

Article

Leaching Requirement for Cotton Under Film-Mulched Drip Irrigation with Brackish Water

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Abstract

Film-mulched drip irrigation (FMDI) is used increasingly for cotton (*Gossypium hirsutum* L.) production in arid regions. However, salts often accumulate in the soil, eventually leading to soil salinization and crop failure when using FMDI with brackish water inappropriately. Evaluation of the leaching requirement (LR) for cotton under FMDI with brackish water that comprehensively considers cotton yield, water saving, soil conditions, and economic benefits needs to be investigated more completely. The present study compared the cotton growth for different leaching fractions (LF) under FMDI with brackish water and provides comprehensive analysis of LR for cotton and its relationships with soil conditions. A higher LF was related to a lower cotton yield when the LF was larger than 0.15. Moreover, a larger LF led to a lower ratio of reproductive growth and irrigation water productivity when the LF was larger than 0.2. A high soil water content (SWC) strip was observed in the 40–60 cm soil layers for all scenarios. Moreover, a higher SWC proportion in the deeper soil layers as for LF_{0.15} or LF_{0.2} may also be beneficial to cotton growth. Soil salinity decreased with decreases in irrigation water quantity when the LF was lower than 0.2, but increased when the LF was higher than 0.2. Either too much or too little irrigation water was not beneficial from an economic perspective. Our study indicated that the LR values between 0.05 and 0.15 were recommended for FMDI when the total dissolved solids for brackish water is within 1.61–3.21 g L^{−1}. Integrated strategies, including optimized irrigation-fertilizer management, groundwater depth monitoring, and halophyte intercropping, are required to sustain production while mitigating secondary salinization and groundwater pollution under FMDI with brackish water.

Keywords: leaching requirement; cotton; film-mulched drip irrigation; soil conditions; arid region



Academic Editor: William Frederick Ritter

Received: 17 May 2026

Revised: 30 June 2026

Accepted: 8 July 2026

Published: 25 July 2026

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1. Introduction

Cotton, a major cash crop in Xinjiang, northwest China is known to have a relatively high tolerance for salinity [1–3]. Film-mulched drip irrigation (FMDI) has been used widely for cotton (*Gossypium hirsutum* L.) irrigation in Xinjiang [4–7]. The FMDI technique can reduce water use and increase water use efficiency compared to furrow irrigation. Shallow brackish water with total dissolved solids (TDS) of 1–3 g L^{−1} is widely distributed and

exhibits great potential for agricultural irrigation to compensate for a lack of available fresh water in Xinjiang. FMDI with brackish water is used increasingly in Southern Xinjiang because of the abundant supply of brackish groundwater. While using the prior irrigation technique, FMDI requires minimal irrigation, while potentially providing additional nutrition (e.g., Mn and B) from brackish water [8]. However, most salts accumulate in the top soil, eventually leading to soil salinization and limiting cotton yield when using brackish water improperly [9]. Therefore, it is important to evaluate the leaching requirement (LR) of cotton under FMDI with brackish water to support agricultural irrigation while avoiding secondary salinization [10,11].

For the study of the soil salt accumulated status in the root zone and leaching irrigation with FMDI, Corwin and other researchers [11] proposed a steady-state LR model in which the LR is defined as the minimum leaching fraction (LF) to achieve the maximum yield of a given crop. The LF is defined as the ratio of the quantity of infiltrated water draining past the root zone [12]. Moreover, researchers have used the steady-state LR model for different crops and evaluated the model performance of irrigation effects [13–15]. Soil LR guidelines have been reviewed and showed that LR was a beneficial quantitative factor for soil salt leaching closely associated with crop productivity [16]. Some studies found that the spatially varying soil wetting patterns that occur under drip irrigation caused localized leaching, concentrated near the drip line [17,18]. FMDI creates a localized, transient wetting front with pronounced spatial heterogeneity in water and salt distribution. Salt accumulates predominantly at the wetting front periphery rather than being uniformly leached downward, thereby altering leaching efficiency [19]. The steady-state LR models overestimate leaching requirements under field conditions compared to transient models and may not be applicable under FMDI [20]. Corwin and Grattan discussed that most of the water moves downward and laterally and that no matter how much water is applied, salt accumulates in the root zone with very little or no downward (leaching) flow [11]. Moreover, with the increasing amount of irrigation, there was an increased depth of the depth of wetting front, which caused the accumulated soil salt to move downward to the deeper soil layers [6]. It is thus important to consider localized leaching and to evaluate the LR for a given crop under FMDI with brackish water in arid and semi-arid regions.

To obtain the optimal FMDI scheme, soil water flow and salt transport for one growth season or several years were measured and numerically simulated to consider a longer period [21]. Previous researchers have considered different scenarios related to cotton growth and their impacts on yield [9,22–25]. Other researchers have focused on crop simulation [26,27]. Another group of researchers has investigated vapor and energy transport under FMDI [28–31]. Finally, fertilization of cotton under FMDI was also studied to recommend optimal fertilizing regimes [31–34]. More locally focused investigations considered ecological issues such as the spatial characteristics of residual film [35], saline wasteland reclamation [34] and the relationship of groundwater depth and salinization [36]. Based on this wide variety of studies, researchers have made many recommendations to improve the use of FMDI. However, the optimal LF range under such conditions has not been clearly defined, particularly regarding how different LF levels affect cotton yield, reproductive growth, irrigation water productivity (IWP), and soil salt accumulation simultaneously. Furthermore, the interactive effects of LF on vegetative vs. reproductive growth, and on deep-layer soil water storage that may benefit subsequent seasons, have rarely been quantified. The purpose of this investigation is to fill this knowledge gap by comprehensively examining the LR for cotton under FMDI with brackish water that considers the cotton yield, irrigation water productivities, soil conditions, and economic benefits. By addressing

these gaps, our findings can provide practical LF recommendations for sustainable cotton production under FMDI with brackish water.

The specific objectives of this study were to: (i) evaluate the effects of different leaching fractions on cotton growth and yield; (ii) analyze soil water and salinity dynamics under FMDI; and (iii) analyze soil water and salinity dynamics under FMDI.

2. Materials and Methods

2.1. Study Area

The experiments were carried out at the Irrigation Experimental Station of the Ministry of Water Resource of the People's Republic of China in southern Xinjiang, China ($41^{\circ}35' \text{ N}$, $86^{\circ}10' \text{ E}$), from March 2018 to September 2019. The study area (Figure 1) is located 901 m above mean sea level and has a mean annual temperature of 11.5° C , with warm summers and relatively cool winters. There is abundant sunlight in the area, on average, more than 8 h per day. The area has an extreme arid climate with annual precipitation and potential evapotranspiration rates of approximately 58.6 and 2540 mm, respectively. The mean annual wind speed is approximately 0.77 m s^{-1} . Compared with 2018, the 2019 season was characterized by slightly higher total precipitation and mean temperature, but these differences were not statistically significant (t -test, $p > 0.05$) for most growth stages. Surface fresh water from Peacock River with an average salinity of 0.94 g L^{-1} and brackish water from a local deep well with an average salinity of 2.87 g L^{-1} were used to irrigate cotton plants during the growing season. Loamy sand was the predominant soil texture at the field site and the bulk density was 1.59 g cm^{-3} . The saturated soil water content (θ_s) of soil layers was about 0.40. The depth to water table in the cotton field during the cotton growing season ranged from 11.38 to 14.82 m.

