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Enhancing wheat growth and sandy soil conditions through improved T-tape drip irrigation management

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Abstract

This study aimed to evaluate the effects of operating pressure, spacing between field pipes, and irrigation level on soil moisture distribution, salinity, and plant growth indicators under a T-tape drip irrigation system cultivated with wheat (Triticum aestivum L.). A field experiment was conducted during the winter season of 2024–2025 in Safwan district, Basrah Governorate, Iraq. The experiment included three operating pressures (0.75, 1.00, and 1.25 m), three pipe spacings (20, 30, and 40 cm), and two irrigation levels (100% and 80% of cumulative pan evaporation), arranged in a split–split plot design within a randomized complete block design (RCBD) with three replicates. Results showed that reducing pipe spacing to 20 cm significantly improved soil moisture distribution and reduced soil salinity compared with wider spacings. Increasing operating pressure enhanced water distribution uniformity and decreased electrical conductivity. Full irrigation (100% Ep) significantly improved soil moisture conditions and reduced salt accumulation compared with 80% Ep. In addition, plant growth indicators, including plant height, dry matter, grain yield, and water use efficiency, were significantly affected by the studied factors, with the highest values recorded under narrow spacing and higher operating pressure. Significant interaction effects were observed among the studied factors. The combined treatment of 20 cm spacing, 1.25 m operating pressure, and 100% Ep irrigation level achieved the best soil moisture conditions, lowest salinity levels, and highest plant growth and yield performance under sandy soil conditions.

Keywords: T-tape drip irrigation, wheat, sandy soil, operating pressure, pipe spacing, irrigation level

Introduction

Drip irrigation has become one of the most effective irrigation methods for enhancing agricultural production and improving water utilization, especially in arid and semi-arid environments where water resources are increasingly limited. By applying water directly to the crop root zone through a system of pipes and emitters, this irrigation method reduces losses associated with evaporation, runoff, and deep percolation. Consequently, it achieves higher water use efficiency than traditional irrigation techniques, including surface and sprinkler irrigation systems (Hossain *et al*., 2017; Alsalami *et al*., 2025). Beyond its contribution to water conservation, drip irrigation can also help preserve soil physical properties by minimizing surface sealing, reducing compaction, and limiting soil erosion. These advantages support the maintenance of a favorable environment for root growth and crop development (Du *et al*., 2023). Nevertheless, the localized application of water remains one of the major challenges associated with drip irrigation systems. Water movement is generally concentrated around the emitters, resulting in uneven wetting patterns and the accumulation of salts near the margins of the wetted zone. This phenomenon becomes more pronounced in sandy soils because of their high infiltration rates, limited water retention capacity, and rapid drainage characteristics. Such conditions may restrict root expansion, reduce nutrient availability, and ultimately affect crop performance. The movement and distribution of water within the soil profile under drip irrigation are strongly influenced by emitter discharge and hydraulic operating conditions. These factors determine the dimensions and configuration of the wetted soil volume and influence the advancement of the wetting front. Recent investigations have highlighted the importance of optimizing design and management parameters to improve water distribution and

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control salinity under drip irrigation. Faloye *et al.* (2025) demonstrated that both emitter discharge and irrigation duration substantially affect the dimensions of the wetted zone and the resulting soil moisture distribution. Likewise, Shabani *et al*. (2025) reported that soil texture, irrigation volume, and application time are among the principal factors governing wetted zone geometry, which is critical for effective irrigation system design. Furthermore, Selim *et al*. (2013) emphasized the significant role of irrigation management practices and soil properties in regulating water and salt dynamics within the root zone. Other studies have also pointed out the need to balance irrigation practices in order to optimize crop yield while maintaining water use efficiency and controlling soil salinity (Fereres & Soriano, 2007; Kang *et al*., 2017).

Several operational and design variables influence the performance of drip irrigation systems, among which operating pressure, spacing between emitters or lateral lines, and irrigation level are particularly important. Operating pressure affects emitter discharge rates and application uniformity, thereby influencing soil moisture distribution and solute movement. The spacing between lateral pipes controls the degree of overlap between adjacent wetted zones, which is essential for achieving more uniform soil moisture conditions and enhancing salt leaching. Irrigation level is another key management factor because it determines the amount of water supplied to the crop and influences the balance between crop productivity and water conservation under conditions of limited water availability. Although numerous studies have examined various aspects of drip irrigation management, information regarding the interactive effects of operating pressure, lateral pipe spacing, and irrigation level under T-tape drip irrigation systems remains limited, particularly in sandy soils of arid environments such as southern Iraq. Previous research has often focused on the influence of individual factors, while comparatively little attention has been given to their combined effects on soil moisture distribution, salinity behavior, crop growth, and irrigation efficiency. Therefore, this study was conducted to investigate the interaction effects of operating pressure, field pipe spacing, and irrigation level on soil moisture distribution, soil salinity, growth characteristics, grain yield, and water use efficiency of wheat (*Triticum aestivum* L.) cultivated under a T-tape drip irrigation system in sandy soil conditions.

