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RESEARCH PAPER

Comprehensive evaluation of saline-alkali tolerance in different wheat (*Triticum aestivum*) varieties throughout the entire growth cycle

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Abstract

To investigate the salt tolerance of different wheat varieties and identify those suitable for cultivation in saline-alkali soil, 64 predominantly promoted wheat varieties were cultivated in artificial salt ponds. This study aimed to analyze the effects of salt stress on wheat during different growth stages. Correlation analysis, principal component analysis (PCA), and cluster analysis were conducted on eight agronomic traits of these 64 wheat varieties to evaluate their salt tolerance. The results indicated that yield and effective panicle number exhibited the highest coefficients of variation. Correlation analysis revealed a positive relationship between panicle length and both yield and plant height, as well as a strong positive correlation between yield and effective panicle number. Through PCA and clustering methods, the 64 wheat varieties were categorized into five main groups, while the eight agronomic traits were consolidated into three key principal components.

Keywords

Wheat, agronomic traits, salt-alkali tolerance, yield traits

Introduction

Soil salinization poses a significant global challenge.and has garnered widespread attention. As a soil type widely distributed on land, saline-alkali land has also attracted great attention to its related issues (Revngasamy 2010; Rios et al. 2017). Approximately 5.3×10^8 hectares of farmland are affected by salinity, which is close to 25% of the total land area of the earth (Zhang et al. 2002; Mohamed and Kurup 2012; Khoroshev 2022), China currently has a saline-alkali land area of about 36 million hm^2, accounting for about one-third of the total arable land area. In addition, due to improper irrigation methods, more than 6.7 million hm^2 of secondary salinized land have been formed. Although these lands are still available for cultivation, crop yields have decreased significantly (Qiu 2019; Lu et al. 2025). Under the influence of human activities, trace amounts of sodium chloride (NaCl) in irrigation water are one of the main factors leading to soil salinization. Additionally, the rise of groundwater level is also an important cause of salinization (Li et al. 2014; Hassani et al. 2021; Zhu et al. 2021; Yang et al. 2022). Excessive accumulation of salt in the soil poses a significant obstacle to the growth of crops, which not only weakens yield, but also affects the quality of products, thus restricting the sustainable development of agriculture (Liao et al. 2007; Jun et al. 2008). During the growth and development of crops, salt stress can interfere, causing different degrees of negative effects on seed germination, seedling growth and final yield (Munns and Gilliham 2015; Wang and Xia 2018). Not only does saline-alkali stress affect the absorption of nutrients by crops, but also causes nutrient imbalance in plants, leading to problems such as plant dwarfing and delayed growth and development (Wang et al. 2021); in severe cases, it can even cause

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crop death and severely impact crop yield (Peng et al. 2020). In China, saline-alkali land is a rare reserved land resource. To explore and utilize saline-alkali land and tap its potential, the key lies in having high-quality salt-tolerant seeds. By breeding salt-alkali-tolerant crops to improve the salt resistance of plants during their growth on saline-alkali land, we can not only alleviate the damage caused by saline-alkali land to plants but also increase the yield and benefits of cultivation, thereby promoting the sustainable development of agricultural science (Wang et al. 2017). Therefore, how to efficiently utilize saline-alkali soil on a large scale and breed new salt-tolerant crop varieties is an important approach to achieving the sustainable development of agriculture in China and even the world, and it holds significant ecological and economic value (Munns and James 2003).

Wheat (*Triticum aestivum*) is one of the main food crops in northern country and occupies an important position in human diet. However, the common problem of soil salinization in North China has had a significant negative impact on the growth and development of this crop, which in turn has caused its yield to decline (Wang et al. 2011; Kaushal 2016; Guo 2017; Xu et al. 2021; Deng et al. 2023). At the same time, human activities have intensified soil salinization, which has a significant impact on wheat planting (Upadhyay and Singh 2015; Shafiq et al. 2025). Salt stress, as a key abiotic stress factor, significantly inhibits the photosynthetic efficiency of wheat, interferes with its normal growth process, and ultimately leads to yield reduction (Munns 2002; Gururani et al. 2015). The salt tolerance of wheat varieties shows significant differences according to different genotypes (Khan et al. 2007; Sharma et al. 2020). In most wheat-growing areas of China, the seedling stage of wheat coincides exactly with the salt return period, which exerts a significant adverse impact on its growth. The level of salt tolerance at the seedling stage was a fundamental guarantee for ensuring complete seedling emergence of wheat (Ma et al. 2005). In order to further explore the salt tolerance of wheat varieties in Hebei Province, screening varieties suitable for planting in saline-alkali land was of great significance to solve the food security problems of the province and the country. In this paper, the agronomic characters and yield performance of 64 wheat varieties (lines) in saline-alkali soil in Hebei province were analyzed, and their salt tolerance during the entire growth period was comprehensively evaluated through principal component analysis and cluster analysis, aimed to provide a basis for screening more excellent saline-alkali tolerant wheat varieties in Hebei province.