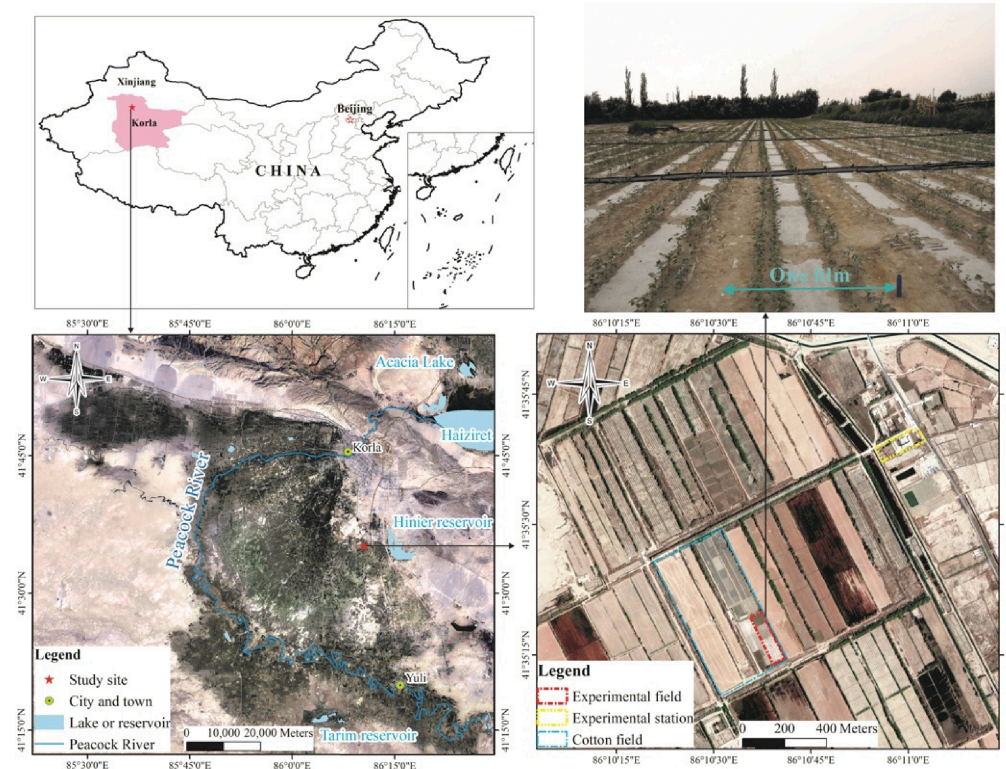


Figure 1. The locations of the field experimental site.

2.2. Experimental Treatments and Procedures

Cotton cv. Xinluzhong 35 was sown in April every year when mulched with degradable plastic film. Two irrigation lines were installed for every four rows of cotton as shown in Figure 2. The distance between the irrigation lines was 60 cm, and there was 20 cm between two cotton rows. The cotton plants along each row were spaced 10 cm apart. The non-mulched area of naked soil was 40 cm wide. Fertilizers, including urea, monopotassium phosphate, compound fertilizer, and potassium sulphate, were applied with irrigation water in which fertilizer was distributed evenly from the second irrigation cycle to the eleventh irrigation cycle and farm manure was applied when the cotton seeds were sown following the local fertilization schedules [9].

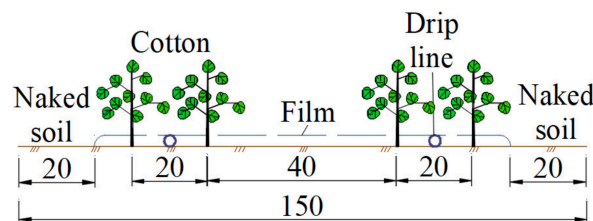


Figure 2. Schematic diagram of the cotton planting mode in the field experimental site (distances are in cm).

The FMDI experiments were laid out followed a randomized block design with three replicates. Each block contained 3 plots, and the assignment of treatments to plots within each block was randomized using a random number generator (Microsoft Excel®). Each plot measured 10 × 18 m with a buffer zone of 1 m between adjacent plots to minimize lateral water movement. Irrigation water and the distribution of control experiments were calculated using potential evapotranspiration (ET_p) multiplied by crop coefficients (K_c) [28]. The amounts of irrigation water and K_c for different cotton growth stages are listed in Table 1. Six cotton growth stages are usually recognized during the irrigation period: early budding, budding, early flowering, flowering boll setting, late boll setting, and boll opening. The deep percolation under FMDI was derived through water balance inversion [28], from which the LF was then calculated. Table 2 summarizes the control and leaching irrigation experiments. Specifically, two control irrigation experiments were carried out in which freshwater (C-F) or brackish water (C-B) was used for irrigation, and eight leaching irrigation treatments were studied with LF values of 0.05, 0.1, 0.15, 0.2, 0.25, and 0.3, respectively. Drippers along each irrigation line were spaced 30 cm apart and the discharge rate was 2.0 L h⁻¹ per dripper. A five-day irrigation event frequency was applied for all treatments with the same water amounts, which followed a traditional irrigation schedule for cotton in the study areas. In addition, before sowing, flood irrigation using fresh water was applied for each treatment, following the local practices with irrigation volumes of 225 mm.

Table 1. Potential evapotranspiration (ET_p) and crop coefficients (K_c) of cotton for different growth stages.

Stages	Early Budding (S-1)	Budding (S-2)	Early Flowering (S-3)	Flowering and Boll Setting (S-4)	Late Boll Setting (S-5)	Boll Opening (S-6)
ET_p (mm day ⁻¹)	7.40	7.40	7.46	7.46	7.44	7.44
K_c	0.38	0.5	1.1	1.25	1.25	0.88

The FMDI with brackish water experiments were carried out in the same cotton field from 2008 to 2018. The irrigation-event frequencies were from 5 to 7 days total of 14 or 15 times during the whole cotton growing season. Specially, the irrigation volumes were about 375, 420, 525, 518.5 and 606.3 mm in 2008, 2009–2010, 2012–2015, 2017 and 2018, respectively.

Table 2. Irrigation schedules for control irrigation treatments (CI) and leaching irrigation treatments (LI) (irrigation volumes are in mm).

Treatments	Irrigation Times	1	2	3	4–10	11–13	14	Total Volumes
	Stages	S-1	S-2	S-3	S-4	S-5	S-6	
	Irrigation Volumes per Time							
CI	C-F	14.1	18.5	41.0	46.6	46.5	32.7	572.0
	C-B	14.1	18.5	41.0	46.6	46.5	32.7	572.0
LI	LF _{0.05}	14.8	19.4	43.1	48.9	48.8	34.3	600.6
	LF _{0.10}	15.5	20.4	45.1	51.3	51.2	36.0	629.2
	LF _{0.15}	16.2	21.3	47.2	53.6	53.5	37.6	657.8
	LF _{0.20}	16.9	22.2	49.2	55.9	55.8	39.2	686.4
	LF _{0.25}	17.6	23.1	51.3	58.3	58.1	40.9	715.0
	LF _{0.30}	18.3	24.1	53.3	60.6	60.5	42.5	743.6

2.3. Field Measurements and Laboratory Test

The plant height of four representative cotton plants for each plot during different cotton growth stages were measured. Meanwhile, the stem, leaves, and fruit of the four cotton plants for each treatment were collected and rinsed with deionized water, oven dried and weighed to calculate the dry weight (DW) of the cotton samples. Final yield was obtained from a 6.67 m² area for each plot on 10 September 2018 and 16 September 2019, respectively. The irrigation water productivities (IWP) for different treatments were calculated as the yield divided by the volume of applied irrigation water.