Materials and Methods

Study area

The field experiment was conducted during the winter growing season of 2024–2025 in Safwan district, southwest of Basrah Governorate, Iraq. The experimental field is located at latitude 30° 8′ 28″ N and longitude 47° 36′ 47″ E. Figure 1. The soil of the study area was classified as sandy loam belonging to the Typic Quartzi Psamments sub.

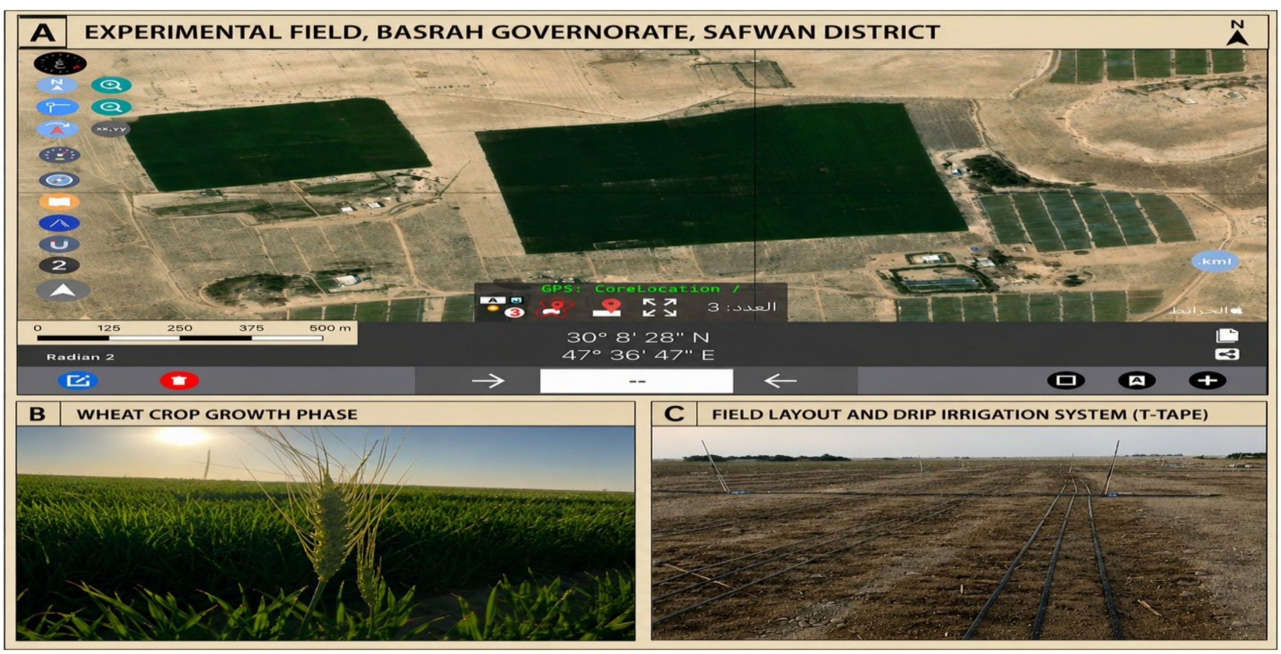

Figure 1: Geographical location and fieldwork preparations; (A) Experimental Field, Basrah Governorate, Safwan District (B) Plot preparation and surface irrigation pipe system, (C) Wheat crop growth

Table 1: Physical and chemical properties of the study soil

Properties			Soil depth (cm)		
			0 – 15	15-30	30-40
Sand		g kg $^{-1}$ soil	846	822	769
Silt			106	109	146
Clay			43	62	72
Soil texture			sandy loam	sandy loam	Sandy loam
Mean weight diameter (MWD)			0.120	0.105	0.98
Bulk density (mg m^{-3})			1.72	1.64	1.47
Partical density (mg m^{-3})			2.72	2.70	2.65
Porosity %			36.76	39.25	44.52
Field capacity% (pw%)			21.62	21.23	20.78
Wilting point (pw %)			9.8	9.2	8.9
Saturated water conductivity (cm. $minute^{-1}$)			20.6	19.3	19.8
Total carbonates (g kg^{-1})			147.00	136.00	128.00
EC (dS m^{-1}) 1:1			4.14	2.79	2.69
pH 1:1			7.97	8.24	8.37
dissolved ions	Ca++	millimoles L^{-1}	4.312	4.125	3.825
	Mg++		3.875	4.125	3.45
	Na+		13.95	13.075	11.35
	K+		1.355	1.015	0.975
	HCO_3^{-1}		1.86	1.915	1.66
	SO_4^{-2}		11.7	12.965	10.115
	Cl-		27.25	23.00	20.5
	$CO3^{-2}$		0.0	0.0	0.0
Irrigation water		EC(dS m^{-1})	6.39		
		pH	7.19		

Soil sampling and analysis

Soil samples were collected before planting from three depths: 0–15, 15–30, and 30–45 cm. The collected samples were air-dried, gently crushed, and passed through a 2-mm sieve before laboratory analysis. Physical and chemical soil properties were determined according to the standard procedures described by. Black *et al* (1965), Page *et al.* (1982). The measured soil properties are presented in Table 1.

