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Addressing the Deficit Irrigation Dilemma: A Comparative Analysis of Full and Deficit Irrigation Effects on Soil Attributes

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ABSTRACT

Background: To boost water productivity in light of the current water crisis, the deployment of deficit irrigation must be scrutinized for its negative impacts on soil salinity. The primary objective of the present investigation is to determine the link between the amount of total irrigation water used and its impact on various soil parameters. The research also compared full-deficit-irrigation and soil salinity correlation.

Methods: The trial was configured in a Randomized Block Design with eight treatments having various irrigation levels alongside three replications for two seasons *i.e.,* winter of 2021-22 and 2022-23 in Navsari, Gujarat, India. Three irrigation methods *viz.* FDR soil moisture sensor-based irrigation for T_1 to T_4, Pan evaporation fraction based-irrigation for T_5 to T_7 and Cropwat 8.0 model-based irrigation for T_8 were deployed.

Result: The findings of this study indicated that irrigation volume had considerable effects on soil EC, whereas other soil characteristics had non-significant results. The treatment with the least irrigation volume (T_5) had the highest soil EC, whereas, the lowest EC was reported in full irrigation treatment (T_1). The outcome of the experiment confirmed the strong negative association between irrigation volume and soil salinity. To boost water productivity while maintaining soil salinity, treatments with deficit irrigation at moderate levels (90% FC, 80% FC and 70% FC) *i.e.* T_2, T_3, T_4 and T_8 were recommended.

Key words: Climate change, Correlation matrix, Deficit irrigation, Soil EC, Soil salinity, Water productivity.

INTRODUCTION

Climatic changes associated with global warming are potential threats to the agricultural sector as these factors critically affect the backbone of farming-water and soil (Arora, 2019; Champaneri and Patel, 2021). Furthermore, by the year 2050, the world population might reach 12 billion bar and providing them food and nutritional security with declining irrigation water and agricultural land is a challenging task for the farming sector (Fróna *et al.,* 2019). Since irrigated agriculture doubles crop output when compared to rain-fed agriculture, it needs to be prioritized more. However, unpredictable rainfall conditions in arid and semi-arid climates made irrigated agriculture an indispensable aid to optimize crop production.

Irrigation is still necessary for the effective production of crops, nevertheless, it can have certain negative impacts, such as waterlogging and salinization of agricultural land if applied erratically (Isidoro and Grattan, 2010). To apply water judiciously and increase Water Productivity (WP) with an adequate quantity, there must be a precise application method. Given the current water crisis and projected severity in the future, to improve Water Use Efficiency (WUE) in farming, water-saving irrigation methods are necessary (Champaneri *et al.,* 2023). A Deficit Irrigation (DI) approach coupled with a drip irrigation system can be a sensible way to tackle WUE-related concerns in the agriculture sector.

DI refers to the principle of applying a certain level of water deficiency to a plant at specific times (at a particular crop growth stage) or throughout the growing stages. The goal of the comprehensive approach of DI is to maximize WP while minimizing or eliminating yield loss (Khapte *et al.,* 2019; Patanè *et al.,* 2011). DI has its own merits and drawbacks. Many researchers, including Chang *et al.* (2021); Nangare *et al.* (2016); Ragab *et al.* (2019) and Wu *et al.* (2021) highlighted the benefits of DI in the aspect of

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produce quality, WP and WUE with minimal or no yield loss. Conversely, research on the drawbacks of DI, particularly in the area of soil properties, is lacking.

A research work was executed by Nagaz *et al.* (2012) on pepper yield and soil salinity influenced by various DI regimes *i.e.,* full irrigation, various levels of DI and farmer's management practices. The maximum yield and lowest Electrical Conductivity (EC) of soil were recorded under full irrigation treatment. Alternatively, increased soil EC levels were detected with DI treatments and farmer management practices. According to Ding *et al.* (2020), DI might enhance soil salinity and sodicity, particularly in dry and semi-arid climatic locations necessitating proper management measures to ameliorate soil deterioration. Other studies, such as Alkhasha *et al.* (2019); Aragüés *et al.* (2014); Domínguez *et al.* (2011) have revealed comparable outcomes on the impact of DI on soil salinity.

