

Effects of saline water irrigation on the soil salinity, yield and quality of field-grown winter jujube (*Ziziphus jujuba* Mill. “Dongzao”)

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Research Article

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Abstract

[Aims] The shortage of freshwater resources and soil salinization have always been considerable challenges for agricultural production in the Yellow River Delta. Safe and efficient use of saline water resources is thus urgently needed.

[Methods] To reveal the effects of irrigation with underground saline water on soil salinity, yield and quality of drip-irrigated winter jujube, a field trial was conducted from 2020 to 2022. The experiment was conducted with 5 levels of blending a mix of groundwater and freshwater, namely, 1.7 (T1), 3.3 (T2), 4.9 (T3), 6.5 (T4) and 8.1 (T5) dS·m⁻¹.

[Results] The results for three aspects were as follows: (i) Soil surface salinity accumulation occurred when the irrigation water salinity was greater than 4.9 dS·m⁻¹ in 2020, and salinity was maintained in balance in the following two years owing to adequate rainfall during the planting period. (ii) Compared to T1, irrigation with 3.3 dS·m⁻¹ or 4.9 dS·m⁻¹ of saline water had no significant effect on yield, and the winter jujube yield decreased with increasing irrigation water salinity. (iii) Saline water irrigation improved winter jujube quality, as evidenced by the increase in soluble sugar, total soluble solids, titratable acid, vitamin C and flavonoid contents. When the irrigation water salinity ranged from 4.9 dS·m⁻¹ to 8.1 dS·m⁻¹, the comprehensive quality was within the appropriate scope.

[Conclusions] Considering the yield, quality and salt accumulation of winter jujube, drip irrigation is conducive to ensuring the sustainability of winter jujube with saline water salinities less than 4.9 dS·m⁻¹.

1. Introduction

The winter jujube (*Ziziphus jujuba* Mill.) is an economically important and widely cultivated fruit tree grown in the Yellow River Delta (YRD). Winter jujube is a valuable and unique resource in Zhanhua District, Binzhou city, Shandong Province and is referred to as "Chinese wonder fruit". The area under winter jujube cultivation in Zhanhua Province is approximately 20000 hm², with an annual production of approximately 2.75×10⁸ kg of jujube fruits (Li et al., 2022). However, shortages of freshwater resources and soil salinization are two restrictions in developing local agriculture. As an alternative source of freshwater, shallow underground saline water resources in this area are abundant and widely distributed. Winter jujube is considered moderately tolerant to salinity (Zhou et al., 2021); therefore, underground light salt water is a useful option. The scientific and rational utilization of saline water is highly important for addressing the supply and demand of water resources.

The selection of an appropriate irrigation technique is also a key issue in the utilization of saline water. In this study, winter jujube was irrigated with local underground saline water via drip irrigation. Compared with conventional surface irrigation, drip irrigation, which has the advantages of low flow and long operation times and can increase soil moisture and prevent secondary soil salinization, has been widely implemented in many parts of China to combat water shortages (Han et al., 2022; Yang et al., 2020) and is thus regarded as the most suitable method for saline water irrigation. However, saline water irrigation can still result in salt accumulation in the soil, salt stress in plants and physiological drought (Bouksila et al., 2013). Currently, there are fewer studies on the use of saline water drip irrigation for winter jujube.

In terms of the soil response, ensuring that the soil quality does not deteriorate is an important goal for the sustainable development of agriculture with saline water irrigation. It is generally believed that as the mineralization or salt content of irrigation water increases, soil salt accumulation increases (Zhang et al., 2015). Most of the salt generated by irrigation water accumulates in the unsaturated soil layer, and the degree and depth of accumulation are related to the salt content and irrigation amount of the irrigation water, rainfall, irrigation method, irrigation system, soil properties, among other factors (Pang et al., 2010; Yuan et al., 2019). Li et al. (2022) showed that the water–salt regulation method can effectively leach soil salt. With the increase in the saline water irrigation period, the soil salinity can also be maintained at a balance. Therefore, reasonable brackish water irrigation can also achieve a balance of soil salinity.

Producing high-quality and high-yield crops is not only a concern for farmers but also a popular topic among researchers. Crops accumulate both inorganic and organic solutes and change their physiological function to cope with environmental stresses, which leads to changes in yield and quality (Alagoz et al., 2023). Wang et al. (2017) demonstrated that in the southern arid region of Xinjiang, the use of brackish water with a salinity ranging from 2.36 to 3.39 g·L⁻¹ for mixed irrigation had minimal impacts on cotton growth and yield and irrigation water use efficiency. Yang et al. (2019) confirmed that saline water irrigation can improve tomato quality by changing the flavour, nutritional status, storage, and other quality indicators. El-Mogy et al. (2018) irrigated tomato with slightly saline water ranging from 1.2 to 7.5 dS·m⁻¹ and reported that tomato yield decreased by 50% when water with a salinity level of 7.5 dS·m⁻¹ was used. However, the soluble solids and sugar contents in the fruits increased with increasing electrical conductivity. Therefore, the goal of this study was to use brackish water irrigation to improve crop quality without significantly reducing crop yield.

Irrigation with saline water, if feasible, can reduce the demand for freshwater for irrigation. The effect of drip irrigation with saline water on winter jujube, however, has not been studied sufficiently. Therefore, the objective of the present study was to evaluate the effects of irrigation with a combination of saline water on the soil salinity, yield and quality of winter jujube. In this study, saline water drip irrigation was used to (1) explore the effects of drip irrigation with different salinity levels of irrigation water on soil salinity, (2) determine the response of winter jujube yield to different salinities of drip irrigation water, (3) analyse the effects of saline water drip irrigation on winter jujube quality, and (4) determine the salinity threshold of saline water drip irrigation in the YRD through comprehensive assessment of soil salinity and winter jujube yield and quality. The findings of this study will enrich the understanding of saline water irrigation in the YRD and be highly important for the safe use of saline water for winter jujube cultivation and sustainable agricultural development.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted during 2020–2022 on coastal saline land in Zhanhua (37°34′-38°11′N, 117°45′-118°21′E) in northern Binzhou city, Shandong Province. The field station has a typical temperate monsoon climate with an annual precipitation of approximately 554 mm, mostly occurring during June–September. According to the USDA soil classification, the soil in our experimental field was sandy loam soil, with a clay (< 0.002 mm) content of 5.46%, a silt content (0.002 ~ 0.05 mm) of 27.83% and a sand content (0.05 ~ 2 mm) of 66.72%. During the initiation of the experiment in 2020, the topsoil at the experimental site was loam (above 10% clay, 45% silt and 45% sand), had a pH of 8.07, a SOM content of 12.88 g·kg⁻¹, a bulk density of 1.40 g·cm⁻³, and a field capacity of 29.1%. The soil properties of the 0 ~ 100 soil layers at the beginning of the study are presented in Table 1.