Experimental design

The experiment included three factors: operating pressure (P1 = 125 cm, P2 = 100 cm, and P3 = 75 cm), distance between field pipes (S1 = 20 cm, S2 = 30 cm, and S3 = 40 cm), and irrigation level (I1 = 100% Ep and I2 = 80% Ep). Irrigation water requirements were estimated using the Class-A evaporation pan method. The experiment was arranged in a split–split plot design within a randomized complete block design (RCBD) with three replicates. Operating pressure treatments were assigned to the main plots, irrigation levels to the subplots, and distances between field pipes to the sub-sub plots. The total number of experimental units was 54. Each experimental unit was 7 m long, while plot widths varied according to field pipe spacing treatments.

Irrigation system and crop establishment

A T-tape drip irrigation system was used in all treatments. Each experimental unit contained three lateral lines. Operating pressure was controlled using piezometers and control valves installed at the beginning of each lateral line. Wheat (*Triticum aestivum L.*) was planted in November 2024.

Soil moisture determination

Soil moisture content was determined gravimetrically at depths of 0–15, 15–30, and 30–45 cm during mid-season and at the end of the growing season. Soil samples were oven-dried at 105°C for 24 h, and moisture content was calculated on a dry-weight basis.

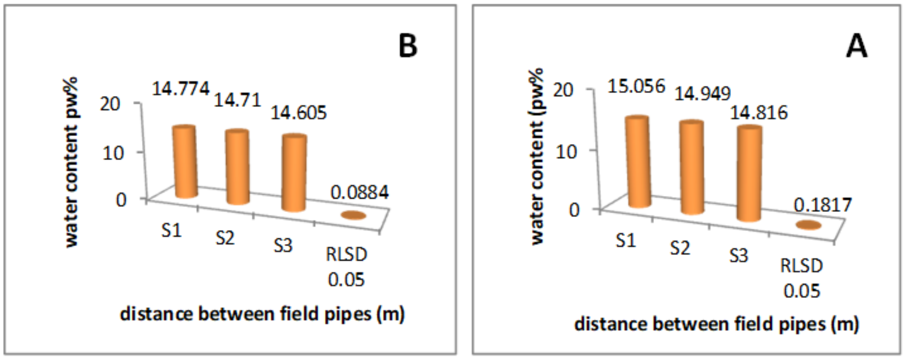

Figure 2: The effect of the distance between field pipes on Moisture content value %,(A) at beginning of the season, (B) at end of the season

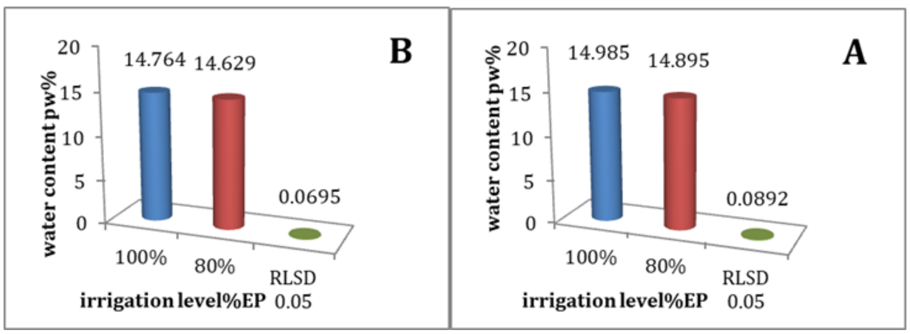

Figure 3: Effect of irrigation level on moisture content values (%) ,(A) beginning of season ,(B) end of season

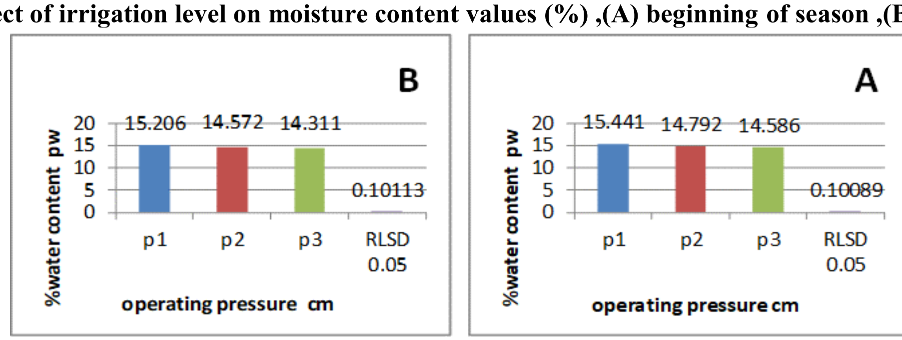

Figure 4: Effect of operating pressure on moisture content value % ,(A) at beginning of season, (B) at end of season

