA, 2001; *Van* Cleemput *et al.*, 2008; Zapata, 1990):

$$\%Ndff = \frac{\%\,^{15}N\,atom\,excess\,plant}{\%\,^{15}N\,atom\,excess\,fertilizer} \times 100 \quad (3)$$

$$DM\ yield = FW \times \frac{10000}{area\ harvested} \times \frac{SDW}{SFW} \quad (4)$$

$$NY = DM\ yield \times \frac{\%N}{100} \quad (5)$$

$$FNY = NY \times \frac{\%Ndff}{100} \quad (6)$$

$$\%NUE = \frac{FNY}{Rate\ of\ N\ application} \quad (7)$$

Where: % Ndff is the % N derived from the fertilizer (%), DM yield is the dry matter yield per unit area (kg ha^{-1}), % N is the % total N in the crop (%), FW is the fresh weight of the crop (kg), SDW is the subsample crop dry weight (kg), SFW is the subsample crop fresh weight (kg), NY is the total nitrogen content of the crop throughout the experiment (kg ha^{-1}), FNY is the amount of nitrogen uptake by the crop (kg ha^{-1}), and % NUE is the nitrogen use efficiency (%) of the fertilizer nutrients absorbed by the plant compared to the rate of fertilizer added.

WP represent the ratio between the seed yield and the seasonal applied water and WUE is an indicator of the efficiency of irrigation in increasing crop yield, the WP and WUE were determined using Equation 8 and 9 as kg m^{-3}, respectively, and calculated according to (Abuarab *et al.*, 2020; Bozkurt and Mansuroglu, 2018; Fayed and Sheta, 2021; Ibrahim *et al.*, 2021; Soureshjani *et al.*, 2019):

$$WP = \frac{Seed\ yield\,(kg)}{Seasonal\ water\ use\ from\ sowing\ to\ harvest\,(m^3)} \quad (8)$$

$$WUE = \frac{Aboveground\ dry\ matter\,(kg)}{Seasonal\ water\ use\ from\ sowing\ to\ harvest\,(m^3)} \quad (9)$$

Data were subjected to an ANOVA analysis of variance for three factors of irrigation water and five replicates. The MSTAT-C (version 2.10) computer package was used for analysis (Russell, 1986). When the ANOVA was significant at a 5% probability level, the least significant difference (LSD) test and Duncan Multiple Range Test were used for mean comparison (Duncan, 1955).

3. Results

3.1. Performance and variation in active and passive solar still

Solar stills' performance largely depends on environmental factors like solar radiation and ambient temperature. The solar still productivity was examined in this study in relation to solar radiation and ambient temperature. The monthly average variations of output solar still productivity for active and passive solar stills are shown in Table 3. In August 2021, the active solar still had an average monthly output of 3100 ml m^{-2}, while the passive solar still had an average output of 2270 ml m^{-2} at maximum monthly average water temperatures 80.3 ^{o}C and 75.0 ^{o}C, and inner glass cover temperatures 77.4 ^{o}C and 73.8 ^{o}C for the active and passive solar stills, respectively. Under the same conditions of maximum monthly average solar radiation values and an ambient temperature of 1093 W m^{-2}, 49.1 ^{o}C. In December 2020, the minimum monthly average productivity for solar stills was 730 ml m^{-2} for active solar stills and 535 ml m^{-2} for passive solar stills, at minimum monthly average water temperatures of 56.3 ^{o}C and 50.5 ^{o}C and inner glass cover temperatures of 53.6 ^{o}C and 47.8 ^{o}C, respectively, under the same condition of monthly average solar radiation and ambient temperature of 754 W m^{-2}, 32.9 ^{o}C, respectively.

Throughout the days from 9:00 am to 2:00 pm, there was an increase in the variation of daily average values of output solar still productivity for active solar stills due to variations in average solar radiation, ambient, water, and inner glass cover temperatures. The temperature difference between the inner glass cover and the water was used to calculate the solar still's productivity. More thermal energy was directed toward the solar still basin, increasing the temperature difference between the water and the inner glass cover. Overall, passive solar stills are more efficient than active solar stills throughout the year; the vice versa is true in the case of productivity.

3.2. Effect of water levels on growth traits and productivity

The plant fresh weight, plant height, pod number, and pod fresh weight of green beans grown under different irrigation water regimes were graphically illustrated in Fig 3. It is clear that plant fresh weight was significantly increased with increasing irrigation water regime. In this regard, the fresh weight of plants irrigated with T1 was relatively higher than that of those irrigated with T2 and T3 by approximately 67.3% and 107%, respectively. At the same time, plants irrigated with the T2 regime recorded a relative increase in fresh weight of about 24% over those irrigated with the T3 regime. It means that the green bean plants' growth and fresh weight were significantly impacted by deficit irrigation. A similar trend was noticed with the plant height, which tends to decline with a decreasing irrigation water regime. Deficit irrigation under T3 resulted in a relative decrease in plant height of about 41% and 22% less than those recorded with irrigation under the T1 and T2 regimes, respectively. In another turn, the full irrigation regime T1 produced the highest green bean plant height values compared to other regimes.

