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Comparison of capillary wick and trickle irrigation systems by assessing the effects of fertigation in various soil textures on growth traits of greenhouse cucumber plant

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ABSTRACT

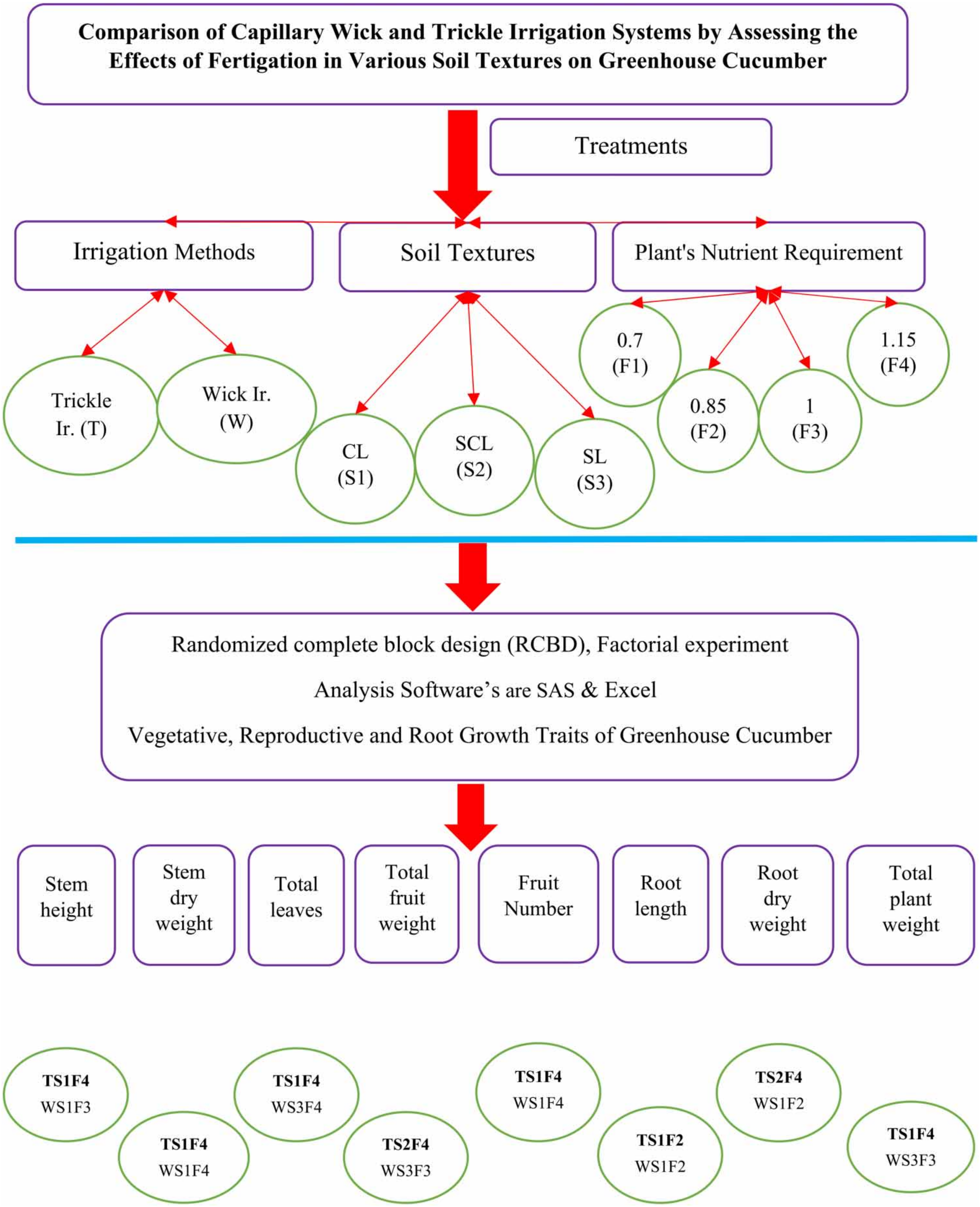
This study aimed to evaluate the capillary wick irrigation (CWI) influence on the cucumber's growth characteristics when compared to trickle irrigation (TI) over the two growing seasons. The study incorporated three different soil textures, namely clay loam (CL) – S1, sandy clay loam (SCL) – S2, and sandy loam (SL) – S3, along with four fertilizer levels (F1, F2, F3, and F4) applied at 0.7, 0.85, 1.0, and 1.15 times the plant's nutrient requirements. According to the study findings, the combination of F4 fertilizer with TI yielded the best results in terms of reproductive traits, resulting in an average of 18.66 fruits and a total fruit weight of 1,229.5 g. In the case of CWI, the highest number of fruits and their combined weight were observed at the F3 fertilizer level, with 13.42 fruits and 846.3 g, respectively. The study also revealed that TI with soil texture S1 produced the highest average yield for all growth traits, while CWI with the lighter soil texture S3 exhibited superior results in vegetative and reproductive growth traits. The maximum fruit weight (1,460.26 g) was achieved using TI and S1F4, and the highest fruit weight (995.57 g) was obtained from S3F3 when using CWI.

Key words: capillarity, fertilizer levels, irrigation methods, soil texture, subsurface

HIGHLIGHTS

- This study assesses the impact of capillary wick irrigation (CWI) on the growth characteristics of greenhouse cucumber plants, in comparison with trickle irrigation (TI).
- Soil texture is one of the most important factors determining the growth traits and yield of plants.
- Using fertilizers helped to increase cucumber fruit production.
- Capillary wick irrigation (CWI) systems require no technical skills, pump, and energy.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The rising global food demand necessitates enhanced plant biomass and yield to meet these requirements, achieved through heightened plant efficiency (Singh *et al.* 2013). Crop production hinges not solely on seed quality but also on critical factors like growth stages, fertilizer type, and irrigation methods (Abdelaziz & Abdeldaym 2018). In greenhouse cultivation, meticulous control of seedling fertility, with a primary emphasis on plant nutrition, takes on a critical role in this pursuit (Brace 2017). Amid the global challenge of water scarcity, the need to control water consumption in agriculture is paramount. This involves adopting efficient irrigation methods like drip irrigation and precision agriculture to reduce water wastage. It also requires the supervision and regulation of water use, the cultivation of drought-resistant crop varieties, and the promotion of water-efficient agricultural practices. The adoption of integrated water resource management, which balances the needs of agriculture, industry, and the environment, is essential to ensure the sustainable utilization of this precious resource. Beyond its significance in agriculture, responsible water management is a global imperative, addressing necessities such as food security, environmental preservation, and economic stability (Zeng *et al.* 2009; RezaeeKormenani *et al.* 2022).