Materials and methods

Experimental materials and site

The test materials are 64 provincial-reviewed or national-reviewed wheat varieties mainly promoted by various regions in Hebei Province in recent years (Table 1). They are provided by many companies and scientific research units and will be sown in salt pond in October 2023 at Cangxian Xihuayuan Hebei China (38.29°N, 116.72°E).

Experimental design

The identification in the salt pond adopted a randomized design, with two salt concentration gradients set: 0 (control) and 0.3% (salt stress). The salt pond was sized 6×6 meters. In each pond, 60 rows were planted, with each row being 1.5 meters long. 60 seeds were sown in each row, and the row spacing was 20 centimeters. The experiment was repeated twice, and the control variety was Jiemai 19 (JM19). The fertility level of the salt-tolerance identification was the same as that of the control, and the same field management measures were adopted. No irrigation was carried out throughout the growth period. The emergence stage, heading stage, and maturity stage of each treatment were recorded, and the whole row was harvested for variety evaluation.

Date analysis

Process and analyze data using Excel 2019, conduct analysis of variance (ANOVA), correlation analysis, principal component analysis (PCA), and membership function analysis with SPSS 19.0, and perform cluster analysis and graphing via Origin 2024. Evaluate the salt tolerance of wheat varieties using the salt tolerance coefficient and the comprehensive evaluation D-value for salt tolerance. The calculation formula is as follows(Yu et al. 2017; Zhang et al. 2017; Zhao et al. 2025):

Salt tolerance coefficient of each trait = measured value under salt treatment/measured value under control conditions:

$$U(X_i) = U(X_i - X_{min}) / U(X_{max} - X_{min})$$

In the formula: U is the membership function value of each trait; X_i is the measured value of the trait of the i-th variety; X_{min} and X_{max} are the minimum and maximum values of a certain trait of the tested varieties.

$$W_i = Pi \sum_{i=1}^{n} P_i$$

In the formula: W represents the importance of the common factor among all common factors; P_i is the correlation coefficient between the trait of each variety and the salt-tolerance coefficient, representing the contribution rate of the common factor of each variety.

Results

Effects of salt Stress on wheat at different growth stages

It can be seen from Table 2 that salt stress exerts a significant impact on the growth period of different wheat varieties. Under salt stress, the emergence period of most varieties was delayed compared with the control, which was characterized by delayed germination, slow seedling growth, hindered

Table 1. The name of the tested material.

Number	Name	Region	Number	Name	Region
1	Bomai7	Cangzhou/China	33	Yuzhou810	Shijiazhuang/China
2	Bomai20	Cangzhou/China	34	Kexing789	Shijiazhuang/China
3	Womai323	Handan/China	35	Jinhe991	Shijiazhuang/China
4	Xiangmai517	Handan/China	36	Hengmai30	Hengshui/China
5	Xiangmai518	Handan/China	37	Xiaoyan60	Cangzhou/China
6	Xiangmai519	Handan/China	38	Xiaoyan155	Cangzhou/China
7	Xinmai169	Shijiazhuang/China	39	Jimai60	Shijiazhuang/China
8	Shimai26	Shijiazhuang/China	40	Jimai262	Shijiazhuang/China
9	Yingbo700	Xingtai/China	41	Hengyu3	Hengshui/China
10	Shannong28	Shijiazhuang/China	42	Henong128	Baoding/China
11	Huamai9518	Shijiazhuang/China	43	Jimai782	Shijiazhuang/China
12	Jinnong58	Shijiazhuang/China	44	Lunxuan45	Shijiazhuang/China
13	Jinhuafeng1	Shijiazhuang/China	45	Heng136	Hengshui/China
14	Henong085	Baoding/China	46	Jiamai361	Shijiazhuang/China
15	Aoyan398	Shijiazhuang/China	47	HengS29	Hengshui/China
16	Aoyan68	Shijiazhuang/China	48	Hengmai26	Hengshui/China
17	Shimai26	Shijiazhuang/China	49	Jimai418	Shijiazhuang/China
18	Jinnong328	Shijiazhuang/China	50	Cangmai12	Cangzhou/China
19	Womai33	Handan/China	51	Hannong1412	Handan/China
20	Huiyan66	Shijiazhuang/China	52	Heng9966	Hengshui/China
21	Zhongmai122	Shijiazhuang/China	53	Tianmai206	Shijiazhuang/China
22	Longmai88	Shijiazhuang/China	54	Zhongmai12	Shijiazhuang/China
23	Longmai2	Shijiazhuang/China	55	Cangami6005	Cangzhou/China
24	Lunxuan103	Shijiazhuang/China	56	Zhongmai36	Shijiazhuang/China
25	Hansheng3160	Handan/China	57	JInmai100	Cangzhou/China
26	Hanshengheimai1	Handan/China	58	Jinmai108	Cangzhou/China
27	Wanfeng826	Shijiazhuang/China	59	Yunhan1392	Cangzhou/China
28	Wanfeng505	Shijiazhuang/China	60	Chang7080	Cangzhou/China
29	Hongmai15-1	Shijiazhuang/China	61	Pinyu8161	Cangzhou/China
30	Henong7276	Baoding/China	62	Yunhan1512	Cangzhou/China
31	Henong8324	Baoding/China	63	Hengmai33	Hengshui/China
32	Fuzhao5066	Handan/China	64	Hengmai36	Hengshui/China

root development, reduced stress resistance and yellowing of leaves. At the same time, the heading date and maturity date were 1–5 days earlier than that of the control, indicating that salt stress inhibited crop growth and led to delayed heading. It showed that salt stress not only affects the growth and development of wheat, but also affects its growth and development cycle, especially the heading and maturity stage.

