Yuzuncu Yil University
Journal of Agricultural Sciences
(Yüzüncü Yıl Üniversitesi Tarım Bilimleri Dergisi)
https://dergipark.org.tr/en/pub/yyutbd
ISSN: 1308-7576
e-ISSN: 1308-7584

Research Article

The Effect of Reclaimed Wastewater and Clean Water Applications on the Yield and Quality Parameters of Bean (*Phaseolus vulgaris* L.)

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Article Info

Received: 07.12.2025
Accepted: 27.02.2026
Online published: 29.04.2026
DOI: 10.29133/yyutbd.1837453

Keywords

Deficit irrigation,
Phaseolus vulgaris L.,
Reclaimed wastewater

Abstract: This study examined the effects of different irrigation methods, water quality, and irrigation levels on yield components and water-use efficiency of bean (*Phaseolus vulgaris* L.) under semi-arid climate conditions. The main objective of the study was to manage water use in the most efficient way while maintaining production efficiency in areas with limited water resources. This study is a field trial conducted in 2024 to compare surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) systems using three water sources of varying quality:freshwater (FW), reclaimed wastewater (RW), and mixed water (MW; 50% RW + 50% FW). Irrigation water amounts were determined from cumulative evaporation measured with a Class A pan, and four irrigation levels were established at 100%, 75%, 50%, and 25% of the full irrigation requirement. Seasonal evapotranspiration ranged from 116.0 to 468.8 mm. Water use efficiency (WUE) and irrigation water use efficiency (IWUE) ranged from 1.42 to 5.49 kg m^{-3} and 1.72 to 6.62 kg m^{-3}, respectively. Morphological traits included plant height (20.10–52.44 cm), stem diameter (9.83–10.05 mm), root length (15.44–27.40 cm), root weight (22.01–35.05 g), pod length (13.21–15.64 mm), and pod width (1.52–1.92 mm). Yield decreased significantly with increasing drought stress, indicating high sensitivity to irrigation levels. RW treatments outperformed FW in both yield and water-use efficiency, while MW produced results similar to RW, suggesting its potential as an alternative. Research findings indicate that integrating RW and MW with SDI and SSDI systems could be an effective strategy for ensuring sustainable bean production in arid and semi-arid regions.

To Cite: Er, H, Gürbulak, M G, Korkut, Ö, Kuşlu, Y, 2026. The Effect of Reclaimed Wastewater and Clean Water Applications on the Yield and Quality Parameters of Bean (*Phaseolus vulgaris* L.**).** *Yuzuncu Yil University Journal of Agricultural Sciences*, (1): 1837453.
DOI: https://doi.org/10.29133/yyutbd.1837453

1. Introduction

Drought has become a growing global problem, exacerbated by the misuse and inadequate management of existing water resources, threatening food insecurity, specifically in arid regions (Ahmed et al., 2022; Rahimi et al., 2023; Kilic et al., 2025). The agricultural sector is at the centre of this crisis as it consumes approximately 80–85% of the world's water resources. (Mahmoud and El-Bably, 2019; Elbashier et al., 2023).

Increasing water-use efficiency and evaluating alternative irrigation sources are critical to mitigating rising water pressure in semiarid regions. Therefore, the combined use of limited irrigation regimes and reclaimed wastewater stands out as an important approach for water conservation and the sustainability of agricultural production (Younas and Younas, 2022; Agustina et al., 2024; Christou et al., 2024). Wastewater is used as an irrigation water source in agriculture on approximately 20 million hectares worldwide (Hashem and Qi, 2021; Er and Kuslu, 2026). Due to its high nutrient content, wastewater is used as an alternative to traditional fertilizers, helping reduce the costs associated with synthetic fertilizer use (Sharma and Singhvi, 2017; Er and Kuslu, 2025). While wastewater irrigation is generally carried out after primary treatment in low-income countries, tertiary-treated reclaimed water is often used for agriculture in arid regions of high-income countries (Jaramillo and Restrepo, 2017). Wastewater has a positive effect on increasing the productivity of agricultural soils due to the organic matter it contains, as well as hadoro nutrients such as N, P, and K, and microelements such as Fe, Mn, Zn, and Cu (Al-Suhaibani et al., 2021; Verma et al., 2023). Numerous studies show that the use of reclaimed wastewater in agriculture improves soil properties and positively influences yield parameters for different plants (Farhadkhani et al., 2018; Gatta et al., 2020; Ammeri et al., 2023; Mkilima, 2025). However, untreated sewage can pose an environmental risk by causing excessive accumulation of nutrients and pollutants (Nyika, 2022). In this context, irrigation techniques such as subsurface drip irrigation (SSDI) and surface drip irrigation (SDI), which prevent direct contact between wastewater and the edible portions of the crop, are preferred for ensuring safe and efficient water application. Drip irrigation systems that apply water at low pressure to the soil surface (SDI) or below it (SSDI) are attracting attention because they reduce evaporation losses, save water, and increase IWUE (Ayars et al., 2015; Al-Ghobari and Dewidar, 2018).

