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Productivity, Quality and Yield Stability of Sugar Beet (Beta Vulgaris l.) Varieties under Surface and Subsurface Drip Irrigation in Newly Reclaimed Sandy Soils

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Abstract

Objective: *Efficient irrigation management combined with suitable cultivars is essential for improving sugar beet productivity and quality under water-limited conditions. This study evaluated the effects of surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) on growth characteristics, yield, and quality traits of three sugar beet varieties (Heba, Sirana, and Peti) over two successive growing seasons.*

Methods: *Two field experiments were conducted during two winter seasons of 2020–2021 and 2021–2022 at Research and Production Station of the National Research Centre, El-Nubaria El-Behera Governorate. The experiment was arranged using split-plot design with three replications and data were analyzed using the combined analysis of both seasons.*

Results: *The results demonstrated that SSDI significantly improved growth characteristics, particularly root diameter and biomass accumulation, compared with SDI. Root and sugar yields were also markedly increased under SSDI. Among the tested varieties, Heba exhibited superior performance, recording the highest values of growth parameters, total biomass, root yield, and sugar yield, followed by Sirana, while Peti showed the lowest performance. A significant interaction between irrigation systems and varieties was observed, where the combination of SSDI and Heba produced the highest root and sugar yields. Quality parameters were also significantly affected; SSDI reduced sodium and α-amino nitrogen contents while maintaining acceptable sugar concentrations, resulting in improved technological quality.*

Conclusion: *The findings indicate that subsurface drip irrigation combined with a high-performing cultivar such as Heba represents an effective strategy to enhance sugar beet productivity, quality, and water-use efficiency under newly reclaimed sandy soil conditions.*

Keywords: Subsurface Drip Irrigation, Surface Drip Irrigation, Water Us Efficiency, Impurities, Quality Parameters, Sugar Yield, Varieties of Sugar Beet

1. Introduction

Sugar beet (*Beta vulgaris* L.) has become one of the most strategic crops for sugar production in Egypt due to its adaptability to newly reclaimed lands and its relatively short growing cycle compared with sugar cane. Unlike sugar cane, which requires a long growing season and large quantities of irrigation water, sugar beet completes its life cycle in nearly half the time and demonstrates higher water productivity, making it more suitable under conditions of increasing water scarcity and climate variability [1,2]. In response to rising domestic sugar demand, Egypt has significantly expanded the cultivated area of sugar beet as part of a national strategy to reduce dependence on imports. Official agricultural statistics indicate that the cultivated area increased from approximately 600,000 fed in 2022 to about 620,000 fed in 2023, with continued expansion in newly reclaimed sandy soils, particularly in Northern Egypt and the Nubaria region [3,4]. This expansion underscores the economic importance of sugar beet and its critical role in enhancing national sugar self-sufficiency. Despite this expansion, sugar beet productivity and quality remain highly dependent on agronomic practices and environmental conditions. Among these, cultivar selection, nitrogen fertilization, sowing date, plant density, and irrigation management are key determinants of crop performance. Previous studies have highlighted that genetic variability among sugar beet cultivars significantly influences root yield, sugar yield, sucrose concentration, and juice purity, especially under stress conditions such as water limitation and sandy soil environments [5,6]. Therefore, identifying high-performing, water-efficient cultivars is essential for improving productivity under marginal conditions. Water availability is widely recognized as one of the most critical constraints to agricultural production in arid and semi-arid regions [7,8]. This challenge is further exacerbated in sandy soils, which dominate many newly reclaimed areas in Egypt. Such soils are characterized by low water-holding capacity, high infiltration rates, and poor nutrient retention, resulting in substantial water losses through deep percolation and increased nutrient leaching when conventional irrigation methods are applied [9-11]. Consequently, improving irrigation efficiency is imperative for sustaining crop productivity and resource use efficiency under these conditions. Advanced irrigation technologies, particularly drip irrigation systems, offer promising solutions to these challenges. Surface drip irrigation (SDI) enhances water use efficiency by delivering water directly to the root zone, thereby minimizing evaporation and runoff losses [12,13]. However, subsurface drip irrigation (SSDI), where emitters are installed below the soil surface, has gained increasing attention due to its superior ability to reduce soil evaporation, improve root-zone moisture distribution, and enhance nutrient availability. Recent studies have demonstrated that SSDI can significantly improve sugar beet root yield, sugar yield, and water use efficiency, while simultaneously reducing nitrate leaching and deep percolation losses in sandy soils [2,14]. Furthermore, comparative studies indicate that SSDI often provides more stable soil moisture conditions and higher economic returns than SDI under water-limited environments [15,16]. However, despite the growing body of research on drip irrigation systems, there remains a limited understanding of the interactive effects between irrigation methods and sugar beet varietal performance under sandy soil conditions in newly reclaimed areas of Egypt. In particular, insufficient attention has been given to evaluating how different irrigation systems influence both yield quantity and quality traits across multiple cultivars under water-limited environments. Therefore, the present study aims to evaluate the effects of two irrigation systems surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) on the quantitative and qualitative yield characteristics of three sugar beet varieties grown under sandy soil conditions. This study is expected to provide valuable insights for optimizing irrigation management and cultivar selection to enhance sugar beet productivity and water use efficiency in newly reclaimed lands.

