ISSN: 2472-3703 DOI: 10.6911/WSRJ.202606_12(6).0001

Effect of Brackish Water Irrigation on Cotton Growth and Yield Based on Multi-method Comprehensive Evaluation

Nan Zhang, Jiangtao Du

School of Architecture and Hydraulic Engineering, Bingtuan Xingxin Vocational and Technical College, Xinjiang 841000, China

Abstract

In order to explore the effects of different concentrations of brackish water irrigation on the growth and yield of cotton, clarify the appropriate threshold of brackish water irrigation for cotton, and alleviate the shortage of fresh water resources and the problem of brackish water utilization in cotton areas, five brackish water irrigation gradients were set up in this study. The agronomic traits such as plant height, leaf area, number of fruit branches and yield components such as single boll weight, number of bolls per plant and seed cotton yield were systematically measured. Combined with three evaluation methods of entropy weight-TOPSIS, grey correlation analysis and principal component analysis, the growth and production performance of cotton under different brackish water treatments were comprehensively quantified in multiple dimensions. The results showed that the salt stress of brackish water had a significant gradient inhibitory effect on the vegetative growth and reproductive growth of cotton. With the increase of irrigation water salinity, the plant height, leaf area and fruit branch number of cotton showed a continuous downward trend. Among them, leaf area was the most sensitive to salt stress, which was the core dominant index affecting the comprehensive growth of cotton. Compared with the clear water control, the photosynthetic organ formation and reproductive growth of cotton treated with high concentration of brackish water were inhibited, and the single boll weight and the number of bolls per plant were significantly reduced, resulting in a significant reduction in seed cotton yield. The yield of T4 treatment was 24.19 % lower than that of CK. The order of the three evaluation models was highly consistent, which was CK > T1 > T2 > T3 > T4. The traits and yield of cotton treated with low salt T1 only decreased slightly, and the yield reduction was only 3.17 %, which could maintain a high production level. In summary, mild brackish water irrigation has little effect on cotton production and can be popularized and applied in saline water-deficient cotton areas, while medium and high concentrations of brackish water stress will significantly inhibit cotton growth and reduce production capacity, which should be strictly avoided in production. This study can provide theoretical basis and technical support for the safe and efficient utilization of brackish water resources in cotton fields and the stable and high-yield cultivation of cotton.

Keywords

Brackish water irrigation; salt stress; agronomic traits; yield; comprehensive evaluation.

1. INTRODUCTION

In arid and semi-arid regions, the shortage of freshwater resources has become the core bottleneck restricting the large-scale and stable production of cotton. As an unconventional water resource with abundant reserves and low development cost, the rational utilization of brackish water is of great strategic significance for alleviating agricultural water pressure and expanding irrigation water sources. However, if the high concentration of soluble salt in brackish water is not properly managed, it is easy to cause secondary salinization of soil, inhibit the growth and development of cotton through multiple mechanisms such as osmotic stress, ion toxicity and metabolic disorder, and threaten the stability and sustainable production capacity of cotton field ecosystem. Therefore, it is a key scientific problem to systematically explore the influence mechanism of different salinity brackish water on the whole process of cotton morphogenesis-photosynthetic function-yield composition ', and scientifically define its safe irrigation threshold, so as to realize the efficient utilization of water resources in salinized areas and the stable and high yield of cotton[1-2].