Salinity is an imminent threat altering agricultural productivity all over the world, affecting 20% of cultivated area and 33% of irrigated land. Climate change, excessive groundwater consumption, increased use of low-quantity-quality water in irrigation and the widespread use of irrigation associated with intensive farming can all exacerbate this process (Machado and Serralheiro, 2017; Silva *et al.,* 2021). Many crops suffer from high soil salinity. The EC of a saturated soil paste extract is the standard technique for evaluating agricultural salinity (Mora *et al.,* 2017). Considering this, the present investigation was designed to assess soil salinity (EC) as well as other soil parameters under various DI regimes and irrigation techniques based on Frequency Domain Refractometry (FDR) moisture sensor, Pan Evaporation Fraction (P_{EF}) and Cropwat 8.0 model. The major objectives of this study are as follows: (1) To investigate the impact of different irrigation quantities (DI levels) on multiple soil characteristics; (2) To compare the impact of full irrigation and DI on various soil parameters; and (3) To investigate the correlation between total irrigation water applied and various soil parameters.

MATERIALS AND METHODS

Experimental area

As an approach to determine the effect of various levels of DI on soil physico-chemical parameters, the experiment was conducted for two consecutive winter seasons *i.e.,* 2021-22 and 2022-23 in the tomato field at Vegetable Research Farm, Regional Horticultural Research Station (RHRS), ASPEE College of Horticulture (ACH), Navsari Agricultural University (NAU), Navsari, Gujarat, India at 20°57′ North (N) latitude and 72°54′ East (E) longitude with an altitude of 11.89 m above mean sea level. According to agro-climatic conditions of Gujarat state, Navsari falls under the 'South Gujarat Heavy Rainfall Zone, Agro-Ecological Situation (AES) III'. The climate of this zone is typically tropical and monsoonal. During the course of the experiment, the mean maximum and minimum temperatures vary in the range of 27.0°C - 37.5°C and 11.0°C - 23.1°C, respectively.

Soil properties

The soil of the experimental area is locally known as 'black cotton soil'. As per the soil taxonomy, the experimental soil belongs to order *Inceptisols*, sub-order *Ochrepts*, sub-soil group *Vertic ustochrepts,* a group of *Ustochrepts* under the soil series of Jalalpore, South Gujarat (Shrivastava *et al.,* 1994). Several physicochemical characteristics of soil samples examined before the experiment are given in Table 1.

Treatment details

In an attempt to accomplish the objective of the experiment, eight treatments were laid out in randomized block design (RBD) along with three replications. The experimental treatments involved varying levels of irrigation *viz.* T_1: FDR soil moisture sensor-based irrigation at 100% Field Capacity (FC) (Control-Full irrigation); T_2: FDR soil moisture sensor-based irrigation at 90% FC; T_3: FDR soil moisture sensor-based irrigation at 80% FC; T_4: FDR soil moisture sensor-based irrigation at 70% FC; T_5: Irrigation at 0.4 P_{EF}; T_6: Irrigation at 0.6 P_{EF}; T_7: Irrigation at 0.8 P_{EF} and T_8: Irrigation based on simulation of Cropwat 8.0 model (70% FC). The quantity of irrigation water according to treatments was applied at every alternate day through a surface drip irrigation system. Treatments T_1 to T_4 were applied based on moisture data from the FDR soil moisture sensor using the method described by Gupta (2009). Treatments T_5 to T_7 were applied using P_{EF} data based on Class - A pan evaporimeter (Allen *et al.,* 1998). Treatment T_8 was implemented with irrigation schedules prepared by the Cropwat 8.0 model (Savva and Frenken, 2002).

Soil sample analysis

Composite soil sample from the depth of 0-30 cm was taken from the experimental field with the help of a soil auger before the initiation of the experiment alongside, a total of twenty-four soil samples were collected at the same depth after the completion of the experiment from each treatment in all replications during both the years to analyze various soil parameters. Soil samples collected were dried,

Table 1: Physico-chemical characteristics of soil samples collected before investigation.