2. *Materials and Methods.*

Two field experiments were conducted at the Agricultural Production and Research Station, National Research Centre, Nubaria Province, Behaira Governorate, Egypt, during two successive winter seasons, 2020/2021 and 2021/2022. The objective of this study was to investigate the effect of surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) on the growth and yield characteristics of three sugar beet varieties (Heba, Sirana, and Peti CV). Sowing was carried out on the first of October. The varieties used in this study were imported from Germany through the Ministry of Agriculture and Land Reclamation, Egypt. Soil samples were randomly collected from the experimental sites at a depth of 30 cm before soil preparation. The soil was classified as sandy. Chemical analyses were performed according to in the first season and in the second season Table (1) **[17,18]**.

Mechanical Analysis:

Sand		Silt 20-0µ%	Clay < 2µ%	Soil texture
Course 2000-200µ%	Fine 200-20µ %			
45.93	37.27	11.93	4.78	Sandy

Chemical Analysis:

pH 1:2.5	EC dSm^{-1}	$CaCo_3$	OM%	Soluble Cations meq/l				Soluble anions meq/l			
				Na+	K+	Mg+	Ca++	CO3--	HCO3-	Cl-	SO4--
7.37	1.15	4.93	0.15	0.53	0.15	0.72	1.07	0.02	1.42	0.52	0.76

Macro and Micro-Nutrients Analysis:

Available nutrients						
Macro ppm		Micro ppm				
N	P	K	Zn	Fe	Mn	Cu
47.54	10.15	66.57	0.17	1.37	0.30	0.05

Table (1): Some Physical and Chemical Characteristics of the Experimental Soil

A split-plot design with three replications was used. Irrigation systems were allocated to the main plots, and sugar beet varieties were assigned to the sub-plots. Each sub-plot measured 21 m^2, including six ridges of 50 cm width and 7 m length. The preceding crop was maize. Seeds were sown in hills spaced 20 cm apart. Thinning was performed at the 4-leaf stage (approximately 30 days after sowing) to maintain one plant per hill. Phosphorus fertilizer was applied at a rate of 30 kg P_2O_5 fed^{-1} in the form of calcium super phosphate (15.5% P_2O_5) before sowing. Nitrogen fertilizer was applied at 80 kg N fed^{-1} as ammonium sulfate (20.5% N) in two equal doses; the first dose was applied after thinning and the second dose 30 days later. Potassium fertilizer was applied at 24 kg K_2O fed^{-1} as potassium sulfate (48% K_2O) before the second irrigation. Other cultural practices, including irrigation, weed control, and pest management, were carried out according to standard recommendations for sugar beet cultivation. At harvest (201 days after sowing in both seasons), ten guarded plants were randomly sampled from each sub-plot to determine the following traits:

- **Growth Characters:** Root length and diameter (cm), root, top fresh weight per plant (g), and root, top dry weight per plant (g) were measured.
- **Juice Quality Traits and Impurities.** Total soluble solids (TSS %) was measured using a digital refract meter. Sucrose percentage (S %) was determined using a saccharometer on lead acetate extracts of fresh macerated roots according to **[19]**. Juice purity percentage (JP %) was calculated as the ratio of sucrose % to total soluble solids using the method of **[20]**. Sodium (Na) and potassium (K) contents (meq/ 100 g^{-1} beet) were determined in the digested solution using a flame photometer according to **[21]**. Alpha-amino nitrogen (α-amino N) was measured using the blue number method with double-beam filter photometry **[22]**.

Impurities were calculated using the equation:

Impurities (%) = 0.343 (Na + K) + 0.094 (α-amino N)

Recoverable sugar percentage (RS %) was calculated as:

RS% = (S% − 0.29) − [0.343 (Na + K) + 0.094 (α-amino N)]

Sucrose loss to molasses percentage (SLM %) was estimated as:

SLM% = 0.343 (K + Na) + 0.094 (α-amino N) − 0.31 [23] .

Yield Determination

Plants from the four central ridges of each sub-plot were harvested to estimate **root yield** and **top yield** (ton/fed). **White sugar yield (WSY, ton/fed)** was calculated using the following equation:

WSY = Root yield (ton/fed) × RS% / 100.