Table 3. Monthly average variations of ambient, water, and inner temperatures, efficiency and output productivity for an active and passive solar still.

Month	Ambient temperature (T_a) (°C)	Water temperature (T_w) (°C)	Inner temperature (T_{gi}) (°C)	Productivity (ml m^{-2})	Efficiency (η) (%)
Active Solar Still					
October 2020	42.2	72.0	70.6	1250	4.4
November 2020	33.0	57.0	54.3	790	3.0
December 2020	32.9	56.3	53.6	730	1.9
May 2021	40.2	75.8	73.6	1810	7.6
June 2021	46.7	77.6	74.4	2200	4.4
July 2021	47.2	78.3	75.3	2650	8.8
August 2021	49.1	80.3	77.4	3100	11.2
Passive Solar Still					
October 2020	42.2	63.0	62.1	908	12.2
November 2020	33.0	50.6	48.0	575	10.5
December 2020	32.9	50.5	47.8	535	9.2
May 2021	40.2	69.5	66.3	1340	17.7
June 2021	46.7	70.5	67.9	1580	20.5
July 2021	47.2	72.6	69.6	1950	24.7
August 2021	49.1	75.0	73.8	2270	28.1

Irrigation with the T1 regime significantly increased the number of pods and fresh weight. The reduction in water requirement at T2 and T3 resulted in a severe reduction in pod number, accounting for 42% and 67%, respectively, less than those indicated under a full irrigation regime at T1. Similarly, deficit irrigation regimes induced decreases in pods' fresh weight accounted for 45% and 74% under T2 and T3, respectively. On the other hand, the full irrigation regime T1 significantly improved the pod's numbers and fresh weight, which relatively increased by about 72% and more than twofold; 84% and nearly close to threefold, for pod numbers and fresh weight under T2 and T3, respectively.

Increasing water stress significantly affected the dry matter yield of green bean plants' pods, shoots, and roots (see Fig. 4). Fully irrigated plants reflected increased pods' dry weight over those treated with either T2 or T3 irrigation water regimes. The pods' dry weight was nearly close to the shoots, and both were significantly higher than root dry matter yield. All plant parts tended to decrease with increasing irrigation water deficits. In the case of pods' dry weight, the yield of plants irrigated with T1 was relatively increased by about 82% and 180% over those irrigated with T2 and T3, respectively. Similar percentages were recorded for shoot dry weight, while in the case of roots, the relative increases were 54% and 143% for the same sequences.

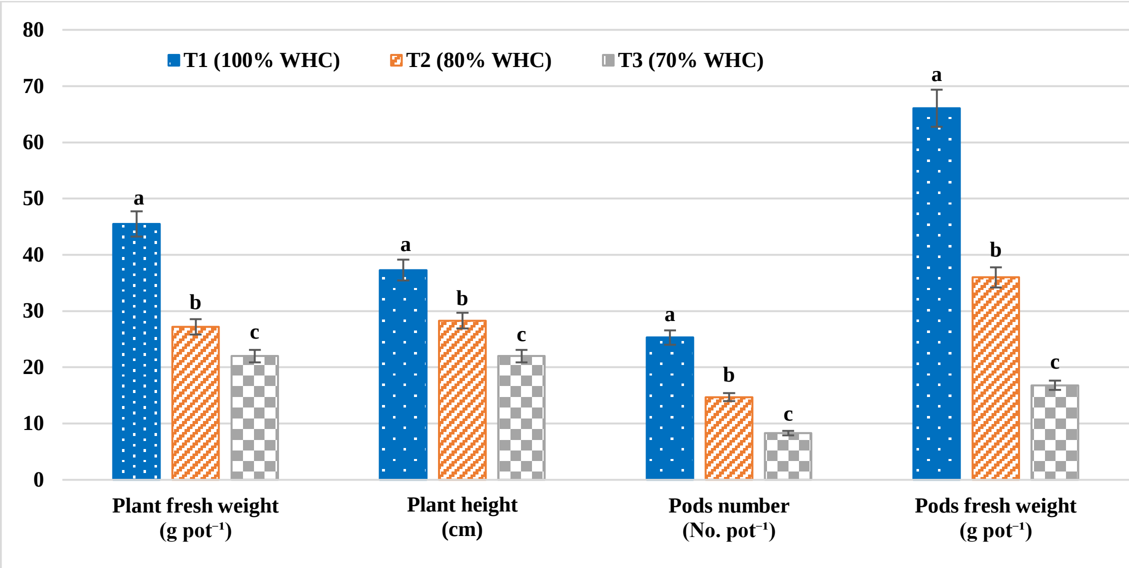


Fig. 3. Effect of irrigation water regime on the plant fresh weight, plant height, pod number, and pod fresh weight of green bean plants.