Cucumber holds a prominent position among global agricultural crops, serving diverse daily purposes. This semi-tropical vegetable ranks fourth in worldwide production, following tomatoes, onions, and cabbage (Crosby 2008). Enhancing cucumber production, in terms of quantity and quality, hinges on optimizing environmental factors like light intensity and temperature. Additionally, effective management of pests, diseases, and the judicious use of organic and chemical fertilizers are integral aspects of this process (Hu *et al.* 2011). Water holds a pivotal role in cucumber production and its quality. The cucumber plant features a shallow root system, with roughly 85% of its root volume concentrated within the upper 30 cm layer of the soil. Consequently, insufficient water in this upper soil layer can trigger a range of physiological alterations, including shifts in the root-to-stem ratio, diminished root surface area, and leaf count reduction, ultimately resulting in reduced plant growth and yield (Hashem *et al.* 2011).

Soil texture, a critical factor impacting plant growth traits and yield (Ikram *et al.* 2012), exhibits geographical variation while remaining temporally stable, influencing numerous physical and chemical soil properties (Ebrahimi Khoosfi *et al.* 2012). Moreover, the utilization of fertilizers fosters vegetative growth and augments fruit production in plants (Abdelaziz & Abdeldaym 2018). As per a study by Mahmoud *et al.* (2009), achieving the highest cucumber yield is attainable when 75% of the nitrogen is sourced from minerals and 25% from organics. Additionally, elevating the proportion of organic nitrogen results in a reduction in nitrate concentration in the petiole, while enhancing soil nitrogen, phosphorus, and organic matter content. Multiple references indicate that the optimal nitrogen fertilizer requirement for cucumbers spans from 10 to 200 kg/ha, a range that is subject to fluctuations based on regional climate, soil composition, and the specific cultivar in use (Chinatu *et al.* 2017; Jose & Keith 2017). Lim *et al.* (2015) conducted a study investigating the influence of soil texture on cucumber fruit yield, nitrogen use efficiency, and water use efficiency in a greenhouse with subsurface drip fertilization. Their results revealed that cultivating cucumbers in loam or clay soil yielded greater benefits compared to sandy loam (SL) soil when employing subsurface drip fertilization in a greenhouse.

In potted plant cultivation, three frequently utilized irrigation methods include sprinkler irrigation, trickle irrigation (TI), and subsurface irrigation. The subsurface irrigation category encompasses three methods: ebb and flow, capillary mat, and capillary wick irrigation (CWI) (Son *et al.* 2006). Wick irrigation (WI) or CWI systems are user-friendly, low-maintenance, and do not necessitate technical expertise, energy-consuming pumps, or advanced filtration. They offer a consistent, continuous water supply to plants, effectively minimizing the risk of drought stress at minimal costs. This approach is adaptable, even in infertile soils with poor water quality (Bhatt & Kanzariya 2017). As per Lauren (2013), WI eliminates the requirement for a pumping system and leverages the soil and root's negative potential energy to transport water to the field, thereby reducing irrigation expenses while meeting the plant's requirements. This irrigation method surpasses others in efficiency, aligns with environmental concerns, and enhances water and nutrient absorption by plants while minimizing losses (Bainbridge 2002). Worldwide research has demonstrated that WI is viable in severe drought conditions, regions with limited water resources, and even areas with abundant water availability (Felipe & Bareng 2022). In Adelaide, Australia, Semananda *et al.* (2016) conducted a comparison between WI and a surface irrigation system at a 30 cm soil depth for tomato plants. Their study revealed that WI significantly reduced water usage by 50% in comparison to the surface irrigation method. In a related study, RezaeeKormenani *et al.* (2022) reported that in WI, tomato plants do not experience water stress due to the continuous availability of water. These findings collectively indicate that the WI system promotes plant growth, enhances both wet and dry matter production, and improves water productivity in tomato plants. Abioye *et al.* (2020) conducted a comparison between TI and WI in cantaloupe cultivation, revealing that WI outperformed TI in terms of water use efficiency and product quality. In terms of water use efficiency, CWI demonstrated a remarkable efficiency of 19 g/L, surpassing the efficiency of drip irrigation which achieved 4.85 g/L. This highlights the effectiveness of CWI in maximizing water utilization while ensuring optimal hydration for plants. Felipe & Bareng (2022) noted that the number of wicks used did not significantly affect the yield of lettuce, but the size and diameter of the wick played a pivotal role. Furthermore, an economic analysis indicated that 41.92% of the initial investment cost could be recouped after three cropping cycles.

Establishing drip irrigation systems involves substantial costs associated with the installation of pumps, filters, and automation equipment. Furthermore, the non-automated nature of certain irrigation systems requires continuous oversight to precise control of irrigation timing and water volume. Consequently, it becomes crucial to embark on a range of research endeavors with the goal of introducing affordable and effective irrigation methods, with a particular focus on advancing underprivileged regions. Given the scarcity of research comparing wick and TI methods in cucumber plants with varying nutritional levels and different soil textures, it becomes crucial to investigate this comparison. This study aims to evaluate the effectiveness of WI combined with fertigation in three distinct soil textures, while also comparing it to the traditional TI method. By analyzing the effects of these irrigation techniques on various growth characteristics, the results of this research can lay the groundwork for future studies and advancements in WI techniques for diverse crops and fields.

2. RESEARCH METHOD

To evaluate the influence of CWI and WI irrigations on greenhouse cucumber plants in diverse soil textures, combined with four fertigation levels, and to compare growth traits with TI, this research was carried out in the research greenhouse at Razi University. The greenhouse is located at a longitude of 47° 6′ 23″ E, latitude 34° 23′ 20″ N, and an altitude of 1,320 m above sea level. This tunnel-type greenhouse has a height of 3 m and a 4.4-m-wide opening. It is equipped with eight percent anti-UV plastic covering, shading, underfloor heating pipes along the wall, a heating system and a cooling system, ventilation fans, and air circulation. The cultivation occurred in the first half of March and the latter part of August the following year, using a pot method within a soil culture bed. Nagene variety greenhouse cucumber seedlings, aged 14 days, were planted in a randomized complete block design (RCBD) as part of a factorial experiment. Two irrigation methods, TI and CWI, were employed, along with four fertilizer levels (0.7 (F1), 0.85 (F2), 1.0 (F3), and 1.15 (F4) times the plant's nutrient requirement). This experimentation was conducted across three different soil textures: clay loam (CL) – S1, sandy clay loam (SCL) – S2, and SL – S3. Each combination was replicated three times in pots with dimensions, including a bottom diameter of 24 cm, an opening diameter of 28 cm, and a height of 30 cm. Fertilizer tanks situated at the beginning of the branch from the main pipe were utilized to feed plants via TI. Irrigation laterals were connected to these fertilizer tanks, allowing soluble fertilizer to be introduced during irrigation.

The preparation of the fertilizer solution followed the guidelines outlined in the table for fertigation and the nutritional requirements of greenhouse cucumber plants, with a solution concentration ranging from 0.5 to 1.2 g/L of irrigation water to prevent excessive electrical conductivity (EC) increase (Papadopoulos 1994). The fertilizers used in this study included NPK (20–20–20) fertilizers at a quantity of 630 kg, 220 L of micronutrients throughout the growing season, 100 kg of urea fertilizer, and 50 kg of potassium per hectare during the fruiting stage at the F3 fertigation level. The values for other fertilizer levels were also calculated and applied in accordance with their specified ratios. For WI, a tank equipped with a water level regulator was installed at the start of each sub-line, with the lateral lines connected to these tanks. These tanks served the purpose of regulating suction height and facilitating the fertilization process. Figure 1 provides a visual representation of the components of WI and an overview of the greenhouse (Supplementary Table 1).