Statistical Analysis.

Data collected for growth, yield, and quality traits were subjected to statistical analysis according to **[24]**. Mean comparisons were performed using the least significant difference (LSD) test at 5% probability level, following **[25].**

2.1. Experimental Design and Irrigation System.

The field experiment was arranged in a split-plot design. The main plots were assigned to irrigation system treatments **(SDI and SSDI)**, while the three sugar beet varieties were assigned to sub-plots. Two experimental plots, each measuring 28 × 11 m^2, were divided into two main plots of 12.5 × 11 m^2 for the irrigation treatments, leaving 1 m between the main plots and along the sides of the field. Each main plot was further divided into three equal sub-plots of 3.5 × 11 m^2 for the sugar beet varieties, leaving 1 m between sub-plots. An automatic irrigation system was installed to provide precise irrigation depths at the required times. The system included a centrifugal pump with a discharge of 100 m^3 h^{-1}, equipped with a control head consisting of filters, a pressure regulator, pressure gauges, a flow meter, and control valves. A 1**-inch PE Venturi injector** (suction capacity 34–279 L h^{-1}) was used for fertigation. The mainline (PVC, 110 mm diameter, 6 bar) connected to sub-main lines (PVC, 75 and 63 mm diameter, 6 bar) feeding the manifold lines. Each sub-plot was supplied via a solenoid valve and discharge gauge, with twelve solenoid valves connected to a control panel. Lateral lines (PE, 16 mm diameter, 4 bar) with built-in emitters (discharge 4 L h^{-1} at 1 bar, emitter spacing 0.30 m) were installed. For SDI, the laterals were laid on the soil surface; for SSDI, they were buried 0.15 m below the soil surface. The distance between laterals was 0.70 m, and each lateral line was 11 m long. The layout of the field experiment is illustrated in **Fig (1).**