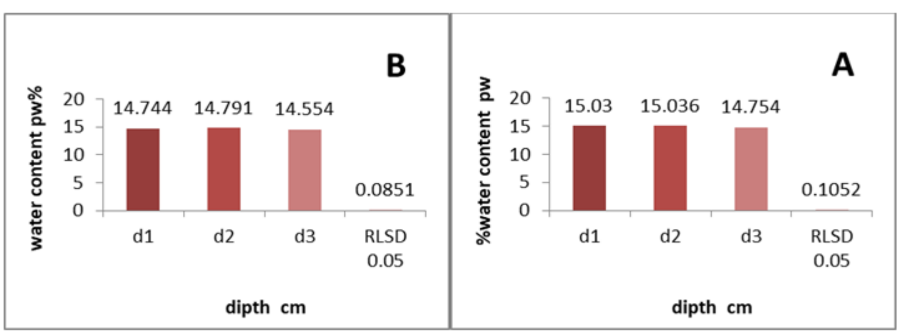

Figure 5: Effect of the soil depth on moisture content value (pw%), (A) at beginning of season, (B) at end season

Soil salinity determination

Soil salinity distribution was evaluated by measuring electrical conductivity (EC) of the soil-water extract (1:1). Soil samples were collected from the same depths used for moisture determination during the two sampling periods. Electrical conductivity (EC) of the soil-water extract (1:1) was measured using a WTW EC meter following standard laboratory procedures.

Statistical analysis

The experimental data were statistically analyzed using GenStat (18th Edition, VSN International Ltd., Hemel Hempstead, UK). The experiment was arranged as a split–split plot design within a randomized complete block design (RCBD) with three replications. Operating pressure treatments were allocated to the main plots, irrigation levels to the subplots, and field pipe spacing treatments to the sub-subplots. Analysis of variance (ANOVA) was performed to evaluate the effects of the studied factors and their interactions on the measured parameters. Whenever significant differences were detected, treatment means were compared using the Least Significant Difference (LSD) test at the 0.05 probability level.

Results

The results of the statistical analysis of the study showed highly significant differences ($p < 0.001$) in soil moisture content (PW%) under the T-tape drip irrigation system due to variations in field pipe spacing, irrigation level, operating pressure, and soil depth during the beginning and end of the growing season (Figures 2–6). The highest soil moisture content values were recorded under the narrow spacing treatment (S1, 20 cm), reaching 15.056% and 14.774% at the beginning and end of the season, respectively, whereas the widest spacing treatment (S3, 40 cm) recorded the lowest values. In contrast, the 100% Ep irrigation treatment significantly exceeded the 80% Ep treatment, recording 14.985% and 14.764% during the two periods, respectively. The results further indicated that operating pressure had a highly significant effect on soil moisture distribution, with treatment P1 (1.25 m) recording the highest values of 15.441% and 15.206%, while the lowest values were observed under P3 (0.75 m).

The result also showed variation in soil moisture content across soil depth and interaction treatment. Depth d2

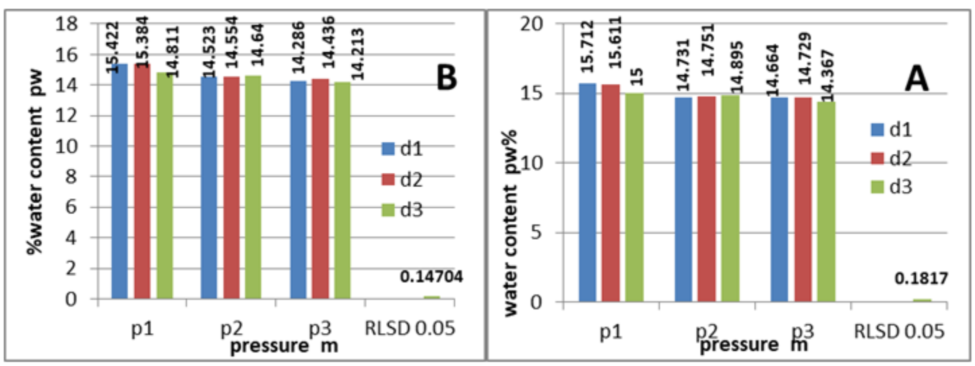

Figure 6: The effect of the interaction between operating pressure and soil depth factors on moisture content value (pw%), (A) at beginning of season, (B) at end season