Effect of salt stress on agronomic characters of wheat

Table 3 shows that the result was highly consistent with the physiological damage mechanisms of salt stress – induces root ion imbalance (e.g., excessive Na^+ accumulation and K^+ loss), which inhibits cell elongation and division, directly impeding the development of plant height. Meanwhile, the high-salt environment damages the leaf photosynthetic system (e.g., chlorophyll degradation and reduced photosynthetic enzyme activity), reduced photosynthate accumulation. This shortens the grain filling duration and lowers the grain filling rate, ultimately restricting panicle development (manifested as shortened panicle length) and forming a cascading inhibition effect on "vegetative growth-reproductive growth". The largest coefficient of variation under salt stress conditions is plant height 15.99%, followed by ear length 14.29%. Under non-salt stress conditions, the highest coefficient of variation was 12.36%, followed by grain filling speed of 8.64%, and the lowest coefficient of variation was 3.38%. It can be seen that there were great differences in wheat's response to salt under salt stress, and there were also great differences in salt tolerance among varieties. The skewness of plant height and filling time was positive, indicating that their values were mostly distributed above the average value; while the skewness of ear length and filling rate was negative, indicating that their values were mostly concentrated below the average value; while ear length and filling rate were below the average value.

Effect of salt stress on wheat yield traits

Wheat yield traits represent a central manifestation of genotype-environment interactions. As the primary limiting factor in agricultural production within dry saline-alkali lands, salt stress significantly compromises the stability of yield components through mechanisms such as disrupting ion homeostasis and inhibiting photosyn-

Table 2. Effects of salt stress on wheat at different growth stages.