Table 1
Physical and chemical properties of the initial soils (0 ~ 100 cm) at the experimental sites

Soil layer (cm)	Soil particle size distribution			Soil texture	Bulk density (g·cm ⁻³)	Field capacity (%)	Soil salinity (g·kg ⁻¹)	pH (1:5)	Soil organic matter (g·cm ⁻³) ³
	Clay (%)	Silt (%)	Sand (%)						
0 ~ 20	9.70	44.89	45.41	Loam	1.391	26.10	1.32	8.07	12.88
20 ~ 40	5.87	27.26	66.87	sandy loam	1.561	27.50	2.45	8.39	12.65
40 ~ 60	5.04	28.40	66.56	sandy loam	1.520	29.40	1.63	8.53	12.01
60 ~ 80	4.06	19.50	76.44	loamy sandy	1.602	29.10	1.06	8.59	11.81
80 ~ 100	7.65	45.52	46.83	Loam	1.426	28.70	1.08	8.60	11.84

2.2. Experimental design

Irrigation water was provided to winter jujube at five levels (1.7 (T1), 3.3 (T2), 4.9 (T3), 6.5 (T4) and 8.1 dS·m⁻¹ (T5)) of salinity, with saline water composed of mixed saline shallow groundwater and fresh tap water in different proportions. The compositions of the groundwater and freshwater used in this study are presented in Table 2. The trees were planted with 2.0-m within-row spacing and 3.0-m interrow spacing, and their height was 2.0 ~ 2.5 m. The experimental plots were arranged in a randomized block design, with each treatment having three replicate plots of 198 m² in size (22.0 m × 9.0 m). Three rows of jujube trees were treated as one treatment, and adjacent treatments were separated by one row of jujube trees to eliminate the effect of lateral movement of soil water. Before sowing, a total of 20000 kg·hm⁻² of chicken manure organic fertilizer was applied to the plots. In the winter jujube trees, mineral fertilizer was applied on the basis of 750 kg·hm⁻² of N, 330 kg·hm⁻² of P₂O₅, and 980 kg·hm⁻² of K₂O in the forms of urea, simple superphosphate, and potassium chloride, respectively. In the early flowering and fruit set stages, topdressing was applied by applying 60% and 40% of the total fertilizer.

Table 2
Total dissolved solids, electrical conductivity (EC) and hydrochemical ion contents of the two water sources (April 2020)

Water type	EC (dS·m ⁻¹)	K [±] (ppm)	Na [±] (ppm)	Ca ²⁺ (ppm)	Mg ²⁺ (ppm)	Cl ⁻ (ppm)	SO ₄ ²⁻ (ppm)	HCO ₃ ⁻ (ppm)	CO ₃ ²⁻ (ppm)
Saline water	7.14	28.9	1020	202	210	1700	812	20.3	375
Freshwater	1.14	6.99	127	61.4	24.5	150	193	20.8	117

Because of the temperate monsoon climate with simultaneous rain and heat in the YRD, rainfall alone can basically sustain the growth of winter jujube. However, a short period of drought often occurs in the early growth stages (mid-April–late June). Four to ten irrigation events were scheduled during the growing period for the trees in the traditional irrigation mode. The irrigation and precipitation distributions from 2020 to 2022 are presented in Table 3. The entire growing season of winter jujube was divided into the bud burst to leafing stage (BLS, mid-April–late-May), flowering to fruit set stage (FFS, late May–late-June), fruit growth stage (FGS, late June–late August), and fruit colouring to maturation stage (FCMS, early September–early October), as shown in Fig. 1.

Table 3
Irrigation and precipitation during the winter jujube growing season from 2020 to 2022

Year	2020				2021				2022			
Growth stage	Irrigation date	Precipitation/mm	Irrigation quota/mm		Irrigation date	Precipitation/mm	Irrigation quota/mm		Irrigation date	Precipitation/mm	Irrigation quota/mm	
BLS	4/24	70.5	24		4/29	60.3	24		4/26	203.8	24	
	5/1		24		5/6		24		-		-	
FFS	5/30	57.6	24		6/17	124.8	24		5/26	76.1	24	
	6/13		24		-		-		6/13		24	
FGS	7/15	244.9	24		8/14	268.4	24		7/18	384.9	24	
	8/22		24		-		-		-		-	
FCMS	9/4	55.3	24		-	120.1	-		9/1	103.7	24	

2.3. Data collection and measurements

2.3.1 Soil water and salinity

Soil samples were randomly collected at depths of 0 ~ 20 cm, 20 ~ 40 cm, 40 ~ 60 cm, 60 ~ 80 cm and 80 ~ 100 cm from the soil surface by a soil auger. The sampling locations were 20 cm away from the jujube roots. A small portion of each layer was separated and put into an aluminium box for the soil water content (SWC) test via the oven-drying method, in which the soil samples were dried to a constant weight at 105 °C for 24 h. The residual soil samples were air-dried, ground and screened using a 2-mm sieve. The electrical conductivity ($EC_{1:5}$) of the mixed solution, which was prepared from the soil and water at a 1:5 ratio by weight, was measured. The soil $EC_{1:5}$ of the main root zone in each treatment was represented by the mean value of the three sampling sites. The $EC_{1:5}$ was then measured using a DDS-307A conductivity meter (Shanghai Precision & Scientific Instrument Co. Ltd., Shanghai, China). According to the linear empirical formula proposed by Hossain et al. (1993), the average electrical conductivity of the saturated soil extract (EC_e) within the soil profile was calculated as follows:

$$EC_e = \left(2.46 + 3.03 \frac{\gamma}{\theta_{sat}} \right) EC_{1:5} \quad (1)$$

where γ is the soil bulk density ($\text{g}\cdot\text{cm}^{-3}$) and θ_{sat} is the saturated soil moisture content ($\text{cm}^3\cdot\text{cm}^{-3}$).

2.3.2 Plant yield

The fruits were harvested on 30 September, 7 October and 29 September for the 2020, 2021 and 2022 seasons, respectively. Winter jujube fruits were picked and weighed following conventional harvest practices. The yield was calculated based on the fruit weight and planting density and given as Y ($\text{kg}\cdot\text{hm}^{-2}$).

The relative yield (Y_r), which was the yield from irrigation with different percentages of saline water compared to that from irrigation with only fresh groundwater, was calculated as follows:

$$Y_r(Sx) = \frac{Y(Sx)}{Y(S0)} \times 100\% \quad (2)$$

where $Y(S_x)$ is the yield of T1 ~ T5 and $Y(S_0)$ is the yield of the treatment irrigated only with freshwater.

When analysing the relationship between irrigation water salinity and relative yield, the Mass–Hoffman crop salt tolerance function model was introduced.

$$Y_r = 100 - K(C - T) \quad (3)$$

where C is the irrigation water salinity, T is the salinity threshold, and K is the percent yield decrease per unit salinity increase.

An alternative crop salt tolerance calculation method (Schiattone et al., 2017) was proposed based on previous studies.

$$Y_r = \left[\frac{Y_m}{1 + (C/C_{s0})^p} \right] \quad (4)$$

where C_{50} is the salinity at which the yield is reduced by 50%, and p is an empirical constant.

2.3.3 Fruit quality indicators

From each tree, 15 jujubes of similar size, uniform colour, and ripeness were randomly collected. Fruit diameters in the horizontal and vertical directions were measured using a Vernier calliper (DL91150, DELI, Zhejiang, China), and the fruit morphology index (FMI) was calculated as the ratio of vertical to horizontal diameter. The weights of single fruits (SFW) and kernels were measured using a balance with an accuracy of one ten-thousandth. The fruit water content (FWC) was measured using the oven-drying method. Titratable acidity (TA) was assayed by the titration method as described by Jiang et al. (2018), total soluble solids (TSS) were measured by a Brix refractometer (PAL-1, ATAGO Co., Ltd., Tokyo, Japan), and soluble sugar (SS) was measured by anthrone colorimetry. The vitamin C (VC) content was measured by the 2,6-dichloroindophenol titrimetric method. The flavonoid content was quantified using the sodium nitrite–aluminium nitrate colour development method (Zhang et al., 2010).