Particulates	Initial value
Sand (%)	10.80
Silt (%)	25.70
Clay (%)	63.90
Dry Bulk Density (g cc^{-1})	1.27
Wet Bulk Density (g cc^{-1})	1.62
Field capacity (FC) (%)	31.51
pH	6.800
EC (dS m^{-1})	0.560
Organic carbon (%)	0.68
Available N (kg ha^{-1})	301.06
Available P_2O_5 (kg ha^{-1})	33.39
Available K_2O (kg ha^{-1})	376.32

grinded, processed and sieved through a 2 mm sieve and then used for various analysis. The following techniques were used for evaluating various soil characteristics: soil pH and EC (dS m^{-1}) using Potentiometric and Conductometric methods, respectively as described by Jackson (2014); soil organic carbon (%) by Walkley and Black (1934), available phosphorus (kg ha^{-1}) and available potassium (kg ha^{-1}) using Spectrophotometric and Flame photometric methods, respectively by Jackson (2014); available nitrogen (kg ha^{-1}) by Alkaline $KMnO_4$ method as suggested by Subbiah and Asija (1956).

Statistical analysis

The recorded data pertaining to all the observations studied in the presented investigation were subjected to statistical scrutiny for judicious interpretation. The standard method of Analysis of Variance (ANOVA) technique appropriate to the pooled RBD was followed as described by (Gomez and Gomez, 1984). Treatment means were compared based on the Least Significant Difference (LSD) test, which was statistically significant when $P \leq 0.05$ using "agricole" statistical package in R studio. Pooled analysis was conducted for the data of the two experimental years. Multiple comparisons between the observations of full irrigation (T_1) and deficit irrigation (T_2-T_8) treatments were done using GraphPad Prism software. Pearson's correlation coefficients were used to evaluate correlations between pooled data of the total irrigation water applied and various soil characteristics using "corrplot" and "ggplot2" packages in R studio.

RESULTS AND DISCUSSION

In the present experiment, various methods for estimation of irrigation quantity *i.e.,* FDR soil moisture sensor-based irrigation, P_{EF}-based irrigation and irrigation based on simulation of the Cropwat 8.0 model were used. All these various irrigation approaches along with a variety of irrigation regimes directly influence the amount of water applied in a particular treatment which leaded to a major impact on soil parameters. Data regarding the total amount of irrigation water applied under each treatment during both the years and water saved based on pooled data are given in Table 2.

Data related to several soil properties impacted by experimental treatments are presented in Table 3 and 4. In this study, different irrigation treatments had a substantial impact on soil EC, T_1 treatment, where the highest volume of irrigation water was used, had the lowest soil EC (0.515 dS m^{-1}) readings. The highest soil EC (0.703 dS m^{-1}) value was discovered in the T_5 treatment that used the least irrigation water.

Table 2: Total amount of irrigation water applied and water saved during the experimental tenure.

Treatments	Total amount of water applied (mm ha^{-1})			Water
	2021 - 22	2022 - 23	Pooled	saved (%)
T_1: FDR soil moisture sensor-based irrigation at 100% FC (Control)	945.69	860.78	903.24	0%
T_2: FDR soil moisture sensor-based irrigation at 90% FC	805.49	764.46	784.98	13.09%
T_3: FDR soil moisture sensor-based irrigation at 80% FC	718.13	672.55	695.34	23.02%
T_4: FDR soil moisture sensor-based irrigation at 70% FC	518.54	516.03	517.28	42.73%
T_5: Irrigation at 0.4 P_{EF}	104.78	104.73	104.75	88.40%
T_6: Irrigation at 0.6 P_{EF}	157.17	154.03	155.60	82.77%
T_7: Irrigation at 0.8 P_{EF}	209.57	205.38	207.47	77.03%
T_8: Irrigation based on simulation of Cropwat 8.0 model	534.59	471.99	503.29	44.28%

Table 3: Impact of various irrigation levels on pH and EC of soil.