Number	Name	Sowing Date	Emergence stage			Heading stage			Maturity stage		
			Control	Salt Stress	Days Delayed Compared to Control	Control	Salt Stress	Days Advanced Compared to Control	Control	Salt Stress	Days Advanced Compared to Control
1	Bomai7	10/5	10/12	10/13	-1	4/26	4/23	3	6/3	5/31	3
2	Bomai20	10/5	10/12	10/13	-1	4/25	4/23	2	6/2	5/30	3
3	Womai323	10/5	10/12	10/14	-2	4/22	4/21	1	5/31	5/28	3
4	Xiangmai517	10/5	10/12	10/13	-1	4/24	4/22	2	5/30	5/28	2
5	Xiangmai518	10/5	10/12	10/15	-3	4/23	4/20	3	5/30	5/29	1
6	Xiangmai519	10/5	10/12	10/14	-2	4/22	4/19	3	6/2	5/30	3
7	Xinmai169	10/5	10/12	10/15	-3	4/23	4/22	1	6/2	5/30	3
8	Shimai26	10/5	10/12	10/14	-2	4/24	4/21	3	6/2	5/30	3
9	Yingbo700	10/5	10/12	10/14	-2	4/25	4/23	2	6/2	5/30	3
10	Shannong28	10/5	10/12	10/16	-4	4/24	4/22	2	6/3	5/31	3
11	Huamai9518	10/5	10/12	10/16	-4	4/23	4/22	1	5/31	5/29	2
12	Jinnong58	10/5	10/12	10/15	-3	4/24	4/23	1	5/30	5/29	1
13	Jinhuafeng1	10/5	10/12	10/17	-5	4/23	4/22	1	5/30	5/29	1
14	Henong085	10/5	10/12	10/16	-4	4/25	4/22	3	5/30	5/27	3
15	Aoyan398	10/5	10/12	10/17	-5	4/24	4/22	2	5/31	5/27	4
16	Aoyan68	10/5	10/12	10/13	-1	4/23	4/21	2	5/30	5/28	2
17	Shimai26	10/5	10/12	10/14	-2	4/24	4/22	2	5/30	5/27	3
18	Jinnong328	10/5	10/12	10/14	-2	4/26	4/24	2	5/31	5/28	3
19	Womai33	10/5	10/12	10/13	-1	4/25	4/24	1	5/30	5/27	3
20	Huiyan66	10/5	10/12	10/13	-1	4/26	4/23	3	5/30	5/27	3
21	Zhongmai122	10/5	10/12	10/13	-1	4/24	4/22	2	5/30	5/26	4
22	Longmai88	10/5	10/12	10/13	-1	4/23	4/22	1	5/31	5/26	5
23	Longmai2	10/5	10/12	10/14	-2	4/23	4/21	2	6/1	5/27	5
24	Lunxuan103	10/5	10/12	10/14	-2	4/22	4/20	2	5/31	5/27	4
25	Hansheng3160	10/5	10/12	10/16	-4	4/23	4/19	4	5/31	5/26	5
26	Hanshengheimai1	10/5	10/12	10/17	-5	4/21	4/20	1	5/30	5/27	3
27	Wanfeng826	10/5	10/12	10/15	-3	4/23	4/21	2	5/31	5/26	5
28	Wanfeng505	10/5	10/12	10/16	-4	4/23	4/22	1	5/30	5/27	3
29	Hongmai15-1	10/5	10/12	10/18	-6	4/25	4/23	2	5/31	5/27	4
30	Henong7276	10/5	10/12	10/16	-4	4/23	4/22	1	5/30	5/28	2
31	Henong8324	10/5	10/12	10/17	-5	4/25	4/22	3	5/31	5/27	4
32	Fuzhao5066	10/5	10/12	10/18	-6	4/24	4/23	1	5/30	5/27	3
33	Yuzhou810	10/5	10/12	10/18	-6	4/25	4/23	2	5/30	5/26	4
34	Kexing789	10/5	10/12	10/18	-6	4/26	4/23	3	6/1	5/30	2
35	Jinhe991	10/5	10/12	10/18	-6	4/26	4/24	2	6/2	5/29	4
36	Hengmai30	10/5	10/12	10/17	-5	4/25	4/24	1	5/31	5/27	4
37	Xiaoyan60	10/5	10/12	10/14	-2	4/23	4/22	1	5/29	5/26	3
38	Xiaoyan155	10/5	10/12	10/14	-2	4/24	4/22	2	5/30	5/27	3
39	Jimai60	10/5	10/12	10/14	-2	4/25	4/23	2	6/2	5/29	4
40	Jimai262	10/5	10/12	10/13	-1	4/26	4/24	2	6/2	5/29	4
41	Hengyu3	10/5	10/12	10/13	-1	4/24	4/23	1	5/30	5/27	3
42	Henong128	10/5	10/12	10/14	-2	4/27	4/24	3	5/29	5/26	3
43	Jimai782	10/5	10/12	10/13	-1	4/26	4/23	3	5/28	5/26	2
44	Lunxuan45	10/5	10/12	10/13	-1	4/26	4/23	3	5/29	5/25	4
45	Heng136	10/5	10/12	10/12	0	4/25	4/22	3	5/29	5/25	4
46	Jiamai361	10/5	10/12	10/14	-2	4/23	4/22	1	5/28	5/26	2
47	HengS29	10/5	10/12	10/12	0	4/24	4/23	1	5/30	5/27	3
48	Hengmai26	10/5	10/12	10/12	0	4/23	4/22	1	5/29	5/26	3
49	Jimai418	10/5	10/12	10/15	-3	4/25	4/23	2	6/1	5/29	3
50	Cangmai12	10/5	10/12	10/14	-2	4/26	4/25	1	6/2	5/30	3
51	Hannong1412	10/5	10/12	10/15	-3	4/26	4/24	2	6/2	5/30	3
52	Heng9966	10/5	10/12	10/14	-2	4/24	4/23	1	5/31	5/27	4

Number	Name	Sowing Date	Emergence stage			Heading stage			Maturity stage		
			Control	Salt Stress	Days Delayed Compared to Control	Control	Salt Stress	Days Advanced Compared to Control	Control	Salt Stress	Days Advanced Compared to Control
53	Tianmai206	10/5	10/12	10/14	-2	4/26	4/24	2	6/2	5/30	3
54	Zhongmai12	10/5	10/12	10/13	-1	4/27	4/24	3	6/2	5/29	4
55	Cangami6005	10/5	10/12	10/12	0	4/25	4/24	1	5/31	5/27	4
56	Zhongmai36	10/5	10/12	10/14	-2	4/26	4/22	4	6/2	5/30	3
57	JInmai100	10/5	10/12	10/16	-4	4/24	4/23	1	5/29	5/26	3
58	Jinmai108	10/5	10/12	10/16	-4	4/28	4/26	2	6/3	5/30	4
59	Yunhan1392	10/5	10/12	10/13	-1	4/25	4/23	2	5/31	5/27	4
60	Chang7080	10/5	10/12	10/14	-2	4/24	4/23	1	5/30	5/26	4
61	Pinyu8161	10/5	10/12	10/13	-1	4/23	4/21	2	5/29	5/26	3
62	Yunhan1512	10/5	10/12	10/13	-1	4/26	4/22	4	6/2	5/29	4
63	Hengmai33	10/5	10/12	10/14	-2	4/25	4/23	2	6/1	5/30	2
64	Hengmai36	10/5	10/12	10/13	-1	4/25	4/23	2	6/1	5/29	3
CK	Jiemai19	10/5	10/12	10/13	-1	4/26	4/25	1	6/3	5/29	5

Table 3. Performance of agronomic traits of different wheat varieties.