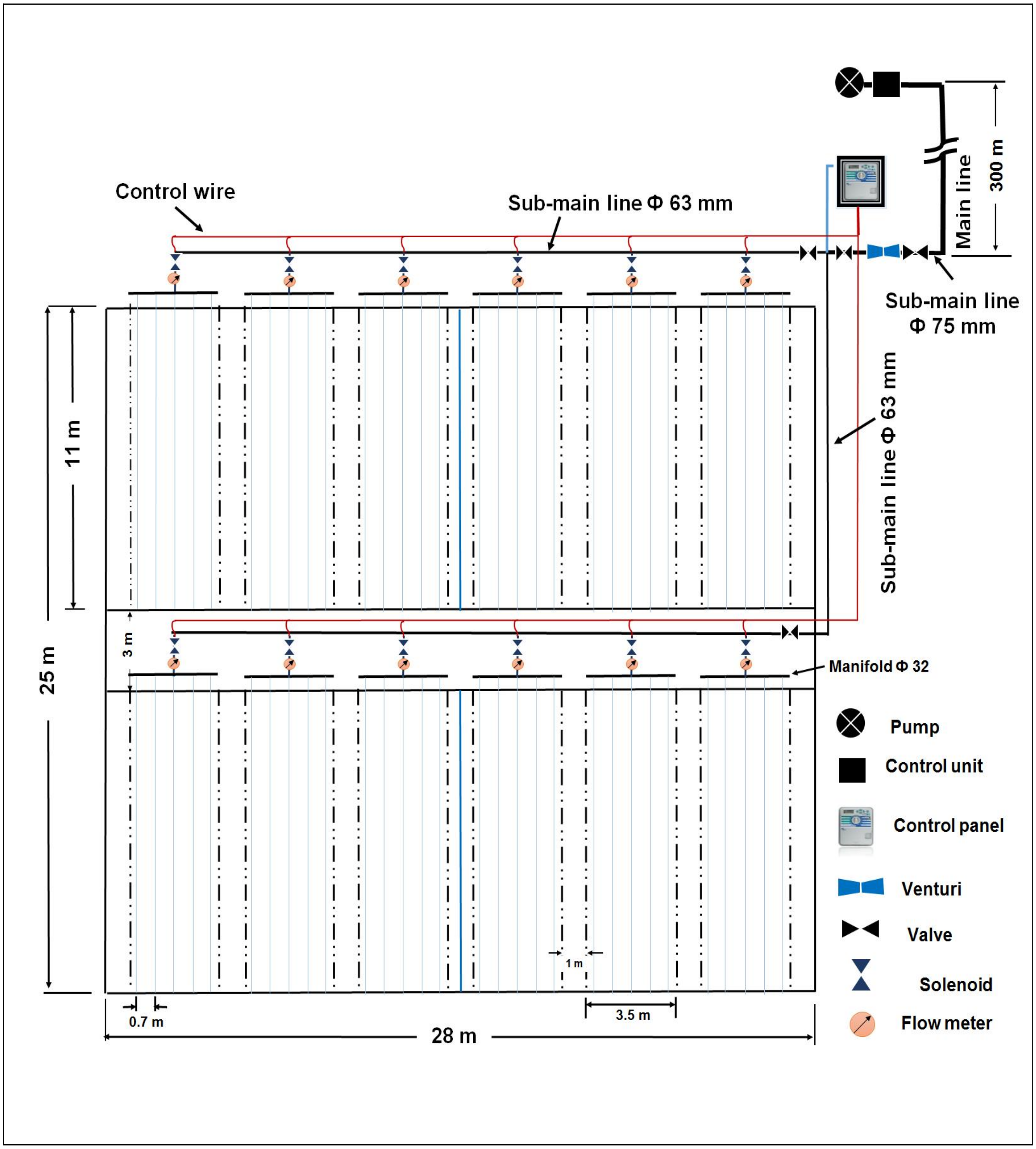

Figure (1): Layout of the field experiment

3. Results and Discussion

The combined analysis of the two growing seasons (Tables 2 &3) demonstrated that irrigation systems, sugar beet varieties, and their interaction significantly affected growth characteristics. The results provide clear evidence that both water management and genetic background play a crucial role in determining biomass accumulation and root development under the studied conditions.

I. Effects Irrigation System: Subsurface drip irrigation (SSDI) significantly enhanced plant growth compared with surface drip irrigation (SDI). While root length showed only minor variation between treatments, SSDI slightly increased root diameter (9.99 cm) compared with SDI (9.81 cm). More importantly, SSDI markedly improved biomass accumulation, with total fresh weight reaching 127.11 g plant^{-1} versus 106.53 g plant^{-1} under SDI. A similar trend was observed for dry weight (53.55 vs. 48.42 g plant^{-1}, respectively). This improvement can be explained by the ability of SSDI to maintain a more stable soil moisture environment in the root zone, ensuring continuous water availability and reducing evaporation losses. Such conditions enhance root activity, nutrient uptake, and overall physiological performance. These findings are consistent with earlier reports indicating that subsurface drip irrigation improves water-use efficiency and crop productivity through optimized water delivery [26,27]. In addition, drip irrigation systems have been widely recognized for their role in improving sugar beet growth under different environmental conditions while conserving water resources [28].

II.Varietal Performance: Highly significant differences were observed among the tested varieties, reflecting substantial genetic variability. Heba consistently outperformed the other varieties, recording the highest fresh and dry biomass, followed by Sirana, while Peti showed the lowest growth performance. The superiority of Heba may be attributed to its greater photosynthetic capacity and more efficient assimilate partitioning toward root development. In contrast, the relatively lower performance of Peti suggests limited adaptability to the experimental conditions. These results emphasize the importance of genotype selection in maximizing sugar beet productivity, as varietal differences strongly influence plant response to irrigation regimes and environmental factors. Similar findings have been reported in previous studies, highlighting the variability in growth and yield among sugar beet cultivars [29,30].

III. Effects of interaction: The interaction between irrigation systems and varieties was significant for most growth traits, indicating that varietal performance is highly dependent on the irrigation method applied. Heba under SSDI achieved the highest values of root length (22.68 cm) and fresh biomass (73.50 g plant^{-1}), confirming its strong responsiveness to improved water availability. Sirana also showed improved growth under SSDI, particularly in fresh weight accumulation. In contrast, Peti exhibited relatively low growth under irrigation systems, indicating limited responsiveness .Interestingly, dry matter accumulation showed a different pattern, with Sirana under SDI recording the highest dry weight (63.63 g plant^{-1}). This suggests that some genotypes may favor dry matter accumulation under moderate water supply rather than maximizing fresh biomass. Such responses reflect differences in physiological adaptation strategies, particularly in biomass partitioning and water-use efficiency. The superior performance observed under SSDI can be attributed to improved soil water distribution and enhanced nutrient availability within the root zone. These conditions promote root expansion and increase resource uptake efficiency. These findings agree with previous studies demonstrating that optimized irrigation and fertigation strategies enhance sugar beet growth and yield, particularly under water-limited environments [31-33]. Furthermore, the differential varietal response observed in this study supports earlier reports emphasizing the importance of matching irrigation systems with suitable genotypes [34]. In addition, the variation in dry weight among treatments suggests a trade-off between fresh biomass accumulation and dry matter concentration. Previous research has shown that reduced irrigation can decrease fresh yield while increasing dry matter percentage, reflecting adaptive responses to water stress conditions [35,36].