Crop productivity in dry farming is largely limited by water scarcity, and achieving stable quality in irrigated systems under drought stress depends heavily on optimal crop selection (Ashrafi and Razmjoo, 2010). Bean seeds are rich in protein, vitamins, minerals, and dietary fiber, and also contain bioactive compounds such as phenolic compounds, enzyme inhibitors, and oligosaccharides (Kiymaz et al., 2020). It is stated that these compounds are associated with positive health effects against chronic diseases such as diabetes, obesity, cardiovascular disorders, and cancer. Globally, more than 60% of bean production occurs in regions frequently exposed to prolonged drought, while only about 7% is cultivated under irrigated conditions. Moreover, common bean is among the most drought-sensitive legumes (Campos et al., 2021). This high sensitivity makes bean a suitable model crop for evaluating water management strategies in arid and semiarid agricultural systems. However, the literature indicates that studies combining different irrigation methods with treated wastewater applications to improve bean response to water stress and enhance water-use efficiency are quite limited. This study aimed to compare reclaimed wastewater and freshwater applications using various irrigation techniques and levels in Erzurum province and to determine their effects on bean yield, physiological traits, and water productivity.

2. Materials and Methods

2.1. Experimental site

During the 2024 growing season, from May to September, fieldwork was conducted at the Atatürk University Plant Production Application and Research Center (39°56.01′ N, 41°14.11′ E, 1830 m altitude) in Erzurum, Türkiye (Figure 1).

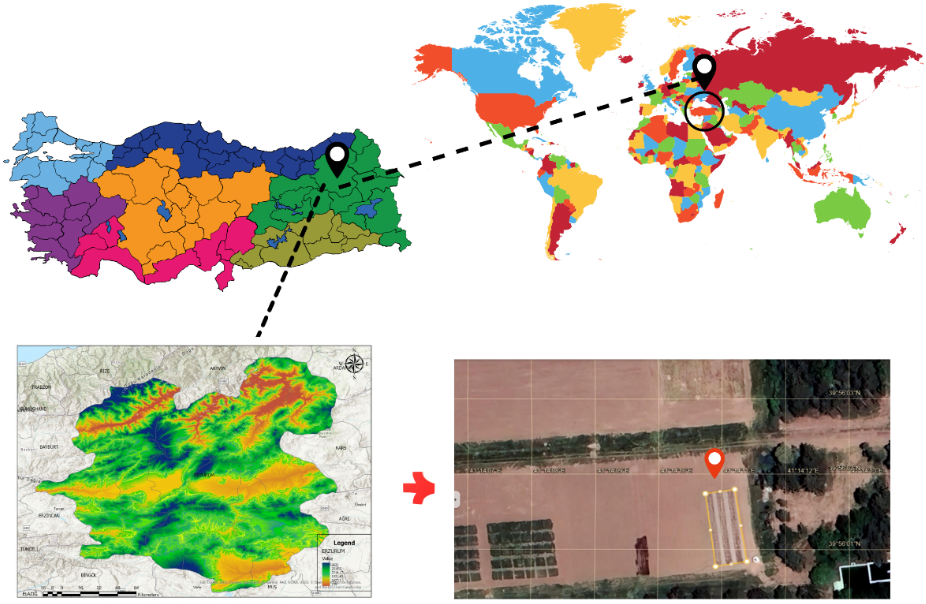

Figure 1. Location of the experimental site.

Long-term climatic data for the experimental site, as well as data specific to the 2024 growing season, were obtained from the Erzurum Regional Directorate of Meteorology (Figure 2). Erzurum is located in a continental climate zone and experiences a harsh continental climate. Summers are generally dry and cool, whereas winters are cold and snowy. The diurnal temperature range is considerably high. Long-term climate data collected between 1929 and 2023 indicate a mean yearly air temperature of 5.8 °C, with minimum and maximum values of –37.2 °C and 36.5 °C, respectively. The region receives an average of 431.5 mm of precipitation annually. During the study period, the mean monthly temperature was 16.8 °C, and the peak temperatures reached 29.2 °C. The total precipitation recorded during the growing season (May–September 2024) was 339.5 mm. The average monthly precipitation over this period was 67.9 mm.