2.4. Statistical analysis

Analysis of variance (ANOVA) was performed using SPSS Statistics 26.0 software (SPSS 19.0, Inc., USA). All the data are presented as the average values of three replicates. The data for each year were analysed separately. The least significant difference (LSD) test was performed to compare the differences among treatments in terms of growth, yield and fruit quality characteristics at the 0.05 level of probability. The figures were created using OriginPro 2020b (OriginLab, USA). Principal component analysis (PCA) was used to normalize the quality characteristics of the different salinity treatments, determine the eigenvalues and contribution rates, and determine the quality scores of the different treatments.

3. Results

3.1. Rainfall and irrigation

Figure 2 shows the precipitation, number of irrigation events and cumulative precipitation during the winter jujube growing season from 2020 to 2022. The growing season precipitation was 428 mm, 574 mm, and 745 mm for 2020, 2021, and 2022, respectively. Compared with the mean annual precipitation (487 mm) in the rainy season in this area, the precipitation in 2021 and 2022 was approximately 87 mm and 358 mm greater, respectively, than usual. The amounts of irrigation with saline water were 168 mm, 96 mm and 120 mm in 2020, 2021 and 2022, respectively, as shown in Fig. 2.

3.2. Change characteristics of average soil water and salinity

3.2.1 Soil water

A proper balance of salt and water in the soil is the key to ensuring the yield and quality of winter jujube. The variation pattern of the soil water content in the 0 ~ 100 cm soil layer over the three years was generally consistent, so only the vertical distribution of the soil water content in 2020 is provided (Fig. 3).

The difference lies in the fact that the SWC in the later stage of winter jujube growth in 2021 and 2022 was greater than that in the same period in 2020 due to the impact of rainfall. The SWC was always higher than 12%, which was more than 50% of the total available water. The lower limit of the optimal SWC in the rhizosphere soil at each growth period of winter jujube was determined by the Forest Society of Binzhou city, and there was no water stress in any treatment during the three-year experiment. In the 0 ~ 60 cm layer, the observed SWC fluctuated greatly. The SWC showed a “wavy change” with time; the relatively high points occurred after irrigation and after rain, and the relatively low points occurred before irrigation and before rain. However, it is worth noting that the 20 ~ 60 cm SWC in the different salinity treatments exhibited the following order: T5 > T4 > T3 > T2 > T1. The 3-year average SWC in the 20 ~ 60 cm layer in T5, T4, T3 and T2 was 11.8%, 8.7%, 9.4% and 6.4% greater than that in T1, respectively.

3.2.2 Soil salinity

Figure 4 shows the mean salinity ($EC_{1:1.5}$) distribution in the soil profile at the beginning and end of each year. The trend of soil salinity for all treatments throughout the soil profile was similar. The mean $EC_{1:1.5}$ of the 0 ~ 100 cm soil depth for the T1 ~ T5 treatments was 0.52 dS·m⁻¹, 0.51 dS·m⁻¹, 0.49 dS·m⁻¹, 0.51 dS·m⁻¹, and 0.52 dS·m⁻¹, respectively. At the end of the 2020 experiment, the mean $EC_{1:1.5}$ at the 1.0 m soil depth increased significantly with increasing irrigation water salinity. The mean $EC_{1:1.5}$ increased even with 1.7 dS·m⁻¹ saline irrigation, which may have been induced by fertigation. At the 0 ~ 100 cm depth, the soil salinity in the T4 and T5 treatments increased significantly from 0.51 dS·m⁻¹ and 0.52 dS·m⁻¹ to 0.77 dS·m⁻¹ and 0.81 dS·m⁻¹, respectively. However, the mean $EC_{1:1.5}$ at the 0 ~ 100 cm soil depth decreased slowly at the beginning of the experiment in 2021. Moreover, the mean $EC_{1:1.5}$ at the end of the experiment greatly decreased and was not positively related to the irrigation salinity. At the beginning of the 2022 experiment, the soil salinity in the soil profile up to 0 ~ 100 cm increased from 0.35 dS·m⁻¹ (after harvesting in 2021) to 0.40, 0.41, 0.41, 0.45 and 0.51 dS·m⁻¹ for T1, T2, T3, T4 and T5, respectively. Similar to the situation in 2021, although saline water was irrigated in 2022, the 0 ~ 40 cm soil salinity decreased again due to rainfall. Compared with that in the first soil sample collected in April 2020, the soil salinity in the T1 ~ T5 treatments decreased by 56.4%, 24.7%, 12.4%, 5.6%, and 0.6%, respectively.

3.3. Yield of winter jujube

Figure 5(a) shows the yields of winter jujube under the different treatments over the three years. Compared with those in the T1 treatment, the yields of winter jujube irrigated with water salinity at 3.3, 4.9, 6.5, and 8.1 $\text{dS}\cdot\text{m}^{-1}$ decreased by 6.4%, 2.9%, 14.1%, and 20.3%, respectively, in 2020; decreased by 0.5%, 2.0%, 5.3%, and 12.1%, respectively, in 2021; and decreased by 6.3%, 8.6%, 14.0%, and 19.1%, respectively, in 2022. The yield decreased with increasing irrigation water salinity, and there was a significant negative correlation between the two when the irrigation water salinity exceeded $6.5 \text{ dS}\cdot\text{m}^{-1}$. Furthermore, based on the linear function of the Mass-Hoffman crop salt tolerance model, the response of the winter jujube relative yield to irrigation water salinity is illustrated in Fig. 5(b). The thresholds of irrigation water salinity were $1.79 \text{ dS}\cdot\text{m}^{-1}$, $2.19 \text{ dS}\cdot\text{m}^{-1}$, and $1.72 \text{ dS}\cdot\text{m}^{-1}$ from 2020 to 2022; when the irrigation water salinity exceeded these values, the winter jujube yield decreased by approximately 3.11%, 1.79%, and 2.56%, respectively, per $1 \text{ dS}\cdot\text{m}^{-1}$ increase in 2020, 2021, and 2022. The salt tolerance threshold has not decreased annually, which indicates that a cumulative effect does not exist in terms of the impact of salt on yield.

The response of the winter jujube relative yield to EC_e according to the linear function of the Mass-Hoffman crop salt tolerance model is illustrated in Fig. 6. Because there is an evident interannual difference in the relationship between relative yield and EC_e , a modified crop salt tolerance discount function was introduced to describe the relationship between the relative yield and EC_e in the root zone. According to the linear function, the soil salinity threshold that winter jujube can endure without any yield reduction was $4.51 \text{ dS}\cdot\text{m}^{-1}$. Above this threshold, the relative fruit yield decreased by 3.43% for each additional $1 \text{ dS}\cdot\text{m}^{-1}$. According to the discount function, the relative fruit yield of winter jujube decreased to 50% when the EC_e of the rootzone was $12.64 \text{ dS}\cdot\text{m}^{-1}$. Specifically, when the relative yield of winter jujube decreased to 50% and 85%, the average soil conductivity (soil salinity) in the $0 \sim 100 \text{ cm}$ soil layer during the growth period was $0.72 \text{ dS}\cdot\text{m}^{-1}$ (0.19%) and $1.03 \text{ dS}\cdot\text{m}^{-1}$ (0.27%), respectively, in this study.