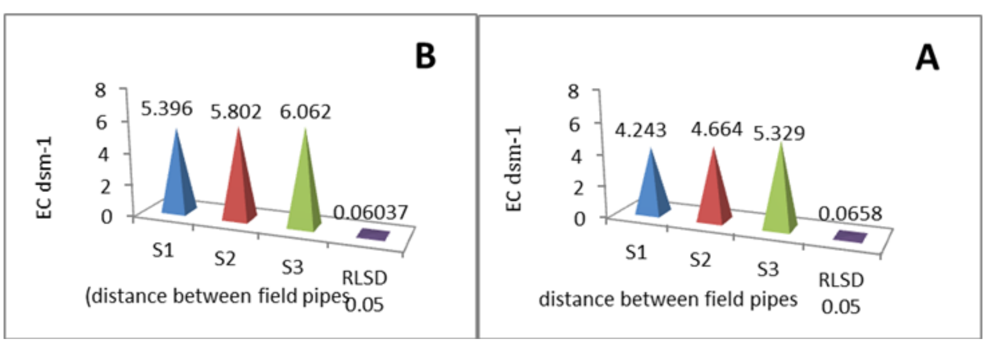

Figure 7: The effect of the distance between field pipes on electrical conductivity value (dS m^{-1}), (A) at beginning of the season, (B) at end of the season

(15-30 cm) recorded the highest moisture value followed by d1(0-15 cm), and the lowest value recorded at d3 (30-45 cm). While, the interaction between soil depth and operating pressure showed also high values at d2 which combin with operating pressure p2 and p3 except at p1 the d1 recorded the highest value. Soil moisture content for all treatments decreased at the end of the growing season due to increased temperature and evapotranspiration demand so soil moisture depletion accelerated. Generally, these results demonstrate the important role of operating pressure, field pipe spacing and irrigation level in improving soil moisture contents and distribution under sandy soil conditions.

Salt distribution

The results of the statistical analysis of the study showed highly significant differences ($p < 0.001$) in soil electrical conductivity (EC) values under the T-tape drip irrigation system due to variations in field pipe spacing, irrigation level,

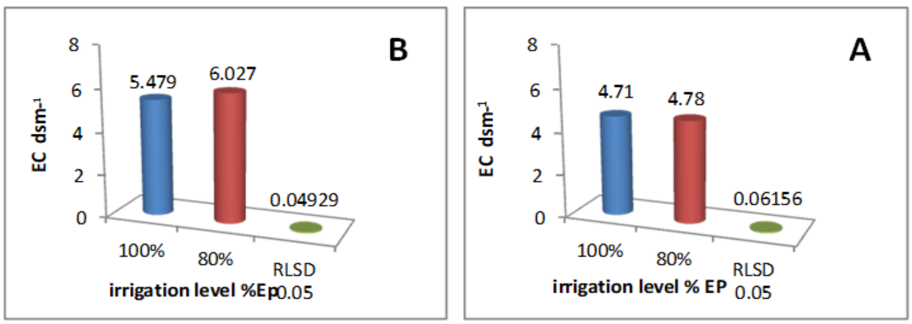

Figure 8: Effect of irrigation level on electrical conductivity (dS m^{-1}) value, (A) at beginning of the season, (B) at end of the season correct dS m^{-1} on y-axis (There must be space between dS and m^{-1})

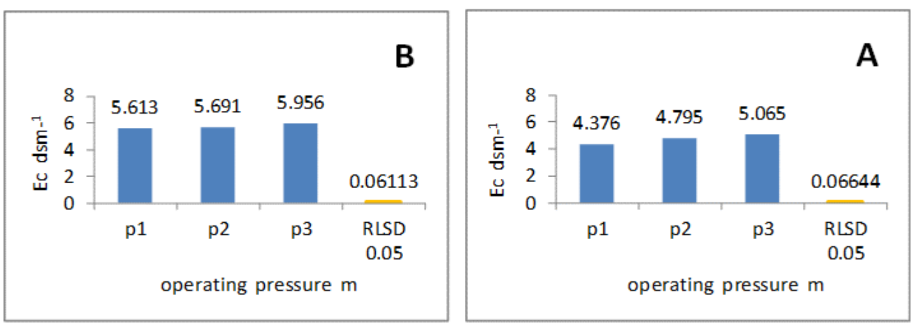

Figure 9: Effect of operating pressure on electrical conductivity (dS m^{-1}) value, (A) at beginning of the season, (B) at end of the season correct dS m^{-1} on y-axis (There must be space between dS and m^{-1}). Ec should be corrected as EC

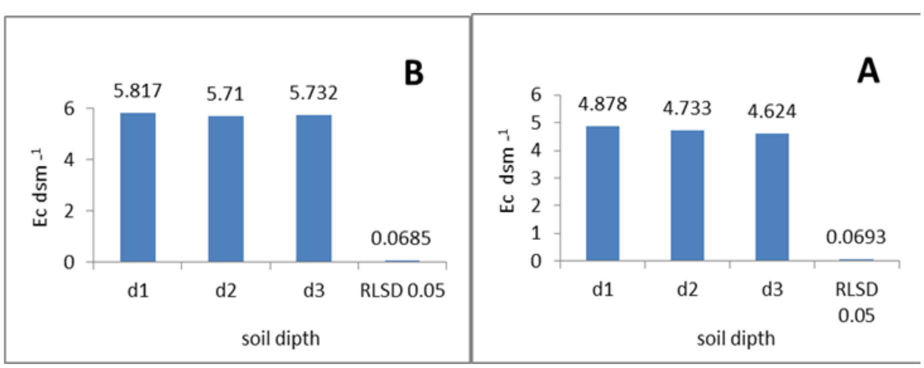

Figure 10: Effect of soil dipth on electrical conductivity (dSm^{-1}) value, (A) at beginning of the season, (B)at end of the season correct dS m^{-1} on y-axis (There must be space between dS and m^{-1}). Ec should be corrected as EC