IV. Agronomic Implications: The present study highlights the importance of integrating efficient irrigation systems with appropriate varietal selection to achieve sustainable sugar beet production. SSDI proved to be a superior irrigation method for enhancing biomass accumulation and improving water-use efficiency .From an agronomic perspective, the use of SSDI in combination with high-performing varieties such as Heba can maximize productivity while optimizing water and nutrient use. This approach is particularly relevant under arid and semi-arid conditions, where water scarcity is a major limiting factor. These findings are in line with recent studies emphasizing the role of advanced irrigation management in sustainable agricultural systems [37].

Treatment	**Root (cm)**		**Fresh weight /plant (g)**			**Dry weight / plant (g)**		
	Length	Diameter	Top	Root	Total	Top	Root	Total
SDI	21.1	9.81	56.95	49.58	106.53	24.09	24.33	48.42
SSDI	20.71	9.99	66.02	61.09	127.11	24.16	29.39	53.55
L.S.D at 5%	20.53	0.6	1.7	1.05	2.5	NS	0.19	1.4
Heba	21.09	10.83	72.02	68.33	140.35	25.05	34.20	59.25
Sirana	20.72	10.18	57.20	47.32	104.52	27.95	27.07	55.02
Peti	19.78	8.69	55.25	50.35	105.60	19.37	19.32	38.69
L.S.D. at 5%	0.9	0.3	1.2	1.02	2.1	0.15	0.41	1.3

Table (2): Effect of irrigation systems and varieties on some growth characteristics of sugar beet plants in two seasons (combination of two seasons)

Irrigation system	**Varieties**	**Root (cm)**		**Fresh weight /plant (g)**			**Dry weight / plant (g)**		
		Length	Diameter	Top	Root	Total	Top	Root	Total
SDI	Heba	19.51	10.53	70.53	67.03	137.57	25.77	36.47	62.24
	Sirana	21.83	10.93	53.40	41.07	94.47	30.07	33.57	63.63

	Peti	19.73	8.50	46.93	40.63	87.57	16.63	18.13	34.83
SSDI	Heba	22.68	10.73	73.50	69.63	143.13	24.33	31.93	56.27
	Sirana	19.61	9.83	61.00	53.57	114.57	25.84	20.57	46.40
	Peti	19.83	8.87	63.57	60.07	123.63	22.10	20.50	42.60
L.S.D at 5%	0.89	0.85	1.8	1.3	3.3	0.63	0.69	1.7	

Table (3): Effect of Interaction between sugar beet varieties and irrigation systems on growth of sugar beet (combination of two seasons)

3.1. Yield and its components

I. Effect of Irrigation Systems on Root Biomass, and Yield: The data presented in Table (4) clearly demonstrate that irrigation system significantly influenced most growth and yield parameters of sugar beet. Subsurface drip irrigation (SSDI) resulted in superior performance compared to surface drip irrigation (SDI), as evidenced by the significant increases in root length (36.16 vs. 33.20 cm) and root diameter (7.53 vs. 6.52 cm). This improvement in root morphology was directly reflected in higher fresh root weight per plant (1155.86 vs. 998.52 g) and total biomass (1403.94 vs. 1240 g). Consequently, root yield was significantly enhanced under SSDI (18.28 ton/fed) compared to SDI (17.15 ton/fed), accompanied by a slight increase in sugar yield (3.64% vs. 3.33%). The L.S.D test confirmed that these differences were statistically significant for most traits, except for top fresh weight, which showed no significant variation ($p > 0.05$).The superiority of SSDI can be attributed to improved soil moisture distribution within the root zone, reduced evaporation losses, and enhanced nutrient availability, which collectively promote root development and biomass accumulation. These findings are consistent with previous studies indicating that subsurface irrigation enhances water use efficiency and crop productivity under water-limited conditions [38,39]. Furthermore, improved root yield and sugar accumulation under SSDI have also been reporte dinsugar beet by [40], supporting the current results.

II. Varietal Performance and Genetic Variability in Yield Traits: Significant varietal differences were observed for all studied traits (Table 4), indicating the strong influence of genetic factors on sugar beet productivity. The Heba variety consistently outperformed the other tested cultivars, recording the highest values for root length (35.87 cm), fresh root weight (1182.23 g/plant), total biomass (1482.23 g/plant), root yield (18.72 ton/fed), and sugar content (3.75%). In contrast, Sirana and Peti exhibited comparatively lower values. The superior performance of Heba may be attributed to its enhanced genetic capacity for assimilate production and efficient partitioning toward the storage root. Such varietal differences have been widely reported, where genotype plays a decisive role in determining yield potential and physiological efficiency [41]. However, the results also suggest that high yield potential may be associated with increased impurity accumulation, as observed later in quality traits. This highlights a potential trade-off between yield and technological quality, which has been documented in previous studies. The interaction between varietal performance and irrigation system further indicated that Heba achieved maximum productivity under SSDI conditions, confirming that optimal agronomic practices enhance the expression of genetic potential [42]. These findings align with recent research emphasizing the integration of improved cultivars with efficient irrigation systems to maximize sugar beet productivity [43,44]. These results also suggest potential implications for water-saving strategies in sugar beet cultivation, particularly in regions facing water scarcity, where subsurface irrigation can provide both economic and environmental benefits [45].