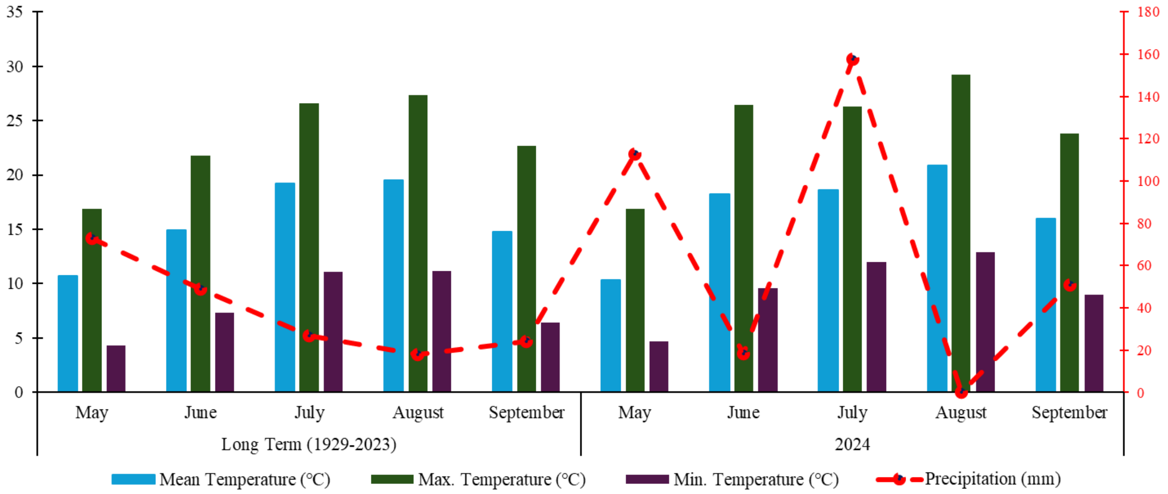

Figure 2. Monthly climatic data for the research site over a long period of time and an experimental year. Left axis: temperature (°C), right axis: precipitation (mm).

According to the USDA classification, the soil in the study area has a clay loam texture. The available water-holding capacity for the 0–90 cm soil profile was calculated to be 150.39 mm. The soil properties measured at a depth of 0–30 cm are as follows: pH 7.48, EC 1.25 dS m^{-1}, organic matter 1.14%, $CaCO_3$ 1.38%, total N 0.06%, available K_2O 1441 kg ha^{-1}, and available P_2O_5 60.5 kg ha^{-1}.

2.2. Experimental design

The bean (*Phaseolus vulgaris* L.) cultivar Gina, known for its adaptation to the regional ecological conditions, was used in this experiment. Fertilization practices in the trial area were planned based on soil analyses, and 60 kg N ha^{-1} (ammonium sulfate) and 4 kg P_2O_5 ha^{-1} (triple superphosphate) were used in all plots. Seeds were first sown in trays and grown in the greenhouse of Atatürk University's Plant Production Application and Research Center. After reaching the four-leaf stage, the seedlings were transplanted to the field on June 9, and harvesting was performed on September 21.

The study was conducted in a completely randomized factorial design with three replications. Each plot measured 8 m × 1.5 m and consisted of three rows of plants. Row spacing was 0.40 m, and within-row spacing was 0.33 m. To minimize border effects, a buffer distance of approximately 0.35 m was left between the outer rows and the plot edges on both sides.

2.3. Irrigation systems and treatments

To evaluate irrigation performance, the experimental field was divided into two sections, each implementing one irrigation method: subsurface drip irrigation (SSDI) and surface drip irrigation (SDI). Each irrigation method was assessed using three different water qualities—freshwater (FW), reclaimed wastewater (RW), and a mixed water solution (MW) consisting of 50% FW and 50% RW—combined with four irrigation levels: I100 (full irrigation), I75 (25% deficit), I50 (50% deficit), and I25 (75% deficit). Irrigation was applied through a drip system composed of 16 mm lateral lines equipped with emitters delivering 4 L h^{-1} at an operating pressure of 100 kPa. The system infrastructure included both main and lateral pipes with a 50 mm diameter. For the subsurface drip irrigation system, lateral lines were buried at a depth of 25 cm below the soil surface, which is considered appropriate for shallow-rooted crops such as common bean, thereby delivering water directly to the active root zone while minimizing soil evaporation losses. Similar to the surface system, lateral spacing was maintained at 0.40 m to ensure homogeneous soil moisture conditions within the plots. Freshwater was supplied from a well located within the research site, while reclaimed wastewater was obtained from the Erzurum Municipality Biological Wastewater Treatment Plant. Water quality analyses for both freshwater and treated wastewater during the experimental period are summarized in Table 1. The results confirmed that all measured parameters remained within acceptable limits for soil health, plant growth, and irrigation system safety (Ayers and Westcot, 1989; Kanber and Ünlü, 2010).