At present, salt stress significantly regulates the process of vegetative growth and reproductive growth of cotton, and there is an obvious gradient response characteristics of crops to salt concentration. Cotton can adapt to mild salt stress through its own osmotic adjustment mechanism under low salt environment, and there is no significant damage to growth index and yield traits. However, high salt stress significantly inhibited plant longitudinal growth, leaf expansion and branch differentiation, resulting in decreased plant height[3], decreased leaf area, decreased number of fruit branches, and greatly weakened plant photosynthetic production capacity and dry matter accumulation level. At the level of yield formation, salt stress will disturb the steady state of carbon and nitrogen metabolism in cotton, hinder the transport and distribution of photosynthetic products to reproductive organs, increase the abscission rate of buds and bolls[4], reduce the number of bolls per plant and single boll weight, and ultimately lead to a significant reduction in seed cotton yield. At present, most studies focus on the analysis of the effect of salt stress on a single index of cotton. The systematic coupling study of cotton ' morphological growth-photosynthetic structure-yield composition ' under different brackish water gradients is relatively weak[5], and the single evaluation method has the problems of strong subjectivity, one-sided indicators, and insufficient convincing results. It is difficult to comprehensively and objectively quantify the comprehensive growth performance and production potential of cotton under different brackish water treatments.

Based on this, this study set up gradient brackish water irrigation treatments , and systematically studied the effects of different concentrations of brackish water on key agronomic traits and yield of cotton. By measuring the vegetative growth indexes such as plant height, leaf area index and fruit branch number, and the yield components such as single boll weight, boll number per plant and seed cotton yield, the gradient response law of cotton growth and productivity to brackish water stress was clarified. At the same time, three objective evaluation models of entropy weight-TOPSIS, grey correlation analysis and principal component analysis were introduced to avoid the limitations of single evaluation method. The comprehensive production performance of cotton under different treatments was quantified from multiple dimensions and levels, and the optimal brackish water irrigation gradient suitable for cotton planting was screened. The purpose of this study is to clarify the internal mechanism of brackish water stress inhibiting cotton growth and yield formation, and to clarify the safe irrigation threshold of brackish water, so as to provide theoretical support and technical reference for the efficient and safe utilization of brackish water resources in salinized cotton fields and the stable and high-yield cultivation of cotton in arid and water-deficient areas.

2. MATERIALS AND METHODS

2.1. Experimental Design

The test factor was salt level. In this experiment, ' Xinluzhong 38 ' was used as the test object, and the experiment was carried out in the intelligent water conservancy test site of the School of Architecture and Water Conservancy Engineering of Xingxin Vocational and Technical College of the Corps. The annual average temperature in this area is 11 ± 1 ° C, the annual average

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202606_12(6).0001

rainfall is 50 mm, and the annual evaporation is 2500 mm. Bottomless soil column was used to select field undisturbed soil for experiment. The soil column specification was 30 cm in diameter and 40 cm in height. Five salt levels were set in this experiment, namely 2g / L (T1), 4g / L (T2), 6g / L (T3), 8g / L (T4) and control group (CK).

2.2. Measuring Items

2.2.1 Plant Height

From the seedling stage of cotton, the plant height (from the ground to the top of the main stem) was measured by scale and vernier caliper every 10 days.

2.2.2 LAI

Starting from the bud stage of cotton, the area of plant height and stem diameter of cotton was selected, and the leaf area index of cotton was measured by Sunscan canopy analyzer every 15 days in each growth period of cotton.

2.2.3 Number Of Fruit Branches

Five representative cotton plants with uniform growth were selected in each plot. In the early stage of boll opening, the bolls of the first to third fruit branches of the main stem were divided into lower bolls, the bolls of the fourth to sixth fruit branches were divided into middle bolls, and the bolls of the seventh and above fruit branches were divided into upper bolls.

2.2.4 Production

At maturity stage, 3.2m2 (1.6m × 2.0m) representative sample points were randomly selected in each plot, and the seed cotton yield was measured.