By manipulating the water levels within the tanks, the suction height in the 16 mm wick pipes was regulated, enabling water to be transported to the vicinity of the plant roots via the wick. These wicks were constructed using a combination of wool, rayon, and polyester fibers. Figure 2 shows the diagram of the discharge-suction a wick with a wall pipe of 16 mm.

The arrangement of the sub-connections in the WI system involved a three-way branching from a 16 mm pipe for each pot. Initially, a polyester wick filter with a length of 4 cm was positioned, followed by a wick pipe measuring 45 cm in length. This wick pipe was affixed to the pot's wall through a hole, extending from the pot's body into the soil to a depth of 5 cm. Apart from its role in water transfer, the 16 mm wall wick pipe served the additional function of preventing water from evaporating along the wicks en route to the pot. It also hindered water from dispersing into the surrounding soil until it reached a designated point near the plant roots, thereby promoting an even distribution of moisture within the soil. At the base of the pots, a drainage pipe was set up, and a 5 cm layer of sand was placed around the drainage pipe. In each treatment, irrigation was

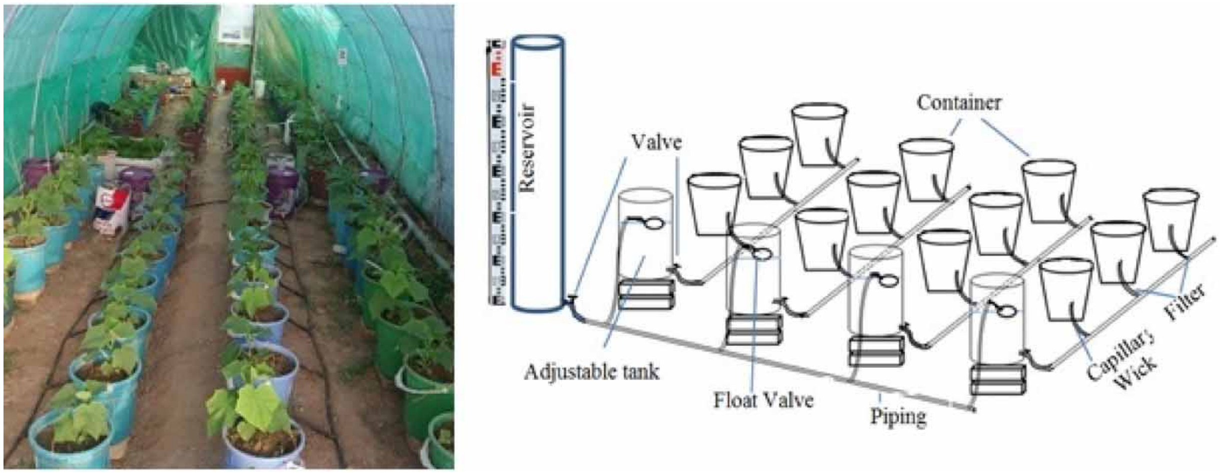


Figure 1 | Instructions for setting up the wick irrigation system and an overview of the greenhouse featuring both irrigation methods.

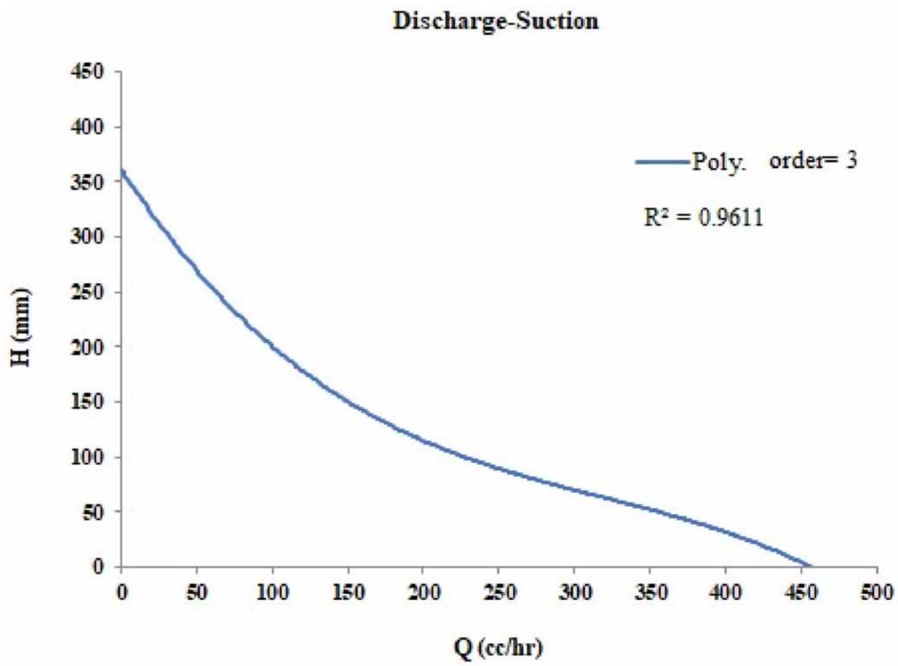


Figure 2 | Diagram of the discharge-suction a wick with the wall pipe of 16 mm.

carried out in accordance with the respective irrigation method and the plant's water requirements. WI was executed in a capillary and continuous manner, ensuring that it met the plant's self-irrigation needs while maintaining soil moisture close to field capacity. The water volume used was quantified and calculated using an altimeter in the reservoir. For TI, irrigation scheduling involved controlling the volumetric soil moisture levels using a digital soil moisture meter (PMS-714) to ensure they remained above the maximum allowable depletion level, while also considering leaf appearance to prevent plant stress. This system utilized Netafim-controlled drippers with a flow rate of 4 L/h and a pressure of 12 m. The required pressure for the drip irrigation system was 15 m, which was supplied through a water tank positioned at an elevated location. The water quantity used in TI was estimated by measuring the water output from the nozzles. Figure 3 illustrates the volumes of irrigation water used during two growing seasons, comparing the TI and CWI methods.

In the first 120-day growing season, the cucumber plants received 680 and 596 mm of irrigation water through TI and CWI, respectively. This amount was calculated based on the height of water over the average surface area of the pot (531 cm^2).

