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Article

Breakthroughs and Practical Challenges of Agricultural Biotechnology in Crop Improvement on Saline-Alkali Lands

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ABSTRACT
The expansion of saline-alkali land area and the aggravation of soil secondary salinization have become major constraints affecting global agricultural sustainability and food security. Agricultural biotechnology, as an innovative means to break through the bottleneck of traditional saline-alkali land improvement, has achieved remarkable breakthroughs in recent years in the aspects of salt-alkali tolerant crop breeding, soil microecological regulation, and integrated improvement of saline-alkali land. This paper focuses on the innovative progress of agricultural biotechnology in crop improvement on saline-alkali lands, including the innovative application of gene editing technology, the development of functional microbial resources, the optimization of multi-omics joint analysis technology, and the construction of integrated improvement models of biotechnology and agronomic measures. On this basis, the practical challenges faced by the industrialization application of agricultural biotechnology in saline-alkali land crop improvement are deeply analyzed, such as technical localization, cost control, industrial chain construction, and policy support. Finally, targeted countermeasures and suggestions are put forward to promote the industrialization development of agricultural biotechnology in saline-alkali land crop improvement, and its application prospects in ensuring food security and promoting sustainable agricultural development are prospected. This study provides a new perspective and practical reference for the in-depth application of agricultural biotechnology in saline-alkali land governance and crop improvement.

Keywords: agricultural biotechnology; saline-alkali land; crop improvement; gene editing; microbial resources; industrialization application; practical challenges

1. Introduction

Saline-alkali land is a widespread land type on Earth, which is formed by the accumulation of soluble salts and alkaline substances in the soil under the combined action of natural factors and human activities. According to the latest data released by the Food and Agriculture Organization of the United Nations (FAO, 2025), the global saline-alkali land area has exceeded 1.2 billion hectares, accounting for 8.0% of the total global land area, and the annual expansion rate is 1.5-2.0%. Among them, the cultivated land affected by salinization accounts for 22% of the total cultivated land, which directly leads to a reduction of 10-25% in global crop yield every year. In China, the total area of saline-alkali land is about 105 million hectares, distributed in 17 provinces (autonomous regions and municipalities directly under the Central Government), of which 20.3 million hectares are cultivated saline-alkali land. With the acceleration of urbanization and the irrational use of water and soil resources, the secondary salinization of cultivated land in arid, semi-arid and coastal areas is becoming increasingly serious, which further exacerbates the contradiction between China‘s limited cultivated land resources and the growing demand for food.

Traditional saline-alkali land improvement technologies, such as physical drainage, chemical amendment and agronomic regulation, have certain limitations in practical application: physical improvement has high engineering cost and easy recurrence; chemical amendment may cause secondary environmental pollution; agronomic regulation has a long cycle and slow effect, which is difficult to meet the demand of rapid improvement of saline-alkali land and efficient crop production. In recent years, with the rapid development of modern biotechnology, agricultural biotechnology has gradually become the core force in the field of saline-alkali land crop improvement due to its advantages of high efficiency, precision, environmental protection and sustainability. Unlike the traditional „passive adaptation“ improvement mode, agricultural biotechnology realizes the „active improvement“ of saline-alkali land and crops through modifying crop genetic traits, regulating soil microecological environment and optimizing crop-soil interaction, which has opened up a new path for the efficient utilization of saline-alkali land resources.

At present, agricultural biotechnology has achieved a series of innovative breakthroughs in saline-alkali land crop improvement: gene editing technology has realized the precise modification of crop salt-alkali tolerance genes, overcoming the limitations of traditional transgenic technology; functional microbial resources screening and modification technology has improved the ability of microorganisms to regulate soil salinization and promote crop growth; multi-omics joint analysis technology has deeply revealed the molecular mechanism of crop adaptation to saline-alkali stress, providing a theoretical basis for targeted crop improvement; the integrated application of biotechnology and agronomic measures has further improved the effect of saline-alkali land improvement and crop yield increase.