3. RESULTS AND ANALYSIS

3.1. Effects Of Different Concentrations of Brackish Water on Plant Height

The plant height of cotton is a key morphological index to measure the response of vegetative growth to water and salt stress, which can accurately reflect the growth dynamics of plants under different brackish water irrigation conditions. As shown in Table 1, the plant height of each treatment group showed a typical pattern of ' rapid growth in the early stage, slow growth in the middle stage, and slight decline in the later stage ' throughout the growth period, and the difference between different salinity treatments reached a significant level. With the increase of irrigation water salinity, the average plant height in the whole growth period decreased systematically : compared with the control (CK), T1 to T4 treatments decreased by 2.37 %, 14.82 %, 28.72 % and 36.41 %, respectively. The plant height of all treatments ranged from 10.0 to 92.5 cm, and the peak value of CK was 92.5 cm at 115 days after sowing, which was significantly higher than that of T1 (1.40 %), T2 (16.65 %), T3 (39.10 %) and T4 (56.95 %). This trend confirms that salt stress interferes with water absorption and metabolic balance through the dual mechanisms of osmotic inhibition and ion toxicity, forcing plants to shift resources from growth to stress defense, thereby inhibiting plant height development.

Table 1. The variation law of plant height under different concentrations of brackish water

Treatment	35d	58d	75d	95d	115d	140d
CK	17	41	91	91.5	92.5	90
T1	14	39	87	91.8	91.2	90
T2	13	33	78	79	79.3	78
T3	12	32	63	64	66.5	64
T4	10	28	59	57	59	56

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202606_12(6).0001

3.2. Effects of Different Concentrations of Brackish Water on Leaf Area

Leaf area, as a core morphological index to characterize the photosynthetic capacity and biomass accumulation potential of plants, is highly sensitive to salt stress. As shown in Table 2, during the whole growth period of cotton, the leaf area difference between different salinity brackish water treatments reached a significant level, and showed a systematic decreasing trend with the increase of irrigation water salt concentration. Compared with the control (CK), the average leaf area of T1 to T4 treatments decreased by 16.83 %, 42.82 %, 54.23 % and 61.80 %, respectively, indicating that salt stress had a strong inhibitory effect on leaf expansion. The leaf area of each treatment ranged from 0.09 to 12.82 dm 2, and reached the peak at the flower and boll stage, which was 98.77 %, 88.21 % and 0.59 % higher than that at the seedling stage, bud stage and boll opening stage, respectively, highlighting this stage as a key window for vegetative growth and photosynthetic organ formation. At 115 days after sowing, the leaf area of CK treatment reached the maximum, which was significantly higher than that of T1, T2, T3 and T4 treatments, with an increase of 18.07 %, 42.26 %, 54.43 % and 63.27 %, respectively. This phenomenon is due to osmotic stress and ion toxicity caused by high salt environment, resulting in decreased stomatal conductance, decreased cell turgor and blocked mesophyll cell division, thus limiting leaf expansion.

Table 2. Variation of leaf area under different concentrations of brackish water

Treatment	35d	58d	75d	95d	115d	140d
CK	0.01	0.32	1.8	2.15	2.25	1.83
T1	0.01	0.28	1.42	1.78	1.83	1.62
T2	0.01	0.25	0.98	1.18	1.3	1.09
T3	0.01	0.18	0.8	0.95	1.02	0.85
T4	0.01	0.17	0.7	0.75	0.82	0.73

3.3. Effects Of Different Concentrations Of Brackish Water On The Number Of Fruit Branches

Fruit branch number is a key morphological index to measure the yield potential of cotton, which is directly related to the effective boll number and the final seed cotton yield. As shown in Table 3, the development of fruit branches under brackish water irrigation did not increase with the increase of salt concentration, but showed a significant inhibition trend, indicating that high salt environment could not promote the construction of reproductive structure. The number of fruit branches of the control (CK) treatment was the best, and the average value of the whole growth period was 9.03 %, 21.63 %, 25.86 % and 31.96 % higher than that of T1, T2, T3 and T4 treatments, respectively. The dynamic range of the number of fruit branches in each treatment was 1 to 13, of which the flowering and boll stage reached the peak, accounting for 32.52 % of the total growth period, while the number of fruit branches at the seedling stage was the least, accounting for only 5.20 %, highlighting that the flowering and boll stage was the core stage of reproductive growth. At 115 days after sowing, the number of fruit branches of CK treatment reached the highest value, which was significantly better than that of T1, T2, T3 and T4, with an increase of 9.94 %, 21.45 %, 24.77 % and 30.87 %, respectively. This inhibitory effect is due to the fact that salt stress interferes with the balance of carbon and nitrogen metabolism in plants, resulting in the priority of assimilates to maintain osmotic regulation rather than reproductive organ differentiation.