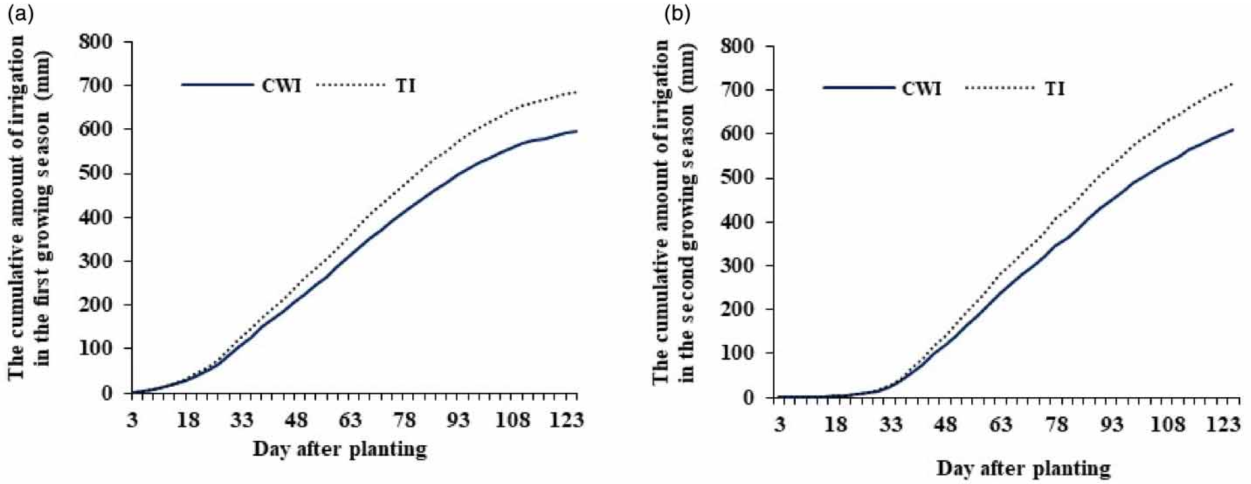


Figure 3 | Quantities of irrigation during the first phase (a) and the second phase (b) of cultivation, employing the trickle irrigation and capillary wick irrigation methods.

Likewise, during the second growing season, spanning 123 days, the plants were provided with 702 mm of water via TI and 608 mm via WI. Uniform weed control, pest management, and disease prevention measures were applied across all treatments. Tables 1 and 2 detail the physical and chemical characteristics of the soil and the irrigation water used.

This research assessed various growth parameters of the cucumber plant, encompassing vegetative, reproductive, and root development traits. These parameters included plant height, stem dry weight, leaf count, fruit count, total fruit weight, average root length, number of root branches, root dry weight, and plant fresh weight. Harvesting of cucumbers took place during the first growing season, spanning from 1 May to 20 June, and during the second growing season, from 3 November to 25 December. The cucumbers were collected at their appropriate sizes while still attached to the plant. Each harvested fruit was delicately placed in labeled envelopes. Subsequently, the number of fruits was tallied, and their length was measured using a ruler. Furthermore, the weight of each fruit from every plant was precisely determined using a digital scale with a precision of 0.001 g. At the end of the growth season, the plant's stem was separated and dried in an oven at 70 °C for 72 h to measure its dry weight using a scale. The number of leaves was determined by counting them at the end of the cucumber plant growth season. The cucumber shoot weight was also measured using a digital scale at the end of the growth season. The height of the cucumber plant was measured during the plant growth season using a tape measure. To compute the root dry weight at the end of the growth season, all the roots underwent thorough washing under medium-pressure running water to minimize damage, with the soil adhering to the roots being meticulously removed. The roots were submerged in a rectangular container

Table 1 | Physical and chemical characteristics of soil

Soil	Soil texture	Sand (% (	Silt (%)	Clay (%)	(OC) (%)	P (ppm)	K (ppm)	ρb (g cm^{-3})	Volumetric humidity (%) Saturated moisture	Field capacity	Wilting point
S1	Clay loam	33	31	36	1.15	15.18	211	1.3	50	39	22
S2	Sandy clay loam	55.5	20.7	23.8	0.63	10.21	120	1.43	47	32	17
S3	Sandy loam	65.2	16.3	18.5	0.35	9.17	70	1.5	41	22	11

Table 2 | Chemical characteristics irrigation water

EC (µs/cm)	pH –	Ca^{2+} (ppm)	Mg^{2+} (ppm)	Na^{+} (ppm)	K^{+} (ppm)	SO_4^{2+} (ppm)	Cl^{-} (ppm)	CO_3^{2-} (ppm)	CO^{3-} (ppm)	NO^{3-} (ppm)	PO_4^{2-} (ppm)	SAR $(mmol/L)^{0.5}$
260	7.1	200	150	22	4.2	48	100	80	300	0.118	0.137	0.29

filled with water to a depth of about 5 cm. The roots were carefully separated, and the length of the primary root was measured, along with counting the number of branches. After the roots were taken out of the water, their dry weight was determined by subjecting them to a dry oven and employing a digital scale. Subsequently, the collected data underwent statistical analysis using SAS 9.4, and a mean comparison was conducted utilizing Duncan's multiple range tests.

3. RESULTS AND DISCUSSION

Table 3 presents the outcomes of the composite variance analysis, highlighting the impact of various treatments on the vegetative, reproductive, and root growth traits of cucumber plants throughout the growth season. The results indicated that the influence of the growing season and fertilizer was statistically significant for all vegetative, reproductive, and root growth traits at a 1% probability level. Additionally, the effect of soil was statistically significant for all plant growth traits, except for root dry weight, at a 1% probability level. Notably, the result showed that the impact of irrigation was insignificant for stem dry weight, leaf count, and root branch count. It was, however, significant for root length at a 5% probability level and significant for other traits at a 1% probability level. The obtained findings are consistent with prior research. For instance, Şimşek *et al.* (2005) reported a significant impact of irrigation on the yield and yield components of cucumber plants at a 5% probability level. In a study by Lim *et al.* (2015), which explored the influence of soil texture on greenhouse cucumber production and water use efficiency, the effect of texture was found to be significant at a 5% probability level. Furthermore, Prabhu *et al.* (2006) noted in their study that various fertilizer levels had a significant impact on cucumber yield at a 1% probability level. The effect of interactions between soil and the growing season on the stem dry weight, leaf count, fruit count, and plant fresh weight were significant at a 5% probability level, whereas stem height, leaf count, root length, and root branch count were significant at a 1% probability level. However, no significant effects were observed for fresh fruit weight and root dry weight. Furthermore, an examination of the mutual effects of irrigation method and growing season revealed that, except for fruit fresh weight, all other traits exhibited significance at the 1% probability level. Previous research by Liu *et al.* (2017) has extensively examined the interplay between irrigation method and growing season on cotton vegetative traits. Their findings indicated that plant height and leaf area index displayed significance at a 5% probability level, while cotton yield was affected at a 1% probability level due to these interactions.