Treatments	pH (Initial Value: 6.800)			EC (dS m^{-1}) (Initial Value: 0.560)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
T_1: FDR soil moisture sensor-based irrigation at 100% FC (Control)	6.827^a	6.867^a	6.847^a	0.503^c	0.527^b	0.515^b
T_2: FDR soil moisture sensor-based irrigation at 90% FC	6.780^a	6.803^a	6.792^a	0.510^c	0.573^b	0.542^b
T_3: FDR soil moisture sensor-based irrigation at 80% FC	6.743^a	6.763^a	6.753^a	0.553^{bc}	0.577^b	0.565^b
T_4: FDR soil moisture sensor-based irrigation at 70% FC	6.660^a	6.750^a	6.70^{5a}	0.577^{abc}	0.587^b	0.582^b
T_5: Irrigation at 0.4 P_{EF}	6.503^a	6.543^a	6.523^a	0.700^a	0.707^a	0.703^a
T_6: Irrigation at 0.6 P_{EF}	6.523^a	6.543^a	6.533^a	0.687^a	0.700^a	0.693^a
T_7: Irrigation at 0.8 P_{EF}	6.557^a	6.553^a	6.555^a	0.670^{ab}	0.700^a	0.685^a
T_8: Irrigation based on simulation of Cropwat 8.0 model	6.727^a	6.737^a	6.732^a	0.570^{abc}	0.597^{ab}	0.583^b
Year mean	6.665	6.695	6.680	0.596	0.621	0.609
Significance	NS	NS	NS	S	S	S
LSD (0.05)	0.736	0.693	0.480	0.132	0.111	0.083

Table 4: Impact of various irrigation levels on organic carbon, available nitrogen, available phosphorusand available potassium of soil.

Treatments	Organic carbon (%) (Initial Value: 0.68)			Available N (kg ha^{-1}) (Initial Value: 301.06)			Available P_2O_5 (kg ha^{-1}) (Initial Value: 33.39)			Available K_2O (kg ha^{-1}) (Initial Value: 376.32)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
T_1: FDR soil moisture sensor-based irrigation at 100% FC (Control)	0.59^a	0.62^c	0.60^b	275.97^a	301.06^a	288.51^a	29.16^a	30.00^a	29.58^b	360.64^a	372.52^a	366.58^a
T_2: FDR soil moisture sensor-based irrigation at 90% FC	0.59^a	0.62^{bc}	0.60^b	275.97^a	301.06^a	288.51^a	29.83^a	30.34^a	30.08^{ab}	362.88^a	374.76^a	368.82^a
T_3: FDR soil moisture sensor-based irrigation at 80% FC	0.60^a	0.63^{bc}	0.62^{ab}	280.15^a	305.24^a	292.69^a	29.83^a	30.67^a	30.25^{ab}	365.12^a	377.00^a	371.06^a
T_4: FDR soil moisture sensor-based irrigation at 70% FC	0.61^a	0.64^{abc}	0.63^{ab}	280.15^a	305.24^a	292.6^{9a}	30.16^a	30.67^a	30.42^{ab}	367.36^a	379.24^a	373.30^a
T_5: Irrigation at 0.4 P_{EF}	0.66^a	0.69^a	0.68^a	292.69^a	309.42^a	301.06^a	31.84^a	32.35^a	32.09^a	374.08^a	385.96^a	380.02^a
T_6: Irrigation at 0.6 P_{EF}	0.65^a	0.68^{ab}	0.67^{ab}	288.51^a	309.42^a	298.97^a	31.50^a	31.68^a	31.59^{ab}	371.84^a	383.72^a	377.78^a
T_7: Irrigation at 0.8 P_{EF}	0.63^a	0.66^{abc}	0.64^{ab}	284.33^a	309.42^a	296.87^a	31.17^a	31.68^a	31.42^{ab}	371.84^a	383.72^a	377.78^a
T_8: Irrigation based on simulation of Cropwat 8.0 model	0.62^a	0.64abc	0.63^{ab}	280.15^a	305.24^a	292.69^a	30.83^a	31.34^a	31.09^{ab}	369.60^a	381.48^a	375.54^a
Year mean	0.62	0.65	0.63	282.24	305.76	294.00	30.54	31.09	30.82	367.92	379.80	373.86
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD (0.05)	0.120	0.060	0.066	19.561	29.609	21.880	3.215	3.409	2.249	34.596	38.180	25.451

However, most of the soil factors, including soil pH, soil organic carbon, available nitrogen, available phosphorus and available potassium exhibited statistically non-significant results in experimental treatments. Though maximum data regarding soil organic carbon, available nitrogen, available phosphorus and available potassium were recorded in the T_5 treatment while, the lowest data were registered in the T_1 treatment. In contrast, maximum soil pH was recorded under T_1 treatment while lower soil pH was noted under T_5 treatment.