However, despite the remarkable progress, the industrialization application of agricultural biotechnology in saline-alkali land crop improvement still faces many practical challenges, such as the mismatch between technical achievements and local production conditions, the high cost of biotechnology application, the imperfect industrial chain, and the insufficient policy support and public acceptance. In view of this, this paper systematically combs the innovative breakthroughs of agricultural biotechnology in saline-alkali land crop improvement, deeply analyzes the existing practical challenges, and puts forward targeted countermeasures and suggestions, which is of great significance for promoting the industrialization development of agricultural biotechnology in saline-alkali land governance, ensuring food security and promoting sustainable agricultural development. This study is in line with the positioning of Agro-Biotechnolog journal, which focuses on the innovative application and industrialization development of agricultural biotechnology in agricultural production.

2. Innovative Breakthroughs of Agricultural Biotechnology in Crop Improvement on Saline-Alkali Lands

In recent years, with the in-depth integration of agricultural biotechnology and life science, information science and other disciplines, a series of innovative breakthroughs have been made in the field of saline-alkali land crop improvement, which have significantly improved the efficiency of saline-alkali land utilization and crop salt-alkali tolerance. This section focuses on the innovative application of key biotechnology and its breakthrough achievements.

2.1 Precise Modification of Crop Salt-Alkali Tolerance by Gene Editing Technology

Gene editing technology, represented by CRISPR-Cas9, CRISPR-Cpf1 and base editing technology, has become a core technology in crop genetic improvement due to its advantages of high precision, high efficiency and low off-target rate. Different from traditional transgenic technology which introduces exogenous genes, gene editing technology realizes the precise modification of endogenous salt-alkali tolerance genes of crops, which not only improves the salt-alkali tolerance of crops, but also avoids the potential safety risks of exogenous gene introduction, and has higher public acceptance.

In terms of crop salt-alkali tolerance gene editing, researchers have achieved a series of breakthroughs. For example, Zhang et al. (2025) used base editing technology to modify the OsHKT2;1 gene of rice, which regulates the absorption and transport of K+ and Na+, and obtained rice varieties with significantly improved salt tolerance. The modified rice varieties can grow normally under 200 mmol/L NaCl stress, and the yield in moderate saline-alkali land is increased by 30% compared with the wild type. Unlike the traditional overexpression of OsHKT2;1 gene, base editing only modifies the key sites of the gene, avoiding the adverse effects of excessive gene expression on crop growth. Zhao et al. (2024) used CRISPR-Cas9 technology to edit the TaSOS2 gene of wheat, which is a key gene in the SOS signal pathway, and significantly improved the salt-alkali tolerance of wheat. The edited wheat lines had higher SOD and POD activity under saline-alkali stress, and the accumulation of reactive oxygen species (ROS) was reduced by 45%, which effectively alleviated the oxidative damage caused by saline-alkali stress.

In addition, gene editing technology has also realized the simultaneous modification of multiple salt-alkali tolerance genes, overcoming the limitation that single gene modification can only improve salt-alkali tolerance to a certain extent. Chen et al. (2025) used multi-gene editing technology to simultaneously modify three key genes (OsNHX1, OsP5CS and OsDREB2A) related to rice salt-alkali tolerance, and obtained rice varieties with comprehensive salt-alkali tolerance improvement. The varieties can adapt to severe saline-alkali land with salt content of 0.6-0.8%, and the yield is increased by 28% compared with the single gene modified varieties. This breakthrough has provided a new method for the comprehensive improvement of crop salt-alkali tolerance.

2.2 Screening and Modification of Functional Microbial Resources for Saline-Alkali Land Regulation

Soil microorganisms are important participants in the material cycle and energy flow of saline-alkali land, and some functional microorganisms can reduce soil salinity and alkalinity, promote crop growth and enhance crop salt-alkali tolerance. In recent years, with the development of microbial separation and purification technology, metagenomics technology and genetic modification technology, the screening and modification of functional microbial resources for saline-alkali land regulation have achieved important breakthroughs, and a variety of high-efficiency functional microbial strains and microbial inoculants have been developed.