Soil water content (SWC) and soil salinity (EC) at different depths and different locations were monitored at various depths down to 100 cm. The SWC and EC of both naked and mulched soil profiles (Figure 2) were observed. The SWC was monitored in situ using L520 Neutron Probe (Institute for Application of Atomic Energy, JAAS, Nanjing, China) and Stevens Hydra Probe (Stevens Water Monitoring Systems Inc., Beaverton, OR, USA) soil sensors, while SWC in the top soil layer (soil depth of 0–20 cm) was monitored using MP160 moisture probes (ICT International Pty Ltd., Armidale, Australia).

Soil samples were collected following the SWC monitoring schedule to further obtain 1:5 soil/water suspensions (by weight). The EC analysis was obtained using a conductivity meter (DDS-307, INESA Scientific Instrument Co., Ltd., Shanghai, China). The EC of the 1:5 soil/water suspension was further referred to as $EC_{1:5}$. Soil salinity levels as EC_e were inferred based on the measured values of soil $EC_{1:5}$, and EC_e was calculated using $EC_e = 17.61 \times EC_{1:5}$ [9].

3. Results

3.1. Cotton Vegetative Growth

Cotton heights versus time for all treatments are depicted in Figure 3. The highest cotton height of 73.8 cm was obtained in the scenario of C-F, and the lowest height of 64.5 cm was obtained in the scenario of LF_{0.2} on 30 July. Cotton height increased about 51.83 and 48.7 cm for scenarios of LF_{0.05} and LF_{0.3}, and increased above 44.6 and 38.7 cm for scenarios of C-B and LF_{0.2} from 30 June to 30 July, respectively. Therefore, it was observed that the

cotton height for the scenarios of $LF_{0.05}$ and $LF_{0.3}$ grew faster than in the scenarios of C-B and $LF_{0.2}$. The highest increase in the cotton plant height was observed in the scenarios of C-F and $LF_{0.15}$, while the lowest was obtained in the scenario of $LF_{0.3}$. Moreover, the increased values of cotton plant height in the early flowering and boll setting growing season decreased as follows: C-F = $LF_{0.15}$ > $LF_{0.1}$ > $LF_{0.25}$ > $LF_{0.05}$ > C-B > $LF_{0.2}$ > $LF_{0.3}$.

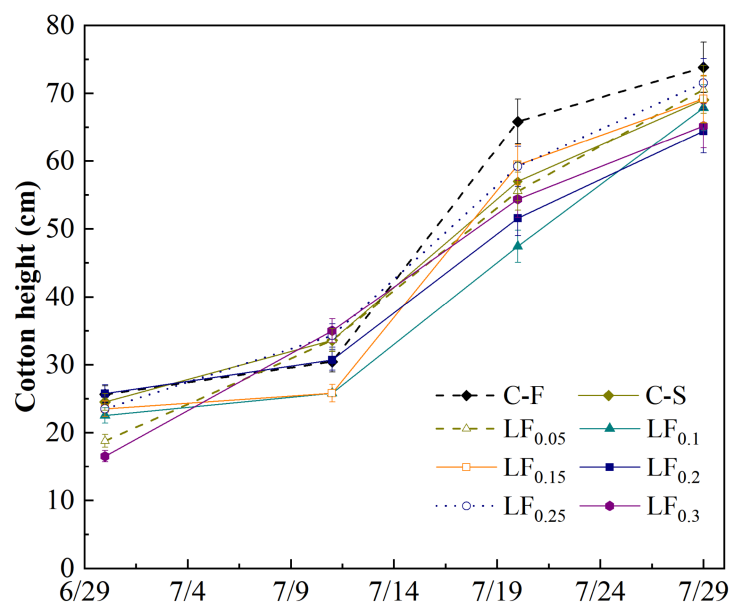


Figure 3. Cotton height changes dynamically over different periods of time under film-mulched drip irrigation for different irrigation treatments.

Figure 4 shows the temporal trends of cotton stem dry weight and flower-boll dry weight ratios for different treatments. The ratios of stem dry weight decreased slightly from 35.62 to 25.67% and 39.66 to 25.22% since the early growing stage for $LF_{0.15}$ and $LF_{0.2}$, respectively. However, the ratios of the stem dry weight of C-F, C-S and $LF_{0.05}$ increased substantially in the early flowering growing stage from 30.39 to 43.13%, 26.37 to 42.9% and 36.5 to 57.67%, respectively. The cotton flower-boll dry weight ratio of 36.57% for $LF_{0.3}$ was lower than in other scenarios during the late boll setting growing stage. In conclusion, a lower irrigation amount might result in a higher ratio of vegetative growth in the early flowering growing stage, whereas a larger LF might lead to a lower ratio of reproductive growth when the LF values are larger than 0.2.

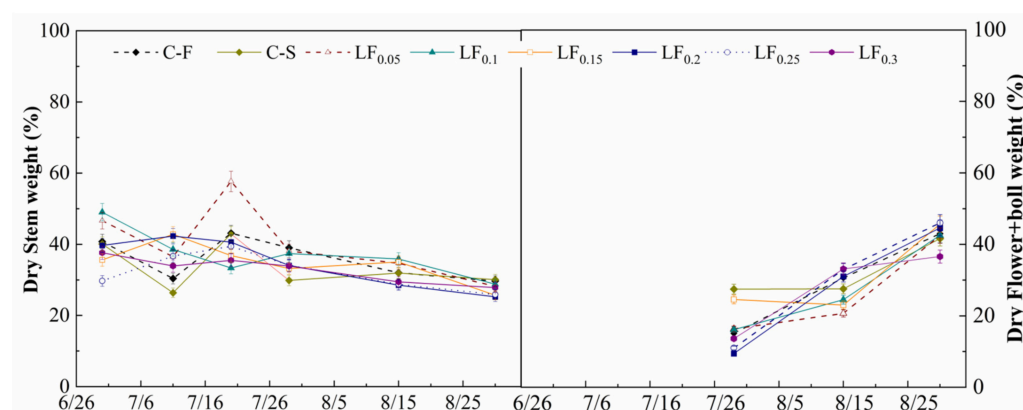


Figure 4. Temporal trends of cotton dry weight ratios over different periods of time under film-mulched drip irrigation for different treatments.

3.2. Cotton Yield and Irrigation Water Productivities

Cotton yield and IWP for different treatments in 2018 and 2019 are presented in Table 3. The variability in cotton yield in 2018 for various treatments decreased as follows: $LF_{0.15} > LF_{0.05} > LF_{0.1} > C-S > LF_{0.2} > C-F > LF_{0.25} > LF_{0.3}$, while the variability for IWP decreased in the order of $LF_{0.15} > LF_{0.05} = C-B > C-F > LF_{0.1} > LF_{0.2} > LF_{0.25} > LF_{0.3}$. The maximum yield (7143 kg ha^{-1}) and IWP (1.09 kg m^{-3}) were obtained for the treatment of $LF_{0.15}$, whereas the minimum yield (5177 kg ha^{-1}) and IWP (0.7 kg m^{-3}) were obtained for the treatment of $LF_{0.3}$.