Considering the context of the multiple comparisons between the full irrigation treatment (T_1) and the remaining deficit irrigation treatments (T_2 - T_8) (Fig 1), the majority of the soil parameters, including soil pH, available nitrogen, phosphorus and potassium recorded non-significant results across all compressions. Conversely, in the case of soil EC, all combinations except T_1 vs T_2 and T_1 vs T_3 exhibited a significant difference. While soil organic carbon noted a greater difference only in the T_1 vs T_5 combination.

Recognizing the correlation between the total amount of irrigation water applied and pooled data of all the soil attributes (Fig 2), a strong negative linkage was detected between the total amount of irrigation water applied and various soil parameters *viz.* soil EC (-0.986), soil organic carbon (-0.959), available nitrogen (-0.965), available phosphorus (-0.970) and available potassium (-0.979). On the other hand, it was observed that soil pH (0.988) was positively associated with the total amount of irrigation water used. Considering EC, a positive correlation was registered with soil organic carbon, available nitrogen, available phosphorus and available potassium, whereas soil pH adversely interacted with these elements. A strong positive linkage was observed between soil organic carbon and nitrogen, phosphorus and potassium that were readily available in the soil.

As per the results, soil salinity (EC) was observed to be rise in proportion to a decline in irrigation volume, which might due to the reason that, there was less significant

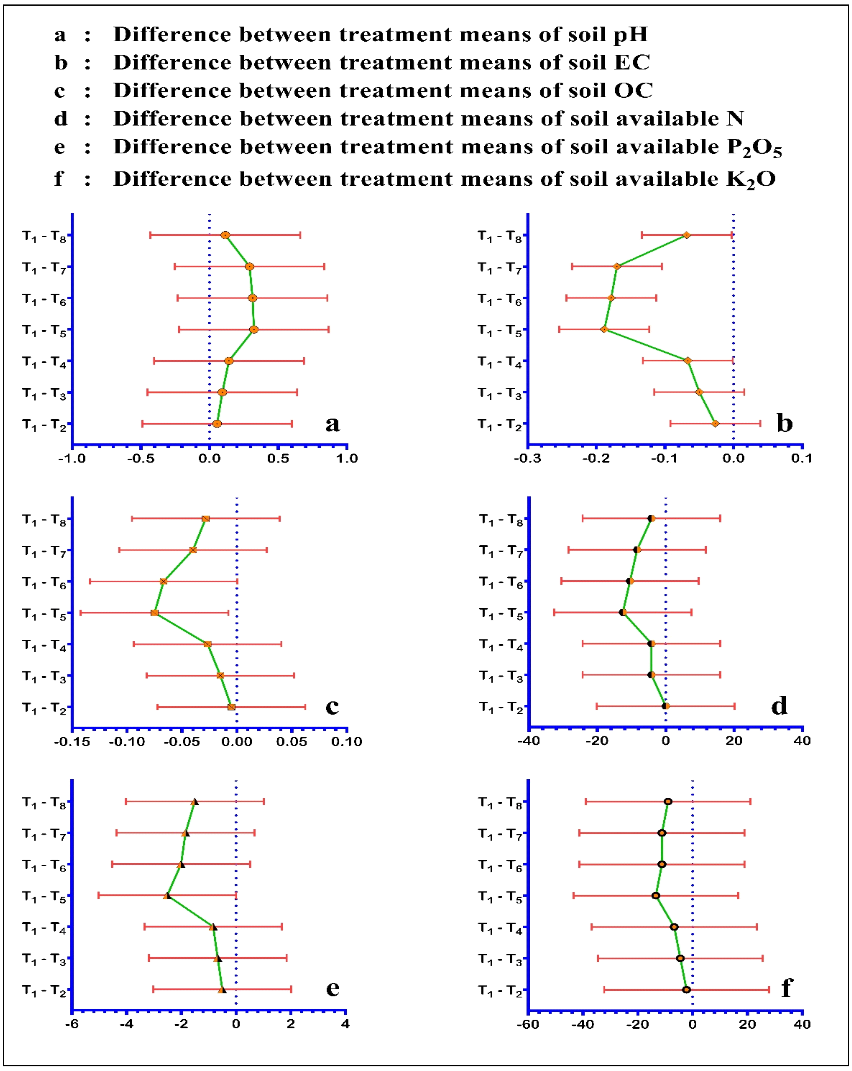


Fig 1: Multiple comparisons between full irrigation (T_1) and deficit irrigation (T_2 - T_8) for various soil parameters (Fisher's LSD).