Table 3. The change rule of fruit branch number under different concentrations of brackish water

Treatment	35d	58d	75d	95d	115d	140d
CK	1	4	11	12	13	12
T1	1	4	10	11	12	11
T2	1	3	9	10	11	10
T3	1	3	8	9	10	9
T4	1	2	7	8	9	8

3.4. Effects Of Different Concentrations Of Brackish Water On Yield

As the core economic output index of cotton, seed cotton yield directly quantifies the inhibitory effect of salt stress on crop productivity. As shown in Table 4, with the increase of salt concentration in irrigation water, single boll weight, boll number per plant and seed cotton yield showed a systematic downward trend, revealing the significant negative impact of salt on reproductive growth. In all treatments, the single boll weight ranged from 5.06 to 5.87 g, and the control (CK) performed best, which was 3.07 %, 4.22 %, 6.57 % and 14.73 % higher than T1, T2, T3 and T4 treatments, respectively, indicating that the high salt environment weakened the cotton boll filling ability. Especially, the boll number per plant and seed cotton yield of T4 treatment were the lowest, which were significantly lower than those of CK by 27.96 % and 24.19 %, respectively. This phenomenon is due to the fact that salt stress interferes with reproductive development through a dual mechanism: on the one hand, osmotic stress limits water absorption, resulting in blocked flower organ development and increased bud and boll shedding; on the other hand, excessive accumulation of Na triggers ion toxicity, disrupts cellular metabolic homeostasis, and inhibits the effective transport and distribution of assimilates to cotton bolls.

Table 4. Yield components of different concentrations of brackish water

Treatment	Boll weight	The bell number per plant	Raw cotton yield
CK	5.87	15.77	3207.4
T1	5.69	14.24	3105.6
T2	5.63	13.46	2858.7
T3	5.50	12.33	2532.1
T4	5.06	11.36	2431.6

3.5. Overall Merit

The The comprehensive evaluation system based on entropy weight method and TOPSIS model effectively avoids the human bias introduced by subjective weighting, and objectively quantifies the weight of each index through information entropy. The results show that the leaf area index (LAI) has the highest weight, highlighting its decisive role as a leading factor in the comprehensive growth of cotton. This index is directly related to photosynthetic capacity, canopy structure and biomass accumulation efficiency, and is the core parameter to evaluate the physiological state of plants under salt stress. According to the comprehensive closeness score calculated by TOPSIS, CK treatment performed best, with a score of 1.0000 ; the scores of T1 to T4 treatment decreased in turn, and finally decreased to 0.0000, forming a clear sequence of advantages and disadvantages : CK > T1 > T2 > T3 > T4. This ordination system revealed that with the increase of irrigation water salinity, cotton showed a synergistic deterioration trend in key traits such as plant height, fruit branch number, leaf area, single boll weight and boll number, resulting in a significant decline in overall production performance. The internal mechanism is that salt stress interferes with carbon assimilation and distribution and reproductive organ

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202606_12(6).0001

development through the dual pathways of osmotic inhibition and Na toxicity, and weakens the source-sink coordination ability.

Grey correlation analysis objectively quantifies the closeness of each treatment to the ideal state by constructing an ideal reference sequence containing the optimal values of all indicators. The higher the correlation value is, the closer the comprehensive performance is to the optimal cultivation level. The results of this study showed that the correlation degree of the control (CK) treatment was as high as 0.9999, ranking the first. The correlation degree of T1 to T4 treatment showed a continuous decreasing trend, and the order was CK > T1 > T2 > T3 > T4, which was highly consistent with the comprehensive evaluation results of entropy weight method-TOPSIS, and the robustness of the evaluation system was cross-validated. The ordination clearly revealed that the low-salt environment (CK) was most conducive to the synergistic optimization of cotton agronomic traits and yield components ; although T1 was slightly deteriorated, it still maintained high production performance. With the increase of irrigation water and salt concentration, T2, T3 and T4 were inhibited by osmotic stress and ion toxicity, which led to the systematic decline of plant height, leaf area, fruit branch number, single boll weight and boll number, and finally showed the simultaneous decline of yield and growth potential. This rule confirms that there is a significant negative dose-effect relationship between salt stress intensity and cotton comprehensive production performance, highlighting the key role of regulating the salt environment in the root zone to achieve high and stable yield.