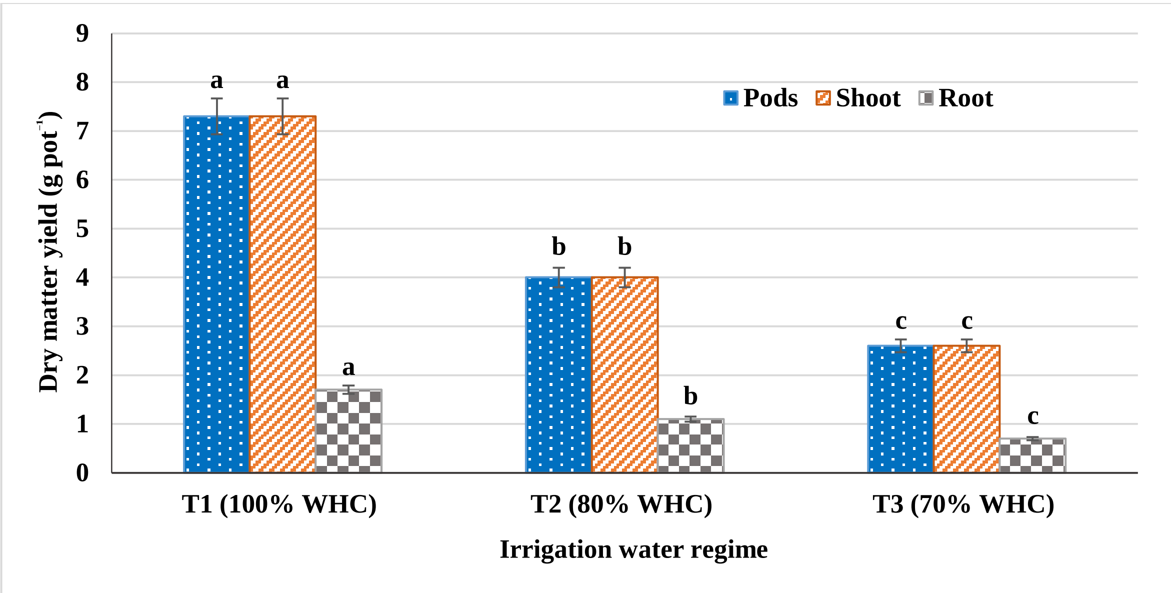


Fig. 4. The effect of irrigation water regimes on the dry matter yield of the green bean crop's pods, shoots, and roots.

3.3. Water productivity (WP) and water use efficiency (WUE)

WP and WUE were graphically illustrated in Fig 5. The data showed that the fully irrigated plants (T1) contained a higher WP than those that were subjected to water stress (T2 and T3). It means fully irrigated plants produced high biomass per cubic meter of water compared to other irrigation water regimes. In this respect, WP under T1 was relatively higher by about 53% and 164% over those recorded with T2 and T3, respectively. At the same time, WP increased by about 72% under T2 compared to T3 conditions. In general, the WP sharply decreased with increasing water deficit. Concerning the WUE, the data indicated a similar trend to those mentioned in the WP. It seems that irrigation water was more efficiently used by plants irrigated with the T1 regime, followed by the T2 and T3 water regimes. The difference between T2 and T3 seems to be slight. Therefore, economically, the T3 water regime could be recommended under deficit water conditions.