Treatment	**Root (cm)**		**Fresh weight /plant (g)**			**Sugar beet yield (ton/fad)**		
	Length	Diameter	Root	Top	Total	Root	Top	Sugar
Surface	33.20	6.52	998.52	241.48	1240	17.15	3.74	3.33
Subsurface	36.16	7.53	1155.86	248.08	1403.94	18.28	4.58	3.64
L.S.D at 5%	0.91	0.32	69.9	N.S	70.10	0.77	0.33	NS
Heba	35.87	7.33	1182.23	300.00	1482.23	18.72	5.04	3.75
Sirana	34.72	6.98	1045.27	249.72	1294.99	17.38	3.75	3.46
Peti	33.45	6.77	1004.07	184.62	1188.69	17.05	3.69	3.23
L.S.D at 5 %	0.48	0.32	85.23	30.7	91.50	0.47	0.17	NS

Table (4): Effect of irrigation systems and varieties on yield of sugar beet (combination of two seasons)

III. Interaction Effects between Irrigation System and Variety on Yield and its Components: The interaction between irrigation systems and sugar beet varieties had a significant effect on yield and its components (Table 5), indicating that varietal response depends strongly on water management practices. Across all varieties, SSDI consistently resulted in higher values compared to SDI. The highest performance was recorded for Heba under SSDI, which produced maximum root length (37.43 cm), root diameter (8.53 cm), and fresh root weight (1210.33 g/plant), leading to the highest sugar yield (3.97 ton/fed). Under SDI, the same variety showed comparatively lower values, confirming the positive impact of SSDI on enhancing growth and yield. This improvement can be explained by the ability of SSDI to maintain stable soil moisture conditions, enhance nutrient uptake, and reduce water losses through evaporation. Similar findings have been reported by and, who demonstrated that improved irrigation systems significantly enhance plant growth and productivity [46,47]. The variety Sirana also showed a positive response to SSDI, with increased root fresh weight (1191.13 g/plant) and sugar yield (3.74 ton/fed) compared to SDI. In contrast, Peti exhibited the lowest performance under both irrigation systems, suggesting lower adaptability to the tested environmental conditions. Top biomass increased under SSDI for all varieties, particularly in Heba (302.23 vs. 248.87 g/plant under SDI). While increased vegetative growth may enhance photosynthetic capacity, the efficient allocation of assimilates to the root remains essential for maximizing sugar yield. The results indicate that SSDI promotes a favorable balance between shoot and root growth, which is consistent with findings by [40]. Overall, these results confirm that the interaction between genotype and irrigation management is a key determinant of sugar beet productivity. Similar conclusions have been reported by and, emphasizing that combining suitable cultivars with optimized irrigation practices is essential for improving both yield and quality [48,49]. The observed improvements under SSDI, particularly with Heba and Sirana, also support its potential role in enhancing water use efficiency under semi-arid conditions [50,51].

Irrigation systems	Varieties	Root (cm)	Fresh weight /plant (g)			Sugar beet yield (ton/fad.)		
		Length	Diameter	Root	Top	Root	Top	Sugar
SDI	Heba	34.30	7.00	1173.33	248.87	18.60	3.96	3.70
	Sirana	32.87	6.43	1024.43	191.43	16.46	3.50	3.27
	Peti	32.43	6.13	797.80	177.80	14.97	3.43	2.86
SSDI	Heba	37.43	8.53	1210.33	302.23	19.80	5.80	3.97
	Sirana	36.57	7.10	1191.13	297.77	18.83	4.28	3.74
	Peti	34.47	6.97	1066.10	250.57	17.64	3.99	3.49
L.S.D at 5%	0.82	0.46	120.4	43.51	0.50	0.66	0.41	

Table (5) Effect of Interaction between sugar beet varieties and irrigation systems on yield sugar beet (Combination of two seasons)