Table 3. Cotton yield and irrigation water productivities (IWPs) for different treatments.

Treatments	Irrigation Volumes ($\text{m}^3 \text{ ha}^{-1}$)	Cotton Yield (kg ha^{-1})			IWP (kg m^{-3})		
		2018	2019	Average	2018	2019	Average
C-F	5720	$5998 \pm 480 \text{ e}^{\S}$	$7474 \pm 599 \text{ a}$	6736	$1.05 \pm 0.08 \text{ e}$	$1.31 \pm 0.10 \text{ a}$	1.18
C-B	5720	$6170 \pm 827 \text{ d}$	$6253 \pm 96 \text{ f}$	6211	$1.08 \pm 0.14 \text{ d}$	$1.09 \pm 0.02 \text{ f}$	1.09
$LF_{0.05}$	6006	$6480 \pm 1127 \text{ b}$	$6507 \pm 80 \text{ d}$	6493	$1.08 \pm 0.19 \text{ b}$	$1.08 \pm 0.01 \text{ d}$	1.08
$LF_{0.1}$	6292	$6226 \pm 1032 \text{ c}$	$6498 \pm 168 \text{ d}$	6362	$0.99 \pm 0.16 \text{ c}$	$1.03 \pm 0.03 \text{ d}$	1.01
$LF_{0.15}$	6578	$7143 \pm 799 \text{ a}$	$7045 \pm 44 \text{ b}$	7094	$1.09 \pm 0.12 \text{ a}$	$1.07 \pm 0.01 \text{ b}$	1.08
$LF_{0.2}$	6864	$6006 \pm 789 \text{ e}$	$6573 \pm 175 \text{ c}$	6290	$0.87 \pm 0.11 \text{ e}$	$0.96 \pm 0.03 \text{ c}$	0.91
$LF_{0.25}$	7150	$5347 \pm 556 \text{ f}$	$6070 \pm 968 \text{ g}$	5709	$0.75 \pm 0.08 \text{ f}$	$0.85 \pm 0.14 \text{ g}$	0.80
$LF_{0.3}$	7436	$5177 \pm 446 \text{ g}$	$6358 \pm 183 \text{ e}$	5767	$0.70 \pm 0.06 \text{ g}$	$0.85 \pm 0.02 \text{ e}$	0.78

Notes: $\S$ Different letters in columns indicate significant differences ($p < 0.05$, t -test) within different irrigation treatments.

The variability in cotton yield in 2019 for various treatments decreased as follows: $C-F > LF_{0.15} > LF_{0.2} > LF_{0.05} > LF_{0.1} > LF_{0.3} > C-S > LF_{0.25}$, while the variability for IWP decreased in the order of $C-F > C-S > LF_{0.05} > LF_{0.15} > LF_{0.1} > LF_{0.2} > LF_{0.25} = LF_{0.3}$. The maximum yield (7474 kg ha^{-1}) and IWP (1.31 kg m^{-3}) were obtained for the treatment of C-F, and the minimum yield (6070 kg ha^{-1}) and IWP (0.85 kg m^{-3}) were obtained for the treatment of $LF_{0.25}$.

Two characteristics emerge from the above results: (i) a higher LF value was related to a lower cotton yield when LF was higher than 0.15 and (ii) a higher LF value related to a lower IWP when the LF value was higher than 0.2.

The cotton yield under different irrigation volumes (IVs) and total dissolved solids (TDS) for the irrigation water with saline water irrigation treatment in the last several years in the same study area are shown in Table 4. As the LR is defined based on the maximum yield, the LR of FMDI with brackish water for cotton in the study area was 0.15 of the highest cotton yield and the IWP was obtained for this scenario with an IV of 657.8 mm (Table 4). The correlation between irrigation water quantities and cotton yield for the FMDI with brackish water is depicted in Figure 5. Higher cotton yield was obtained as the IV increased from 481.5 to 686.4 mm. Cotton yield tended to increase with the IV when the IV was smaller than 481.5 mm but decreased when the IV was larger than 686.4 mm (Figure 5).

Table 4. Cotton yield for different irrigation volume (IV) irrigation treatments under mulched drip irrigation with saline water in the last several years in the same study area.

IV (mm)	Yield (kg ha^{-1})	TDS ^a (g L^{-1})	References
300.0	4030	2.98–3.21	[36]
375.0	4868		
420.0	4845	2.98–3.21	[8]
441.5	4609	2.02–2.46	2017 experimental data
481.5	6731		
518.5	6022		

Table 4. Cont.

IV (mm)	Yield (kg ha ⁻¹)	TDS ^a (g L ⁻¹)	References
572.0	6212	1.61–1.71	2018–2019 experimental data
600.6	6494		
629.2	6362		
657.8	7094		
686.4	6290		
715.0	5709		
743.6	5768		
772.2	5036		

Note: ^a TDS: total dissolved solids.

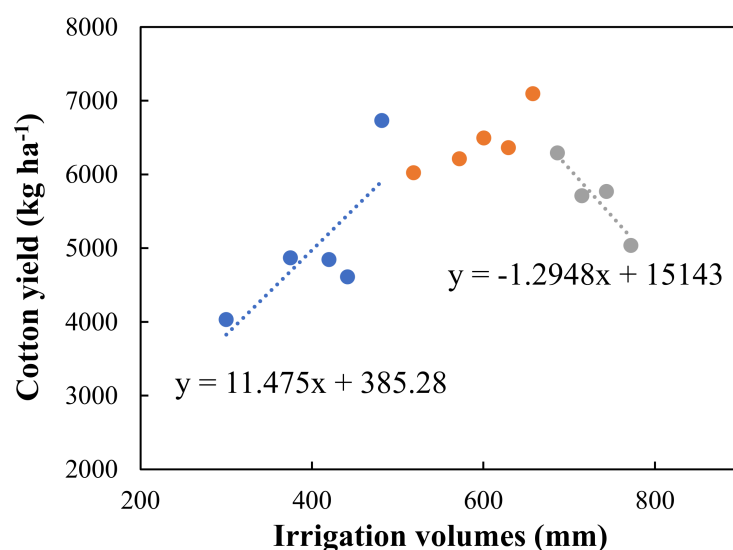


Figure 5. The correlation curve between irrigation volumes and cotton yield under film-mulched drip irrigation with brackish water.

3.3. Soil Water Content

The soil water content (SWC) in the mulched soil at different depths during the cotton growing season for different treatments is shown in Figure 6. The topsoil layer (0–10 cm) was the driest with the lowest SWC of about $0.07 \text{ cm}^3 \text{ cm}^{-3}$ for all treatments before irrigation. SWC fluctuated more widely at the depth of 40–60 cm than at other soil layers and the SWC values were larger with average values of $0.15\text{--}0.26 \text{ cm}^3 \text{ cm}^{-3}$ for all scenarios except for $\text{LF}_{0.3}$. The SWC values in the layer of 40–60 cm depth were clustered close to third quartile for the scenarios of C-F, C-B and $\text{LF}_{0.05}$. The average SWC values were lower than $0.15 \text{ cm}^3 \text{ cm}^{-3}$ in the layer of 0–20 cm for all treatments in the growing season except for the scenario of $\text{LF}_{0.3}$ which was about $0.16 \text{ cm}^3 \text{ cm}^{-3}$.