operating pressure, soil depth, and their interactions during the beginning and end of the growing season (Table 2; Figures 7–12). High EC values were observed under the widest field pipe spacing treatment S3 (40 cm), reaching 5.329 and 6.062 dS m^{-1} at the beginning and end of the growing season, respectively. In contrast, the narrow spacing treatment S1 (20 cm) recorded the lowest EC values of 4.243 and 5.396 dS m^{-1} during the two periods. Similarly, the 100% Ep irrigation treatment reduced EC values to 4.71 and 5.479 dS m^{-1} compared with the 80% Ep treatment, which recorded the highest salt accumulation levels. The results also indicated that operating pressure significantly affected EC distribution, as the high-pressure treatment P1 recorded lower EC values than the low-pressure treatment P3 due to improved wetting

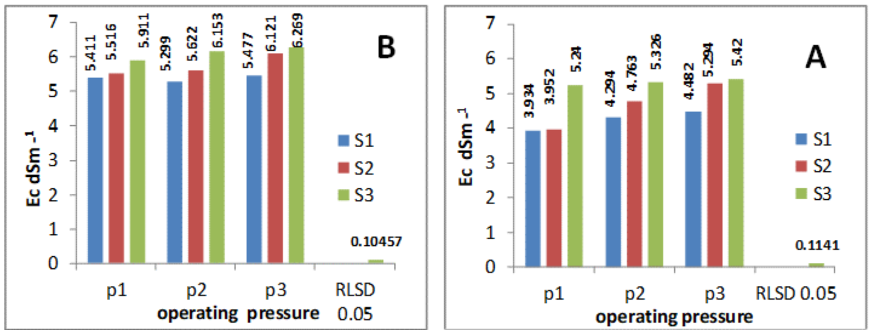

Figure 11: Effect of the interaction between the operating pressure factor (m) and Distance between field pipes (cm) on electrical conductivity values (dS m^{-1}), (A) at beginning of the season, (B)at end of the season correct dS m^{-1} on y-axis (There must be space between dS and m^{-1}). Ec should be corrected as EC

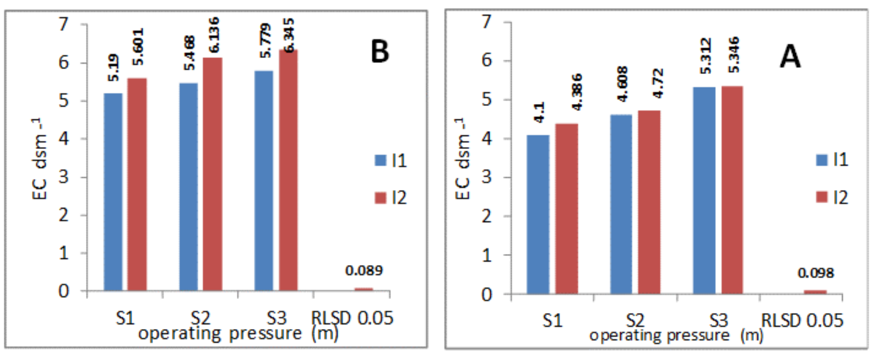

Figure 12: The effect of the interaction between the Irrigation level factor and the distance between field pipes factor on electrical conductivity values (dSm^{-1}), (A) at beginning of the season, (B)at end of the season correct dS m^{-1} on y-axis (There must be space between dS and m^{-1}).

Table 2: The effect of triple interaction between operating pressure (m), Distance between pipes and irrigation level on electrical conductivity value (dS m^{-1})

end of season			start of the season			seasons	
Pressure (m)			Pressure (m)			Irrigation level	Distance between pipes(cm)
P3	P2	P1	P3	P2	P1		
5.253	5,200	5.118	4.417	4.260	3.623	I1	20
5.701	5.398	5.704	4.548	4.329	4.281	I2	
5.943	5.247	5.214	5.246	4.728	3.683	I1	30
6.594	5.997	5.818	5.342	4.799	4.186	I2	
5.767	5.773	5.797	5.410	5.308	5.218	I1	40
6.476	6.533	6.026	5.430	5.344	5.262	I2	
	0.159			0.1697		RLSD 0.05	

front expansion and enhanced salt leaching away from the root zone.