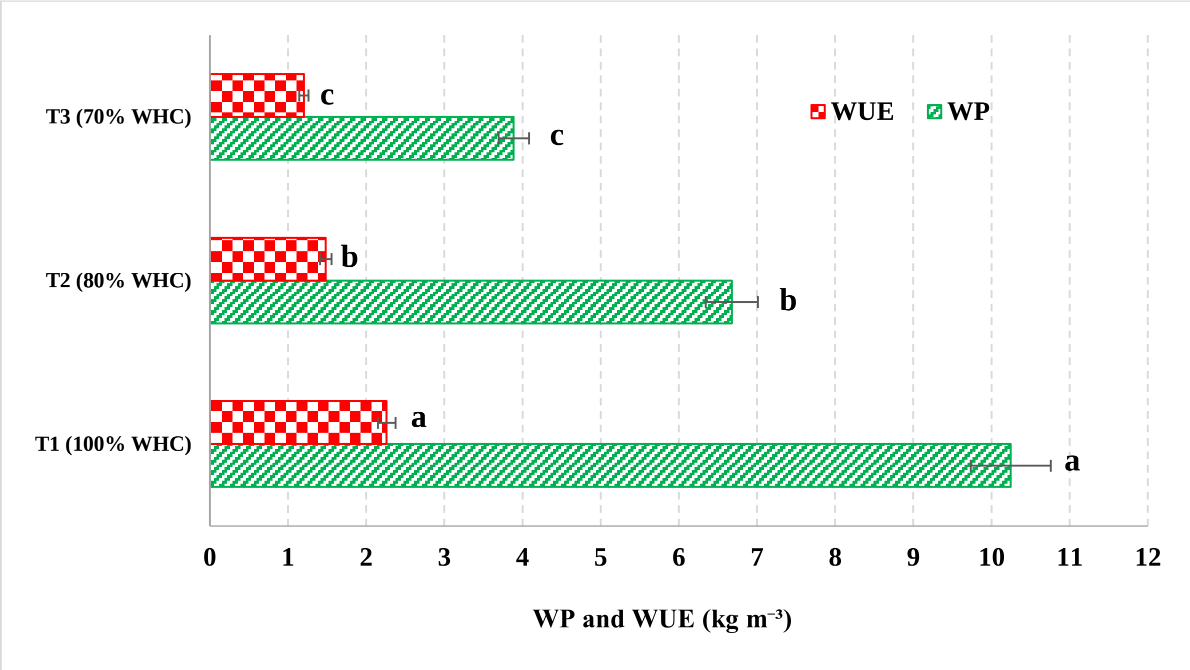


Fig. 5. Effect of irrigation water regimes on WP and WUE by green bean plants.

3.4. Macronutrient nutrient uptake (NPK)

NPK uptake by different plant organs as affected by irrigation water regimes was graphically illustrated in Fig 6. Plants irrigated with T1 had significantly higher NPK uptake by various parts than those recorded with T2 and T3 water regimes. The lowest values of NPK uptake were detected under the T3 water regime. Among different plant parts, N and P accumulation in shoots was higher than in pods and roots under the T1 and T3 regimes. In contrast, in the case of the T2 regime, N and P uptake by pods was higher than that in shoots and roots, while in the K uptake, the opposite observation was recorded in shoots and pods under T1, and the same direction was recorded for T2 and T3.

Generally, the lowest values of N uptake were in roots. This holds true under all irrigation water regimes. Also, N accumulated in different plant parts tended to decrease with increasing deficit water. Relatively, N uptake by pods of plants irrigated with the T1 regime was increased by about 26% and more than twofold over those of T2 and T3, respectively. At the same time, those irrigated with the T2 regime induced an increase nearly twofold over those irrigated with the T3 regime. Concerning N uptake by shoot, irrigation at the T1 regime resulted in relative increases of about 99% and 113% over T2 and T3, respectively, while the T2 regime reflected an increase of about 57% over the T3 regime. Similarly, nitrogen accumulation in roots was significantly improved by increasing irrigation water for T1, comparable to the other two water regimes (T2 and T3). Relatively, it increases by about 40% and more than twofold over the T2 and T3 regimes, respectively. The comparison between T2 and T3 water regimes reflected an increase in N uptake by the roots of plants treated with T2, accounting for 119% more than those treated with the T3 water regime.

Phosphorus uptake by different plant parts has the same behaviour as nitrogen behaves under different irrigation water regimes. Also, it tends to decrease with an increasing deficit water regime. Under T1 and T3, it accumulated much more in the shoot than in pods and roots. In the case of T2, P accumulated more in pods, followed by shoots, and P in roots came next. Comparatively, P in pods of pea plants irrigated with T1 was increased by about 3% and more than twofold over the T2 and T3 regimes, respectively. In the same way, the T2 regime's induced relative increases in P accumulated in pods accounted for more than twofold increases over the T3 water regime. In the case of shoot, these relative increases affected by the T1 regime were 48% and more than twofold over T2 and T3, respectively, while T2 resulted in a relative increase of about 131% over the T3 water regime. Root-P tended to increase with high water regime T1 over other regimes reflecting relative increase accounted for 39% and 170% for the same sequence. Additionally, the T2 regime increased by about 94% over the T3 water regime.