3.2. Quality traits

I. Impact of Irrigation Systems and Varieties on Root Impurities and Quality Index: The results presented in Fig. (2) Indicate that irrigation system significantly affected root impurities (Na%, K%, and α-amino nitrogen) as well as the quality index (QZ %). SSDI reduced Na% and α-amino nitrogen compared to SDI, which is advantageous for sugar processing as these compounds interfere with sucrose extraction and crystallization [52]. The reduction in impurities under SSDI may be attributed to decreased salt accumulation in the upper soil layers and improved nutrient balance within the root zone. These findings are in agreement with, who reported improved juice quality under subsurface irrigation in arid environments [53]. Among the tested varieties, Heba showed the highest impurity levels, particularly under SDI, whereas Peti recorded the lowest values under SSDI, suggesting better tolerance to salinity and reduced uptake of undesirable ions. Sirana exhibited intermediate behavior, indicating moderate adaptability. The quality index (QZ %), which integrates impurity effects and sugar content, was highest in Heba under SDI but remained high in Sirana and Peti under SSDI. Improvements in QZ% under SSDI support findings by, who reported that optimizing subsurface irrigation increases sugar beet quality by promoting balanced nutrient uptake and reduced soil salinity [54,55].

II. Effect on Sucrose Content, Total Soluble Solids, and Juice Purity: As illustrated in Fig. (3), sucrose percentage and total soluble solids (TSS %) were slightly higher under SDI, whereas SSDI significantly improved juice purity. This suggests that while SDI may enhance short-term sugar accumulation, SSDI contributes to better overall processing quality. Peti, despite having lower sucrose content, achieved higher purity under SSDI due to reduced impurity levels. In contrast, Heba maintained the highest sucrose content across irrigation systems but also exhibited higher impurity levels, indicating a trade-off between sugar quantity and quality. These findings are consistent with, who reported that improved irrigation management enhances juice purity even when sucrose content is not maximized [56].

III. Combined Effects of Irrigation System and Variety on Sugar Yield and Processing Quality: Data in Table (6) confirm that SDI resulted in slightly higher sugar content (14.30%) compared to SSDI (14.02%). However, SSDI significantly reduced

Na% and α-amino nitrogen, leading to improved technological quality.Among the varieties, Heba recorded the highest sugar content (14.95%) but also the highest impurity levels, while Peti exhibited the lowest sugar content (13.60%) but superior purity. Sirana showed balanced performance between yield and quality traits. These results highlight the importance of balancing yield and quality when selecting suitable management practices. The interaction between irrigation system and cultivar plays a decisive role in achieving this balance. Similar conclusions were reported by, emphasizing the importance of integrating irrigation strategies with varietal selection to optimize sugar beet production [57].

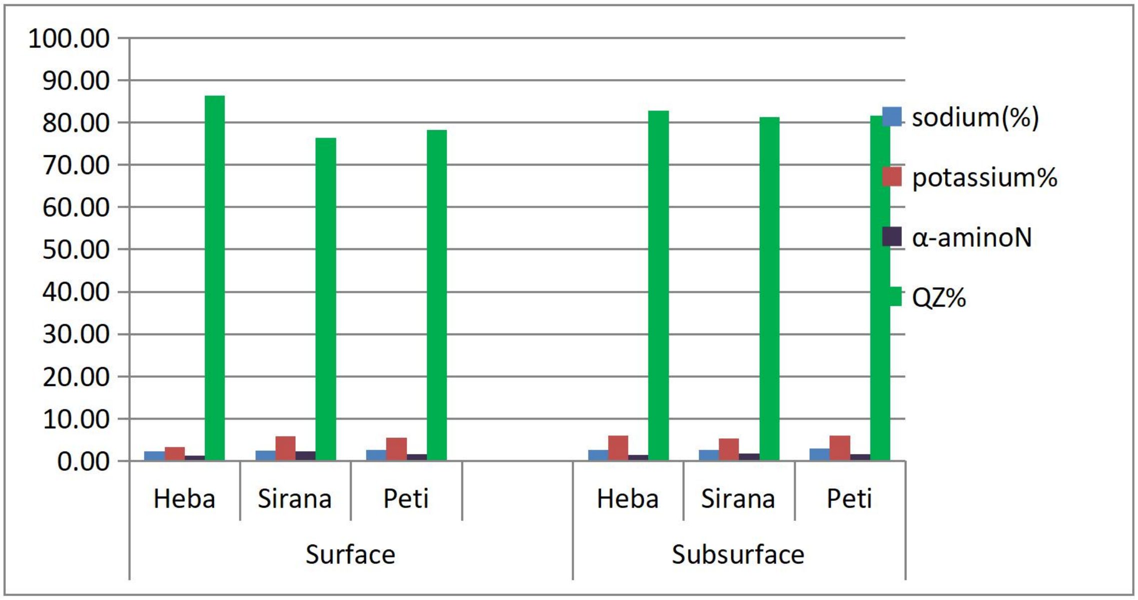

Figure (2): The interaction effect of irrigation system and varieties on root impurities (meq/100g)