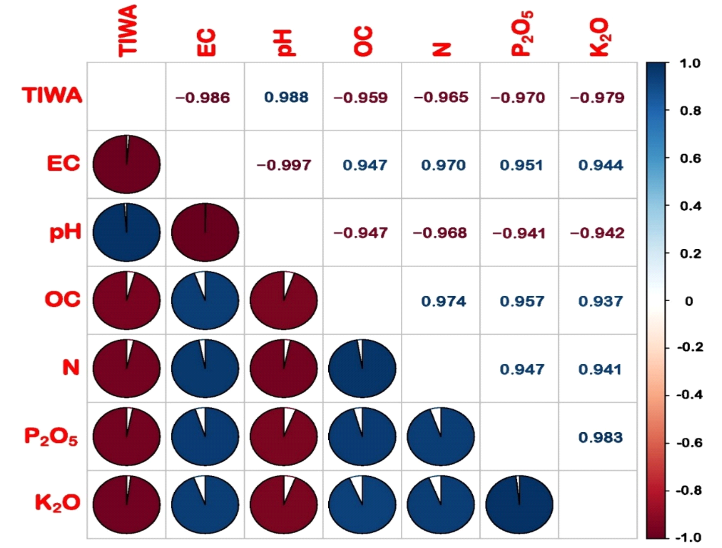
leaching and dilution of salts when a lower volume of irrigation was applied. Hence, greater soil salinity was found with lower irrigation volume treatments. Lower values of EC in higher irrigation volume treatments might be caused by optimal leaching with higher dilution of salts in treatments with greater irrigation levels, which results in less salt building up in the soil (Nagaz *et al.,* 2012). The results confirm the significant negative correlation between total irrigation water applied and EC (Kim *et al.,* 2016).

Higher irrigation volumes might lead to more leaching and dilution of acidic substances from the soil profile, reducing their concentration in the soil solution. As a result, the soil becomes less acidic and the pH increases. Excess water can reduce soil acidity through dilution. Soils with higher water content have a larger volume of water available to buffer acidic substances, resulting in a decrease in the concentration of hydrogen ions (H^+) which leads to a rise in pH (Demir, 2020). This phenomenon leads to a strong positive association between soil pH and total irrigation water applied (Kim *et al.,* 2016).

Due to water stress, plants under treatments with reduced irrigation volumes produce less above-ground biomass and residues. Because of this, a greater percentage of plant residue may persist in the soil rather than being used for growth or breaking down. These plant leftovers aid in the accumulation of organic carbon in the soil. Additionally, low moisture levels slow down microbial activity and the breakdown of organic matter, which results in a larger buildup of organic carbon in the soil (Rath and Rousk, 2015). This outcome supports the strong negative linkage between total irrigation water applied and soil organic carbon (Gülser *et al.,* 2015).

The amount of water in the soil has a considerable impact on nitrogen, phosphorusand potassium availability. Adequate water is necessary for the process of nitrification, where ammonium (NH_4^+) is converted into nitrate (NO_3^-), making it available for plant uptake This may account for the reduced available N content in soil under higher volume irrigation treatments. Contrarily, a higher N content in soil may be caused by a lack of water in lower-volume irrigation treatments, which can impede nitrification and reduce the amount of nitrate available to plants, leading to a higher accumulation of N (Qu *et al.,* 2019). Higher irrigation volumes improve the solubility and availability of P_2O_5 and K_2O to plants, which reduces the buildup of accessible P_2O_5 and K_2O in the soil. Additionally, increased vegetative and reproductive growth in higher irrigation volume treatments requires more nutrient intake, which may be the cause of the decreased available N, P_2O_5 and K_2O concentration in the soil and the negative association of these parameters with a total amount of irrigation water applied (Ding *et al.,* 2020).