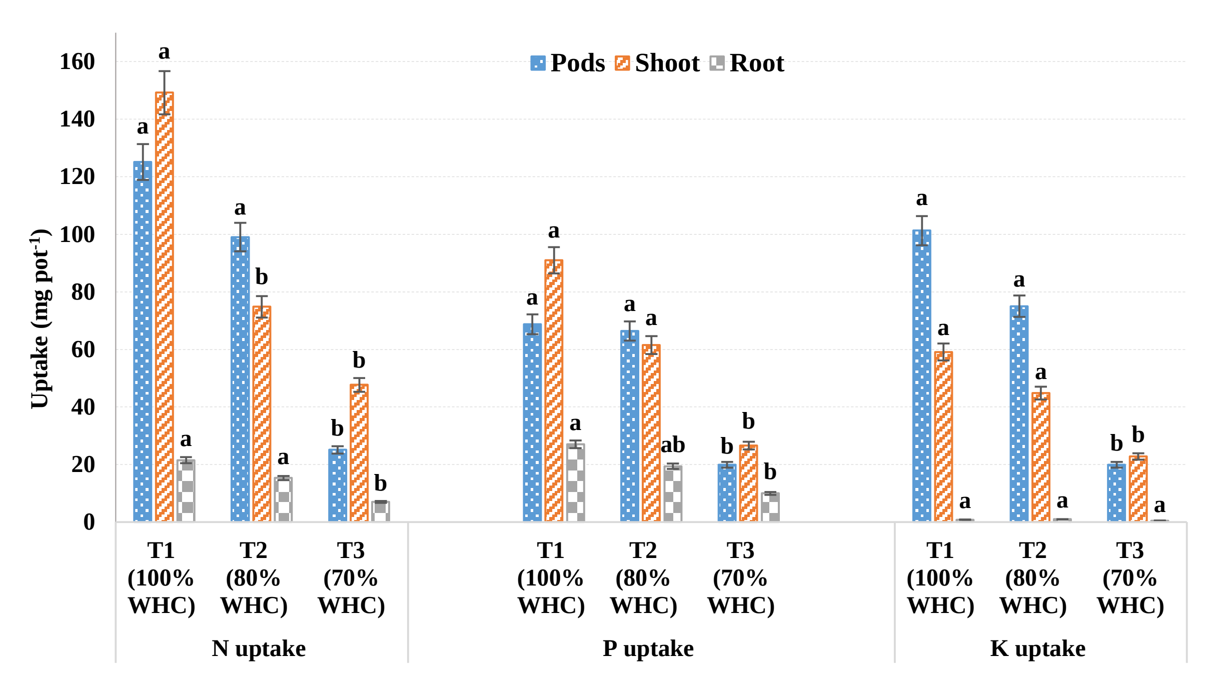


Fig. 6. The effect of irrigation water regimes on the NPK uptake by green bean pods, shoots, and roots.

Potassium accumulated in different green bean plant parts showed a significant positive response to a high irrigation water regime in T1 compared to T2 and T3 regimes. The K accumulated in pods was much higher than in shoots and roots. The increasing water deficit significantly impacted different plant parts' uptake of potassium. In this respect, the lowest K uptake by pods, shoots, and roots was recorded at the T3 water regime. Comparatively, pods of plants irrigated with T1 uptake more K accounted for 35% and more than fourfold over those accumulated under T2 and T3, respectively. In addition, T2 resulted in more than a twofold increase in K uptake by pods over that induced by the T3 water regime. Likewise, K in the shoots was increased by about 32% and 159% in the T2 and T3 water regimes, respectively. Irrigated with T2 showed relative increases in shoot-K of about 96% over the T3 water regime. Under T3 treatment, K uptake by shoots was slightly, but insignificantly, higher than K accumulated in pods or roots. In this respect, T2-induced relative increases in K uptake by roots accounted for 25% and 117% over those recorded at T1 and T3 water regimes, respectively.

3.5. Nitrogen estimation for experiment with ^{15}N

Applying a stable ^{15}N isotope following the isotope dilution concept allowed us to estimate the portion of N derived to green bean plant parts from the chemical fertilizer added. Accurate estimates of Ndff (% or mg pot^{-1}), depending on the isotope dilution concept, showed a significant positive response to an increase in irrigation water. At the same time, they were negatively affected by increasing irrigation water deficits.

Data graphically illustrated in Fig 7 indicated that percentages of nitrogen gained by pods, shoot, and root of green bean crop from chemical fertilizer added was significantly higher under the water deficit regime (T3) than percentages estimated under moderate and high irrigation water regimes. In this case, it was clear that more than 50% of nitrogen uptake by pods was derived from fertilizer, while 23% and 5% were gained from fertilizer by shoot and root, respectively. It proves fertilizer-N was mobilized and actively translocated to upper parts, including pods and shoots. The high accumulation of nitrogen fertilizer in pods followed by shoots and roots holds true under all irrigation water regimes. In this regard, the irrigation water regimes could be arranged as follows, T3 > T1 > T2 regime.

Another different picture was drawn when Ndff was estimated as mg pot^{-1} from the total N accumulated by different plant components. The absolute values of the N portion derived from fertilizer followed the same trend, whereas it was higher in pods, followed by shoots, and then roots. In contrast with Ndff, absolute values of Ndff by pods, shoots, and roots seems to be significantly higher under irrigation at T1 than those indicated at either T2 or T3 regimes. Based on the absolute values of Ndff, the plant organs could be arranged as pods > shoots > roots. On the same basis, irrigation water regimes could be arranged as follows, T1 > T2 > T3.