Trait	Treatment	Mean	Standard Deviation	Range	Coefficient of Variation (%)	Skewness	Kurtosis
Ear length	Control	8.25	0.28	7.6–8.8	3.38	-0.46	-0.23
	Salt Stress	6.54**	0.94	4.6–7.6	14.29	-0.65	-0.81
Plant height	Control	61.4	7.60	52–85	12.36	1.24	2.87
	Salt Stress	51.5**	8.30	35–70	15.99	0.41	1.29
Filling time	Control	38.7	1.46	36–42	3.75	0.08	-0.73
	Salt Stress	34.59**	1.62	32–38	4.67	0.41	-0.14
Filling rate	Control	1.66	0.14	1.29–1.82	8.64	-0.56	-0.26
	Salt Stress	1.27**	0.11	1.06–1.47	8.87	0.098	-0.54

Note: Compared with the control group, * indicates $P < 0.05$ and ** indicates $P < 0.01$ (independent samples t-test).

thetic metabolism, ultimately resulting in substantial yield fluctuations. As shown in Table 4, among the five measured traits, yield and effective panicle number exhibited the highest sensitivity to salt stress with the most prominent variation characteristics: under salt stress conditions, the yield of the 64 tested wheat materials showed extreme differentiation, with a variation range of 24.88 g to 377.42 g and the corresponding coefficient of variation (CV) as high as 58.10%; this was followed by effective panicle number, which had a CV of 51.41%.Under salt stress, the yields of 64 wheat test materials showed extreme differentiation, with a range reaching 24.88 g – 377.42 g and a corresponding coefficient of variation (CV%) as high as 58.10%. The number of effective panicles followed closely, with a CV% of 51.41%. This result aligns with multiple field trial conclusions. Salt stress reduces wheat tiller number and effective panicle formation rate, making the number of effective panicles the dominant factor determining yield differences, with a reduction as high as 60.7%. Notably, even in the non-salt-stress normal environment, the coefficients of variation (CV) for yield and effective panicle number still reached 29.37% and 30.72%, respectively, which implies that the tested materials exhibit inherent genetic differentiation in the core links of yield formation. Similar findings have also been reported in wheat germplasm resources from the Southwest Wheat Region: the genetic diversity index of yield-related traits was significantly higher than that of qualitative traits, and the genetic differences among varieties directly lead to differences in the stability of trait expression. Therefore, in the selection of wheat varieties for dry saline-alkali lands, these two traits must be prioritized — salt tolerant varieties needed to simultaneously possess the dual characteristics of "stable panicle formation ability" and "controllable yield reduction range" under salt stress. In addition, the regulatory effect of salt stress on spikelet kernel number and thousand-kernel weight should not be underestimated. Table 4 showed that the coefficient of variation (COV) of these two parameters under salt stress was 8.69% and 6.57%, respectively. Although lower than those of yield and effective spikelet number, they were significantly higher than the fluctuation level of traits under conventional non-saline/alkali environments (typically, the COV of thousand-kernel weight was only 2%–4%).

Overall, the impact of salt stress on wheat yield traits exhibits a "targeted nature" and "hierarchical nature" — the high coefficients of variation (CV) for effective panicle number and yield reflect differences in the core salt tolerance capabilities among varieties, while fluctuations in grain number per panicle and 1000-kernel weight indicate the completeness of salt tolerance mechanisms. Currently, "matching varieties to sites" has become the

Table 4. Performance of yield traits of different wheat varieties.

Trait	Treatment	Mean	Standard Deviation	Range	Coefficient of Variation (%)	Skewness	Kurtosis
Yield	Control	278.29	81.73	156.72–519.98	29.37	0.84	0.85
	Salt Stress	117.53**	68.21	24.28–377.42	58.10	1.41	2.54
1000 - grain weight	Control	47.32	3.53	41–55.5	7.46	0.04	0.11
	Salt Stress	42.56**	2.82	36.15–49.1	6.57	0.11	0
Effective panicle number	Control	174.01	53.49	94.0–322.4	30.72	0.79	0.33
	Salt Stress	101.70**	52	21.6–239.0	51.41	0.82	0.2
Number of grains per panicle	Control	34.21	0.72	32.8–35.8	2.11	-0.22	0.74
	Salt Stress	26.28**	2.28	23.3–31.6	8.69	0.87	-0.05
entire growth period	Control	239.1	1.59	236–242	0.66	0.21	-0.94
	Salt Stress	235.7**	1.61	233–239	0.68	0.21	-1.19

Note: Compared with the control group, * indicates $P < 0.05$ and ** indicates $P < 0.01$ (independent samples t-test).

core strategy for the development of saline-alkali lands. In the selection process, salt tolerance should be taken as the core criterion, and priority should be given to varieties that maintain stable effective panicle numbers, exhibit small yield reductions, and can retain a certain level of grain number per panicle and 1000-kernel weight (e.g., Jiemai 20 and Cangmai 6005). By leveraging the inherent salt tolerance regulation capabilities of these varieties to combat environmental stress, a stable improvement in grain production capacity in dry saline-alkali lands can be achieved.