3.4. Quality of winter jujube

Figure 7 shows the changes in winter jujube indicators, such as the fruit shape index, single-fruit weight, fruit moisture content, edible rate, soluble sugar content, total soluble solids, titratable acid content, vitamin C content and flavonoid content, among the three years. The different salinity treatments had no significant effect on the fruit shape index, fruit moisture content or edible rate ($P > 0.05$). However, salinity treatment had a significant effect on the weight of individual fruits ($P < 0.05$). Compared with those in the T1 treatment, the single-fruit weights in the T4 and T5 treatments were 10.87% and 20.35% lower in 2020 and 5.76% and 32.58% lower in 2022, respectively. The contents of soluble sugars, total soluble solids, titratable acid, vitamin C and flavonoids increased with increasing irrigation water salinity. The five contents in the saline water treatments were significantly ($P < 0.05$) greater than those in the T1 treatment in 2020. However, of the five contents soluble sugars and flavonoids were not significantly different in fruits in 2021 ($P > 0.05$), and vitamin C and total soluble solids were not significantly different in fruits in 2022 ($P > 0.05$), which may be due to the reduction in salt stress caused by high rainfall in the later stage of growth. Compared with those in the T1 treatment ($1.7 \text{ dS}\cdot\text{m}^{-1}$), irrigation with $3.3 \text{ dS}\cdot\text{m}^{-1}$, $4.9 \text{ dS}\cdot\text{m}^{-1}$, $6.5 \text{ dS}\cdot\text{m}^{-1}$, and $8.1 \text{ dS}\cdot\text{m}^{-1}$ of saline water resulted in 2.4%, 9.6%, 17.9% and 4.8% increases in soluble sugar content, respectively, in 2020 and 0.2%, 0.9%, 17.9% and 3.3% increases, respectively, in 2022. Similarly, compared with those in the $1.7 \text{ dS}\cdot\text{m}^{-1}$ treatment, the total soluble solids content in the jujubes increased by 5.5%, 12.3%, 14.8%, and 4.9% in 2020 and by 6.7%, 5.9%, 14.1%, and 20.5% in 2021, respectively, with $3.3 \text{ dS}\cdot\text{m}^{-1}$, $4.9 \text{ dS}\cdot\text{m}^{-1}$, $6.5 \text{ dS}\cdot\text{m}^{-1}$, and $8.1 \text{ dS}\cdot\text{m}^{-1}$ saline irrigation. Moreover, the titratable acid content increased by -6.9%, 10.3%, 10.3% and 17.2% in 2021 and 18.2%, 31.8%, 63.6% and 50.0% in 2022, respectively. Compared with those in T1, irrigation with $3.3 \text{ dS}\cdot\text{m}^{-1}$, $4.9 \text{ dS}\cdot\text{m}^{-1}$, $6.5 \text{ dS}\cdot\text{m}^{-1}$, and $8.1 \text{ dS}\cdot\text{m}^{-1}$ saline water increased the vitamin C content by 3.7%, 10.6%, 29.3%, and 8.8%, respectively, in 2020; by 5.1%, 7.7%, 8.6%, and 4.3%, respectively, in 2021; and increased the flavonoid content by 20.9%, 38.4%, 427%, and 37.0%, respectively, in 2020; and by -3.0%, 2.7%, 8.0%, and 3.8%, respectively, in 2022. Thus, irrigation with saline water mainly enhanced the soluble sugar, total soluble solids, titratable acid, vitamin C and flavonoid contents in the fruit, although it reduced the single-fruit weight.

In addition to irrigation water salinity, the soil salinity in the root zone also impacts crop quality. There were interrelated correlations between electrical conductivity ($\text{EC}_{1.5}$) and winter jujube quality, and correlation analyses were performed among the FMI, SFW, FWC, ER, SS, TSS, TA, VC and flavonoids (Fig. 8). Evidently, $\text{EC}_{1.5}$ had a significant positive correlation with FWC, SS, TSS and flavonoids (0.59, 0.64, 0.86, 0.66). There was a highly significant negative correlation between the SS and TA contents, while the SS content had a distinct positive correlation with the TSS (0.63) and VC (0.84) contents. Moreover, the fruit VC content was strongly negatively correlated with the TA content (-0.65) but positively correlated with the TSS content (0.50).

3.5. Optimal irrigation water quality for high-quality winter jujube

According to Fig. 7, it was difficult to achieve the theoretical maximum value of all quality indicators with saline irrigation. Thus, principal component analysis (PCA) was carried out to evaluate the comprehensive quality of the winter jujube. The following nine indices were selected and calculated: FMI (X1), SFW (X2), FWC (X3), ER (X4), SS (X5), TSS (X6), TA (X7), VC (X8) and flavonoids (X9). With the PCA, two indices (F1 and F2) were determined to represent the eight indices with representativeness of 73.97% and 16.35%, respectively, in 2020, which meant that the original physicochemical information of the winter jujube could be explained by these two principal components (PCs). The two PCs can be expressed as follows:

$$\text{PC}_{2020_1} = 0.113X_1 - 0.072X_2 - 0.120X_3 + 0.144X_4 + 0.143X_5 + 0.140X_6 + 0.135X_7 + 0.133X_8 + 0.146X_9 \quad (5)$$

$$\text{PC}_{2020_2} = 0.215X_1 + 0.595X_2 + 0.397X_3 - 0.037X_4 + 0.168X_5 + 0.246X_6 + 0.151X_7 + 0.039X_8 - 0.085X_9 \quad (6)$$

where $\text{PC}_{\text{year}1}$, $\text{PC}_{\text{year}2}$, and $\text{PC}_{\text{year}3}$ are the first and second principal components, respectively.

According to the results of the PCA conducted for 2021, the first three PCs accounted for 94.40% of the total variance, and their contribution rates were 56.96%, 25.52% and 11.92%, respectively. According to the PCA conducted for 2022, the first three PCs accounted for 94.69% of the variance, and their contribution rates were 60.02%, 21.51% and 13.17%, respectively. The three PCs for 2021 and 2022 can be expressed as follows:

$$PC2021_1 = 0.103X_1-0.183X_2-0.181X_3-0.100X_4+0.162X_5+0.186X_6+0.167X_7+0.098X_8+0.100X_9 \quad (7)$$

$$PC2021_2 = 0.033X_2+0.148X_1+0.102X_3+0.349X_4+0.128X_5-0.043X_6-0.041X_7+0.364X_8+0.357X_9 \quad (8)$$

$$PC2021_3 = 0.784X_1-0.063X_2+0.268X_3-0.095X_4+0.050X_5+0.125X_6-0.455X_7-0.092X_8+0.008X_9 \quad (9)$$

$$PC2022_1 = 0.153X_1-0.110X_2-0.114X_3-0.107X_4+0.153X_5+0.164X_6+0.175X_7+0.112X_8+0.177X_9 \quad (10)$$

$$PC2022_2 = 0.277X_2+0.372X_1+0.360X_3+0.146X_4+0.078X_5-0.098X_6-0.006X_7+0.347X_8+0.121X_9 \quad (11)$$

$$PC2022_3 = -0.060X_1+0.046X_2-0.312X_3+0.640X_4-0.327X_5+0.331X_6+0.186X_7+0.260X_8-0.107X_9 \quad (12)$$

The comprehensive evaluation function can be established for 2020 to 2022 by the contribution rate of the PCs as follows:

$$I_{2020} = 0.82F_{2020_1} + 0.18F_{2020_2} \quad (13)$$

$$I_{2021} = 0.60F_{2021_1} + 0.27F_{2021_2} + 0.13F_{2021_3} \quad (14)$$

$$I_{2022} = 0.63F_{2022_1} + 0.23F_{2022_2} + 0.14F_{2022_3} \quad (15)$$

where I_{year} is the comprehensive score.