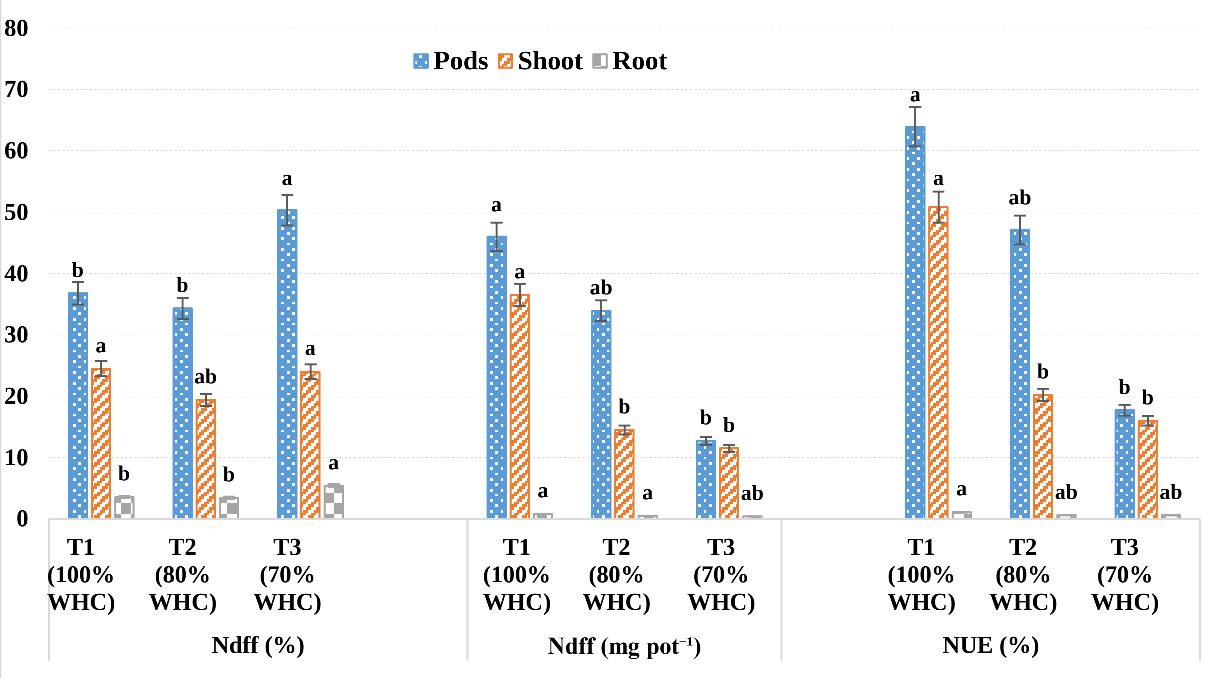


Fig. 7. Ndff (%), NUE (%), and Ndff (mg pot^{-1}) by green bean crop organs as affected by irrigation water regime.

4. Discussion

Plants exposed to different water regimes reflected varied responses. Plant growth traits, including plant fresh weight, plant height, pod number, and pod fresh weight, tended to increase with increasing irrigation water regimes. On the other hand, these growth traits were negatively affected by deficit irrigation (T2 and T3). Literature background from a few decades ago revealed that nitrogen fertilization in collaboration with irrigation water limits plant growth and productivity (Mueller *et al.*, 2012). Therefore, a plant breeding approach (Condon *et al.*, 2004) and proper nitrogen and water management (Quemada and Gabriel, 2016) are needed to enhance their efficiencies. In this respect, (El-Noemani *et al.*, 2009) found that high levels of irrigation water reflected an enhancement of pea vegetative growth. The progress of plant growth as influenced by high irrigation water levels may be attributed to enhancing cell division and enlargement (Hammad, 1991); the availability of water in the root zone of snap beans improved plant water status and ensured better stomatal conductance and assimilation (Abdel-Mawgoud *et al.*, 2005), and plant metabolism (Abdel-Mawgoud, 2006). On the contrary, (Hsiao and Acevedo, 1974) revealed that the yield and plant growth could be reduced as affected by water stress attributable to the reduction in vegetative growth. In addition, a water deficit adversely affects the plant metabolites, which may negatively affect the dry seed yield.

Concerning the effect of irrigation water regimes on growth attributes, (Idnani and Singh, 2008) indicated that three irrigations of *Vigna radiata* resulted in significantly higher plant height, nodule numbers, and weight than two irrigation regimes. A similar trend was observed with grain yield and the number of pods per plant. In the same way, the wheat yield was significantly decreased with decreasing irrigation water level and N fertilizer rate below a specific limit (Shoukat *et al.*, 2021). In accordance with us, (Voor *et al.*, 2018) indicated an increase in hot pepper plant height as the irrigation levels increased. Their relative increases, accounting for 14.3, 19.8, 28.1, and 35.2% at 500, 1000, 1500, and 2000 ml/plant, respectively, were observed. These values are lower than those we have. At the same time, our results are in harmony with those obtained by (Metwaly, 2018), who elucidated that pea growth trait, pod yield, quality, chemical composition, and plant water relations tended to decrease with increasing irrigation water deficit.