Table 1. Physicochemical characteristics of freshwater and reclaimed wastewater

Parameter	RW	FW	Parameter	RW	FW
pH	6.98	7.95	Zn (mg l^{-1})	0.06	-
EC (dS m^{-1})	0.60	0.32	Pb (mg l^{-1})	0.0023	-
Ca (me l^{-1})	2.31	0.93	Cd (mg l^{-1})	-	-
Mg (me l^{-1})	0.86	0.70	Cr (mg l^{-1})	-	-
Na (me l^{-1})	2.85	0.30	TN (mg l^{-1})	6.86	-
K (me l^{-1})	0.91	0.094	TP (mg l^{-1})	1.54	-
CO_3 (me l^{-1})	-	-	TSS (mg l^{-1})	10.59	-
HCO_3 (me l^{-1})	3.79	1.45	KOD (mg l^{-1})	20	-
Cl (me l^{-1})	1.78	0.46	BOD_5 (mg l^{-1})	4.01	-
SO_4 (me l^{-1})	0.13	0.12	SAR (%)	2.26	0.33
B (mg l^{-1})	0.060	0.025	RSC (me l^{-1})	0.62	-0.18
Fe (mg l^{-1})	0.052	0.042	Na%	41.13	14.82
Cu (mg l^{-1})	0.003	-	Fecal coliform (EMS/100 ml)	168	-
Mn (mg l^{-1})	0.011	-	Total coliform (EMS/100 ml)	644	-

'-' : was not detected, RW: reclaimed wastewater, FW: Freshwater.

Irrigation scheduling and applied water amounts were determined using the Class A pan evaporation method. Irrigation was triggered when cumulative evaporation from the Class A pan reached 50 ± 5 mm. The amount of irrigation water was calculated using equation 1: (Ertek, 2011; Ozer et al., 2020).

$$\mathrm{I} = \mathrm{E_p} \times \mathrm{K_{cp}} \times \mathrm{A} \tag{1}$$

where I = amount of irrigation water (L), Ep: Cumulative amount of water that evaporated from the Class-A Pan (mm), Kcp: Plant-pan coefficient (K values for different irrigation levels were selected as 1, 0.75, 0.50, and 0.25), A: Plot area (m^2)(Each plot 12 m^2).

In this study, actual evapotranspiration (ETa) was calculated according to the water balance approach developed by Allen et al. (1998)(Equation 2).

$$\mathrm{ETa} = \mathrm{I} + \mathrm{P} + \mathrm{Cr} - \mathrm{Dw} - \mathrm{Rf} \pm \Delta\mathrm{S} \tag{2}$$

where ETa: Evapotranspiration (mm), I: Amount of irrigation water (mm), Cr: Capillary rise (mm), Dw: Deep percolation (mm), Rf: Amount of runoff (mm), and ΔS: Changes in water content (mm).

At the study site, the soil had a deep profile with no evidence of drainage or salinity constraints. Since no groundwater table influenced the experimental area, capillary rise (Cp) was excluded from the water balance calculations. The effective root zone depth for common bean was set at 90 cm. Soil moisture changes were determined within this effective root depth. Soil moisture content was measured gravimetrically in three soil layers (0–30, 30–60, and 60–90 cm). Deep percolation was considered negligible because irrigation amounts were carefully adjusted according to soil water deficit within the effective root zone, and precipitation during the growing season did not exceed the available soil water storage capacity. Furthermore, soil moisture monitoring below the root zone confirmed the absence of excessive water accumulation. Surface runoff (Rf) was omitted from the water balance, as irrigation was applied at low discharge rates compatible with soil infiltration capacity, and no runoff was observed from the levelled plots during either irrigation or rainfall events. Soil moisture measurements were collected approximately 15–20 cm from the drippers, between two plants in the central rows of each plot, prior to each irrigation event, and at sowing and harvest.

In the study, water use efficiency (WUE)(Equation 3) and irrigation water use efficiency (IWUE)(Equation 3) were calculated according to the formulas developed by Howell et al. (1990):

$$WUE = Y \,/\, ET \tag{3}$$

$$IWUE = Y \,/\, I \tag{4}$$

where IWUE: irrigation water use efficiency (kg m^{-3}); WUE is water use efficiency (kg m^{-3}); I: the amount of irrigation water (mm); Y: the total yield (kg ha^{-1}).

2.4. Yield and physiological trait measurements

Fifteen plants were randomly selected from the two central rows of each plot, and growth and yield parameters, including plant height, root length and weight, stem diameter, pod length and width, and seed yield were measured.

2.5. Statistical Analysis

The data obtained within the scope of the study were analyzed using JMP v19. Differences between groups were examined using analysis of variance (ANOVA), and means were compared using Duncan's multiple-comparison test.

