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Research Progress in Salt-Tolerant Rice: From Salt Tolerance Mechanisms to Industrialization

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Abstract:

In response to global food security challenges and the need to utilize saline-alkali land resources, research and industrialization of salt-alkali tolerant rice (commonly known as "seawater rice") have become cutting-edge hotspots in agriculture. This paper provides a systematic review of the latest advances in the field of seawater rice. First, it introduces current breeding techniques, including traditional methods and molecular breeding approaches such as QTL mapping, marker-assisted selection (MAS), and marker-assisted backcrossing (MAB), which significantly improve the efficiency and precision of introducing salt-tolerant traits into elite varieties. Furthermore, this article summarizes current cultivation management practices and the role of intercropping ecosystems in enhancing both economic and ecological benefits. Finally, the review highlights the broad prospects for the industrialization of seawater rice, while also addressing ongoing challenges, such as adaptation to complex saline-alkaline environments, balancing yield and quality improvement, and diversifying industrial models. In the future, the integration of new technologies—such as multi-omics, gene editing, and genomic selection—is expected to accelerate the development of a new generation of salt-tolerant rice varieties with high yield, superior quality, and strong stress resistance. This will provide an effective solution for ensuring global food security and improving saline-alkali land.

Keywords: salt-alkali tolerant rice; seawater rice; saline-alkali land improvement; seawater rice breeding

1. Introduction

Saline-alkali soil includes saline soil, alkaline soil, and various salinized and alkalized soils, typically formed under natural conditions, especially in arid, semi-arid, and coastal areas. Saline soil refers to a soil category where the soluble salt content reaches a level significantly harmful to crop growth, with electrical conductivity (EC) > 4 dS/m. The critical salt content varies depending on the salt composition, and the soil is less prone to dispersion. Alkaline soil refers to soil containing a high amount of exchangeable sodium that harms plant growth and alters soil properties, with SAR > 13. The composition of alkaline soil is mainly sodium carbonate and sodium bicarbonate, and the soil structure is very poor and highly prone to compaction [1]. Saline-alkali soil refers to soil containing neutral soluble salts and a high proportion of sodium ions, with EC > 4 dS/m and SAR > 13. Traditionally in China, soil with a soluble salt content greater than 1% in the 0–20 cm layer is considered saline-alkali soil. The impact of soil salinization is global, with Central Asia, the Near East, North Africa, and the Pacific regions being the most severely affected [2].

Compared to normal soil, saline-alkali soil has higher pH, sodium ion, and base ion concentrations, but its fertility is much lower. The ability of plants to successfully germinate and grow in saline-alkali soil is inhibited due to: (1) Osmotic stress: The high soluble salt concentration in saline-alkali soil causes the water potential inside plant cells to be higher than outside, leading to water outflow and cell dehydration [3]. (2) Nutrient stress: High salinity causes nutrient imbalance in plants. High concentrations of Na^+ and Cl^- compete with nutrients such as K^+, Ca^{2+}, NO_3^-, and HPO_3^{2-}, leading to plant nutrient disorders. Fortmeier et al. [4] found that Na^+ competes with K^+ for binding sites on the plasma membrane of corn, damaging chloroplast function and causing uncontrolled water loss. (3) Reduced phosphorus availability: The availability of phosphorus is reduced in saline-alkali soil, affecting crop phosphorus uptake. The high pH of saline-alkali soil results in low available phosphorus content. Phosphate ions form precipitates with di- and trivalent metal ions in the soil or are fixed on the surface of soil colloids through specific and electrostatic adsorption, reducing phosphorus availability [5,6]. The excessively high pH of saline-alkali soil also reduces the availability of trace elements (such as iron and zinc), causing plant nutrient deficiencies. Moreover, the availability of iron and zinc in the apoplast of plants growing in saline-alkali soil is further reduced, exacerbating deficiency symptoms.