The SWC in the naked soil at different depths during the cotton growing season for different treatments is shown in Figure 7. The characteristics of SWC distribution were similar to those of SWC in the mulched soil. The lowest SWC of about $0.05 \text{ cm}^3 \text{ cm}^{-3}$ was obtained in the top 0–10 cm soil layer before irrigation which was extremely dry and closed to residual SWC. Also, the average SWC values were lower than $0.15 \text{ cm}^3 \text{ cm}^{-3}$ in the 0–20 cm soil layer for all treatments in the growing season except for the scenario of $\text{LF}_{0.3}$ with an SWC value of about $0.16 \text{ cm}^3 \text{ cm}^{-3}$. The value of the SWC of $\text{LF}_{0.3}$ in the layer of 40–60 cm was $0.08\text{--}0.17 \text{ cm}^3 \text{ cm}^{-3}$ and lower than other soil layers, and it was lower than that of other scenarios. Moreover, the average SWC value was about $0.31 \text{ cm}^3 \text{ cm}^{-3}$ at the depth of 80–100 cm for scenario of C-F and it was larger than that of scenarios C-B and other brackish water irrigation treatments (with the LF value of 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3).

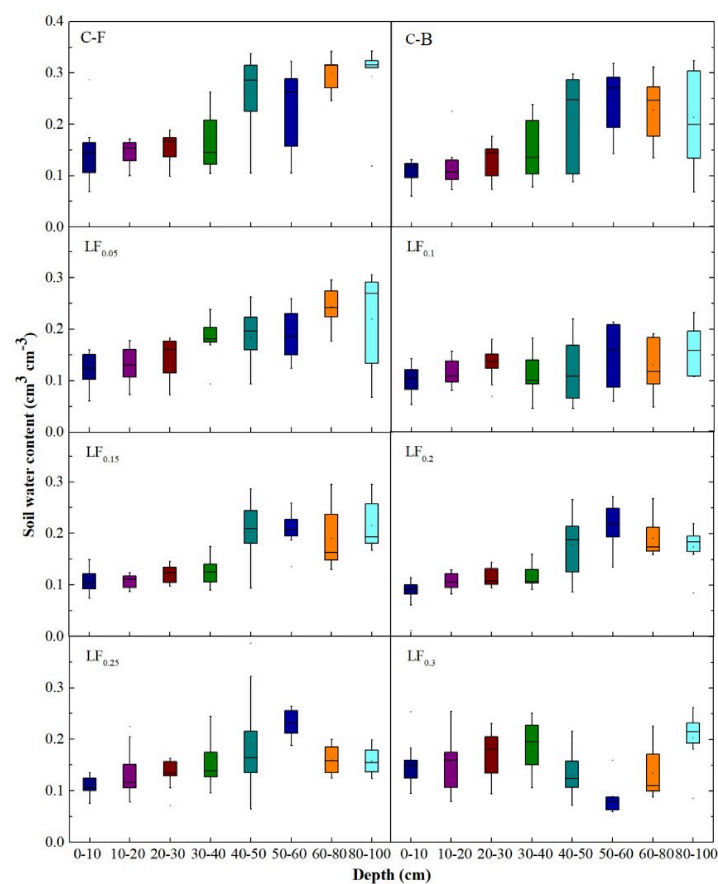


Figure 6. The soil water content in the mulched soil at different depths during the cotton growing season for different treatments.

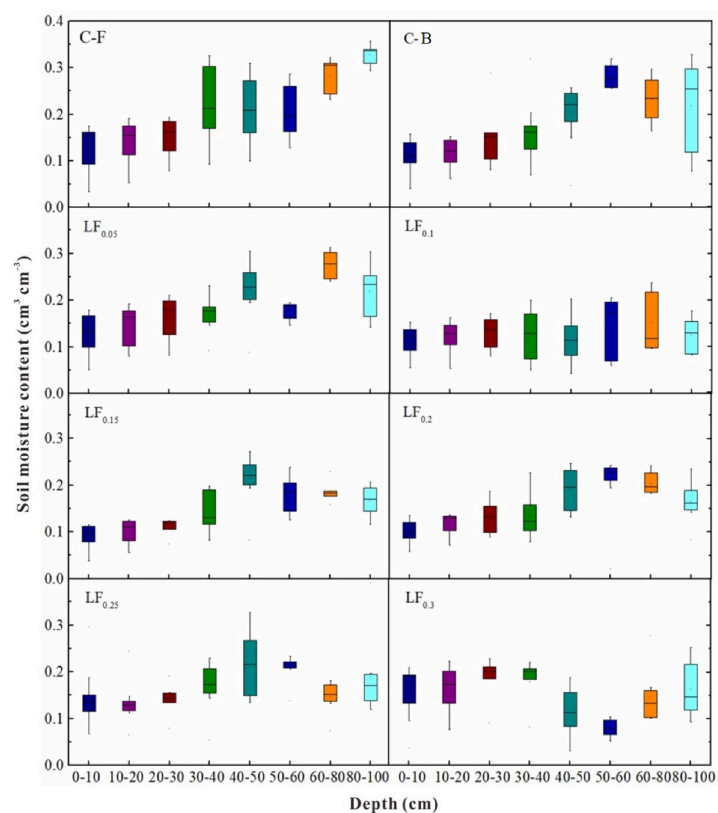


Figure 7. The soil water content in the naked soil at different depths during the cotton growing season for different treatments.

3.4. Soil Salinity

Figure 8 shows the temporal variability of soil EC_e estimated from measured EC_e in the root zone (mulched soil at the depth of 0–40 cm since the cotton roots mainly grew in these depths [9]) for different treatments. The EC_e values were close to each other for all treatments after flood irrigation in April. However, the EC_e values increased substantially for all treatments before mulched drip irrigation and since the freshwater flood irrigation. The EC_e values fluctuated for all scenarios during the mulched drip irrigation period. In the entire cotton growing season, the EC_e values increased slightly from 2.52 to 2.71 dS m⁻¹ and 2.45 to 3.02 dS m⁻¹ for the scenarios of C-F and LF_{0.3}, respectively. However, the EC_e values decreased slightly from 2.11 to 1.9 dS m⁻¹ for the scenario of LF_{0.25}, whereas the EC_e values clearly increased from 2.0 to 2.92, 2.5 to 3.8, 2.0 to 3.82, and 1.6 to 3.61 dS m⁻¹ for the scenarios of C-B, LF_{0.05}, LF_{0.1}, LF_{0.15} and LF_{0.2}, respectively.