Analyzing the interaction between fertilizers and the growing season revealed noteworthy effects. Among vegetative traits, stem height and dry weight exhibited significance at a 1% probability level, while the number of leaves was significant at a 5% probability level. In terms of reproductive traits, fruit fresh weight displayed significance at a 5% probability level, although no significant effect was observed for fruit count and plant fresh weight. In terms of root traits, the interaction demonstrated significance at probability levels of both 1 and 5%. Additionally, in a related study, the combined impact of fertilizer and irrigation on tomato plants across two consecutive years was investigated. The results indicated that this interaction significantly affected fruit production (Mousavifazl *et al.* 2019). The interaction between fertilizer and irrigation methods showed no significance on stem height but was found to be significant at a 5% probability level for stem dry weight. For other traits, this interaction exhibited significance at a 1% probability level. Moreover, this interaction was significant in terms of reproductive and root growth traits at a 1% probability level, while it was found to be significant for root dry weight at a 5% probability level. These results align with findings from related research. For instance, Lenka & Singh (2011) observed that the combined impact of different fertilizer levels and irrigation was significant at a 1% probability level on the biomass and yield of wheat and corn plants. In another study investigating the effect of compost on growth characteristics and nutrient concentration in cucumber plants under moisture stress, researchers reported that the interaction between moisture levels and fertilizer levels significantly influenced fruit count and fruit length at a 1% probability level (Mohasseli & Farbood 2022).

The interactions between the irrigation method and soil texture were significant at a 5% probability level for leaf number and root length. However, the interaction was not significant for root dry weight and showed significance at a 1% probability level for other traits. Finally, the examination of the triple interaction effects (fertilizer × irrigation × soil) and quadruple interaction effects (fertilizer × irrigation × soil × growing season) of the studied treatments revealed that all the analyzed traits held significance at a probability level of 1% (Table 4).

According to Table 4, the data reveal that the interaction between soil types and growing seasons highlights the dominance of (CL) – S1 for most vegetative traits. In all measured traits over the course of two growing seasons, the ranking of soil textures in terms of promoting higher yields in cucumber plant vegetative characteristics was consistently S1, followed by S2, and finally S3. When it comes to reproductive traits, the results indicated that over two growing seasons, (CL) – S1 exhibited

Table 3 | Composite variance analysis table for cucumber growth traits, conducted in a factorial experiment and following a randomized complete block design

		Mean squares								
		Vegetative traits			Reproductive traits		Root organs			
Sources of variation	Degrees of freedom	Stem height (cm)	Stem dry weight(g)	Leaves number	Total fruit weight (g)	Number of fruits	Root length (cm)	Branches number	Root dry weight (g)	Plant fresh weight (g)
Growing season	1	41,786**	217.17**	34,083**	10,667,518.1**	724.5**	821.8**	1,928.7**	0.57**	14,020,481**
Replication	2	1,131.7*	0.01ns	7.90ns	10,584.9ns	1.8ns	0.4ns	1.8ns	0.06*	3,204.5ns
Irrigation system	1	36,832**	0.07ns	0.20ns	2,131,278.8**	357.8**	28.4*	4.7ns	4.29**	2,087,216**
Soil	2	28,585**	56.60**	197.97**	752,959.4**	112.1**	72.2**	306.4**	0.008ns	1,123,760**
Fertilizer	3	8,212.7**	15.56**	103.19**	139,904.9**	44.5**	72.8**	60.0**	0.12**	256,621.5**
Soil × Growing season	2	6,077.7**	1.92*	104.33*	9,389.2ns	17.6*	40.9**	360.6**	0.044ns	29,784.5*
System × Growing season	1	60,066**	30.80**	249.11**	31,641.3ns	82.5**	242.8**	373.8**	2.07**	209,762.5**
Fertilizer × Growing season	3	6,115.5**	2.33**	75.84*	31,478.5*	9.0ns	53.9**	59.2**	0.06*	19,106.9ns
Fertilizer × System	3	459.6ns	2.00*	99.38**	184,193.3**	34.9**	93.5**	197.0**	0.059*	195,884.7**
System × Soil	2	9,191.2**	15.05**	98.55*	685,987.1**	42.2**	29.7*	57.9**	0.021ns	800,796.5**
Fertilizer × System × Soil	12	1,842.8**	3.86**	210.48**	80,040.0**	10.6**	30.7**	69.3**	0.18**	121,194.2**
Fertilizer × System × Soil × Growing season	17	1,063.6**	4.95**	319.59**	210,388.5**	26.8**	32.7**	69.2**	0.13**	253,916.7**
Error	94	244.30	0.55	23.18	9,445.61	3.65	7.08	11.52	0.017	8,952.23
Cv%	–	8.12	10.78	10.85	10.36	13.21	11.38	13.98	13.65	8.04

*, **, and ns show significance at 5%, 1%, and not significant probability levels, respectively.

Table 4 | Average comparison of interaction effects of treatments of growing season × soil, growing season × irrigation system, and growing season × fertilizer on cucumber growth traits

Factor			Vegetative traits			Reproductive traits		Root organs			
Growing season	**Treatment**		**Stem height (cm)**	**Stem dry weight (g)**	**Leaves number**	**Total fruit weight (g)**	**Number of fruits**	**Root length (cm)**	**Branches number**	**Root dry weight (g)**	**Plant fresh weight (g)**
First	Soil	S1	193.41d*	6.82d	30.71f	802.82e	14.46d	23.29abc	28.69b	1.06a	1,027.21e
		S2	167.66gh	5.37d	28.79fg	654.10f	11.50f	20.33cd	32.75a	0.99a	839.55f
		S3	165.29h	4.74e	27.42g	539.47g	10.69f	19.29d	22.35e	1.00a	727.16g
Second	Soil	S1	242.62a	9.17a	59.58b	1,319.94a	17.67a	25.95ab	19.96f	0.87a	1,628.63a
		S2	212.45c	8.28b	62.96a	1,227.12b	17.08ab	26.20a	20.79ef	0.88a	1,520.73b
		S3	173.50f	6.88c	56.68c	1,082.39c	15.38cd	25.08ab	21.08ef	0.92a	1,316.75c
Two-G. season average	Soil	S1	218.02b	8.00b	45.14d	1,061.38c	16.06bc	24.62ab	24.32d	0.97a	1,327.92c
		S2	190.06e	6.83c	45.87d	940.61d	14.29d	23.27abc	26.75c	0.94a	1,180.14d
		S3	169.39g	5.81d	42.05e	810.94e	13.03e	22.18bcd	21.71ef	0.96a	1,021.96e
First	Irrigation system	W	171.02d	5.20e	27.69c	528.98e	9.88e	20.13d	29.36a	0.73d	706.08f
		T	179.88c	6.09d	30.25c	801.95d	14.56c	21.83c	26.50b	1.31a	1,023.20e
Second	Irrigation system	W	245.94a	8.59a	61.09a	1,102.98b	15.89b	27.50a	18.82d	0.84cd	1,406.48b
		T	173.11d	7.62b	58.39a	1,316.65a	17.53a	24.01b	22.40c	0.95c	1,570.93a
Two-G. season average	Irrigation system	W	208.48b	6.90c	44.39b	815.99d	12.88d	23.80b	24.08bc	0.78d	1,056.28d
		T	176.49cd	6.85c	44.32b	1,059.30c	16.04b	22.92bc	24.45bc	1.13b	1,297.07c
First	Fertilizer	F1	168.16g	5.16i	27.61e	566.78i	10.61f	18.33e	26.83b	0.97bcd	743.53h
		F2	179.22ef	5.80g	29.33de	643.00h	11.81e	24.00bc	27.39ab	1.14a	859.51i
		F3	179.11ef	5.44h	27.44e	671.74g	12.14e	21.44cde	30.28a	0.92d	861.97 i
		F4	175.33 fg	6.20f	31.50d	780.35f	14.33c	20.14de	27.22ab	1.05ab	993.55h
Second	Fertilizer	F1	181.55ef	7.14d	58.28ab	1,149.62b	15.83b	24.72abc	19.81ef	0.91d	1,391.18d
		F2	193.55cd	7.92bc	56.94b	1,217.02a	16.33b	25.92ab	18.61f	0.93cd	1,488.97c
		F3	219.16b	8.09b	62.08a	1,235.89a	17.27a	25.06ab	20.64 def	0.88d	1,523.33b
		F4	243.83a	9.29a	61.67a	1,236.73a	17.38a	27.33a	23.39cd	0.86d	1,551.34a
Two- G. season average	Fertilizer	F1	174.86fg	6.15f	42.94c	858.20e	13.22d	21.53cde	23.32cd	0.94bcd	1,067.35g
		F2	186.38de	6.86e	43.14c	930.00d	14.07c	24.96ab	23.0cde	1.04abc	1,174.24f
		F3	199.14c	6.76e	44.76c	953.82d	14.71c	23.25bcd	25.46bc	0.90d	1,192.65f
		F4	209.58b	7.75c	46.58c	1,008.54c	15.86b	23.74bc	25.31bc	0.96bcd	1,272.45e