In recent years, drought caused by global warming and reduced precipitation may affect the salt cycle from deep to surface soil, increasing salt accumulation and exacerbating soil salinization [7]. In saline-alkali soil, crops that cannot adapt to salinity exhibit symptoms similar to drought, such as wilting, slow growth, weakness, early leaf drop, and yield reduction, even under moist conditions. Plants that are more adaptable to salinity are divided into salt-tolerant crops and halophytes. Most of them have special osmotic regulation or salt secretion mechanisms, enabling them to survive in highly saline soil. There are about 3,000 species of halophytes and 1,500 species of salt-tolerant crops globally, which have nutritional potential but are underutilized in agriculture in saline-alkali areas [8]. Halophytes can improve the physical, chemical, and biological properties of soil. For example, kallar grass and Sesbania are recommended as the first plants for reclamation purposes because they not only increase salt leaching but also improve soil physical properties through their well-developed root systems [8-10].

In response to the increasing severity of soil salinization, agricultural producers face two options: engaging in economic activities through non-agricultural employment [11], and adjusting existing planting methods, such as cultivating salt-tolerant varieties [12]. Rice, as the preferred food crop for improving coastal saline-alkali land, has great comprehensive utilization potential. Salt-alkali-tolerant rice, known as “seawater rice,” generally refers to rice varieties that can grow normally in soil with a salt concentration of 0.3% or higher and yield over 300 kg per mu. It has advantages such as salt-alkali tolerance, strong stress resistance, and well-developed root systems. It can germinate normally in salt water with a concentration of 0.9%–1.2%, with roots reaching 30–40 cm deep, enabling better absorption of nutrients and water. It also helps anchor the plants, enhance lodging resistance, and effectively retain sediment from land, reducing silt content in offshore waters [13]. In 1986, Chen Risheng discovered a wild rice strain in beach mudflats. After prolonged selection and breeding, it was finalized as the “Sea Rice 86” line in 1999, becoming the “spark” for future seawater rice.

Saline-alkali land is an important reserve cultivated land resource. The global total area of saline-alkali land is 950 million hectares, with China accounting for 100 million hectares, of which 20 million hectares can be developed for agricultural use [14]. In recent years, China’s cultivated land area has slowly decreased, and the per capita cultivated land area is only one-third of the world average. To address the shortage of cultivated land, the improvement and utilization of saline-alkali land are urgent. This paper aims to systematically review the latest research progress in genetic breeding, cultivation management, and other aspects of seawater rice and discuss the challenges and future directions of its industrialization.

2. Breeding of Seawater Rice

Sri Lanka successfully developed the world’s first salt-tol-

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erant rice material, Pokkali, in 1993 [15]. Since then, efforts to breed salt-alkali tolerant rice have been initiated worldwide. China began research on rice salt tolerance in 1976. After years of breeding efforts by Chen Risheng, China successfully developed the salt-tolerant rice material "Sea Rice 86" in 1991 [16]. In 2016, Academician Yuan Longping established the Qingdao Saline-Alkali Tolerant Rice Research and Development Center, significantly advancing China's rice breeding progress.

2.1 . Conventional Breeding

China's most significant breakthrough in rice research and industrialization has been the utilization of heterosis, specifically in hybrid rice. Academician Yuan Longping emphasized that leveraging heterosis could immediately enhance the yield of salt-alkali tolerant rice. By crossing salt-alkali tolerant rice germplasm with high-yielding, superior-quality rice varieties, individuals with both salt tolerance and desirable agronomic traits were selected from subsequent generations. Due to its salt-alkali tolerance and strong stress resistance, seawater rice provides rich genetic resources for hybrid breeding. China's research on salt-alkali tolerant rice began in the 1950s. Through extensive germplasm collection, salt tolerance identification, evaluation, and breeding of new varieties, numerous salt-tolerant rice varieties have been developed. Examples include the japonica rice varieties Yancheng 156, Yandao 10, and Yandao 12, bred by the Jiangsu Coastal Area Institute of Agricultural Sciences [17].

In the 1990s, Li Xinqi focused on utilizing common genic male sterile materials in rice. Based on this, he explored the technical approach and utilization pathway for the third-generation hybrid rice [18]. In 2015, he successfully developed the third-generation hybrid rice sterile line Gt1s, derived from eat1s, and its corresponding hybrid rice [19]. The third-generation technology employs genetic engineering male sterile lines as a genetic tool for hybrid rice breeding. It combines the advantages of the three-line method (stable sterility) and the two-line method (free combination), while overcoming their limitations. This technology can enhance the success rate of breeding seawater hybrid rice combinations, address the challenges of widespread adaptability across northern and southern regions, and facilitate global dissemination. Academician Yuan Longping's team once planned to utilize third-generation hybrid rice technology for the development of seawater hybrid rice.