The principal component analysis method reduces the dimension of six original indexes such as leaf area index, number of fruit branches, single boll weight, number of bolls, plant height and seed cotton yield by linear transformation, effectively eliminating multicollinearity and information overlap between variables, and extracting a few comprehensive principal components to characterize the overall agronomic performance of cotton. This method objectively reflects the integrated effect of multi-dimensional traits. The lower the comprehensive score, the better the coordination of plant morphogenesis, photosynthetic efficiency and reproductive allocation, and the higher the comprehensive quality. The results showed that the principal component score of the control (CK) treatment was the lowest, ranking the first, reflecting its high synergy between physiological metabolism and yield composition in low salt environment. With the increase of salt concentration gradient of brackish water irrigation (T1 to T4), the score of principal component continued to rise, among which T4 had the highest score and the worst comprehensive performance, and the order was CK > T1 > T2 > T3 > T4.

The three independent evaluation models all obtained a completely consistent comprehensive ranking : CK > T1 > T2 > T3 > T4, which fully verified the high robustness of the conclusions and the consistency between the methods. In this ranking, CK treatment showed the best nutrition-reproductive growth coordination under low salt environment, and the seed cotton yield reached 3207.4 kg • hm^{-2}, with the best comprehensive performance. Although the T1 treatment was affected by mild salt stress, the indicators only decreased slightly, and the seed cotton yield was 3.17 % lower than that of CK. It still maintained a high production potential and could be used as a preferred alternative to mild salinization areas. However, as the stress intensity increased from T2 to T4, cotton growth was significantly inhibited : plant height development was limited, leaf area index decreased, photosynthetic source strength was weakened, and fruit branch differentiation ability decreased, resulting in a simultaneous decrease in single boll weight (5.06-5.87 g) and boll number per plant, which eventually led to a continuous sharp decrease in seed cotton yield. Under T4 treatment, the seed cotton yield was only 2431.6 kg • hm^{-2}, which was 24.2 % lower than that of CK. The gradient response law revealed that salt stress systematically destroys the effective distribution of assimilates to

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202606_12(6).0001

reproductive organs and inhibits source-sink synergy through the dual mechanism of osmotic stress limiting water absorption and Na + poisoning disturbing metabolic homeostasis.

Table 5. Comprehensive evaluation table

Treatment	Entropy weight TOPSIS score	Grey correlation degree	Principal component score	Comprehensive ranking
CK	1.0000	0.9999	-3.1434	1
T1	0.7742	0.8472	-1.7622	2
T2	0.4899	0.6835	-0.0692	3
T3	0.2288	0.5516	1.6650	4
T4	0.0000	0.4629	3.3098	5

4. DISCUSS

Saline brackish water irrigation is a key technical path to cope with the shortage of fresh water resources in salinized areas, and its application potential and ecological risk coexist[6]. In this study, the cascade inhibitory effects of salt stress on vegetative growth, reproductive development and yield formation of cotton were systematically revealed by setting CK (control) and T1-T4 gradient brackish water treatment. With the help of three multi-model comprehensive evaluation systems of entropy weight-TOPSIS, grey correlation analysis and principal component analysis[7], the robust quantification of stress response rules was realized. The results clearly showed that the intensity of salt stress was significantly positively correlated with the degree of cotton growth inhibition, and the three independent evaluation models were highly consistent to obtain the comprehensive ranking of CK > T1 > T2 > T3 > T4, which fully verified the objective existence of the dose effect of salt stress and the reliability of the evaluation conclusions.