In terms of functional microbial screening, researchers have isolated a variety of high-efficiency salt-tolerant functional microorganisms from different types of saline-alkali land. For example, Wang et al. (2024) isolated a salt-tolerant strain Halomonas sp. SL-2 from coastal saline-alkali land, which can secrete salt-tolerant substances and organic acids, reduce soil pH and salt content, and promote crop growth. The strain can survive normally under the condition of 10% NaCl concentration, and inoculating it into coastal saline-alkali land can reduce soil salt content by 25% and increase corn yield by 22%. Fatima et al. (2023) isolated a salt-tolerant phosphorus-solubilizing strain Aspergillus niger Y-3 from inland saline-alkali land, which can dissolve insoluble phosphorus in saline-alkali soil, improve soil phosphorus availability, and enhance crop salt-alkali tolerance. The strain‘s phosphorus-solubilizing capacity under saline-alkali conditions is 3 times that of ordinary phosphorus-solubilizing strains, which has good application prospects.

In terms of microbial modification, researchers have improved the salt tolerance and functional activity of microorganisms through genetic engineering technology, further enhancing their ability to regulate saline-alkali land. For example, Abdul et al. (2024) used genetic modification technology to introduce the betaine synthetase gene (BADH) into the salt-tolerant PGPR strain Bacillus subtilis, which significantly improved the salt tolerance of the strain and its ability to secrete plant growth regulators. The modified strain can survive under 12% NaCl concentration, and inoculating it into saline-alkali land can promote wheat growth by 35% and reduce soil salt content by 30%. In addition, the development of composite microbial inoculants has also achieved important breakthroughs. Zhang et al. (2025) developed a composite microbial inoculant composed of salt-tolerant PGPR, phosphorus-solubilizing fungi and nitrogen-fixing bacteria, which can not only regulate soil salinization, but also improve soil fertility and promote crop growth. Applying this inoculant to saline-alkali land can increase crop yield by 25-30% and improve soil quality continuously.

2.3 Innovation of Multi-Omics Joint Analysis Technology in Revealing Crop Salt-Alkali Tolerance Mechanism

Crop adaptation to saline-alkali stress is a complex process involving multiple genes, multiple metabolic pathways and multiple regulatory networks. Traditional single-omics technology (such as genomics or transcriptomics) is difficult to systematically reveal the molecular mechanism of crop salt-alkali tolerance. In recent years, the innovation and application of multi-omics joint analysis technology (genomics-transcriptomics-proteomics-metabolomics-epigenomics) have deeply revealed the molecular mechanism of crop adaptation to saline-alkali stress, providing a precise theoretical basis for crop salt-alkali tolerance improvement.

The innovation of multi-omics joint analysis technology mainly lies in the establishment of efficient data integration and analysis methods, which realizes the cross-validation and complementary analysis of multi-omics data. For example, Li et al. (2025) used genomics, transcriptomics and metabolomics joint analysis technology to study the salt-alkali tolerance mechanism of the salt-tolerant wheat variety „Xinong 2611“, and identified 8 key regulatory genes and 12 differential metabolites involved in wheat salt-alkali tolerance. These genes and metabolites are mainly involved in ion transport, osmotic adjustment and antioxidant defense pathways, and form a complex regulatory network to improve wheat salt-alkali tolerance. This study provides a precise target for the genetic improvement of wheat salt-alkali tolerance.

Another innovative breakthrough is the combination of single-cell omics technology and multi-omics technology, which realizes the study of crop salt-alkali tolerance mechanism at the single-cell level. Wang et al. (2024) used single-cell transcriptomics and proteomics joint analysis technology to study the response mechanism of rice root tip cells to salt stress, and found that different types of root tip cells have different response modes to salt stress. The cortical cells mainly respond to salt stress through regulating ion transport, while the meristem cells mainly respond to salt stress through regulating cell division and growth. This discovery provides a new perspective for the targeted improvement of crop salt-alkali tolerance.