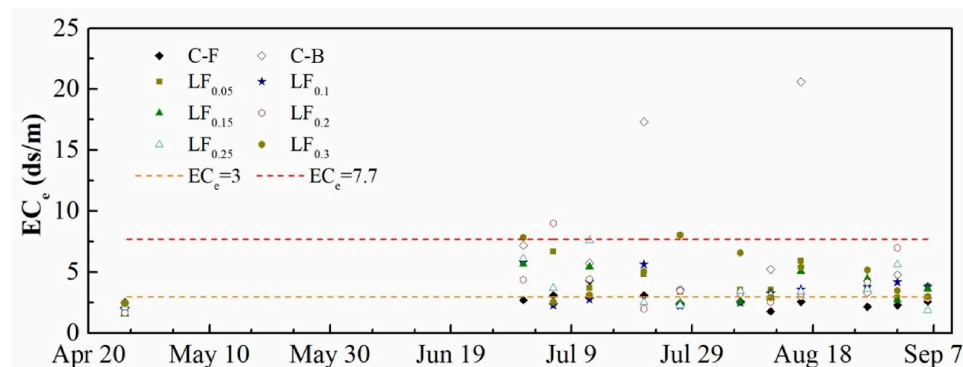


Figure 8. Temporal variability of EC_e in the root zone (mulched soil at the depth of 20–40 cm) for different treatments.

The EC_e in mulched soil estimated from measured $EC_{1.5}$ at different depths during the cotton growing season for different treatments is shown in Figure 9. The highest average soil EC_e of about 5 dS m⁻¹ was observed at depths of 40–50 cm for the scenario of C-F, whereas the highest average soil EC_e of above 38.6 dS m⁻¹ was observed at the depth of 40–50 cm for C-B. The soil EC_e values in the 30–60 cm soil layer were larger than in other layers for C-B and LF_{0.05}. The soil EC_e values of LF_{0.15} and LF_{0.2} were more concentrated across the soil profile than other scenarios. The soil EC_e values of scenario LF_{0.15} were concentrated from 1.9 to 5.9 dS m⁻¹ and the cotton yield of LF_{0.15} was the highest (Table 3). The soil EC_e values of scenario LF_{0.2} varied from 2.0 to 10.9 dS m⁻¹. The highest soil EC_e value of above 10.33 dS m⁻¹ was observed in the 50–60 cm layer for the scenario of LF_{0.25} and the soil EC_e values for other layers varied from 2.0 to 5.9 dS m⁻¹.

The EC_e in naked soil estimated from measured $EC_{1.5}$ at different depths across the cotton growing season for different treatments are shown in Figure 10. The characteristics of soil EC_e distribution were similar to that in the mulched soil. The highest soil EC_e values were obtained in the depth of 40–50 cm for the scenarios of C-F, C-B and LF_{0.05} with values of 15.05, 39.48 and 49.62 dS m⁻¹, respectively, which were larger than those of mulched soil. Similarly, the soil EC_e values of LF_{0.15} across the soil profile were higher than other scenarios. The soil EC_e values of scenario LF_{0.15} ranged from 1.83 to 8.77 dS m⁻¹.

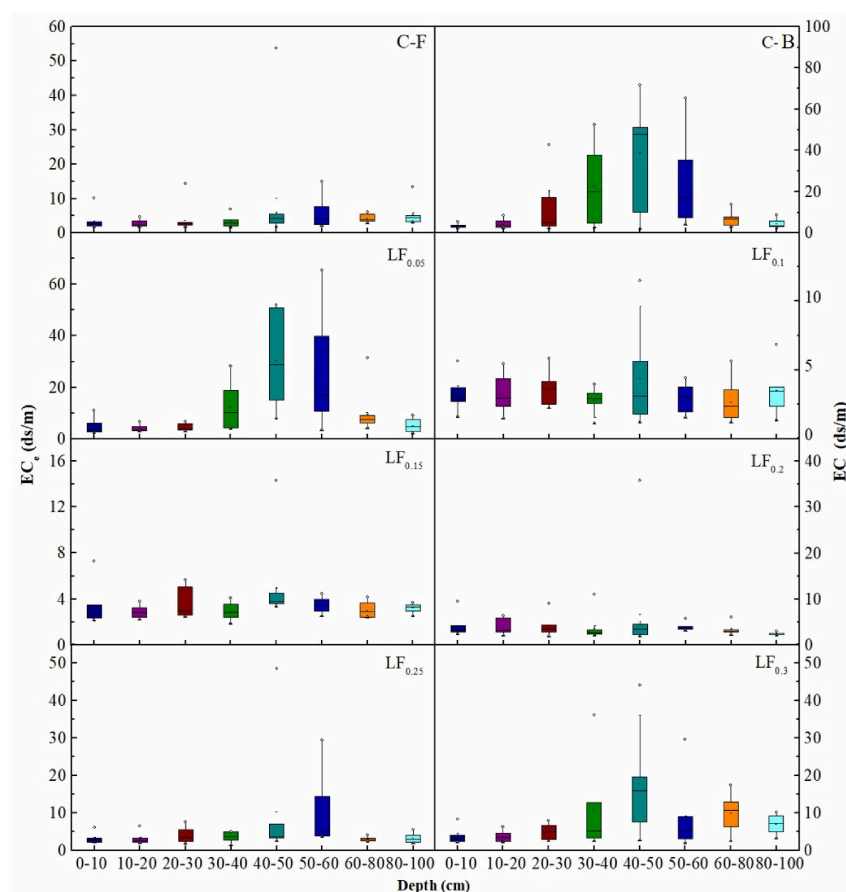


Figure 9. The EC_e in mulched soil for different treatments during the cotton growing season.

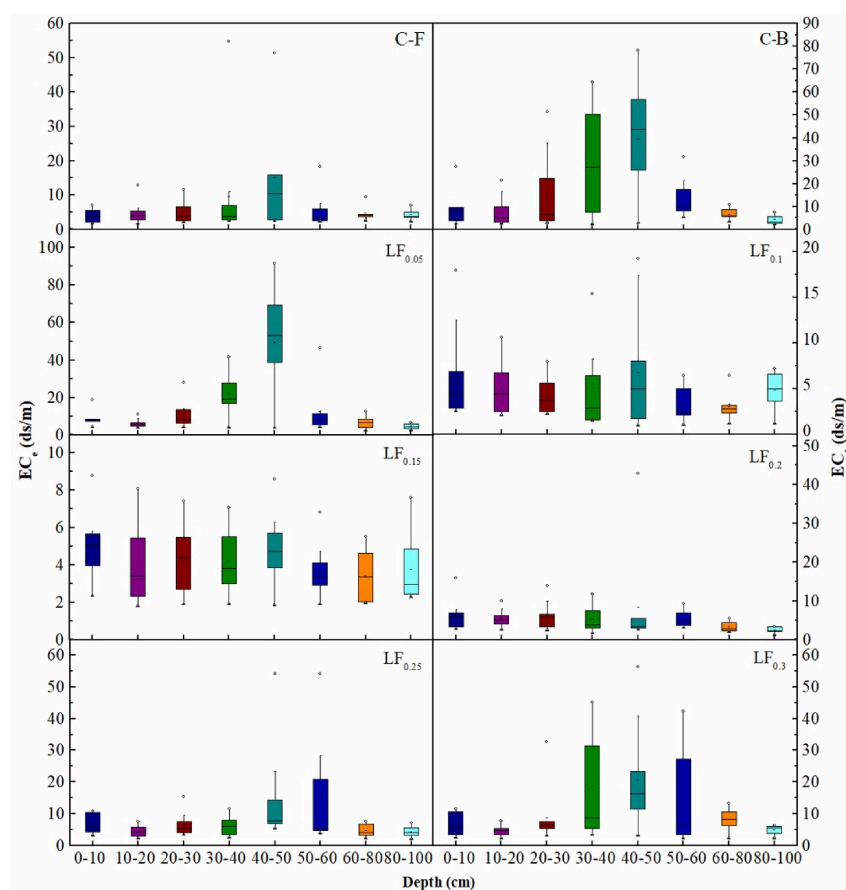


Figure 10. The EC_e in naked soil for different treatments during the cotton growing season.