The comprehensive evaluation results are shown in Table 4. The results indicated that the irrigation water salinity in the 6.5 dS·m⁻¹ treatment had the highest comprehensive score and ranked first among the three years. However, irrigation water salinities of 4.9 dS·m⁻¹, 8.1 dS·m⁻¹ and 8.1 dS·m⁻¹ ranked second in 2020, 2021 and 2022, respectively. The comprehensive score increased with increasing irrigation water salinity from 1.7 dS·m⁻¹ to 4.9 dS·m⁻¹. To obtain high-quality winter jujube, irrigation water with a salinity of 4.9 ~ 8.1 dS·m⁻¹ is recommended based on the present study.

Table 4
Comprehensive score and rank of fruit quality under various salinity treatments

Season	Treatment	Comprehensive score	Rank
2020	T1	0.790	5
	T2	0.826	4
	T3	0.902	2
	T4	0.928	1
	T5	0.855	3
2021	T1	0.592	5
	T2	0.608	4
	T3	0.623	3
	T4	0.659	1
	T5	0.652	2
2022	T1	0.733	5
	T2	0.749	4
	T3	0.787	3
	T4	0.834	1
	T5	0.800	2

4. Discussion

4.1. Effects of irrigation salinity on soil water and salinity

The same amount of irrigation water was applied to all the treatments in our study, and the mean SWC in the 0 ~ 100 cm soil layer increased with increasing salinity, which is consistent with most related research (Chen et al., 2018; Zhang et al., 2020). During the early growth stage of winter jujube, plants consume less water, and most of the soil water consumption is attributed mainly to evaporation from the soil surface; thus, the differences among treatments were small (Fig. 2). In the middle and later stages of winter jujube growth, soil water consumption occurred mainly through plant transpiration, and the SWCs in the treatments irrigated with 6.5 and 8.1 dS·m⁻¹ were significantly ($P < 0.05$) greater than those in the other saline water irrigation treatments during the three growing seasons. This is because under environments with high salt concentrations, the physiological growth activities of crops are limited, and the water consumption of crops is reduced, resulting in a relative increase in SWC (Soothar et al., 2021). In addition, irrigation with high-salinity water will also reduce soil permeability, which is related to the evaporation of soil moisture (Liu et al., 2012). The large range of SWC in the 0 ~ 40 cm soil layer may be a result of precipitation and the associated intense evaporation, and the large range of SWC in the 40 ~ 60 cm soil layer may be a result of subsequent root water absorption. The differences in SWC among the three experimental years were large and were caused mainly by different meteorological factors, such as rainfall.

Soil salt accumulation is a major problem that restricts the application of saline water irrigation to winter jujube. The amounts of irrigation with saline water were 168 mm, 96 mm and 120 mm in 2020, 2021 and 2022, respectively, and the majority of irrigation water during the winter jujube growing season was rainfall. Therefore, soil accumulation and desalination were affected mainly by rainfall and irrigation. Since the total rainfall in 2022 was greater than that in 2020, the rainfall during the winter jujube fruit growth period in 2022 was approximately 1.6 times greater than that in the same period in 2020, and the irrigation amount of saline water was less than that in 2020 (Table 3); thus, the desalination amount in 2022 was greater than that in 2020. In the same year, the higher the salinity of the irrigation water was, the more severe the soil salt accumulation was, which is consistent with the findings of Feng et al. (2021). Compared to the initial soil salinity before sprouting in 2020, the soil salinity in the 0 ~ 100 cm soil layer at harvest in 2022 decreased in the T1 treatment and slightly increased in the T2 and T3 treatments, while it increased significantly in the T4 and T5 treatments. The final soil $EC_{1:5}$ values were all less than 0.6 dS·m⁻¹, which indicated mild salinization. Based on the above results, salinity was leached from the crop root zone by adequate rainfall to ensure water and salt balance. Wu and Wang (2010) reported that salt accumulated in the upper soil layer when wheat was irrigated continuously with 3 g·L⁻¹ mineralization degree of saline water in Hebei during a rainfall deflection year. Several studies of other crops have shown that under monsoon climate conditions, soil salinity increases during the irrigation period and returns to its original value after crop harvest, influenced by rainfall (Wang et al., 2022; Gao et al., 2023). In our experiment, from the perspective of sustainable irrigation, it is not recommended to use water with a salinity > 4.9 dS·m⁻¹ for drip irrigation.

4.2. Winter jujube yield and quality under saline water irrigation

The low yield is another problem that restricts the application of saline water irrigation to winter jujube. In this study, there was little difference in winter jujube yield between treatments during the same growth season, and only the yields of T4 and T5 were significantly ($P < 0.05$) less than that of T1. This means that drip irrigation water with a salinity of ≤ 6.5 dS·m⁻¹ had no significant negative effect on winter jujube. The soil ECe and plant salt tolerance are key factors that can affect jujube yield. Several studies on jujube salinity tolerance have been carried out. The salinity threshold for Fanchang jujube has been previously reported to be 0.136%, above which the yield was reduced by 15% (Ma et al., 1997). Wu and Qi (1985) investigated the response of Jinsi xiaozao jujube to saline water and reported that the salinity threshold for this variety was 0.5%. However, the corresponding value of the ECe threshold was 1.03 dS·m⁻¹ (0.27%), and the salinity tolerance of winter jujube was relatively weak. This indicates that there are significant differences in crop salt tolerance among varieties (Alsafari et al., 2019), but these research results are consistent with the average salt tolerance threshold for fruit tree growth reported by previous research, which is 1.4 dS·m⁻¹ (Jin et al., 2014). The uncertainty of these results may be related to the experimental cultivar and weather conditions (Katerji et al., 2000).

Despite the decrease in yield resulting from irrigation with saline water, fruit quality increased under saline conditions (Abdelgawad et al., 2019). Jujube quality includes various aspects, such as appearance, flavour, and nutritional status. As shown in Fig. 8, the single-fruit weight significantly decreased when jujube was irrigated with a salinity greater than 6.5 dS·m⁻¹ in 2020 and 2022, which is consistent with the findings on tomato of Abdeldym et al. (2020). The reduction in yield could be explained by the fact that a high salt concentration decreases the water potential in plants, which reduces water flow into fruit and limits the rate of fruit expansion. In addition, the soluble sugar and TSS contents increased with increasing irrigation water salinity. Similar results were observed by Moya et al. (2017) with tomato fruits. This result could be due to the lower fruit water content, as high salinity irrigation leads to an increase in the percentage of TSS (Al-Ismaily et al., 2014), or to the adaptation of plants to salt stress by increasing the TSS in fruits (Abuarab et al., 2020). In addition, the titratable acid content increased with increasing irrigation water salinity in our study, which is basically consistent with the findings of Lima et al. (2020) on the pulp of West Indian cherry. According to Lima, this change is related to changes in metabolic and physiological processes in plants caused by salt stress, which increases the synthesis of acids, leading to their accumulation in fruits. VC is considered to be one of the most important antioxidant compounds for human health. Our results support the hypothesis that VC increases with high salinity levels (1.7 ~ 6.5 dS·m⁻¹). The same trend was reported by Marín et al. (2009), who reported that an increase in nutrient solution salinity resulted in an increase in the VC content in red pepper fruits. In addition to irrigation water salinity, the soil salinity in the root zone also impacts crop quality (Cramer et al., 2001). The quality indicators of flavour (i.e., fruit moisture content, soluble sugar content, and total soluble solids content) had a significant ($P < 0.05$) relationship with the ECe (Fig. 8). This indicates that after continuous saline irrigation, there is a significant difference in the soil water and salt environment, which in turn affects crop quality.