2.4 Construction of Integrated Improvement Model of Biotechnology and Agronomic Measures

The single application of agricultural biotechnology has certain limitations in saline-alkali land crop improvement. For example, the effect of crop genetic improvement is limited by soil salinization degree; the effect of microbial biotechnology is affected by agronomic management measures. In recent years, researchers have focused on the integrated application of agricultural biotechnology and agronomic measures, and constructed a series of integrated improvement models, which have significantly improved the effect of saline-alkali land improvement and crop yield increase.

A typical integrated model is the „gene editing crop + microbial inoculant + water-saving irrigation" model. Chen et al. (2025) constructed this model in the saline-alkali land of Hebei Province, China. The gene editing salt-tolerant wheat variety was planted, the composite microbial inoculant was applied, and the drip irrigation water-saving technology was adopted. The results showed that this model could reduce soil salt content by 35%, increase wheat yield by 32%, and save water by 28% compared with the single application of biotechnology. The model realizes the synergistic improvement of crop salt-alkali tolerance, soil environment and water resource utilization efficiency, which is suitable for popularization and application in northern arid and semi-arid saline-alkali land.

Another integrated model is the „functional microbial inoculant + cover cropping + organic fertilizer application" model. Zhao et al. (2024) constructed this model in coastal saline-alkali land of Shandong Province, China. The salt-tolerant cover crop (sesbania) was planted, the functional microbial inoculant and organic fertilizer were applied, and the soil salinization was regulated through the interaction of cover crop, microorganism and organic fertilizer. The results showed that this model could improve soil organic matter content by 20%, reduce soil salt content by 30%, and increase cotton yield by 25%. This model is suitable for coastal saline-alkali land with high soil salinity and low organic matter content.

3. Practical Challenges of Industrialization Application of Agricultural Biotechnology in Crop Improvement on Saline-Alkali Lands

Although agricultural biotechnology has achieved remarkable innovative breakthroughs in saline-alkali land crop improvement, its industrialization application still faces many practical challenges. These challenges involve technology, cost, industrial chain, policy and public acceptance, which restrict the large-scale popularization and application of agricultural biotechnology in saline-alkali land crop improvement.

3.1 Mismatch Between Technical Achievements and Local Production Conditions, and Insufficient Localization Adaptability

Most of the current agricultural biotechnology achievements in saline-alkali land crop improvement are obtained under controlled laboratory conditions or small-scale trial conditions, and there is a serious mismatch between the technical achievements and the local actual production conditions. Saline-alkali land in different regions has great differences in soil type, salinity and alkalinity degree, climate conditions and crop planting system, but the current biotechnology achievements are mostly „one-size-fits-all" and lack targeted localization adaptation.

For example, the salt-tolerant crop varieties bred by gene editing technology in the laboratory have good salt-alkali tolerance under the condition of single salt stress, but in the actual saline-alkali land, crops are often subjected to the combined stress of salt, alkali, drought and other factors, resulting in the significant reduction of the application effect of the varieties. In addition, the functional microbial inoculants developed in northern saline-alkali land have unstable effects in southern coastal saline-alkali land due to the differences in soil pH, temperature and humidity. The insufficient localization adaptability of technical achievements has become an important bottleneck restricting their industrialization application.

At the same time, the research and development of biotechnology achievements are mostly focused on major crops (such as rice, wheat and corn), and there is a lack of targeted biotechnology research and development for local characteristic crops in saline-alkali regions. This also leads to the mismatch between technical achievements and local production needs, and affects the enthusiasm of farmers to adopt biotechnology.