3. Results

3.1. Amount of irrigation water, ET, WUE, IWUE and yield

ET values and irrigation water are given in Table 2. In 2024, for the I100, I75, I50, and I25 applications, 382 mm, 284 mm, 190 mm, and 95 mm irrigation water amounts were applied for the SSDI method, and 385 mm, 288 mm, 192 mm, and 96 mm irrigation water amounts were applied for the SDI method, respectively.

Seasonal ET values were determined as 459.8, 344.5, 226.3, and 116.1 mm for RW application at I100, I75, I50, and I25 irrigation levels in the SSDI method; 466.2, 349.4, 235.1, and 124.1 mm for FW application; and 468.7, 350.3, 234.2, and 123.1 mm for MW application. In the SDI method, seasonal ET values were determined as 468.8, 350.5, 237.3, and 122.1 mm for RW application; 466.4, 349.3, 235.2, and 120.5 mm for FW application; and 466.1, 348.9, 234.6, and 120.2 mm for MW application.

In the SSDI method, ET values ranged from 116.1 to 459.8 mm for RW, 124.1 to 466.2 mm for FW, and 123.1 to 468.7 mm for MW. In the SDI system, ET values varied between 122.1–468.8 mm (RW), 120.5–466.4 mm (FW), and 120.2–466.1 mm (MW). ET exhibited a similar pattern under both SSDI and SDI irrigation methods, with the highest ET values recorded at the I100 irrigation level and the lowest at the I25 level across all water qualities. ET decreased linearly as irrigation amounts were reduced, indicating that water deficit directly limited evapotranspiration demand. These results are consistent with previous studies reporting a decrease in ET values as drought severity increases (Bell et al., 2018; Aydinsakir et al., 2021; Cakmakci and Sahin, 2021).

In the study, WUE increased as irrigation levels decreased, and the highest WUE across all water sources was achieved with the I25 application. In the SSDI method, WUE ranged from 1.86 to 5.48 kg m^{-3} for RW, 1.39 to 4.33 kg m^{-3} for FW, and 1.53 to 4.94 kg m^{-3} for MW, whereas in the SDI system it ranged from 1.74 to 5.01, 1.41 to 4.49, and 1.55 to 5.14 kg m^{-3}, respectively. Similarly, IWUE values increased progressively with increasing water deficit and reached their maximum at the I25 irrigation level. In SSDI, IWUE ranged from 2.24 to 6.70 kg m^{-3} for RW, 1.69 to 5.65 kg m^{-3} for FW, and 1.88 to 6.40 kg m^{-3} for MW; in SDI, the corresponding ranges were 2.12–6.37, 1.71–5.63, and 1.88–6.44 kg m^{-3}. Overall, both WUE and IWUE improved under reduced irrigation, with RW treatments exhibiting the highest water-use efficiency and outperforming FW treatments. MW produced efficiency values comparable to RW, and no significant differences were observed between SDI and SSDI for WUE or IWUE. These findings align with previous research showing that WUE and IWUE generally increase under deficit irrigation conditions and vary depending on irrigation method and water quality. For example, Rasool et al. (2020) reported that drip irrigation provided considerable water savings in maize cultivation compared with furrow irrigation during two consecutive growing seasons. Similarly, Thamer et al. (2021) found that subsurface drip–irrigated maize consumed 55–57% less water than furrow-irrigated maize. Machado and do Rosário (2005) demonstrated that subsurface irrigation produced higher IWUE than surface irrigation in tomato production, whereas Erice et al. (2010) reported a decline in water-use efficiency of alfalfa as drought stress intensified. Research on various plants has likewise shown that decreasing irrigation levels leads to increased WUE and IWUE (Marsic et al., 2012; Bahramloo and Nasseri, 2019). Furthermore, numerous researchers have reported that reclaimed wastewater use results in higher WUE and IWUE than freshwater applications (Karakaya and Ödemiş, 2019; Ghassemi et al., 2020).