Correlation analysis of traits among different wheat varieties under non-salt stress conditions

Fig. 1 showed that for the correlation analysis of salt tolerance coefficients of characters of different wheat varieties under salt stress and non-salt stress conditions, yield showed significant or extremely significant correlation with most variables. The correlation was only obvious with filling time and filling rate, indicating that yield means that yield was an indicator that was comprehensively affected by multiple complex factors, not determined by just a single or a few variables. It may also be affected by the interaction of multiple factors such as environmental factors and the overall adaptability of the variety. The correlation coefficient between plant height and thousand grain weight was positive, which means that there was a positive linear relationship between the two. This showed that varieties with higher plant heights had certain advantages in terms of 1000-grain weight, because taller plants can better accumulate nutrients, thereby promoting the growth and development of seeds related to 1000-grain weight. In this study, ear length was positively correlated with yield and plant height. Among them, the correlation coefficient between yield and ear length reaches 0.74, which was a strong positive correlation, indicating that wheat varieties with longer ear length may have certain advantages in yield. However, other studies have shown that ear length was significantly negatively correlated with yield. In addition, there was also a certain negative correlation between plant height and yield.

The correlation coefficient between yield and effective panicle number was 0.91, showing a highly positive correlation. This showed that to a certain extent, the increase in the number of effective ears may lead to a significant increase in the salt-tolerance coefficient of yield. In wheat planting, the number of effective ears was one of the important factors affecting yield. Yield was negatively correlated with grouting time (correlation coefficient was-0.11), and the correlation coefficient with grouting speed was 0.20, indicating that too long grouting time may have a negative impact on yield, while grouting speed had a relatively weak impact on yield. Therefore, in actual agricultural production or wheat variety breeding, we should focus on variables highly related to yield, such as effective ear number and ear length, and improve wheat yield and salt tolerance by selecting appropriate varieties or optimizing planting management measures. For example, wheat varieties with more effective ear numbers and longer ear lengths can be selected for planting, or how to appropriately shorten the filling time without affecting the filling speed can be studied.

Comprehensive evaluation of the salt tolerance coefficients of wheat agronomic traits

Through principal component analysis, the dimension of 8 agronomic characters was successfully reduced to 3 principal components, with a cumulative contribution rate of 72.02%. These three principal components represent the traits related to yield, filling process and grain size, respectively, and can effectively and comprehensively evaluate the salt tolerance of wheat (Table 5). The contribution rate of the first principal component was 41.61%, and the factors with greater load in the eigenvector are yield, ear length, and effective ear number; the contribution rate of the second principal component was 17.14%, and the factors with greater load in the eigenvector were filling time and filling speed; the contribution rate of the third principal component was 13.27%, and the factor with greater load in the eigenvector was 1000-grain weight. The cumulative contribution rate of these three principal components was 72.02%, indicating that these three principal

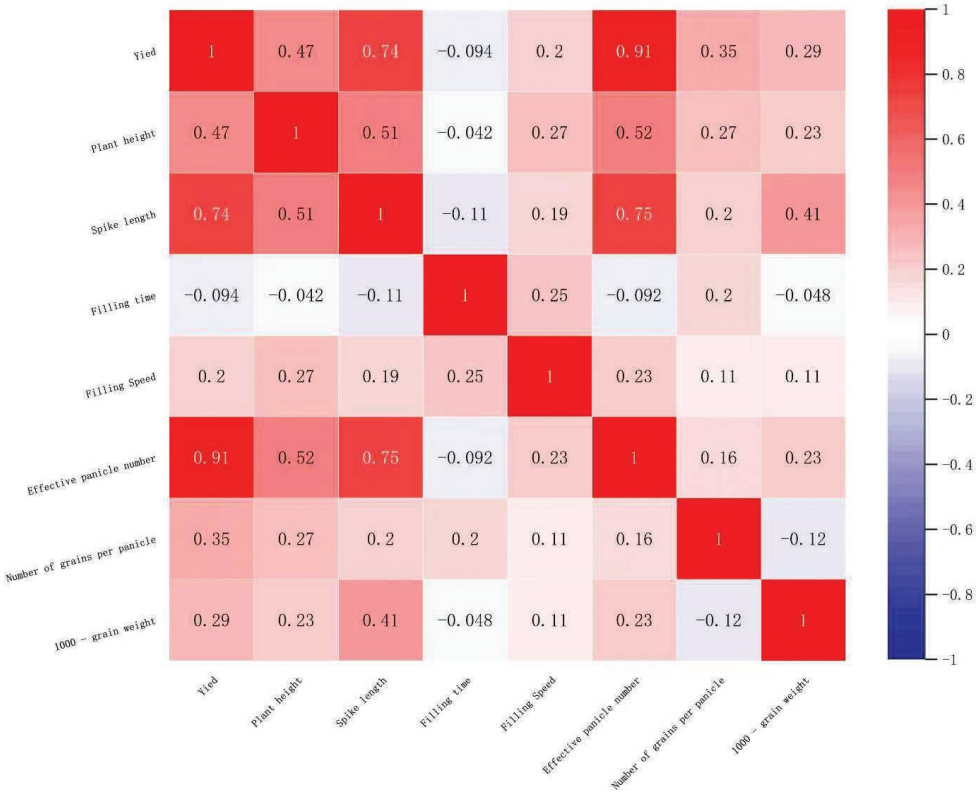

Figure 1. Correlation heatmap of salt tolerance coefficients of traits of different wheat varieties under salt stress and non - salt stress conditions.