3.2 High Application Cost of Biotechnology, and Difficulty in Popularization Among Small-Scale Farmers

The high application cost of agricultural biotechnology is another important challenge restricting its industrialization application. Most of the biotechnology, such as gene editing, multi-omics analysis and microbial inoculant development, requires high-precision equipment, professional technical personnel and high-cost raw materials, which leads to the high cost of biotechnology products and application.

For example, the cost of planting gene-edited salt-tolerant crop varieties is 20-30% higher than that of traditional crop varieties, mainly due to the high cost of seed breeding and propagation. The application cost of functional microbial inoculants is about 1500-2000 yuan per hectare, which is difficult for small-scale farmers in saline-alkali regions to bear. In addition, the application of biotechnology also requires professional technical guidance, but the professional technical personnel in saline-alkali regions are insufficient, and the technical training for farmers is not in place, which further increases the difficulty and cost of farmers‘ adoption of biotechnology.

Most of the saline-alkali regions are economically underdeveloped areas, and the income level of farmers is low. The high application cost of biotechnology makes farmers lack the motivation to adopt biotechnology, which restricts the large-scale popularization and application of biotechnology in saline-alkali land crop improvement.

3.3 Imperfect Industrial Chain of Biotechnology, and Weak Ability of Achievement Transformation

The industrialization application of agricultural biotechnology in saline-alkali land crop improvement requires a complete industrial chain, including research and development, product production, promotion and application, technical service and other links. However, at present, the industrial chain of biotechnology in this field is still imperfect, and the ability of achievement transformation is weak, which affects the industrialization development of biotechnology.

In terms of the research and development link, most of the research and development institutions are universities and scientific research institutes, which focus on theoretical research and laboratory trials, and lack close cooperation with enterprises. The research and development of biotechnology products are not closely combined with market demand, resulting in many technical achievements can only stay in the laboratory stage and cannot be transformed into practical products. In terms of the product production link, the production scale of biotechnology products (such as gene-edited seeds and microbial inoculants) is small, the production technology is not mature, and the product quality is unstable, which affects the market acceptance of products.

In terms of promotion and application and technical service links, the promotion system of biotechnology products is not perfect, and there is a lack of professional promotion teams and technical service institutions. Farmers cannot obtain timely technical guidance and after-sales service in the process of applying biotechnology, which affects the application effect of biotechnology and the enthusiasm of farmers to adopt biotechnology. The imperfect industrial chain leads to the disconnection between research and development, production, promotion and application of biotechnology, and weakens the ability of achievement transformation.

3.4 Insufficient Policy Support and Public Acceptance, and Unfavorable Industrialization Environment

The industrialization application of agricultural biotechnology in saline-alkali land crop improvement is closely related to policy support and public acceptance. At present, the policy support for biotechnology in this field is insufficient, and the public acceptance of some biotechnology (such as gene editing technology) is not high, which creates an unfavorable environment for its industrialization application.

In terms of policy support, although the state attaches great importance to the improvement of saline-alkali land and the development of agricultural biotechnology, the targeted policy support for the industrialization application of biotechnology in saline-alkali land crop improvement is still insufficient. For example, there is a lack of special financial subsidies for biotechnology products (such as gene-edited seeds and microbial inoculants), which cannot effectively reduce the application cost of farmers; the approval process for gene-edited crop varieties is complex and the cycle is long, which affects the speed of industrialization application of gene editing technology; the intellectual property protection system for biotechnology achievements is not perfect, which affects the enthusiasm of research and development institutions and enterprises to invest in biotechnology research and development.

In terms of public acceptance, due to the lack of scientific popularization, the public has misunderstandings about some biotechnology (such as gene editing technology and transgenic technology), and is worried about the safety of biotechnology products. For example, some people believe that gene-edited crops may have potential food safety and environmental safety risks, which affects the market promotion of gene-edited salt-tolerant crop varieties. The low public acceptance has become an important social factor restricting the industrialization application of biotechnology.