2.2 . Molecular Breeding

2.2.1 . QTL Mapping

QTL mapping (Quantitative Trait Locus Mapping) is a technical method used to identify and locate genomic regions controlling quantitative traits. It aims to pinpoint specific quantitative trait loci (QTLs) that significantly influence traits such as salt tolerance within the complex genome, while estimating the contribution effect of each QTL. The salt tolerance of seawater rice is a quantitative trait and can be mapped using QTL methods to support subsequent breeding efforts.

For example, the Saltol region is a major QTL for seedling-stage salt tolerance in rice, located on chromosome 1 [20-22]. It explains 43-70% of the phenotypic variation in salt tolerance at the seedling stage in the IR29 × Pokkali cross. A specific recombinant inbred line (RIL) derived from this cross, FL478, exhibits strong salt tolerance at the seedling stage and is widely used as a valuable donor material in global rice breeding programs to enhance salt tolerance [23].

2.2.2 . Marker-Assisted Selection (MAS)

MAS is an indispensable technique in modern seawater rice breeding. Based on QTL mapping, it acts like a genetic radar, enabling breeders to directly, rapidly, and accurately screen plants carrying superior salt-tolerant genes at the DNA level. This approach has revolutionized the inefficient traditional method of relying solely on field phenotypic screening.

MAS includes the MAB method (Marker-Assisted Backcrossing), which combines molecular marker technology with conventional backcross breeding. Its core objective is to rapidly transfer one or a few desirable genes (e.g., disease resistance, insect resistance, stress tolerance) from a donor parent (which possesses the target trait but may have poor agronomic characteristics) to a recipient parent (typically an elite variety or line lacking the target trait), while retaining the superior genetic background of the recipient parent [24]. Through multiple rounds of marker-assisted backcrossing, the saline-alkali tolerance trait of seawater rice can be rapidly transferred to high-yielding but salt-sensitive varieties, resulting in rice plants that are both high-yielding and salt-alkali tolerant.

2.2.3 . Multi-Gene Pyramiding Breeding

Due to the multifaceted adverse effects of soil salinization on rice growth, development, and yield formation, improving a single gene often has limited effectiveness. Multi-gene pyramiding breeding has thus emerged as a more effective strategy. It simultaneously targets multiple physiological pathways for genetic improvement, combining saline-alkali tolerance with high yield, superior quality, disease resistance, lodging resistance (e.g., by reducing plant height), and resistance to shattering, among other desirable traits.

A team from South China University designed a rapid improvement pathway for Sea Rice 86 based on multi-gene pyramiding breeding. They successfully enhanced seven traits, demonstrating that multi-gene editing is an efficient and effective strategy for rapidly improving crops and creating novel germplasm resources [25].

3. Cultivation Management of Seawater Rice

The selection of salt-tolerant crop varieties must be adapted to local conditions. Choosing appropriate salt-tolerant crops based on the soil salinity and pH of saline-alkali land is the most critical step in saline-alkali agriculture. For example, the Qingdao Seawater Rice Research and Development Center applied two conventional rice varieties better suited to northern regions—22ZS-39 and 22ZS-44—in a demonstration base for coastal saline-alkali soil improvement. Both varieties yielded higher than the control variety Yandao 21 [26].

Seawater rice cultivated in saline-alkali soil requires dynamic adjustment of irrigation strategies based on monitoring data. For instance, rainfall can be fully utilized for natural salt leaching during the rainy season, while in dry or high-evaporation seasons, irrigation frequency should be increased to suppress salt accumulation and ensure full and uniform seedling emergence. Additionally, due to low organic matter content and imbalanced inorganic nutrients in saline-alkali soil, sufficient organic fertilizer and specialized fertilizer for saline-alkali land should be applied in a single dose before sowing [17].