Similar effects of irrigation water regimes were noticed with pods, shoot and root dry weights. In this respect, (Hassan *et al.*, 2020) mentioned that green pea seed yield decreased as deficit irrigation regimes were intensified.; additionally, they discovered that the treatment's maximum average seed yield was 90% ET_c or less at the flowering stage, while, the lowest average value of seed yield was recorded with 70% ET_c treatment for all seasons. In contrast, a 70% ET_c treatment yielded the lowest average seed yield, they explained the lower yield was caused by a higher water deficit level, resulting in slower plant growth and lower nutrient uptake. Other researchers have reached the same findings and explanation of the phenomenon (El-Noemani *et al.*, 2010; Ndimbo *et al.*, 2015; Yassin *et al.*, 2021).

Similarly, cucumber crop growth was declined with deficit irrigation regime comparable to a full irrigation regime (Parkash et al., 2021). Liu et al., (2003, 2005, 2006) attributed the reduction of leaf growth and stomata closing due to the decline in soil water availability, which can occur early stage before the soil dries, which stops water from evaporating into the atmosphere, allowing plants to maintain their water status in water-stressed conditions. In the same way, (Abd El-Mageed et al., 2018; Şimşek *et al.*, 2005) found that deficit water conditions frequently and severely affected dry matter and yield. In harmony, according to our study, vegetative and pod dry biomass decreased under water stress conditions, which led to a decrease in the total above-ground dry biomass (vegetative and pod biomass). According to (Kirnak and Demirtas, 2006), when cucumber plants were exposed to water deficit conditions, the total fruit yield and dry vegetative biomass were consistently estimated to have decreased by more than 50%. Many scientists have recently discussed and reported trends in which the shortage of irrigation water (drought) led to a decline in seed yield, protein, carbohydrates, total phenols, amino acids, macronutrients, and micronutrients in the composition and uptake of the plant suffer from a decrease in chlorophylls that affect photosynthesis (Desoky *et al.*, 2020a; Desoky *et al.*, 2020b; Desoky *et al.*, 2020c; Elrys *et al.*, 2020; Elrys *et al.*, 2019; Erdem *et al.*, 2006; Fouda *et al.*, 2022; Hag *et al.*, 2017; Reddy *et al.*, 2003). To further explain these detrimental effects of irrigation water shortages, it was clarified that deficit irrigation is associated with water stress (Parkash and Singh, 2020), and according to (Costa *et al.*, 2007), it is considered a one irrigation technique that could potentially conserve water is, while the opposite effect occurred in the physiological and biochemical processes of the plant (Yuan *et al.*, 2016); additionally, this effect will be extended to lower the crop's overall yield (Sharma *et al.*, 2019).

The synergistic effect of fully irrigation regime on water productivity (WP) was clear since the fully irrigated plants produced high biomass per cubic meter of water compared to other deficit irrigation water regimes. Water use efficiency (WUE) followed the same behavior. Previous researches after (El-Noemani et al., 2009; Erdem et al., 2006; Işik *et al.*, 2005; Onder *et al.*, 2005; Shoukat et al., 2021; Webber *et al.*, 2006), recorded similar findings. Water use efficiency of green bean grown under green-house conditions was ranged between 26.5 and 32.4 kg m^3 (Buyukcangaz et al., 2008), while it was 4.0 to 17.5 kg m^{-3} for field green bean over two growing cycles under three irrigation methods with six regimes (Bozkurt and Mansuroglu, 2018). Increased irrigation intervals resulted in increased yield and WUE for green bean crops ranges from 24.9 kg ha^{-1} mm^{-1} to 55.4 kg ha^{-1} mm^{-1} during the growth season (Abuarab et al., 2020). On the other hand, Sezen et al. (2005) found that the WUE and IWUE values dropped as irrigation intervals increased (Sezen *et al.*, 2005), while (Metwaly, 2018) indicated that WUE was not affected by the deficit irrigation regime.

It seems that N, P and K uptake by different plant organs was dramatically decreased with increasing deficit irrigation water regime. In the same time, both N and P uptake by shoots were higher than those accumulated in pods and roots consequently. Another picture was drawn where K uptake tended to highly accumulated in pods followed by shoots then roots. These results are confirmed by those of (Metwaly, 2018), who demonstrated that N, P, K, and chlorophyll pigments decreased with increasing irrigation water deficits. This led (Fatthallah and Gawish, 1997) to conclude that the reduced number of branches under stressful circumstances was due to the reduced nutrient uptake, which slowed the physiological processes required for plant growth. According to (Mahmoud, 2000), the effect of water on some quantitative and qualitative changes in specific metabolic processes in the plant cell may be the leading cause of the increase in dry matter in plants grown in soils with high moisture levels. Dealing with NPK nutrients, (Loganathan and Latha, 2016) found that the total uptake of N, P, and K by pigeon peas was enhanced with 100% WRc (water requirement by crop) combined with 125% recommended fertilizer (RDF) comparable with drip irrigation at 100% WRc along with fertigation at 100 percent RDF.