4. Countermeasures and Suggestions to Promote the Industrialization Application of Agricultural Biotechnology

Aiming at the practical challenges faced by the industrialization application of agricultural biotechnology in saline-alkali land crop improvement, this paper combines the innovative breakthroughs of biotechnology and the actual needs of saline-alkali land improvement, and puts forward targeted countermeasures and suggestions to promote the healthy and rapid industrialization development of agricultural biotechnology in this field.

4.1 Strengthen Localization Adaptation Research and Development, and Improve the Matching Degree Between Technical Achievements and Local Production Conditions

First, we should carry out targeted localization adaptation research and development according to the characteristics of saline-alkali land in different regions. We should establish regional research and development centers in different types of saline-alkali regions (such as inland arid saline-alkali land, coastal saline-alkali land and semi-arid saline-alkali land), combine the local soil type, salinity and alkalinity degree, climate conditions and crop planting system, and carry out the research and development of biotechnology products and improvement models suitable for local conditions. For example, in coastal saline-alkali land, we should focus on developing microbial inoculants that can reduce soil salt content and improve soil water retention capacity; in inland arid saline-alkali land, we should focus on breeding salt-tolerant and drought-tolerant crop varieties through gene editing technology.

Second, we should strengthen the research and development of biotechnology for local characteristic crops in saline-alkali regions. We should focus on the local characteristic crops (such as cotton, beet, medlar and sesbania) in saline-alkali regions, carry out the research and development of salt-alkali tolerance improvement biotechnology, and develop targeted biotechnology products and improvement models to meet the needs of local characteristic crop production. Third, we should strengthen the long-term field trial of biotechnology achievements, verify the application effect of biotechnology under actual production conditions, and continuously optimize and improve biotechnology products and improvement models to improve their localization adaptability.

4.2 Reduce the Application Cost of Biotechnology, and Enhance the Affordability of Small-Scale Farmers

First, we should strengthen the research and development of low-cost biotechnology and equipment. We should focus on developing low-cost gene editing technology, multi-omics analysis technology and microbial inoculant production technology, reduce the research and development and production cost of biotechnology products. For example, we can develop low-cost gene editing equipment and reagents, reduce the cost of gene-edited crop variety breeding; we can optimize the production process of microbial inoculants, use low-cost raw materials to produce microbial inoculants, and reduce the production cost of microbial inoculants.

Second, we should strengthen policy subsidies and support. The government should introduce special financial subsidy policies for the application of biotechnology in saline-alkali land crop improvement, subsidize farmers who adopt biotechnology products (such as gene-edited seeds and microbial inoculants), and reduce the application cost of farmers. For example, we can give a subsidy of 30-50% for the purchase of gene-edited salt-tolerant crop seeds and microbial inoculants to improve the enthusiasm of farmers to adopt biotechnology. Third, we should strengthen the training of professional technical personnel and farmers, improve the technical level of farmers, reduce the technical cost of farmers‘ adoption of biotechnology, and enhance the affordability of small-scale farmers.

4.3 Improve the Biotechnology Industrial Chain, and Enhance the Ability of Achievement Transformation

First, we should strengthen the cooperation between research and development institutions and enterprises, and promote the integration of production, education and research. We should encourage universities, scientific research institutes and enterprises to establish cooperative relations, take market demand as the guidance, carry out targeted biotechnology research and development, and promote the transformation of technical achievements into practical products. For example, research and development institutions can be responsible for theoretical research and technical breakthroughs, and enterprises can be responsible for product production, promotion and application, forming a win-win cooperation mechanism.

Second, we should expand the production scale of biotechnology products and improve product quality. We should support enterprises to expand the production scale of biotechnology products, optimize the production process, establish a strict quality control system, and improve the quality and stability of biotechnology products. Third, we should improve the promotion and application system and technical service system of biotechnology products. We should establish a professional promotion team and technical service institution, provide timely technical guidance and after-sales service for farmers, and improve the application effect of biotechnology products. At the same time, we should strengthen the brand building of biotechnology products, improve the market awareness and acceptance of products.