The results further showed variation in soil EC according to soil depth and interaction treatments. The results further showed variation in soil EC according to soil depth and interaction treatment. The surface depth d1 (0-15 cm) recorded the highest EC value because the water and salt move upward by capillary rising to sort surface so salts accumulation when the water evaporated, while depths d2 and-recorded low values due to downward salt leaching. The triple interaction between study factors showed that factorial treatment I1S1P1 (100% EP, 20 cm spacing, and high operating pressure 1.25 m) recorded the lowest EC values, while the highest values were recorded with factorial treatment I2S3P3 (80% Ep, 40 cm spacing, and low operating pressure 0.75 m). Generally, EC values increased at the end of growing season due to increased temperature and evapotranspiration demand, so soil moisture depletion accelerated and salt accumulation within the soil profile, Overall these findings confirm the important role of irrigation management practices in improving salt leaching efficiency and reducing soil salinity under sandy soil conditions.

Discussion

The effect of the distance between field pipes on moisture content

The higher soil moisture content observed under the narrow pipe spacing treatment (S1) can be attributed to the enhanced uniformity of water distribution and the increased overlap of wetting fronts within the root zone under the strip drip irrigation system. The homogeneity and distribution of moisture is achieved due to the bilateral overlap between the wetting fronts of two adjacent pipes (Vishwakarma *et al*., 2023). The decrease in soil moisture content with increasing spacing between field pipes is attributed to reduced horizontal movement in the soil horizontal water movement and a delay in the convergence of wetting fronts around the dripper particularly in sandy soils characterized by high infiltration rate and limited water holding capacity (Bozkurt *et al*., 2006).

Effect of irrigation level on moisture content

The higher soil moisture content at 100% Ep irrigation Level can be attributed to all micropores and most of macropores were filling with water, which helps the soil to retain higher moisture compared to the 80%. Ep irrigation level which leaves some pores not fully saturated, and moisture content appears relatively lower (Bharathi *et al*., 2018. Generally a decrease in moisture content observed at the end of growing season, is attributed to higher temperature and evapotranspiration de leaching to increased water depletion from the soil (Liu *et al*., 2006).

Effect of operating pressure on moisture content

The increase in soil moisture content under higher operating pressure can be attributed to the fact that high pressure leads to greater water discharge from the emitters, allowing for wider horizontal movement and thus a higher percentage of pores filling. Conversely lower operating pressure reduces the discharge rates leads to increasing vertical movement and decreasing horizontal movement so that decreasing the water retention in surface layer of soil (Wang *et al*., 2023). The decrease in soil moisture content at the end of growing season is attributed to higher temperature and evapotranspiration rates leading to increased water depletion from the soil (Liu *et al*., 2006).

Effect of the soil depth on moisture content

The higher soil moisture content at (15 - 30 cm) depth (d2) compared with d1 and d2 can be attributed to this depth distance from the direct influence of sunlight and wind movement, which results in an increase in the rate of evaporation from the surface depth (d1). Also, this intermediate depth (d2) is suitable region to retention water which percolated from d1 depth more than d3 depth where percolation and gravitational drainage losses are more active (Li *et al*., 2024).

The effect of the soil interaction between operating pressure and soil depth factors on moisture content

The significant interaction between operating pressure and soil depth can be attributed to the increasing operating pressure that leads to increase the discharge of emitters, which enhances both lateral and vertical water movement, which increased moisture content, particularly at intermediate depths (d2) Compared with d1 which losses water from the soil surface evaporation or d3 depth which losses the moisture by percolation and gravitational drainage. The reduction in soil moisture content at the end of the growing season is attributed to increased evaporation demand due to higher temperature conditions, which accelerates soil water depletion (Qing *et al*.,2022).

Salt distribution

The effect of the distance between field pipes on electrical conductivity

The variation in soil EC among pipe spacing treatments is mainly attributed to reducing the spacing between field pipes that leads to speed the convergence and overlap of the wetting fronts between the field pipes so that increased soil moisture content which enhanced horizontal and vertical movement of water and increases the efficiency of salt leaching away from the root zone. Narrow spacing improves wetting front interaction, enhances moisture distribution, and promotes salt washing below the root zone, whereas wider spacing reduces washing efficiency and leads to salt accumulation (Ayars *et al*., 1999; Hanson, 2009). The increase in EC at the end of the growing season is mainly due to higher evapotranspiration, which concentrates salts in the soil solution as soil water decreases (Corwin and Lesch, 2005).

Effect of irrigation level on electrical conductivity

The lower EC values under the 100% Ep treatment were likely due to higher soil moisture and improved salts leaching through greater water movement within the soil profile, whereas reduced irrigation at 80% Ep promoted salt accumulation near the wetting front (Danierhan *et al*., 2013). Soil EC increased at the end of the growing season under both irrigation levels because of higher evapotranspiration rates and progressive salt accumulation within the root zone during advanced growth stages (Du *et al*., 2023).