Statistical analysis determined that the effects of different irrigation water qualities and irrigation levels on yield were significant at the $p<0.05$ level (Table 2). Yield decreased in all three water qualities as irrigation levels declined. Under the SSDI method, yields ranged from 6372 to 8568 kg ha^{-1} for RW, 5376 to 6484 kg ha^{-1} for FW, and 6088 to 7204 kg ha^{-1} for MW. In the SDI system, yield values varied between 6124–8184 kg ha^{-1} for RW, 5412–6612 kg ha^{-1} for FW, and 6184–7268 kg ha^{-1} for MW. The highest yield was obtained under the SSDI–RW–I100 treatment. FW consistently produced the lowest yields in both irrigation methods, with pronounced reductions particularly at the I50 and I25 levels. MW-generated yield values are comparable to RW, indicating that mixed water is a viable alternative for agricultural use. To facilitate a comprehensive evaluation of the main effects of irrigation methods, overall mean yield values were calculated across all treatment combinations. The mean yield was 6732.3 kg ha^{-1} for SSDI and 6679.7 kg ha^{-1} for SDI. While SSDI tended to yield slightly higher, the difference was not statistically significant, indicating comparable performance between the two irrigation methods. Furthermore, no substantial differences in yield were observed between SDI and SSDI, suggesting similar performance across both systems. The superior yields obtained with RW are likely attributable to the presence of plant-available nutrients in reclaimed wastewater, which may have contributed to enhanced crop growth compared with other water qualities (Alkhamisi et al., 2017; Rawashdeh, 2017; Yazdani et al., 2018). Many researchers have reported that drought stress reduces crop yield. Researchers across different irrigation levels have consistently shown that increasing water stress decreases yield (Karim et al., 2017; Yeloojeh et al., 2020; Elbashier et al., 2023; Saad et al., 2023).

Table 2. The effects on evapotranspiration (ET), yield, WUE, and IWUE values of various irrigation techniques, irrigation water quality, and irrigation levels

IM	WQ	IL	I (mm)	ET (mm)	Yield (kg ha^{-1})	WUE (kg m^{-3})	IWUE (kg m^{-3})
SSDI	RW	I100	382	459.8 a	8568 a	1.86 d	2.24 d
		I75	284	344.5 b	7732 b	2.24 c	2.72 c
		I50	190	226.3 c	7128 c	3.14 b	3.75 b
		I25	95	116.1 d	6372 d	5.48 a	6.70 a
	FW	I100	382	466.2 a	6484 a	1.39 d	1.69 d
		I75	284	349.4 b	6328 b	1.81 c	2.22 c
		I50	190	235.1 c	6004 c	2.55 b	3.16 b
		I25	95	124.1 d	5376 d	4.33 a	5.65 a
	MW	I100	382	468.7 a	7204 a	1.53 d	1.88 d
		I75	284	350.3 b	7048 b	2.01 c	2.48 c
		I50	190	234.2 c	6456 c	2.75 b	3.39 b
		I25	95	123.1 d	6088 d	4.94 a	6.40 a
		Mean	237.7	307.4	6732.3	2.84	3.52
SDI	RW	I100	385	468.8 a	8184 a	1.74 d	2.12 d
		I75	288	350.5 b	7788 b	2.22 c	2.70 c
		I50	192	237.3 c	6984 c	2.94 b	3.63 b
		I25	96	122.1 d	6124 d	5.01 a	6.37 a
	FW	I100	385	466.4 a	6612 a	1.41 d	1.71 d
		I75	288	349.3 b	6204 b	1.77 c	2.15 c
		I50	192	235.2 c	5876 c	2.49 b	3.06 b
		I25	96	120.5 d	5412 d	4.49 a	5.63 a
	MW	I100	385	466.1 a	7268 a	1.55 d	1.88 d
		I75	288	348.9 b	6972 b	1.99 c	2.42 c
		I50	192	234.6 c	6548 c	2.79 b	3.41 b
		I25	96	120.2 d	6184 d	5.14 a	6.44 a
		Mean	240.2	293.3	6679.7	2.80	3.46
Analysis of variance	IL			***	***	***	***
	WQ			***	***	***	***
	IM			**	***	***	***
	IL*WQ			ns	***	***	***
	IL*IM			ns	***	**	**
	IM*WQ			***	***	***	***
	IM*WQ*IL			ns	***	***	***

IL: irrigation levels, WQ: water quality, RW: reclaimed wastewater, FW: fresh water, MW: mixed water, I:total applied irrigation water, ET: evapotranspiration, IWUE Irrigation water efficiency, WUE water efficiency. Four irrigation levels were applied in the experiment: I25 (25% field capacity depletion), I50 (50%), I75 (75%), and I100 (100%). Mean separation based on Duncan's test indicated that identical letters represent non-significant differences among treatments, while differing letters denote significant variation. Letter groupings were generated based on the three-way ANOVA results, and comparisons were performed across all treatment combinations using Duncan's multiple range test ($p \leq 0.05$).Overall means were also calculated to enable direct comparison of irrigation methods. ns: not significant, ***: $p< 0.001$, **: $p< 0.01$, *: $p< 0.05$.

3.2. Yield components of bean

The effects of different irrigation levels, water qualities, and both subsurface and surface drip irrigation methods on root length, plant height, pod length, root weight, stem diameter, and pod width are presented in Figure 3.