4.4 Strengthen Policy Support and Scientific Popularization, and Create a Favorable Industrialization Environment

First, we should improve the policy support system. The government should introduce targeted policies to support the industrialization application of agricultural biotechnology in saline-alkali land crop improvement, including simplifying the approval process of gene-edited crop varieties, shortening the approval cycle; improving the intellectual property protection system of biotechnology achievements, protecting the legitimate rights and interests of research and development institutions and enterprises; increasing financial investment in biotechnology research and development, supporting the innovation and breakthrough of biotechnology. Second, we should strengthen scientific popularization and improve public acceptance. We should carry out various forms of scientific popularization activities, publicize the principles, application effects and safety of agricultural biotechnology (such as gene editing technology and microbial biotechnology) to the public, eliminate public misunderstandings, and improve public acceptance of biotechnology products.

Third, we should strengthen international cooperation and exchange. We should introduce advanced foreign biotechnology and experience, carry out international cooperation in biotechnology research and development and industrialization application, and promote the upgrading and development of China‘s agricultural biotechnology industry in saline-alkali land crop improvement. At the same time, we should promote China‘s excellent biotechnology products and improvement models to the world, and enhance the international influence of China‘s agricultural biotechnology.

5. Future Prospects

With the continuous progress of science and technology and the increasing demand for efficient utilization of saline-alkali land resources, agricultural biotechnology will play an increasingly important role in saline-alkali land crop improvement, and will show a series of new development trends in the future. In terms of gene editing technology, with the development of precise gene editing technology (such as prime editing and base editing), the modification of crop salt-alkali tolerance genes will be more precise and efficient, and the cycle of crop variety breeding will be further shortened. At the same time, the gene editing technology will be combined with artificial intelligence technology to realize the intelligent design and modification of crop salt-alkali tolerance genes, which will greatly improve the efficiency of crop improvement.

In terms of microbial biotechnology, the screening and modification of functional microorganisms will be more targeted and efficient. With the development of metagenomics technology and synthetic biology technology, it will be possible to screen more efficient functional microbial resources and synthesize new functional microorganisms with multiple functions (such as salt tolerance, phosphorus solubilization and nitrogen fixation) through synthetic biology technology, which will further improve the ability of microorganisms to regulate saline-alkali land. The development of microbial inoculants will tend to be specialized, compound and intelligent, and can be adjusted according to the characteristics of different saline-alkali lands and crops.

In terms of multi-omics technology, the integration of multi-omics technology and artificial intelligence technology will become a new trend. Through the intelligent analysis of multi-omics data, the molecular mechanism of crop adaptation to saline-alkali stress can be more deeply revealed, and the precise prediction and screening of salt-alkali tolerance genes can be realized. At the same time, the combination of multi-omics technology and phenomics technology will realize the rapid identification and evaluation of crop salt-alkali tolerance, which will provide a technical support for the efficient breeding of salt-alkali tolerant crop varieties.

In terms of industrialization development, with the improvement of biotechnology industrial chain, the reduction of application cost and the enhancement of public acceptance, the industrialization application of agricultural biotechnology in saline-alkali land crop improvement will enter a rapid development stage. The integrated improvement model of biotechnology and agronomic measures will be popularized and applied on a large scale in different types of saline-alkali regions, which will significantly improve the efficiency of saline-alkali land utilization and crop yield. Agricultural biotechnology will become an important support for ensuring global food security and promoting sustainable agricultural development. Specifically, in the next 5-10 years, it is expected to realize the large-scale planting of gene-edited salt-tolerant crops in 30% of moderate saline-alkali land globally, and the application rate of functional microbial inoculants in coastal saline-alkali land will reach more than 40%, which will effectively increase the global crop yield by 5-8% and alleviate the pressure of food security. At the same time, the integration of agricultural biotechnology with digital agriculture technology will realize the intelligent monitoring and precise management of saline-alkali land improvement, such as real-time monitoring of soil salinity and crop growth status through Internet of Things technology, and dynamic adjustment of biotechnology application schemes, which will further improve the efficiency and precision of saline-alkali land crop improvement.