Table 5. Principal component analysis values and contribution rates of agronomic traits of different wheat varieties.

Trait	Principal component			Eigenvalue	Contribution rate %	Cumulative contribution rate %
	PC1	PC2	PC3			
Yield	0.913	-0.040	-0.175	3.329	41.61	41.61
Plant height	0.701	0.106	-0.008	1.372	17.14	58.76
Spike length	0.873	-0.162	0.018	1.061	13.27	72.02
filling time	-0.069	0.777	0.308	0.747	9.34	81.36
Filling time	0.351	0.518	0.511	0.661	8.26	89.62
Effective panicle number	0.901	-0.095	-0.094	0.513	6.14	96.03
Number of grains per panicle	0.349	0.582	-0.531	0.267	3.34	99.37
1000 - grain weight	0.424	-0.335	0.619	0.051	0.63	100.00

components can represent the main information of eight traits. It can be seen from the characteristic values that the yield load was the largest, followed by effective ear number, ear length, and 1000-grain weight. Therefore, yield, effective ear number and ear length can be used as important indicators in major wheat-producing areas in Hebei province when screening wheat salt tolerance indicators.

Cluster analysis of salt tolerance coefficients in wheat

Then systematic cluster analysis of different wheat germplasm resources was carried out on D values using square Euclidean distance (Fig. 2). It can be seen from the figure that at the Euclidean distance of 5.0, 64 tested materials can be divided into 5 groups, Group I including 27 wheat resources from Xiangmai519 to Hengmai26, the salt tolerance level was medium; Group II (D-value) including 9 wheat resources from Xiangmai518 to Jinnong58, the salt tolerance level was high; Group III including 5 wheat resources from Wanfeng50 to Jinhe991, the salt tolerance level was sensitive; Group IV including19 wheat resources from Wanfeng50 to Jinmai100, the salt tolerance level was salt tolerance; Group V (D value) contains 10 wheat resources from Hanshengheimai1hao to Wanfeng826, and the salt tolerance level was low; From the above results, it can be inferred that varieties within the same cluster were similar in terms of salt tolerance index. And these varieties may be planted in similar soil salinity environments. However, there may be large differences in salt tolerance among varieties in different clusters. When carrying out agricultural production planning, land improvement, etc., suitable varieties can be selected for planting based on the cluster results to improve crop survival