4.3. Assessment of the safe use potential of saline water

According to the findings of our study, to maintain the soil salinity and winter jujube yield at a relatively appropriate level, the irrigation water salinity should be controlled below $4.9 \text{ dS}\cdot\text{m}^{-1}$. Therefore, saline water with a salinity less than $6.5 \text{ dS}\cdot\text{m}^{-1}$ can be used for temporary and supplementary irrigation of winter jujube, while saline water with a salinity less than $4.9 \text{ dS}\cdot\text{m}^{-1}$ is more conducive to the sustainability of drip-irrigated winter jujube. Although the fruit yield was significantly lower for the $6.5 \text{ dS}\cdot\text{m}^{-1}$ and $8.1 \text{ dS}\cdot\text{m}^{-1}$ treatments than for the $1.7 \text{ dS}\cdot\text{m}^{-1}$ treatment, this does not mean that saline irrigation was unsuitable for winter jujube production. For most crops, there is a trade-off between crop yield and fruit quality (Xiao et al., 2015; Waltz, 2015). If farmers concentrate their attention on fruit yield, other agricultural practices that are effective at alleviating plant salt stress, such as organic matter application (Cao et al., 2016), may still need to be applied to attenuate the disadvantages of saline irrigation to maximize crop yields. However, if fruit quality is considered, the benefits of the $6.5 \text{ dS}\cdot\text{m}^{-1}$ and $8.1 \text{ dS}\cdot\text{m}^{-1}$ treatments may exceed that of the $1.7 \text{ dS}\cdot\text{m}^{-1}$ treatment since they can maintain not only a relatively high yield but also obviously improve fruit quality, as indicated by increases in the vitamin C, soluble sugar and solids, glucose, fructose and sucrose contents (Fig. 7).

Currently, studies on the use of saline water drip irrigation for winter jujube cultivation are rare. Chen et al. (2016) reported that when the summer rainfall is greater than 300 mm, irrigating winter wheat with $5 \text{ g}\cdot\text{L}^{-1}$ saline water can leach soil salt and achieve annual equilibrium. The average annual rainfall in the summer in the research area is 417 mm, which has a good leaching effect on soil salt accumulation. However, after leaching, salt easily moved up and accumulated on the surface under local climate and hydrological conditions. Therefore, the short-term implementation of saline water irrigation may have no significant harmful effect on the soil environment, but this practice may be risky after long-term application. The limitation of this study is that the experimental period was short; thus, it was difficult to determine the underlying mechanism of the effects of saline water irrigation on soil quality. Consequently, the effects of long-term saline water drip irrigation on the soil environment in this area need further investigation.

5. Conclusions

Determining the response of crops and soil under irrigation with different levels of water salinity, as well as ensuring the effective exploitation and utilization of saline water resources, are pressing problems in the high-quality development of agriculture in the Yellow River Delta. In this three-year field experiment (2020–2022), the effects of saline water on soil salinity, winter jujube yield and quality were investigated. The conclusions of the study are as follows: using the appropriate water salinity level for drip irrigation can alleviate water and salt stress and maintain winter jujube yield. Irrigation water salinity levels above this optimum increase soil salinity and significantly reduce yield. The soil salinity at the 0 ~ 100 cm depth did not exceed $0.6 \text{ dS}\cdot\text{m}^{-1}$ (mild salinization soil) when irrigating with a water salinity $\leq 4.9 \text{ dS}\cdot\text{m}^{-1}$, and the soil salinity was maintained at a balance. The winter jujube yield decreased with increasing irrigation water salinity, and the yield decreased considerably when the water salinity was $\geq 6.5 \text{ dS}\cdot\text{m}^{-1}$. In addition, the results showed that the contents of several quality indicators (i.e., soluble solids, soluble sugar, organic acids, and vitamin C) increased with increasing irrigation water salinity, and the salinity of the irrigation water corresponding to the optimum quality of winter jujube was $4.9 \sim 8.1 \text{ dS}\cdot\text{m}^{-1}$. When winter jujube is irrigated with saline water under drip irrigation in a natural environment, comprehensive consideration of stable yields, jujube quality, and prevention of secondary salinization of soil is necessary. According to our three-year field trial, drip irrigation is conducive to ensuring the sustainability of winter jujube with irrigation water salinities less than $4.9 \text{ dS}\cdot\text{m}^{-1}$.

Declarations

CRedit authorship contribution statement

Xin Cong, Guibin Pang, and Zhenghe Xu conceived and designed the research. Xin Cong, Kun Wang, Guibin Pang, and Xiangzhou Dou performed the experiments and analyzed the data. Xin Cong, Tianyu Wang, and Zhenghe Xu wrote the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Figures



Figure 1

Different growth stages of winter jujube: (a) Leaf expansion; (b) flowering; (c) young fruit; (d) fruit expansion; (e) fruit colouration.

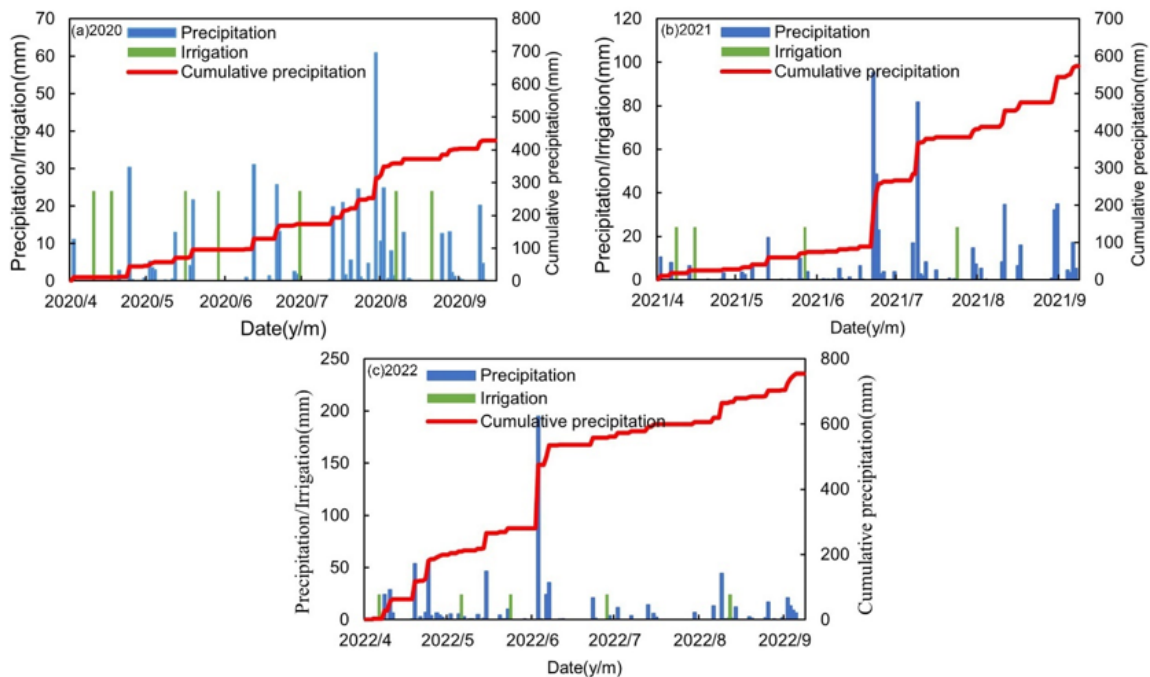


Figure 2

Precipitation and irrigation during the growing season of winter jujube from 2020 to 2022.