In addition, the research and application of agricultural biotechnology in saline-alkali land crop improvement will pay more attention to the coordination of ecological protection and agricultural production. While improving crop salt-alkali tolerance and increasing crop yield, it will focus on protecting the soil microecological environment, reducing the use of chemical fertilizers and pesticides, and promoting the formation of a virtuous cycle of „saline-alkali land improvement - crop yield increase - ecological protection". For example, the development of functional microbial inoculants will not only focus on reducing soil salinity, but also pay attention to improving soil biodiversity; the breeding of salt-tolerant crops will also consider the adaptability of crops to the local ecological environment, avoiding the impact of alien crop varieties on the local ecological balance. This development trend will make agricultural biotechnology play a more important role in the sustainable development of global agriculture.

It is worth noting that the future development of agricultural biotechnology in saline-alkali land crop improvement also needs to pay attention to the equity of technology application. At present, the application of agricultural biotechnology is mainly concentrated in developed countries and large-scale agricultural production areas, while small-scale farmers in developing countries and backward saline-alkali regions have difficulty accessing advanced biotechnology and products due to economic and technical constraints. In the future, with the support of international organizations and governments, it is necessary to strengthen the popularization and application of low-cost biotechnology in developing countries and backward saline-alkali regions, provide technical training and financial support for small-scale farmers, and ensure that more people can benefit from the progress of agricultural biotechnology, so as to promote the balanced development of global agricultural biotechnology in saline-alkali land crop improvement.

6. Conclusions

Agricultural biotechnology has achieved a series of innovative breakthroughs in saline-alkali land crop improvement, including the precise modification of crop salt-alkali tolerance by gene editing technology, the screening and modification of functional microbial resources, the innovation of multi-omics joint analysis technology, and the construction of integrated improvement models of biotechnology and agronomic measures. These breakthroughs have significantly improved the ability of saline-alkali land utilization and crop salt-alkali tolerance, and provided a new path for the efficient utilization of saline-alkali land resources.

However, the industrialization application of agricultural biotechnology in saline-alkali land crop improvement still faces many practical challenges, such as the mismatch between technical achievements and local production conditions, the high application cost of biotechnology, the imperfect industrial chain, and the insufficient policy support and public acceptance. These challenges restrict the large-scale popularization and application of agricultural biotechnology in this field.

To promote the industrialization application of agricultural biotechnology in saline-alkali land crop improvement, we should strengthen localization adaptation research and development, improve the matching degree between technical achievements and local production conditions; reduce the application cost of biotechnology, enhance the affordability of small-scale farmers; improve the biotechnology industrial chain, enhance the ability of achievement transformation; strengthen policy support and scientific popularization, and create a favorable industrialization environment.

In the future, with the continuous progress of biotechnology and the implementation of relevant countermeasures, agricultural biotechnology will play a more important role in saline-alkali land crop improvement, and will realize the large-scale industrialization application in different types of saline-alkali regions. This will not only promote the efficient utilization of saline-alkali land resources, increase crop yield and ensure food security, but also promote the sustainable development of agriculture in saline-alkali regions, which has important theoretical and practical significance. This study provides a new perspective and practical reference for the in-depth application and industrialization development of agricultural biotechnology in saline-alkali land crop improvement. It should be emphasized that the industrialization development of agricultural biotechnology in saline-alkali land crop improvement is a systematic project, which requires the joint efforts of research and development institutions, enterprises, governments and the public. Only by strengthening cooperation, improving policies, reducing costs and enhancing acceptance can we give full play to the potential of agricultural biotechnology and promote the high-quality development of saline-alkali land agriculture globally.

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