Effect of operating pressure on electrical conductivity (dS m^{-1})

The reduction in soil EC with increasing operating pressure may be attributed to the higher emitter discharge rate and the greater expansion of the wetting front, which enhanced soil water distribution and promoted downward water movement within the soil profile. This process increased salt leaching from the root zone and reduced salt accumulation around the active root area, resulting in lower EC values under high-pressure treatments. Improved water application and leaching efficiency under drip irrigation have been reported to facilitate the redistribution of soluble salts away from the root zone, thereby reducing soil salinity levels (Ayers & Westcot, 1985; Danierhan *et al*., 2013).

Effect of soil depth on electrical conductivity

The higher EC values in the surface soil layer may be attributed to salt accumulation resulting from continuous evaporation and the upward capillary movement of dissolved salts toward the soil surface. In contrast, the reduction in EC with increasing soil depth was likely associated with the downward movement and washing of salts through irrigation water within the soil profile (FAO, 2021; Selim *et al.*, 2013). The increase in EC values at the end of the growing season across all soil depths may be related to higher evapotranspiration rates and progressive

Table 3: Analysis of variance (ANOVA) for soil moisture content and soil salinity during the beginning and end of the growing season (F-values)

S.O.V.	d.f.	Calculated – F.			
		at beginning of season		at end of season	
		Water moisture	Salt distribution	Water moisture	Salt distribution
D	2	24.49**	22.44**	14.36**	5.36**
P	2	210.39**	166.63**	193.34**	53.95**
I	1	6.36**	4.98**	12.35**	376.74**
S	2	15.29**	413.38**	6.36**	188.36**
D.P	4	20.43**	0.61 ns	13.26**	1.32 ns
D.I	2	0.011 ns	0.04 ns	0.12 ns	1.25 ns
P.I	2	0.266 ns	0.05 ns	0.02 ns	1.89 ns
D.S	4	0.229 ns	0.64 ns	0.37 ns	0.20 ns
P.S	4	0.323ns	43.08**	1.95 ns	26.37**
I.S	2	0.084ns	13.95**	0.60 ns	7.02**
D.P.I	4	0.352ns	0.00 ns	0.03 ns	0.44 ns
D.P.S	8	0.196ns	0.36 ns	1.91 ns	0.80 ns
D.I.S	4	0.331ns	0.28 ns	0.09 ns	1.05 ns
P.I.S	4	0.262ns	12.59**	0.11 ns	8.12**
D.P.I.S	8	0.196ns	0.17 ns	0.04 ns	1.15 ns

D: soil depth P: operating pressure I: irrigation level S: distance between field pipes
**: highly significant ns: not significant *: significant

salt accumulation during the advanced growth stages.

Interaction between operating pressure factor (m) and distance between field pipes (cm)

The lower EC values under the narrow pipe spacing may be attributed to greater overlap of the wetting fronts, which improved soil moisture distribution and enhanced the washing of salts away from the root zone. In contrast, wider pipe spacing reduced wetting coverage and promoted salt accumulation within the soil surface layers. The variation among operating pressure treatments was more pronounced under the intermediate spacing due to differences in the uniformity of water distribution within the wetted zone (Selim *et al.*, 2013).

Electrical conductivity

The lower EC values under full irrigation with narrow pipe spacing may be attributed to improved overlap of the wetting fronts, which enhanced soil moisture uniformity and increased the washing of salts away from the root zone. In contrast, wider spacing combined with reduced irrigation, limited wetting coverage and reduced salt removal, leading to greater salt accumulation within the soil profile (FAO, 2021). The increase in EC under reduced irrigation was also associated with higher evapotranspiration rates and increased salt concentration in the soil solution (Corwin and Lesch, 2005).

The effect of triple interaction between Operating pressure (m), distance between pipes and irrigation level on electrical conductivity

The lower EC values under the combination of full irrigation, narrow pipe spacing, and high operating pressure may be attributed to improved overlap of the wetting fronts, greater soil moisture distribution, and enhanced washing of salts away from the root zone. In contrast, reduced irrigation combined with wider spacing and low operating pressure limited water movement and salt leaching, resulting in greater salt accumulation within the soil profile (Hanson *et al.*, 2009 Liu *et al.*, 2023).

Conclusion

The combination of high operating pressure, narrow spacing between field pipes, and full irrigation level resulted in improved soil moisture distribution and reduced soil salinity under sandy soil conditions. This improvement can be attributed to the enhanced uniformity of water applications associated with higher operating pressure, which promoted more consistent emitter discharge along the drip lines. In addition, closer spacing between field pipes increased the overlap of wetted soil zones, leading to a more continuous and uniform distribution of moisture within the root zone. When combined with full irrigation, these conditions ensured adequate water supply for plant uptake while reducing dry spots that can concentrate salts. As a result, salts were more effectively leached beyond the active root zone, leading to lower electrical conductivity values compared with less favorable treatment combinations. Overall, these findings emphasize the importance of optimizing T-tape drip irrigation design parameters to improve irrigation efficiency, enhance soil water distribution, and maintain suitable root zone conditions, particularly in sandy soils where rapid drainage and limited water retention can increase salinity.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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