4. Discussion

4.1. Leaching Requirement of Cotton and Its Relationship with Soil Water and Soil Salinity

The objectives of FMDI can be to maintain a high SWC and flush excess salts from the root zone. The SWC in the mulched soil of $LF_{0.3}$ in the layer of 40–60 cm was the lowest with a value of $0.09\text{--}0.19\text{ cm}^3\text{ cm}^{-3}$, possibly because of an increase in cotton transpiration with irrigation water quantity. The average SWC value in the mulched soil was about $0.3\text{ cm}^3\text{ cm}^{-3}$ at a depth of 80–100 cm for the scenario of C-F, which was larger than that of scenarios C-B and other brackish water irrigation treatments (with LF values of 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3) (Figure 6). This may reflect the influence of water salinity on cotton root water uptake [9,37]. The SWC of naked soil was more scattered than that of mulched soil for the scenarios of $LF_{0.25}$ and $LF_{0.3}$ (Figures 6 and 7) which may be because naked soils were affected more easily by the upper boundary flux than mulched soils. The FMDI resulted in a high SWC strip in 40–60 cm soil layers for all scenarios in both mulched and naked soil (Figures 6 and 7). Moreover, the higher SWC proportion in the deeper soil layers as for the $LF_{0.15}$ or $LF_{0.2}$ would also be beneficial to the cotton root growth and yield at the later growing seasons (Figures 6 and 7).

The EC_e values that were higher than 3 dS m^{-1} were classified as mild to moderate salinization grades [38] during the flowering and boll setting and boll opening growing seasons. Cotton plants are known to have a relatively high tolerance for salinity [2,3]. Most of the measured EC_e values in the root zone were lower than that of 7.7 dS m^{-1} for all treatments (Figure 8), which has been recognized as the threshold salinity value for cotton [39].

The soil EC_e values of the mulched soil and naked soils both decreased with the irrigation water quantity when the $LF < 0.2$ but increased with irrigation water quantity when the $LF > 0.2$. This may be because if too little water is applied (e.g., when the LF is 0.05), a salinization zone may form beneath and in close proximity to the drip line [23,39]. Moreover, when LF reached a certain threshold (e.g., when the LF is 0.25) the higher amount of irrigation water may have resulted in substantially more cotton transpiration [40], resulting in higher salt retention in the root zone, causing lower yield and IWP (Table 3).

Under FMDI, salt is redistributed rather than removed: the mulched root zone is desalinated, while salts accumulate in bare inter-row strips and deeper soil layers. A recent meta-analysis reported that salt content in bare areas was 1.9 times that in the root zone, and accumulation in the 40–60 cm layer under mulch was 1.38 times the root-zone level [41]. This pattern is driven by two processes. First, drip irrigation pushes salts downward and laterally toward the bare strips. Second, evaporation from bare soil generates capillary upward flow, concentrating salts at the surface—salt content in the 0–2 cm bare soil layer can be 7–8 times that below 2 cm. In our study, groundwater remained below 11 m, so capillary rise from the water table was negligible; the observed salt accumulation primarily reflects lateral redistribution caused by localized wetting and evaporation from bare strips, rather than upward groundwater transport.

Under these conditions, a leaching fraction (LF) exceeding 0.2 does not indicate effective salt removal. Instead, excessive deep percolation, combined with the localized wetting pattern, drives a “concentration effect” in the deep root zone: water transports salts downward but, due to limited root extraction at depth and intermittent rewetting, salts accumulate below the main root zone (40–60 cm) (Figures 9 and 10). Thus, salt accumulation at $LF > 0.2$ reflects inefficient leaching caused by the mismatch between water flow pathways and actual salt export, rather than excessive irrigation raising the water table [20]. These findings highlight the need for periodic leaching or drainage to manage long-term salt buildup under FMDI.

4.2. Comprehensive Analysis of Leaching Requirement for Cotton Considered Cotton Yield, Irrigation Water Productivities and Economic Benefits

The last ten-year results in the study area including both our study fields and other adjoining fields were reviewed and collected and the IWPs were calculated. The irrigation volumes, cotton yields, IWPs, irrigation and fertilizer regimes of different years are presented in Table 5.

Table 5. Cotton yields and irrigation water productivity of different years and different irrigation and fertilization schemes in the study area.

Irrigation Volumes (mm)	Yields (kg ha ⁻¹)	IWP (kg m ⁻³)	Net Profits (Yuan ha ⁻¹)	TOPSIS Scores	Fertilizer Regimes	References
300.0	4030	1.343	311	0.534	(1) ^a	[42]
375.0	4868	1.298	3120.4	0.596	(1)	[42]
420.0	4845	1.154	2711	0.516	(2)	[8]
441.5	4609	1.044	2686.7	0.495	(6)	Experimental data
450.0	4575	1.017	1632	0.490	(1)	[42]
481.5	6731	1.398	10,550.3	0.803	(6)	Experimental data
495.0	5410	1.093	4205	0.516	(3)	[26]
518.5	6022	1.161	7671.1	0.671	(6)	Experimental data
525.0	5933	1.130	2997.4	0.528	(4)	[43]
525.0	5137	0.978	5206.6	0.368	(5)	[9]
572.0	6170	1.079	6296	0.656	(7)	Experimental data
600.6	6480	1.079	7331	0.675		
629.2	6226	0.990	6222.8	0.615		
657.8	7143	1.086	9564.4	0.696		
686.4	6006	0.875	5100.8	0.544		
715.0	5347	0.748	2453.6	0.451		
726.9	6432	0.885	8187.1	0.552	(6)	Experimental data
743.6	5177	0.696	1664.6	0.423	(7)	Experimental data
772.2	5036	0.652	985.8	0.402		
800.8	5122	0.640	1169.6	0.401		

Note: ^a The numbers (1)–(7) correspond to fertilizer regimes (1)–(7) in Table 6.

Higher cotton yield was observed while the irrigation volumes were 481.5–729.6 mm. The lowest yield was obtained with the lowest irrigation volumes of 300 mm. The lowest IWP was obtained for the largest irrigation volumes of 800.8 mm as for the treatment LF_{0.4}. Most of the yields below 6000 kg ha⁻¹ were obtained while the irrigation volumes were lower than 481.5 mm or higher than 729.6 mm except the results reported by Tan et al. [26] and Huang et al. [43,44] with irrigation volumes of 475 mm and 525 mm, respectively, which showed that the cotton yields were at the intermediate level. The LF values of the top five scenarios were calculated as 0.15, −0.15, 0.05, 0.27 and 0.1, respectively. Thus, the LR was suggested as 0.15 based on the highest yield.