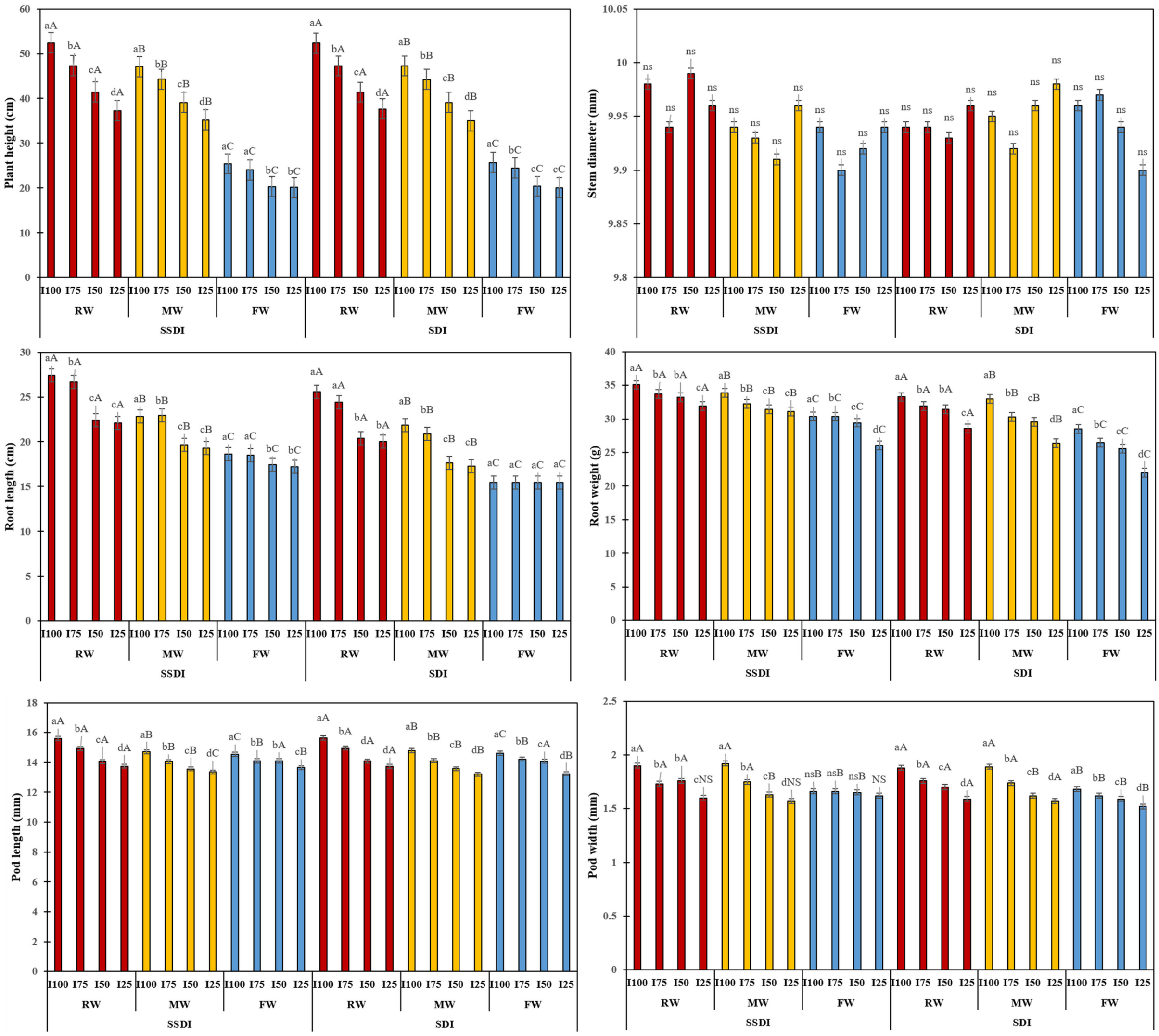

Figure 3. Effect of various irrigation strategies on plant growth criteria and yield components. SSDI: subsurface drip irrigation; SDI: surface drip irrigation; RW: treated wastewater; FW: clean water; MW: equal mixture of FW and RW. Irrigation levels I25, I50, I75, and I100 correspond to 25%, 50%, 75%, and 100% of the full irrigation requirement calculated based on cumulative evaporation measured using a Class A pan. Different lowercase letters within the same column indicate significant differences at the $p<0.05$ level between irrigation levels; different uppercase letters within the same row indicate significant differences at the $p<0.05$ level between water quality treatments.