*In each column, the treatments which mean at least one letter in common is not significantly different from each other.

superior performance in terms of both fruit number and fruit fresh weight compared to other treatments. S2 secured the second position in yield, while S3 consistently demonstrated the lowest yield among the various soil textures for cucumber plant reproductive traits. This outcome can be attributed to the fact that S1, with its superior water and fertilizer retention capabilities, and typically found in nutrient-rich, heavy-textured soils, facilitated higher yields in both vegetative and reproductive traits. Prior research has consistently shown that crops with sufficient water, as opposed to those with limited water, tend to produce larger fruits and overall higher yields (Mao *et al.* 2003; Kumar *et al.* 2007; Zeng *et al.* 2009). As S1 and S2 share heavier soil textures at equivalent moisture levels, a higher suction force is required to draw in water. Consequently, this prompts the roots to extend deeper and develop additional branches to facilitate water absorption. Analysis of root traits over two growing seasons, as well as the average across both seasons, indicated that S2, S1, and S3 exhibited varying levels of suitability in terms of the number of root branches, respectively. The lack of moisture stress, which is the primary catalyst for root development, resulted in no statistically significant differences in the measured traits. Salgado & Cautin (2008) have noted that the number of root branches is directly correlated with water utilization, storage capacity, and soil porosity. Therefore, in soils with moderate to heavy textures that boast optimal porosity, moisture distribution patterns achieve an ideal equilibrium. Consequently, roots in such soil types encounter minimal constraints on both horizontal and vertical growth, ultimately leading to optimal yields.

Based on a comparison of means for the interactions between the irrigation system and growing season, as illustrated in Table 4, and the average yields over two growing seasons, it is evident that in the case of WI, all vegetative traits outperformed TI. However, several factors contributed to TI's superior performance in reproductive traits, despite WI's advantages. These factors include TI's well-established management practices, the increase in soil EC caused by WI compared to TI during the growing season, limited experience with fertigation in WI, the consistency of moisture distribution during the growing season, and only minor fluctuations in soil moisture content with WI. The results clearly indicate differences in production between the two irrigation systems, TI and WI, over the course of two growing seasons. Furthermore, it is worth noting that the disparity between WI and TI decreased, showing improvement during the second growing season compared to the first. This suggests that a deeper understanding and experience with WI can lead to enhanced performance in both vegetative and reproductive traits and ultimately boost overall production. In terms of root growth traits, even though there were no statistically significant differences observed in the average of the two growing seasons, it is essential to highlight that the primary driver of root development is the absence of high moisture stress. The relative advantage of TI over WI can be attributed to the consistently high moisture levels in the soil maintained by WI, which, in turn, led to a relative reduction in root growth. This finding aligns with the results of Shafaie *et al.* (2019), who investigated the impact of soil moisture on cucumber root growth and similarly concluded that increasing soil moisture content tended to diminish root growth. Their study revealed that the treatment with 45% moisture relative to field capacity at the time of irrigation resulted in the greatest root length, as well as the highest fresh and dry weight of the roots.

The analysis of the impact of different fertilizer levels applied during the growing season on various traits indicated that, considering the average yields of both vegetative and reproductive traits over two growing seasons, F4 emerged as the superior treatment. In the case of reproductive traits during the second growing season, there was no statistically significant difference between the nutritional levels of F4 and F3. It is essential to underscore that achieving a proper balance between water and nutrient components in the fertilization program is a pivotal factor influencing cucumber yield and quality. The positive effects of employing high levels of NPK fertilizers on the growth, fruit yield, and quality of cucumbers and other crops have been substantiated by previous researchers (Miller *et al.* 1976; Abdel-Aziz 1998; Feleafel & Mirdad 2013). In terms of root traits, F2 displayed superior performance compared to the other treatments. A noteworthy trend observed in Table 4, based on mean comparisons, is that the yield of both vegetative and reproductive traits during the second growing season exceeded that of the first growing season. This improvement can be attributed to the accumulated experience from the first growing season, more effective management of the irrigation system during the second growing season, and modifications in the management of systems, particularly the WI system for fertilization. Table 5 depicts the interactions between fertilizer in the irrigation method, and soil in the irrigation method.

The analysis of the interaction between fertilizer level and irrigation method, specifically using TI, revealed that F4 exhibited superiority in the majority of the studied vegetative traits. This underscores the positive response of cucumber plant vegetative traits to the proper supply of organic elements in the soil. In a related context, Feleafel *et al.* (2014) documented that employing NPK fertilizers at 125% of the cucumber plant's requirements results in increased plant height, leaf count, branch number, fruit weight, fruit quantity, and overall yield. Conversely, when employing WI for vegetative traits, the results

Table 5 | Comparing the average results of two growing seasons for the combined effects of fertilizer and irrigation method, as well as the interactions between irrigation method and soil type