At the same time, (Sonnenberg *et al.*, 2016) detected a remarkable developments in some photosynthetic parameters of cucumber crops irrigated with a higher amount of water than a lower one using drip irrigation technology in a hydroponic system; they also mentioned that the high irrigation volume helps solubilize the nutrients for optimal plant uptake. This proved the importance of drip irrigation systems as an efficient water-saving technology that can significantly improve crop yield (Castellanos *et al.*, 2013; Silber *et al.*, 2013) and it has led to an increase in the efficiency of water and nutrients (Schumann *et al.*, 2009). Concerning the effect of irrigation water regimes on growth attributes, (Idnani and Singh, 2008) indicated that three irrigations of *Vigna radiata* resulted in significantly higher plant height, nodule numbers and weight, grain yield and pod No. $plant^{-1}$ than two irrigation regimes, while irrigation stress (two irrigations) reversely affected the nitrogen and phosphorus uptake. They attributed the increased N and P uptake under three irrigations compared to two irrigations to adequate moisture availability and, ultimately, more mineralization and uptake of such nutrients. At the same time, they recorded lower water consumption under the two irrigation regimes. Still, the WUE was higher than the three irrigation regimes, which may be attributed to twice-irrigated plants' relatively higher grain yield.

Application of ^{15}N tracer technique (Isotope Dilution Concept) revealed that nitrogen derived from

fertilizer, either as percentage or absolute values, was mostly accumulated in pods followed by shoots then roots. It means that Fertilizer-N was efficiently used by pods rather than shoots and roots. In this regard, Ndff values and NUE% were enhanced by fully irrigation regime comparable to deficit irrigation ones. In harmony, (Aulakh and Malhi, 2005; Gonzalez-Dugo *et al.*, 2010) found that the lack of water affected NUE, which was related to the final nitrogen nutrition index measured at harvest. (El-Hafeez and Bashandy, 2019; Gajri *et al.*, 1993) found a significant interaction between N and water for yield and the dependence of WUE on the N rate and NUE on the water supply. Similar findings were made under Egyptian soil by (Moursy and Ismail, 2021), who discovered that wheat grain absorbed more nitrogen from fertilizer than straw under various fertilization treatments. At the same time, the plants irrigated with 100% ET_c induced higher efficiencies of Ndff and absolute values by either grain or straw. In addition, N fertilizer was efficiently used by grains followed by straw under 100% ET_c, comparable to those recorded with a 50% ET_c regime. (Kim *et al.*, 2008) found that water and nitrogen have beneficial interactions and synergistic relationships. In this respect, Rathore et al. (2017) claimed that using an appropriate deficit irrigation and nitrogen rate combination could improve WP and NUE for wheat in arid regions while decreasing non-beneficial water consumption and increasing yield (Rathore *et al.*, 2017).
Generally, the data of the present work confirmed that green bean plants suffered from deficit irrigation water produced lower pods yield and dry matter yield of shoots and roots as well as NPK uptake. However, plants fully irrigated with required water amounts grew will without drastic and deleterious impacts on yield and nutrients uptake. This phenomenon was proved by $^{15}N/^{14}N$ ratio analysis which confirmed that portion of nitrogen derived from fertilizer and NUE by all plant organs were higher under 100% (T1) irrigation water regime comparable to deficit irrigation regimes.

5. Conclusion

In the current study, which used sandy soil as the cultivation media for green bean plants in an open field under Egyptian conditions, according to the findings, mixed water irrigation of green bean plants at T1 increased WP and WUE compared to two different deficit water regimes (T2 and T3). Similar to this, increasing irrigation water availability to green bean crops improved NPK nutrient uptake by various plant parts. Applying a stable nitrogen isotope, we were able to calculate the precise amount of nitrogen that plants use from chemical fertilizers. The results indicated that the nitrogen fertilizer was concentrated mainly in the pods, followed by the shoots, while the least amount was present in the roots and was very small compared to pods and shoots. It is evidence that the upper plant parts absorbed most of the nitrogen from fertilizer. Therefore, in all water regimes used, Evidently, pods used nitrogen fertilizer more effectively than shoots did. Finally, we suggest the T3 water regime as a water deficit and economic system that could be accepted under water crises and severe climatic changes due to the convergence of the results data from T2 and T3 irrigation systems in most cases.

Author Contributions Statement

Galal Y.G.M.: Writing – review & editing, Validation, Supervision.

Salama M.A.: Writing – review & editing, Writing – original draft preparation, Validation, Methodology, Investigation, Data curation.

Hussien M.A.: Writing – review & editing, Writing – original draft, Validation, Methodology.

Atia M.F.: Writing – review & editing, Resources, Methodology, Investigation.

Eldehn I.F.M.: Sampling collection, Writing – review & editing, Resources, Visualization, Data curation.

Data availability

Data will be made available on request.

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Conflicts of interest

There are no conflicts to declare.

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