As discussed above, the LR was obtained based on the maximum yield. But the FMDI with brackish water would result in some environmental issues [6,9,27]. Therefore, the optimal LR should take more factors into account including soil and groundwater environments, ecological effects and so on. To better evaluate the optimal LR, a multivariate statistical method was used to discuss the benefits and environmental effects. The profit of planting cotton was calculated and the numbers of fertilizer regimes were reviewed, as listed in Table 5. The unit expense and income for each item is listed in Table 6 according to the last five years' market prices. The profit consisted of yield and the expenses included harvesting cotton, water, fertilizer, labor and fields, etc. According to the specific data listed

in Tables 5 and 6 and the prices shown in Table 7, the income, expenses and net profit of planting cotton were calculated and presented in Table 5 for all treatments.

Table 6. The unit price for cotton and planting (fertilizer quantities are in kg ha^{−1}).

Fertilizer Regimes	Diammonium Phosphate	Potassium Sulphate	Urea	Monopotassium Phosphate	Farm Manure	Total Prices (Yuan)	References
(1)	375	300	225		15	2678	[42]
(2)	345	300	345		225	2775	[8]
(3)	98	375	885			3053	[26]
(4)	375		684	300		6098	[43]
(5)		150	226		1800	864	[9]
(6)			1056			1795	Experimental data
(7)			450	225		3465	Experimental data

Table 7. The unit price for cotton and planting.

Items		Unit Price (Yuan)
Cotton (kg)	Yield	6.1
	Harvesting	2.3
Water quantity (m ³)	Surface water	0.3
	Groundwater	0.5
Fertilizers (kg)	Diammonium phosphate	3.56
	Urea	1.7
	Potassium sulphate	3.2
	Monopotassium phosphate	12
Labors and fields (ha a ^{−1})	Irrigation	4000
	Cotton management	2500
	Field rent (ha a ^{−1})	7500
	Planting and facilities	825

As presented in Table 5, the results indicated that either too much or too little irrigation water did produce an economic benefit. Usually, more irrigation water consumption was not helpful to water resource protection while more fertilizer application was also harmful to the soil–groundwater environment [28,45,46]. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [47,48] method was used to analyze the chosen data to obtain the preferred scenarios from all treatments. To evaluate the soil–groundwater environment effect and ecological consequences for all scenarios, net profits, yields, water quantity, IPW and total fertilizer amounts were chosen as key factors. These five indicators together cover economic, agronomic, water-use efficiency, and environmental dimensions, enabling a balanced multi-criteria evaluation. Equal weights (0.2 for each indicator) were assigned as a baseline, assumption-free scenario because there is no prior stakeholder preference survey or expert elicitation specific to our study region. Equal weighting is widely used in exploratory TOPSIS applications to avoid subjective bias, allowing the data structure to determine the ranking given the same weight, and the TOPSIS scores are listed in Table 5.

Scenarios with higher TOPSIS scores were better in both economic and environmental senses. Thus, the scenarios with the ten highest scores were chosen for discussion. As shown in Table 6, for the treatments in the top five scores, the irrigation volumes were

from 481.5 to 657.8 mm with LF values of -0.15 , 0.15 , 0.05 , -0.09 and 0 , respectively. The highest net profit and TOPSIS score were observed in the same scenario with the value of $10,550.3$ Yuan ha^{-1} . The highest yield was obtained in the scenario in which TOPSIS score was the second highest with the value of 7143 kg ha^{-1} while the yield was 6731 kg ha^{-1} for the treatment with the highest TOPSIS score. The scores were approximately equal for the top five scenarios except the highest one with the values of 0.696 , 0.675 , 0.671 and 0.656 , respectively. On the other hand, the sixth-highest score was 0.041 less than the fifth-highest score.

A limitation of the present study is that we did not perform a sensitivity analysis on the weights assigned to the five indicators in the TOPSIS evaluation. Equal weights (0.2 each) were adopted as a neutral, assumption-free baseline scheme, allowing a transparent comparison among treatments without introducing subjective bias. The primary objective of applying TOPSIS here was to provide a preliminary, data-driven ranking rather than to optimize weight selection or to test the robustness of the rankings under alternative preferences. We acknowledge that different stakeholders (e.g., farmers, policymakers, environmental regulators) may assign different weights to economic, water-saving, and environmental objectives. Therefore, future studies should conduct sensitivity analyses using alternative weighting scenarios to examine whether the rankings remain stable. Such analyses would further strengthen the applicability of TOPSIS for multi-criteria decision making in FMDI management.

In general, for all scenarios of concern, the LR values ranged from 0.05 to 0.15 with irrigation volumes of 481.5 to 686.4 mm (Table 4, Figure 5) recommended for the FMDI when the irrigation water TDS was within 1.61 – 3.21 g L^{-1} . However, the environment was complex with dynamic changes in soil conditions. Therefore, we suggest that the local government should regulate the irrigation amount by managing the water unit price according to the consumption to battle the decline of groundwater table depth. The long-term sustainability of FMDI with brackish water deserves caution. Prolonged irrigation without drainage merely shifts salt to deeper layers (1 – 2 m) and bare areas, risking gradual root-zone salinization and requiring periodic leaching or sub-surface drainage. Environmentally, brackish water irrigation can raise soil salinity, reduce nutrient availability, and alter greenhouse gas emissions, with tradeoffs between yield gains and environmental costs. Groundwater contamination is also a concern: nitrate and soluble salts can leach below the root zone, especially under excessive LF (>0.2), posing delayed risks to underlying aquifers in arid regions. Under climate change, rising evaporative demand and water scarcity will further intensify these challenges. Integrated strategies—optimized irrigation-fertilizer management, monitoring of groundwater depth, and intercropping with halophytes [49,50]—are needed to sustain production while mitigating secondary salinization and groundwater pollution.

5. Conclusions

For film-mulched drip irrigation (FMDI) with brackish water (total dissolved solids: 1.61 – 3.21 g L^{-1}), a leaching fraction (LF) of 0.05 – 0.15 is recommended. Our results show that lower irrigation amounts lead to a higher ratio of vegetative growth, whereas LF values exceeding 0.15 reduce cotton yield. When $\text{LF} > 0.20$, reproductive growth and irrigation water productivity (IWP) are further suppressed. From an economic perspective, both insufficient and excessive irrigation are unfavorable. Soil salinity decreases when $\text{LF} < 0.20$ but increases when $\text{LF} > 0.20$. Under film mulching, a high soil water content (SWC) strip persists in the 40 – 60 cm layer across all scenarios. Maintaining LF at 0.15 – 0.20 enhances SWC in deeper layers, which may benefit cotton root development and yield in subsequent growing seasons. Sustaining production under FMDI with brack-

ish water calls for integrated strategies that combine optimized water–fertilizer practices, groundwater monitoring and its relationship with root-zone water–salt movement, and halophyte intercropping to reduce secondary salinization and groundwater pollution risks.

Author Contributions: Conceptualization, Z.W. and W.C.; methodology, Z.W. and W.C.; software, Z.W.; validation, Z.W., W.C. and Y.H.; formal analysis, Z.W.; investigation, Z.W.; resources, Z.W., W.C. and Y.H.; data curation, Z.W., W.C. and Y.H.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W., W.C., Y.H., T.P.A.F., A.D. and Q.C.; visualization, Z.W.; supervision, W.C. and Y.H.; project administration, Y.H.; funding acquisition, Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 42530516).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: We sincerely acknowledge the team of M.G. Jin from China University of Geosciences (Wuhan) for sharing the long-term monitoring data for the study area.

Conflicts of Interest: The authors declare no conflicts of interest.

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