Long-term monitoring of groundwater and soil salinity changes in the cultivation area is essential for seawater rice planting to prevent secondary salinization from affecting the surrounding environment. The essence of seawater rice cultivation management lies not in "irrigating with seawater" but in "creating a low-salt environment in the root zone through precise water and fertilizer management on saline-alkali land." Therefore, ecological models such as "rice-fish/duck/crab" co-culture can be explored to enhance the economic benefits and risk resilience of saline-alkali land utilization.

Shandong Province has gradually developed a comprehensive rice-wheat rotation system. Adopting a two-year rotation cycle of "rice-wheat" allows alternating growth periods of rice and wheat, maximizing soil nutrient utilization and reducing the incidence of pests and diseases. This model holds significant practical importance and enhances the applicability of seawater rice improvement [27].

4. Industrialized Application of Seawater Rice

Large-scale cultivation of seawater rice serves as the foundation for its industrialization. By 2020, the Yuan Longping seawater rice team had expanded the demonstration planting area to 100,000 mu (approximately 6,667 hectares) across China, with an average yield stabilized at over 400 kg/mu, and a maximum yield exceeding 800 kg/mu in some cases. In terms of variety development, researchers are committed to enhancing both the salt-alkali tolerance and yield of seawater rice. For example, Academician Yuan Longping set a goal to develop seawater rice varieties capable of tolerating salt concentrations above 0.8% while achieving yields exceeding 300 kg/mu within three years. The first batch of four varieties approved through the National Saline-Alkali Tolerant Regional Trials provided more options for saline-alkali lands in different regions.

Innovations in cultivation techniques are also crucial. The Qingdao Saline-Alkali Tolerant Rice Research and Development Center explored the "Four-Dimensional Improvement Method," which integrates technologies such as soil conditioning, smart irrigation, breeding of salt-tolerant varieties, and cultivation management. This approach aims to improve soil structure and water-salt balance in saline-alkali lands, creating a better root zone environment for rice growth.

The nutritional composition of seawater rice differs from that of ordinary rice. For instance, the Haihong No. 12 variety contains higher levels of trace elements such as calcium, zinc, selenium, and magnesium compared to Wuchang rice. It is also rich in health-functional factors like anthocyanins, inositol hexaphosphate, and dietary fiber. The rice features a purplish-red bran layer, slender grains, and a soft, smooth texture. When cooked into porridge, it develops a thick, gelatinous consistency with a fresh and mellow taste and a unique taro-like aroma. This product has already been promoted in over 3,000 stores across China [28].

Seawater rice by-products also hold broad utilization potential. The rice bran of seawater rice contains 15-20% oil, and the extracted rice bran oil is rich in natural antioxidants such as vitamin E, which has shown beneficial effects in managing cardiovascular diseases [29]. After treatment with combined enzymatic and bacterial fermentation, seawater rice straw can significantly enhance its nutritional value for use in animal feed and other applications [30].

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5. Conclusions and Prospects

Seawater rice represents a crucial agricultural strategic resource with significant implications for alleviating China's grain supply pressure and arable land crisis. With ongoing research advancements, the seawater rice industry has gradually matured and achieved a series of milestone outcomes. However, in its early stages of development, several challenges remain: the expansion of seawater rice lacks guidance from national strategies and support from government-level laws and regulations; the development and improvement of saline-alkali land are long-term and challenging tasks, requiring tailored management strategies based on regional conditions, with high investments and slow returns; much of the existing research on seawater rice is confined to single-discipline experimental cultivation and yield measurements, lacking effective integration of knowledge from soil science, biology, economics, and other disciplines. Moreover, the promotion models struggle to incentivize farmers [31]. Additionally, there are issues in seawater rice breeding, such as the inability to precisely locate QTLs and the absence of molecular markers matching target QTLs for large-scale screening.

The industrialization of seawater rice is a major strategic initiative to ensure national food security and achieve sustainable utilization of saline-alkali land resources. Despite facing multiple challenges in policy, technology, interdisciplinary collaboration, and breeding in its early stages, these problems can be gradually addressed by improving top-level design, strengthening technological innovation, deepening multidisciplinary integration, breaking through breeding bottlenecks, and innovating industrial models. In the future, the seawater rice industry is expected to transition from "single-point technological breakthroughs" to "systematic solutions," not only providing a model for saline-alkali land agriculture with Chinese characteristics but also contributing "Chinese wisdom" to global food security and ecological restoration.

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