Plant height ranged from 20.10 to 52.44 cm in the study. Similar values were observed between SSDI and SDI irrigation methods. Significant decreases in plant height were observed as irrigation levels decreased. Plant height was greater under reclaimed wastewater irrigation than under clean water irrigation. The highest plant height was observed under I100 conditions, irrigated with treated wastewater. Many studies have reported negative effects of drought stress on plant height (Bhattarai et al., 2020; Chand et al., 2020). Several studies have reported positive effects on plant height from irrigation with increased wastewater (Elliott and Jaiswal, 2012; Alkhamisi et al., 2017). This situation is thought to be due to the high nutrient content of treated wastewater.

In the study, it was observed that, across different irrigation methods, the effects of irrigation level and water quality were not significant on stem diameter. Stem diameter values ranged from 9.83 to 10.05 mm in the study. The highest stem diameter was observed under the RW–I100 treatment in both the SSDI and SDI methods. Several studies have found a negative relationship between deficit irrigation and stem diameter (Chand et al., 2020; Abd El-Mageed et al., 2021). It has also been reported that wastewater applications increase the stem diameter compared to freshwater applications (Mousavi and Shahsavari, 2014; Hamad et al., 2018). The discrepancy between our findings and those reported in the literature is likely attributable to differences in plant species, soil characteristics, climatic conditions, and geographical factors.

Different irrigation methods, water quality, and irrigation levels were found to have statistically significant effects on root length and weight ($p<0.05$). Root length in the study ranged from 15.44 to 27.40 cm, while root weight varied between 22.01 and 35.05 g. The highest root length (27.40 cm) and root weight (35.05 g) were obtained under the SSDI–RW–I100 treatment, whereas the lowest values were observed in the FW–I25 plots. Under increasing water stress conditions, a significant decrease in root length and root weight has been observed. The SSDI method positively influenced root development compared with the SDI method, likely because it delivers water directly to the root zone. Additionally, reclaimed wastewater enhanced root length and root weight more effectively than freshwater and mixed water treatments.

Previous studies have reported that deficit irrigation reduces both root length and root weight (Luo et al., 2015). Similarly, Kong et al. (2023) found that water stress negatively affects root length and root volume. Wastewater applications can also substantially influence root growth across various plant species. Paudel et al. (2016) reported that reclaimed wastewater reduced root growth by 45–55%. In contrast, some studies have shown potential benefits; for example, Sobrinho et al. (2024) indicated that reclaimed wastewater can improve soil porosity and aggregation, thereby enhancing root system development.

The effects of irrigation water quality and irrigation levels on the length and width of the pod were found to be statistically significant, occurring at the $p<0.05$ level. The pod length of the study ranged from 13.21 to 15.64 mm, and the pod width ranged from 1.52 to 1.92 mm. The study revealed no statistically significant differences among irrigation methods; however, higher levels of water stress negatively affected pod length and width. The highest pod length and pod width values were observed in I100 plots. No clear trend was observed regarding the effects of irrigation water quality on bean length and width. Yazdani et al. (2018) reported that crops grown under reclaimed wastewater treatment exhibited greater pod development than those irrigated with freshwater. Similarly, Rawashdeh (2017) found that the greatest pod development occurred under full irrigation (100%). Sezen et al. (2023) also demonstrated that reductions in irrigation levels led to decreases in pod diameter.

Conclusion

This study demonstrated that different irrigation methods and water qualities exerted strong and distinct effects on evapotranspiration, physiological traits, water productivity, and yield of bean (*Phaseolus vulgaris* L.) under different irrigation levels. Irrigation method, level, and quality influenced the crop's morphological characteristics differently; plant height and pod traits were negatively affected by water stress, root development was more pronounced under SSDI, and irrigation water quality generally had limited effects on most morphological parameters. Full irrigation (I100) produced the highest yields, and the RW–I100 combination yielded the best overall performance across both irrigation methods. Although yield declined with decreasing irrigation levels, WUE and IWUE increased, with the highest efficiencies observed under the I25 treatments. RW treatments consistently produced higher yield, WUE, and IWUE than FW, while MW performed closely to RW, indicating its potential as a usable alternative water resource for agriculture. Moreover, no substantial differences were observed between SSDI and SDI in yield or water-use efficiency, as both methods performed comparably. Overall, the findings highlight that the use of RW and MW, particularly under SSDI and SDI methods, represents an effective and sustainable irrigation strategy for bean production in regions facing water scarcity.

Ethical Statement

Since this research is limited to plant studies conducted under agricultural trial conditions, ethical approval was not required.

Conflict of Interest

The author has stated that there is no conflict of interest to be disclosed in this study.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of any images, figures, graphics, tables, or related titles.

Funding Statement

This study was supported by Project No: FCD-2024-13438, funded by Atatürk University Scientific Research Coordination Unit.

Author Contributions

All authors contributed equally to the design, execution, analysis, and writing of this study.

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