In brief, the total amount of irrigation water applied significantly influenced soil EC, showing a strong negative correlation between water quantity and EC levels. Notably, DI treatments (T_2, T_3, T_4 and T_8) resulted in water savings of 13.09%, 23.02%, 42.73% and 44.28% respectively compared to Control-Full irrigation (T_1) (Fig 3). Despite these substantial water savings, these treatments exhibited EC values at par to T_1, suggesting they can be considered for their potential to achieve higher water efficiency while maintaining lower soil salinity levels.



[TIWA= Total irrigation water applied (mm); EC= Soil EC (dS m^{-1}); pH= Soil pH; OC= Soil organic carbon (%); N= Available nitrogen (kg ha^{-1}); P_2O_5= Available phosphorus (kg ha^{-1}); K_2O= Available potassium (kg ha^{-1})]

Fig 2: Pearson r correlation between pooled data of total irrigation water applied and various soil parameters.

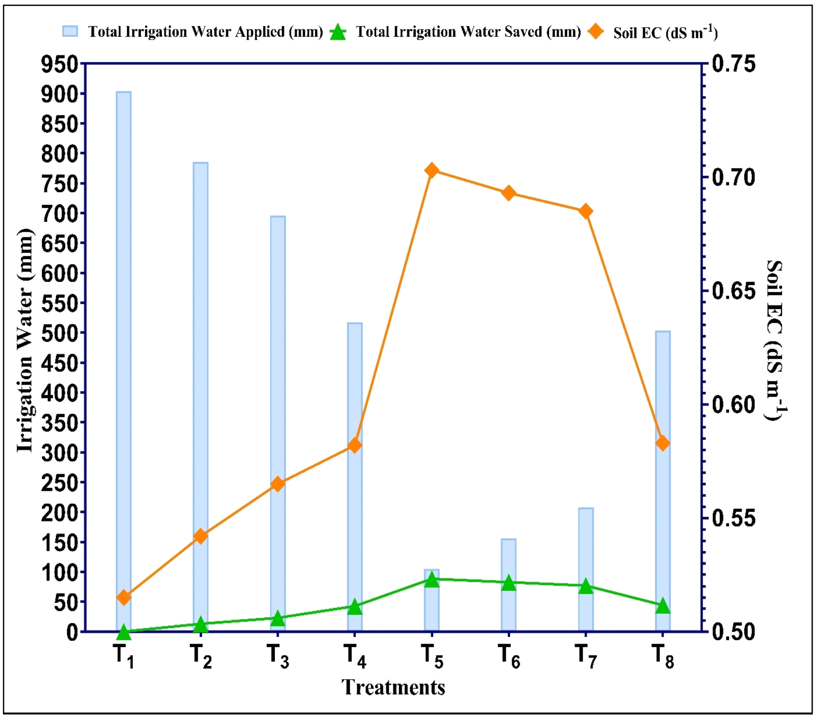


Fig 3: Comparative Analysis of total irrigation water applied, total irrigation water saved and soil EC.

CONCLUSION

The end result of an experiment designed to assess the impact of irrigation water quantity on soil salinity verified the strong negative association between the total amount of irrigation water applied and soil EC. There was no substantial influence of irrigation volume on soil pH, organic carbon, available nitrogen, available phosphorusand available potassium. Data from multiple comparisons of full irrigation and various levels of DI revealed that extreme DI levels increase soil salinity. Thus, in the context of the impending irrigation water crisis and soil salinity difficulties, DI at a moderate level (90% FC, 80% FC and 70% FC) is recommended to boost water productivity while avoiding salt buildup in the soil.

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Author contributions

All listed authors have contributed sufficiently to the work to be included as co-authors. Conceptualization: Dushyant D. Champaneri, Ketan D. Desai and Timur R. Ahlawat; Methodology: Dushyant D. Champaneri, Ketan D. Desai and Prashant K. Shrivastava; Investigation, Writing-original draft, Review and editing, Data curation, Visualization and Formal analysis: Dushyant D. Champaneri; Validation and supervision: Ketan D. Desai, Timur R. Ahlawat and Prashant K. Shrivastava. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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