Factor		Treatment	Vegetative traits: Stem height (cm)	Stem dry weight (g)	Leaves number	Reproductive traits: Total fruit weight (g)	Number of fruits	Root organs: Root length (cm)	Branches number	Root dry weight (g)	Plant fresh weight (g)
Two-G.season average TI	Fertilizer	F1	159.55h*	6.09h	44.22d	908.4d	13.66c	18.66g	22.83f	1.056c	1,115.3c
		F2	172.13g	6.90d	44.0e	1,038.0c	15.83b	25.36a	23.33d	1.23a	1,293.1b
		F3	177.94f	6.44f	42.33f	1,061.3b	16.00b	23.61d	23.08e	1.07c	1,285.5b
		F4	196.39d	7.99a	46.72b	1,229.5a	18.66a	24.05c	28.55a	1.16b	1,494.4a
Two-G.season average CWI	Fertilizer	F1	190.17e	6.21g	41.66g	807.99g	12.77f	24.39b	23.81c	0.82e	1,019.4f
		F2	200.66c	6.82e	42.27f	821.95f	12.30g	24.55b	22.66f	0.84d	1,055.4e
		F3	220.33b	7.08c	47.19a	846.3e	13.42d	22.88f	27.83b	0.726g	1,099.9d
		F4	222.78a	7.49b	46.44c	787.6h	13.05e	23.42e	22.05g	0.74f	1,050.5e
Two-G.season average TI	Soil	S1	217.54a	8.55a	46.5a	1,289.7a	18.6a	25.04a	25.77c	1.12b	1,566.3a
		S2	163.00c	6.75d	45.9b	1,084.8b	15.9b	22.68e	26.35b	1.13ab	1,320.5b
		S3	148.95d	5.26f	40.54e	803.4de	13.7c	21.04f	21.23f	1.14a	1,004.4e
Two-G.season average CWI	Soil	S1	189.84b	6.36e	43.8c	818.5cd	12.40e	24.23b	22.87d	0.82c	1,038.5d
		S2	217.12a	6.91c	45.83b	796.4e	12.7d	23.87c	27.18a	0.75e	1,039.7d
		S3	218.50a	7.42b	43.55d	833.0c	13.50c	23.33d	22.20e	0.79d	1,039.6d

*In each column, the averages that have at least one letter in common are not statistically significantly different from each other (Duncan's method). TiSj and CiSj show a combination of treatments. T and C show TI and CWI, and i and j show level of treatments.

indicated a nearly equivalent yield, with only a slight variation observed at F3 compared to F4. This suggests that WI exhibits higher efficiency at lower fertilizer levels for vegetative traits when compared to TI. These findings are in line with Enche *et al.* (2019) research, which concluded that the utilization of fertilizers with WI proved more effective compared to other irrigation systems in cucumber plants. The outcomes of the interaction between fertilizer levels and irrigation methods on reproductive traits indicated that in the case of TI, the most substantial yield was observed at fertilizer level 4 (F4). In this particular fertilization method used in the study, which is less efficient than WI regarding fertilizer utilization, the application of higher fertilizer levels can be attributed to the increase in nitrogen content within the plants. This increase results in enhanced cell division, as well as carbonization, which subsequently leads to greater fruit length and fruit weight. These findings are in line with the results reported by Phu in 1996. Regarding WI, the findings showed that fertilizer level 3 (F3) outperformed the other fertilizer levels in terms of both reproductive and vegetative traits. In the section focusing on root traits, the analysis of the interplay between various fertilizer levels and irrigation methods demonstrated notable outcomes. In the case of TI, fertilizer level 2 (F2) resulted in higher root dry weight and root length, and fertilizer level 4 (F4) showed an increased number of root branches compared to the other treatment options. On the other hand, with WI, fertilizer level 2 (F2) exhibited superior results in terms of root dry weight and root length, while fertilizer level 3 (F3) produced a higher number of root branches compared to the alternative treatments.

Based on the findings, both irrigation systems demonstrated similar efficiency in utilizing fertilizer for root development, with Fertilizer Level 2 (F2) yielding higher results. These results align with those of Moshbaki Isfahani and Besharati 2015, who also observed the maximum root dry weight in cucumber plants when applying fertilizer at 50% of the recommended rate. Furthermore, Liang *et al.* (2014) conducted a study investigating the impact of fertilizer application methods (conventional spacing, delayed fertilization, and daily fertilization) on root traits and greenhouse cucumber plant yield. Their results indicated that despite using lower fertilizer levels for delayed fertilization compared to the other two methods, it led to better performance in terms of root length, average root diameter, and root volume. These findings are in line with the outcomes of the current study. As per the mean comparison results presented in Table 5, when considering the interaction between irrigation method and soil texture for vegetative traits, it was observed that, under TI, the highest average yield across two growing seasons for most vegetative, reproductive, and root growth traits was associated with Soil Texture S1. Conversely, the lowest yield was seen in Soil Texture S3. Notably, plant fresh weight under TI decreased from Soil Texture S1 to S3, while under WI, it increased from S1 to S3. The reason behind this difference can be attributed to the fact that TI, with its non-continuous water discharge from nozzles, favors agricultural soil with a medium to heavy texture. This type of soil enables efficient water absorption by the plant and provides an adequate water supply, promoting the turgescence of plant cells. As a result, cell division, cell count, and cell volume increase, ultimately leading to enhanced vegetative growth and increased plant fresh weight. Under the WI system, the highest yield for vegetative traits was associated with Soil Texture S3. Notably, there was an increase in the yield of these traits as the soil texture transitioned from heavy to light. This outcome highlights that in the WI system, characterized by a consistent soil moisture level at field capacity, lighter soil textures benefit from increased water movement due to greater macro porosity in comparison to medium and heavy soils. Consequently, this enhanced water movement promotes water absorption, ultimately leading to increased crop yield and growth.

The outcomes of the interaction between soil texture and the irrigation system concerning reproductive traits indicated that under TI, Soil Texture S1 exhibited superiority. In a similar vein, Lim *et al.* (2015) suggested that, in general, when utilizing subsurface drip fertilization in greenhouses, growing cucumbers in loam or CL soils is more advantageous than using SL soil, aligning with the findings of this study. Conversely, under WI, Soil Texture S3 outperformed in terms of fruit fresh weight and the number of ripe fruits, with a noticeable increase in reproductive trait yields as soil texture shifted from heavy to light. In this irrigation system, characterized by high moisture and minimal moisture fluctuations throughout the growing season, lighter soils offer a more favorable environment for root respiration, root mobility, and overall crop production compared to other soil textures. In the research conducted by Abedi Koupai & Mesforoush (2009), when examining the combined impact of soil texture and irrigation quantity, it was observed that reducing irrigation led to a decrease in cucumber yield. However, the reduction in yield was significantly less pronounced in sandy soil compared to CL soil, likely due to the improved ventilation in sandy soil. In a separate study by Ahmadi *et al.* (2010), the influence of various irrigation regimes on different soil textures for potato plants was investigated. Their findings indicated that full irrigation and an SL texture were more favorable for tuber weight, root dry weight, biomass, and leaf area index compared to other soil textures.