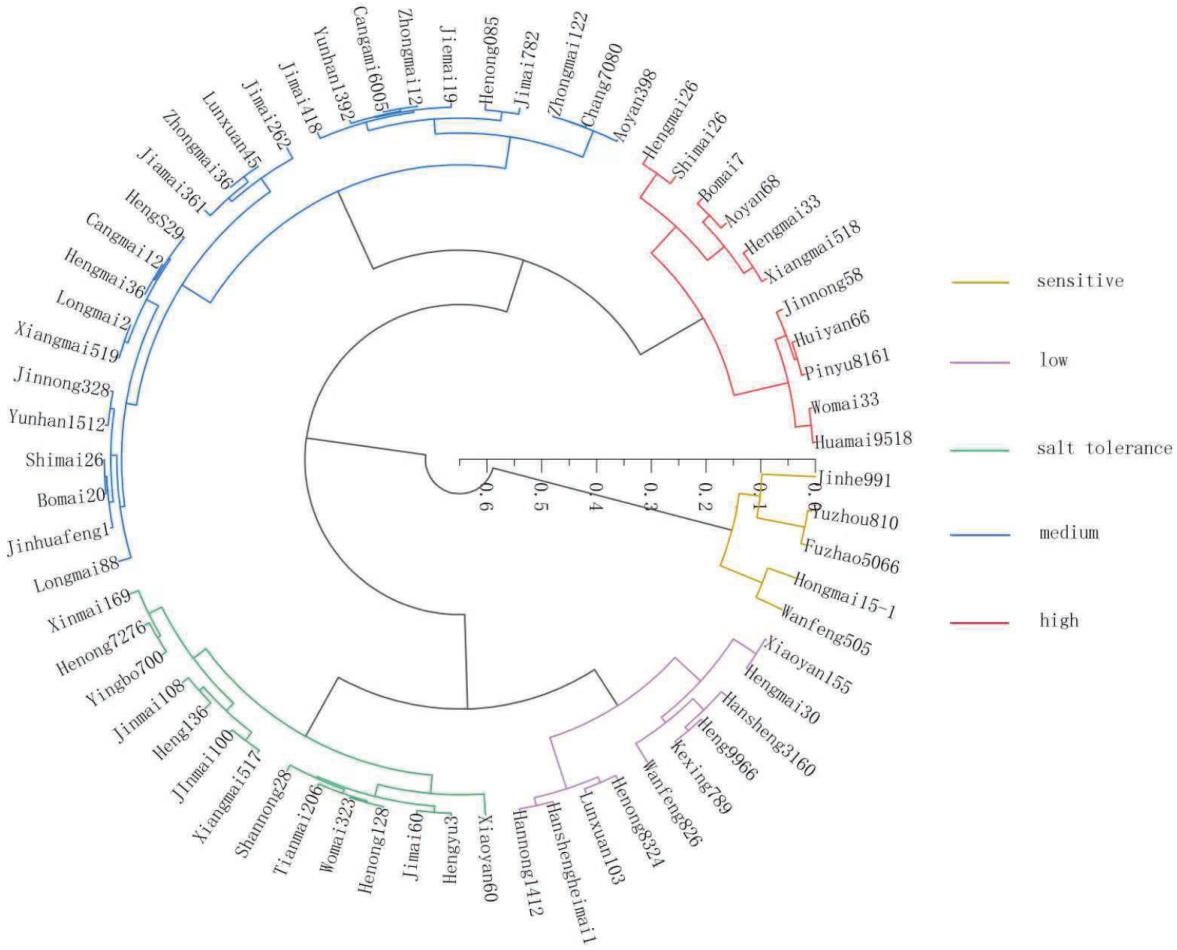

Figure 2. Cluster analysis chart of salt tolerance index.

rate and yield. The choice of threshold values will affect the clustering results. Different thresholds may cause varieties to be divided into different cluster clusters.

Discussion

Genetic diversity of wheat germplasm resources

When evaluating the salt tolerance of wheat varieties, in addition to yield and effective ear number, multiple traits such as wheat plant height and ear length, 1000-grain weight, and filling time must also be comprehensively analyzed. Dividing the salt-tolerant population of wheat varieties will help to deeply explore the characteristics of the varieties and fully explore and utilize the salt-tolerant germplasm resources of wheat. In addition, premature aging occurs in the later stages of growth, the maturity period was 1–6 days earlier than that of the control, and the growth period was shortened, which was consistent with Zheng Chunfang's research results (Wang et al. 2010). From the analysis of coefficient of variation, it can be seen that the coefficient of variation of yield and effective ear number was large, which means that the tested varieties have outstanding variability and contain rich genetic information.

Correlation analysis of wheat germplasm resources

The correlation coefficient reflects the degree of correlation between different traits in wheat. Through correlation analysis, complex relationships between different traits are found, including positive correlations, negative correlations and significant differences (Dong et al. 2012; Zhao et al. 2016; Fu et al. 2023). These findings provide an important theoretical basis for wheat breeding, help screen germplasm resources with excellent comprehensive traits, and further optimize wheat genetic improvement strategies.

Principal component analysis of wheat germplasm resources

In order to accurately reflect the core information of the tested materials while maintaining the essence of the data, this study used principal component analysis method to reduce the dimension and standardize the data, and fuses the original indicators into linear combinations of comprehensive indicators for evaluation (Liu et al. 2006; Pan et al. 2016). For 64 wheat germplasm accessions, principal component analysis (PCA) was performed based on 8 agronomic traits.

Using a cumulative contribution rate of over 72.02% as the screening criterion, the traits were ultimately categorized into 3 principal components. Eigenvalue analysis revealed that grain yield exhibited the highest loading among these principal components, followed sequentially by effective panicle number, panicle length, and 1000-grain weight.

Cluster Analysis of wheat

Cluster analysis was conducted on the salt tolerance traits of wheat varieties in this study, which successfully classified 64 wheat varieties into five distinct categories. This classification not only revealed the genetic diversity among wheat variety resources but also clarified their adaptive capacities to different environmental conditions. These findings hold important guiding value for wheat variety breeding, regional planting planning, and in-depth genetic research.

Conclusion

Through correlation, principal component and cluster analysis on 8 agronomic characters of 64 wheat variety resources in Hebei province, significant correlations were revealed among the characters. Among the coefficients of variation, yield and effective ear number were the largest. Correlation analysis found that ear length was positively correlated with yield and plant height, with a strong positive correlation; yield and effective ear number showed a highly positive correlation. Using principal component analysis (PCA) and clustering methods, 64 wheat varieties can be divided into 4 main categories, while 8 agronomic traits are summarized into 3 key principal components. Focus on variables that are highly related to yield, such as effective ear number and ear length, and improve wheat yield and salt tolerance by selecting appropriate varieties or optimizing planting management measures. For example, wheat varieties with more effective ear numbers and longer ear lengths can be selected for planting, or how to appropriately shorten the filling time without affecting the filling speed can be studied. It can be seen that the impact of salt stress on wheat was a complex process involving multiple aspects such as physiology, biochemistry and ecology. Wheat at different growth stages had different sensitivity to salt stress, and early salt stress may have a chain reaction on later growth and development. Therefore, when growing wheat in saline-alkali land, corresponding management measures need to be taken to reduce the impact of salt stress and improve wheat yield and quality.

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Conflict of interest

The authors declare that they have no conflict of interest.

Author contribution

Niu and Zou designed the experiment, Yu, Wang , Luo, Zhao executed the field research, Zhang, and Wang analyzed the data statistically, Niu wrote the manuscript.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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