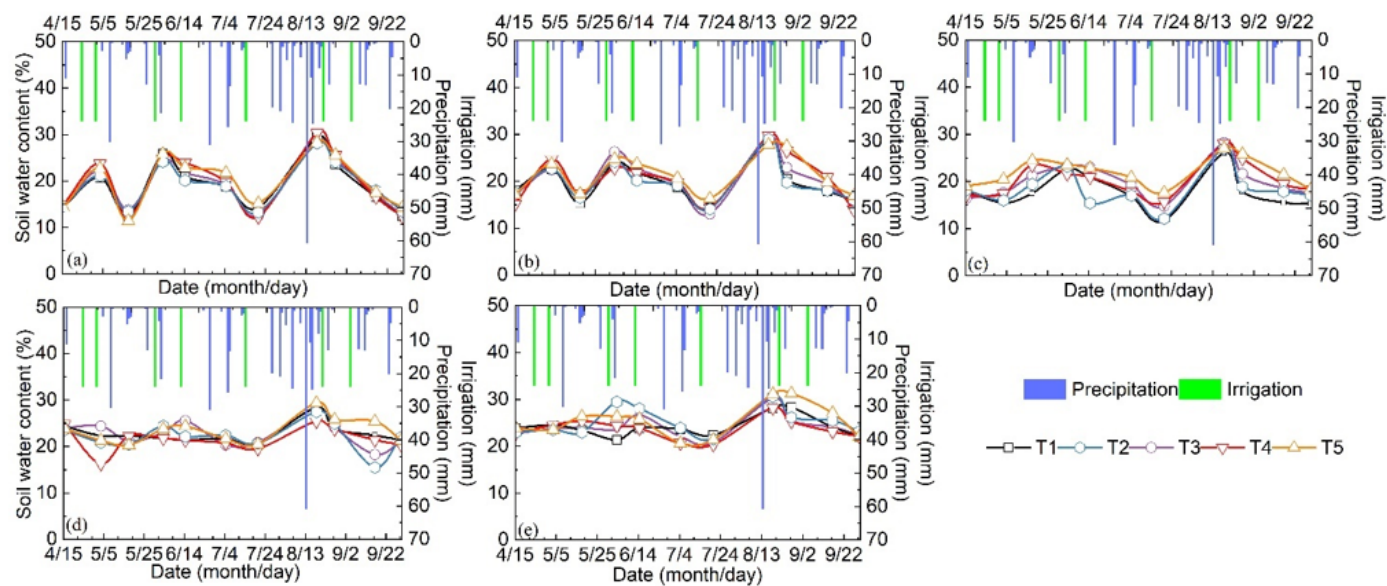


Figure 3

Changes in the vertical distribution of SWC under the different treatments during 2020.

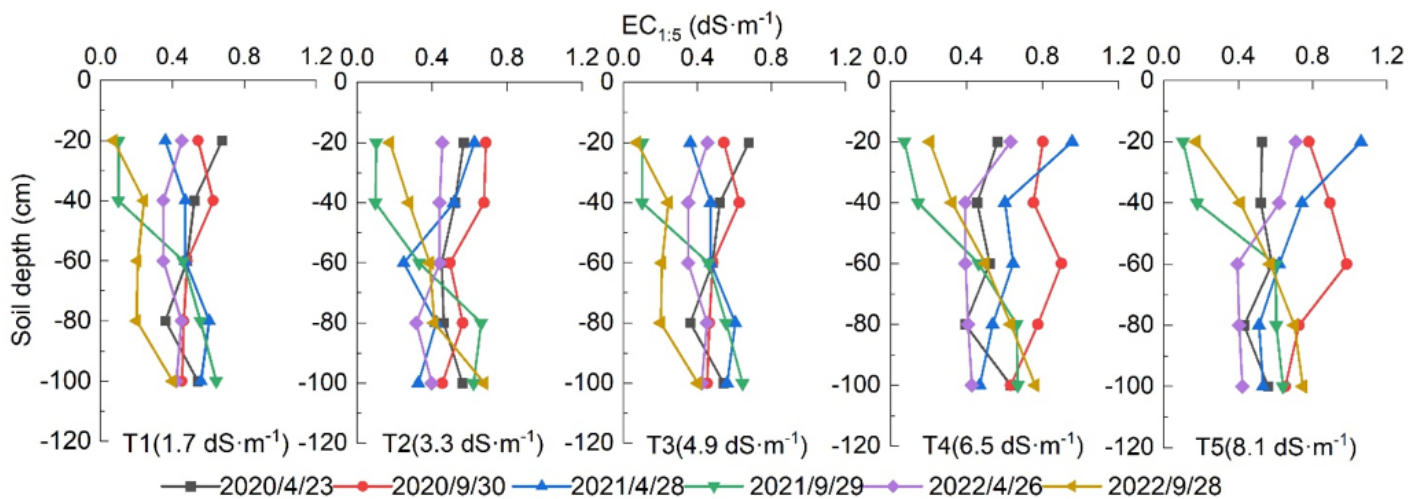


Figure 4

$EC_{1.5}$ under the different irrigation water salinities in the growing season from 2020 to 2022.