Table 6 | Investigating the combined effects of irrigation methods × fertilizer × soil

			Vegetative traits			Reproductive traits		Root organs			
Irrigation method	Soil texture	Fertilizer level	Stem height (cm)	Stem dry weight (g)	Total leaves	Total fruit weight (g)	Number of fruits	Average length (cm)	Number of branches	Dry weight (g)	Total plant weight (g)
TI	S1	F1	190.33f*	8.01cde	50.67bc	1,243.39c	17.17cd	19.00g	24.67c–g	1.04fg	1,505.49d
	S1	F2	188.83f	8.03cde	45.17efg	1,139.29e	18.00bc	28.50a	28.33abc	1.24c	1,409.49e
	S1	F3	236.67b	8.61bc	46.50def	1,315.82b	19.00ab	27.00ab	19.42 hij	1.19cd	1,616.25b
	S1	F4	254.33a	9.56a	43.67fg	1,460.26a	20.17a	25.67bcd	30.67ab	1.00g	1,734.03a
	S2	F1	141.17k	4.93m	39.83hi	768.05o	11.50ij	18.33g	20.83g–j	0.80ijk	936.13n
	S2	F2	172.17g	7.43e–h	44.67efg	1,217.34d	16.67d	22.58ef	22.17f–j	1.12de	1,484.47d
	S2	F3	154.17hi	5.81kl	44.67efg	1,131.72f	16.00d	26.50abc	30.75ab	1.21c	1,330.42f
	S2	F4	184.50f	8.84b	54.50a	1,222.19d	19.33a	23.33def	31.67a	1.40a	1,533.14c
	S3	F1	147.17ijk	5.34lm	42.17gh	713.75t	12.33ghi	18.67g	23.00d–i	1.32b	904.32o
	S3	F2	155.33h	5.25lm	42.17gh	757.53p	12.83ghi	25.00b–e	19.50hij	1.34ab	987.38m
	S3	F3	143.00jk	4.91m	35.83jk	736.23r	13.00gh	17.33g	19.08ij	0.81ij	909.7no
	S3	F4	150.33 hij	5.59lm	42.00gh	1,005.99g	16.50d	23.17ef	23.33d–h	1.10ef	1,216.03h
CWI	S1	F1	187.83f	6.29jk	39.83hi	834.05l	13.33g	23.00ef	24.00d–g	0.84ij	1,043.67l
	S1	F2	201.83e	7.26f–i	44.67efg	876.09i	13.50fg	26.50abc	26.67cde	0.92h	1,133.32ij
	S1	F3	242.33b	7.74def	46.67def	760.98op	12.58ghi	22.33f	25.83c–f	0.72kl	1,022.93l
	S1	F4	242.00b	8.40bcd	44.00efg	861.11j	14.83e	25.08b–e	19.00ij	0.80ijk	1,158.21i
	S2	F1	205.83de	6.97g–j	47.83cde	867.39j	13.50fg	25.67bcd	25.25c–f	0.85 hi	1,114.14j
	S2	F2	227.67c	7.42e–h	49.17cd	845.54k	12.67ghi	23.50def	26.83bcd	0.81ij	1,116.98j
	S2	F3	212.67d	6.71ij	44.33efg	782.58n	13.00gh	23.50def	32.00a	0.68l	1,019.77l
	S2	F4	222.33c	6.57ij	42.00gh	690.03u	11.67hij	22.83ef	24.67c–g	0.68l	908.13o
	S3	F1	176.83g	5.37lm	37.33ij	722.52s	11.50ij	24.50c–f	22.17f–j	0.78ijk	900.39o
	S3	F2	172.50g	5.79kl	33.00k	744.24q	10.75j	23.67def	18.50j	0.81 ij	915.82no
	S3	F3	206.00de	6.80 hij	50.57bc	995.57h	14.67ef	22.83ef	25.67c–f	0.79ijk	1,256.86g
	S3	F4	204.00e	7.53efg	53.33ab	811.66m	12.67ghi	22.33f	22.50e–j	0.76jk	1,085.19k

*In each column, the averages that have at least one letter in common are not statistically significantly different from each other (Duncan's method). TSiFj and CSiFj show a combination of treatments. T and C show TI and CWI, S shows soil, F shows fertigation, and i and j show level of treatments.

As shown in Table 5, the results pertaining to root length and dry weight traits under WI in various soil textures revealed that Soil Texture S1 displayed notably superior performance, marking a significant distinction from other soil textures. In contrast, in the trickle TI, the transition to lighter soil textures (from S1 to S3) had a diminishing effect on root growth, resulting in reduced growth. This difference is attributed to the characteristics of TI, which concentrates water in a specific soil surface area. Changes in soil texture from heavy to light lead to decreased water retention in the soil, subsequently hindering root growth in lighter textures. Under WI, the consistent presence of moisture across all textures curtails root development. Therefore, in relative comparison, the growth of the mentioned traits was more robust in TI than in WI. Table 6 presents the interactions between irrigation methods, soil texture, and fertilizer levels concerning these traits.

The combined impact of soil and fertilizer in TI revealed that the highest yields for stem height, stem dry weight, fruit number, total fruit weight, and total plant weight were associated with the combination of TIS1F4 (the interaction of irrigation methods, fertilizer amounts, and soil textures). Additionally, the number of leaves was notably linked to TIS2F4. This interaction under TI is due to the localized water discharge, which benefits agricultural soils with a medium texture. This texture creates a more efficient wetting pattern, ensuring adequate water absorption by the plant, and ultimately boosting vegetative growth and overall yield. Comparatively, when it comes to nutrient efficiency, using TI rather than WI has resulted in lower fertilizer efficiency, making F4 a more suitable option than F3. Regarding root traits under TI, the results indicated that the combination of TIS2F4 yielded the highest number of branches and root dry weight, while the combination of TIS1F2 resulted in the longest average root length. The outcomes of the interaction between WI and fertilizer revealed that the most substantial yield of vegetative traits in cucumber plants was observed when using CWIS3F3 (the interaction of irrigation methods, fertilizer amounts, and soil textures). This interaction also yielded the highest results for reproductive traits, including the number of fruits and total fruit weight, under CWIS3F3. This pattern indicates that WI maintains soil moisture consistently within the field capacity range. Consequently, in soil textures such as SL, which fall into the category of light soil textures, water movement is expedited due to the presence of macro porosity, resulting in enhanced water absorption and more efficient utilization of soil organic resources. Ultimately, this leads to higher crop yield and growth. In terms of root traits, the results indicated that the combination of CWIS1F2 yielded the highest average root length and root dry weight, while the combination of CWIS2F3 resulted in the greatest number of root branches.

4. CONCLUSION

The study investigated the impact of fertigation with two different irrigation methods (TI and WI) on the growth of greenhouse cucumber plants in various soil textures. The results showed significant interactions between irrigation and fertilizer levels, with TI performing better in terms of vegetative traits and WI performing better in terms of reproductive traits. The study also found that certain soil textures (S1 and S3) and fertilizer levels (F4 and F3) resulted in better plant performance. Based on these findings, it is recommended to use TI in (CL) – S1 and F4 soils, and WI in (SL) – S3 and F3 soils for cucumber cultivation. WI offers higher efficiency in fertilizer consumption, cost reduction, simple management, and healthier produce. Additionally, TI can be used in light soil textures if the necessary organic and mineral substances are provided. Therefore, by implementing these irrigation methods and soil choices, the vision of achieving higher yields and healthier cucumber plants in the future can be realized.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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