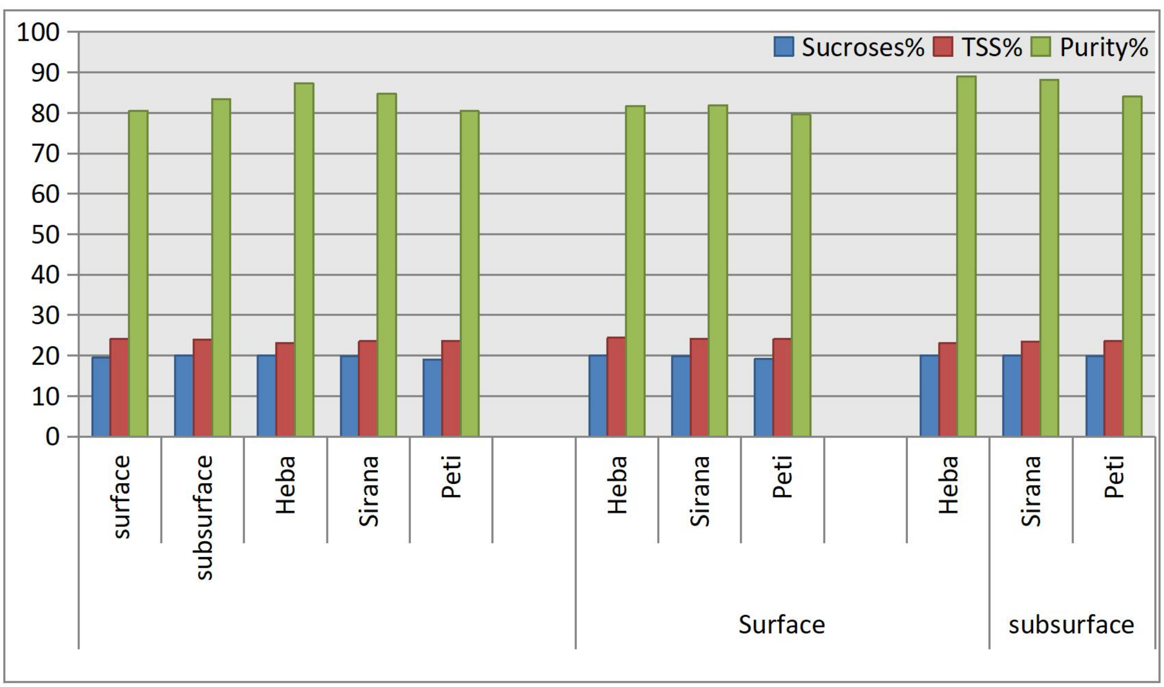

Figure (3): The effect of irrigation system, varieties and interaction on quality traits in sugar beet

Treatment	Sugar%	Na%	P%	α-amino N%	QZ%
Irrigation					
SDI	14.301	2.690	5.602	1.965	82.358
SSDI	14.021	2.300	5.989	1.567	75.744
Variety					
Heba	14.953	2.981	5.898	2.000	79.123
Sirana	13.932	2.303	5.753	1.948	79.098
Peti	13.598	2.200	5.000	1.352	78.933

Table (6): Effect of irrigation systems and varieties on root impurities (meq/100g)

4. Conclusion

Based on the combined analysis of two growing seasons, the present study demonstrates that irrigation system and varietal selection, as well as their interaction, play a decisive role in determining sugar beet productivity and quality under semi-arid conditions. Subsurface drip irrigation (SSDI) proved to be superior to surface drip irrigation (SDI) in enhancing root growth, biomass accumulation, and yield components, resulting in higher root and sugar yields. Moreover, SSDI significantly improved technological quality by reducing root impurities, particularly sodium and α-amino nitrogen, despite a slight reduction in sucrose percentage. Among the tested cultivars, Heba exhibited the highest yield potential and sugar content, while Sirana showed a balanced performance between yield and quality. In contrast, Peti demonstrated lower yield but superior juice purity due to reduced impurity levels. The interaction between irrigation system and cultivar revealed that combining SSDI with high-performing varieties, particularly Heba and Sirana, maximized both yield and quality. These findings highlight the importance of adopting integrated crop management strategies that combine advanced irrigation techniques with suitable genetic materials. Therefore, the use of SSDI in conjunction with high- yielding cultivars is recommended as an effective and sustainable approach for improving sugar beet productivity and quality, especially in newly reclaimed and water-scarce environments.

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Competing Interests

Authors have declared that no competing interests exist.

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Data availability statement:

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

S.K.EAB, designed and farmed plants, and contributed to the statistical analysis. S.K designed and performed the experiment, and was responsible of all the Physiological and biochemical analysis. **GShB**, designed and farmed plants, and contributed to the statistical analysis. And **MSh,GAA** designed and farmed plants, and contributed to the statistical analysis. All authors share in every step of this work and all of them contribute in writing the manuscript.