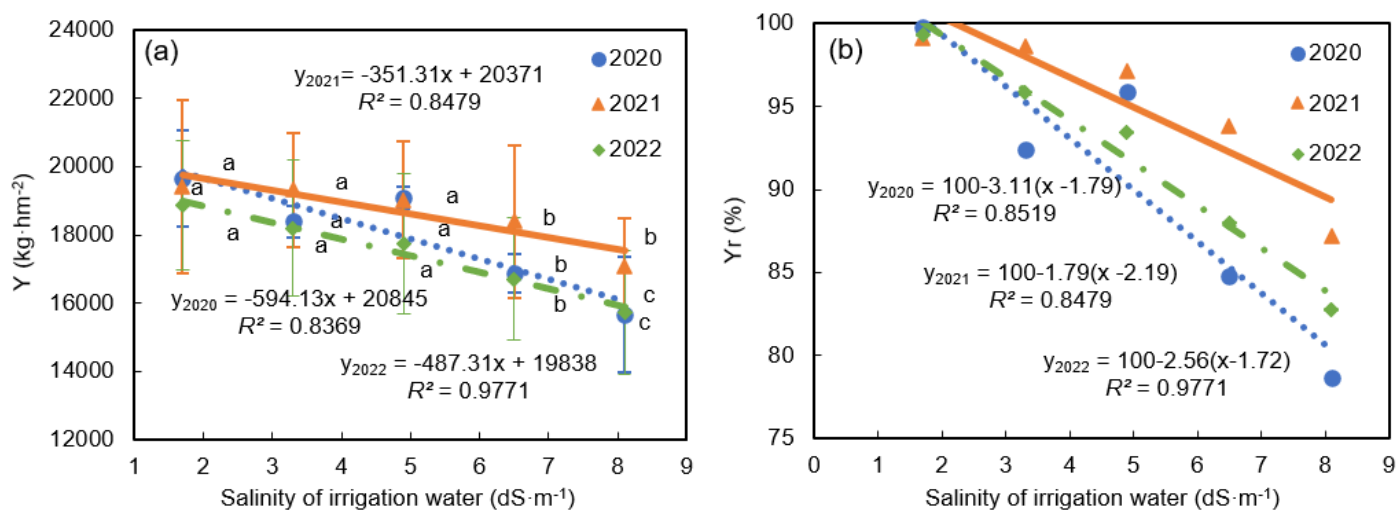


Figure 5

Y and Y_r of winter jujube under different irrigation water salinity treatments

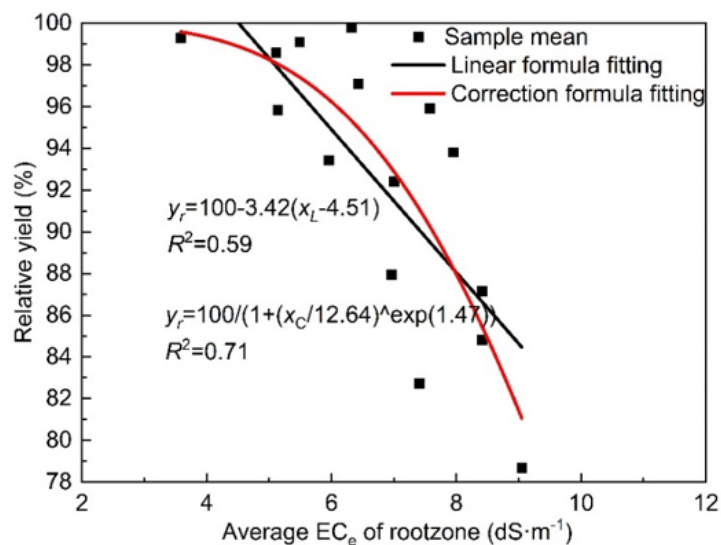


Figure 6

Relative yield of jujube in response to soil EC_e in 2020-2022

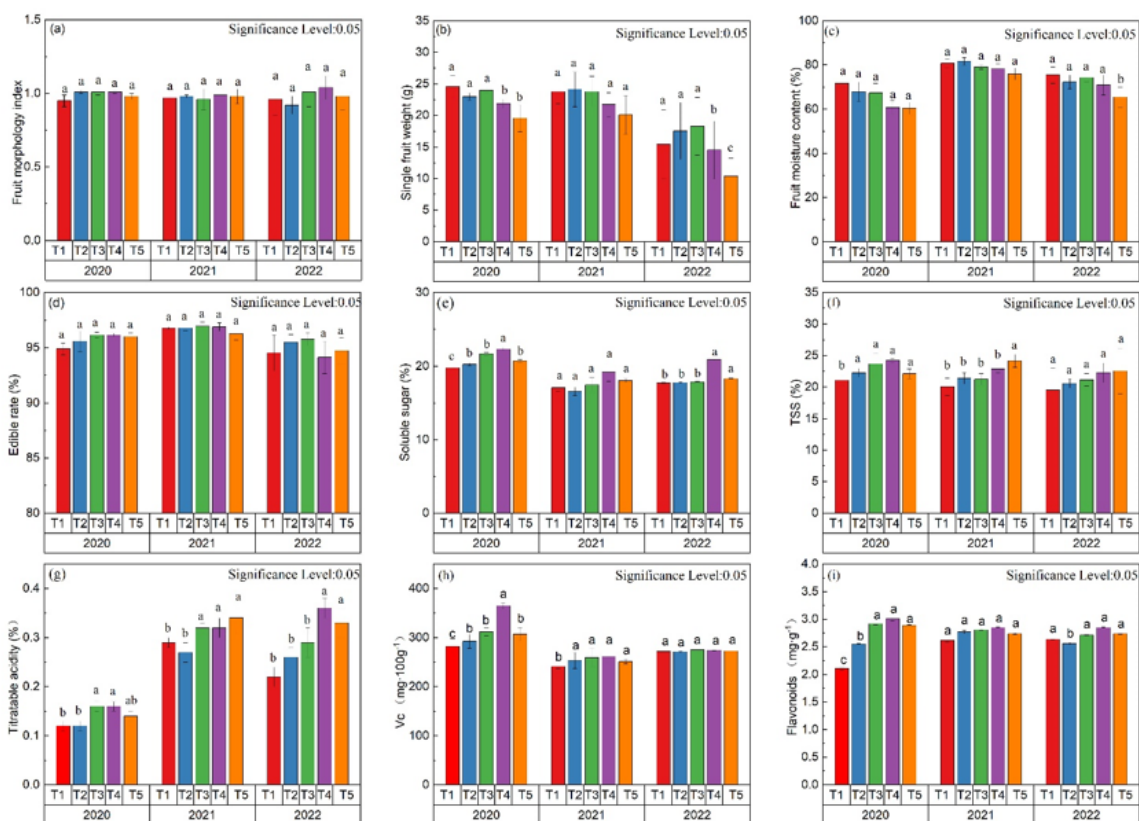


Figure 7

Quality of winter jujube under different irrigation treatments from 2020 to 2022. Values followed by different letters are significantly different at $P < 0.05$ within the same year.

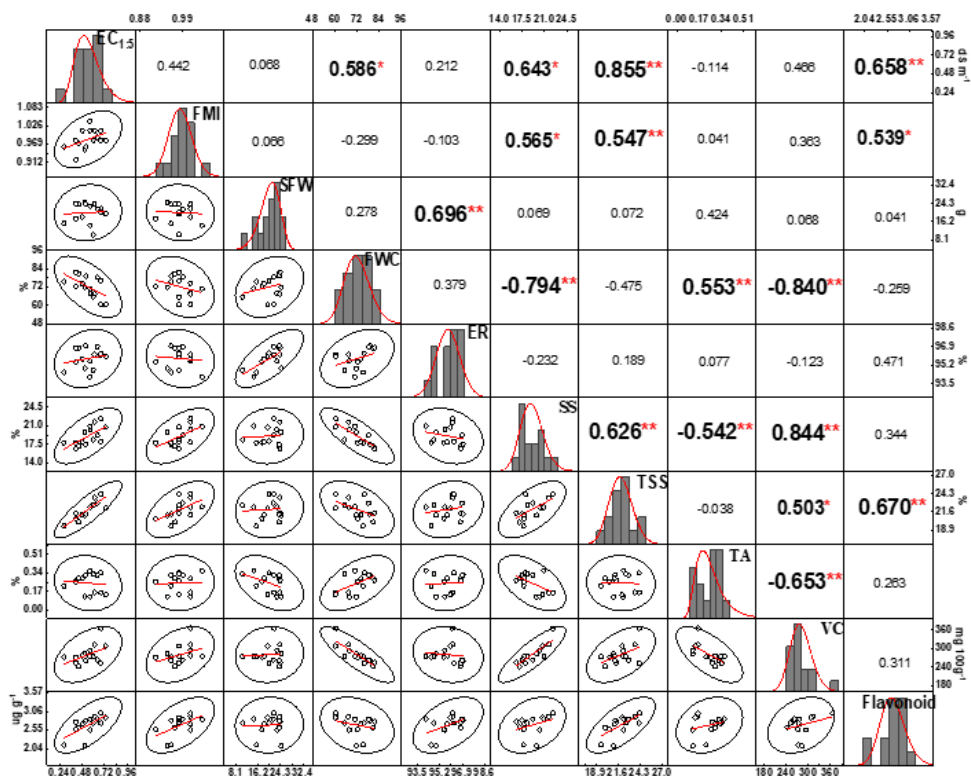


Figure 8

Correlation analysis and multipanel scatter plots of average soil conductivity ($EC_{1.5}$) and fruit quality traits, including the fruit morphology index (FMI), single-fruit weight (SFW), fruit water content (FWC), edible rate (ER), soluble sugar (SS), total soluble solids (TSS), titratable acid (TA), vitamin C (VC), and flavonoids, during the growth period of winter jujube in three growing seasons.