Among many agronomic traits, leaf area index (LAI) was identified as the core factor with the highest weight (0.2120) by entropy weight method, highlighting its physiological dominance in salt stress response. The significant decrease of LAI directly weakens the ability of canopy to intercept photosynthetically active radiation and limits the total production of assimilates, thus constituting the ' source ' end limitation. This finding is highly consistent with the existing research : 0.6 % NaCl salt stress significantly reduced the chlorophyll content and net photosynthetic rate of island cotton seedlings ; 15 dS m 1 salinity also led to the damage of photosynthetic performance of upland cotton. Therefore, LAI is not only a characterization of population structure, but also a key hub connecting vegetative growth and reproductive development[8]. When salt stress increased, plants were forced to preferentially use limited photosynthetic products to synthesize osmotic regulators to maintain cell turgor, rather than for fruit branch differentiation and cotton boll development, resulting in a continuous decrease in the average number of fruit branches with the increase of salt concentration, directly weakening the capacity and activity of ' sink '.

In the end, the destruction of this ' source-sink ' coordination relationship is mainly reflected in the yield composition. Under mild stress T1 treatment, the seed cotton yield was only 3.17 % lower than that of CK, indicating that cotton had strong tolerance to this and had production feasibility. However, under moderate and severe stress T3 and T4, the single boll weight decreased to 5.06-5.87 g, and the number of bolls per plant decreased synchronously, which eventually led to a significant decrease of seed cotton yield by 24.19 % in T4 treatment. Its internal mechanism lies in the dual stress path : on the one hand, the decrease of osmotic potential of soil solution leads to physiological water shortage of plants, which inhibits the expansion of cotton boll cells and dry matter accumulation ; on the other hand, excessive Na accumulates in tissues to produce ion toxicity, interferes with K homeostasis and enzyme activity, and hinders the effective transport and distribution of photosynthetic products to cotton bolls[9].

In summary, this study not only established the core regulatory role of LAI through multi-model cross-validation, but also more accurately defined the safety threshold of brackish water irrigation. CK is the optimal model, and T1 can be used as a feasible alternative for freshwater resource-deficient areas, while T2 and above treatments are not suitable for long-term use due to systemic growth decline and significant yield loss[10]. Future research should combine physiological and biochemical indicators and molecular mechanisms to deeply analyze the upstream regulatory network of LAI on salt stress, and explore the dynamic relationship between irrigation frequency and salt accumulation, so as to construct a more perfect technical system for safe and efficient utilization of brackish water in salinized cotton fields.

5. CONCLUSION

(1) Brackish water irrigation significantly affected the vegetative growth traits of cotton. With the increase of irrigation water salinity, the average plant height, leaf area and fruit branch number of cotton during the whole growth period continued to decrease. Salt stress inhibited the reproductive growth and yield formation of cotton. With the increase of brackish water concentration, single boll weight, boll number per plant and seed cotton yield decreased synchronously.

(2) Entropy weight TOPSIS, grey correlation and principal component analysis were used to carry out multi-index comprehensive evaluation. The evaluation results of the three models were completely unified, and the order of comprehensive performance was CK > T1 > T2 > T3 > T4. The results of entropy weight showed that the weight of leaf area index was the largest, which was the primary factor determining the comprehensive production performance of cotton. Multiple methods confirm each other and prove that the evaluation results are reliable.

(3) Clean water irrigation (CK) is the optimal irrigation method for cotton; under T1 mild brackish water irrigation, the growth and yield of cotton decreased slightly, which could be used as an alternative irrigation mode in saline cotton area with shortage of fresh water resources. The high concentration of brackish water in T2, T3 and T4 significantly inhibited the growth and development of cotton and greatly reduced the yield, which was not suitable for practical production.

ACKNOWLEDGEMENTS

Bingtuan Xingxin Vocational and Technical Collegeschool level project (XJYBKT202626).

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