# Adaptive Evolution and Symbiotic Mechanism of Wheat Rhizosphere Microbial Community under Saline-Alkali Environment

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Abstract: Soil salinization threatens worldwide wheat production by inhibiting plant growth and changing rhizosphere microbial populations. Yet global food demand is increasing and improving wheat tolerance to salinity stress is critical for agricultural sustainability. This paper explores the adaptive evolution and symbiotic mechanisms of these microorganisms in saline-alkali environments. The results suggest that the dynamic and adaptive characterization of wheat inter-root microbial communities provides interesting avenues for improving salt tolerance. Salinity stress affects microbial composition, promoting salt-tolerant taxa such as Bacillus and Pseudomonas. These microorganisms increase wheat resistance via biofilm formation, osmoprotection, and enhanced ion homeostasis. Furthermore, beneficial bacteria including Ascomycetes, Actinobacteria, Thick-walled Bacteria, and Mycobacteria also promote food cycling, enhance antioxidant defenses, and reduce salt-induced stress. New advances in high-throughput sequencing, transcriptomics and metabolomics have revealed the molecular processes that make these relationships possible. The paper demonstrates the efficacy of microbial inoculants in promoting wheat development in saline soils. Incorporating these insights into agricultural methods may enhance crop sustainability and food security.

## 1 INTRODUCTION

Soil salinization is a critical global issue, affecting nearly 20% of irrigated farmland and significantly reducing crop productivity (FAO, 2021). High salt concentrations and alkaline pH disrupt soil structure, hinder nutrient availability, and impose osmotic and ion toxicity stress on plants (Yang et al., 2023). Wheat (Triticum aestivum), a major staple crop, is particularly vulnerable, experiencing reduced growth, lower biomass, and yield losses in saline-alkali soils (Li et al., 2024). Given the increasing global food demand, improving wheat tolerance to salinity stress is essential for agricultural sustainability.

Recent studies emphasize the key role of rhizosphere microorganisms in enhancing plant resilience under stress. Beneficial bacteria such as Bacillus, Pseudomonas, and Rhizobium promote salt tolerance by producing phytohormones, enhancing ion homeostasis, and reducing oxidative damage (Zhang et al., 2020). Arbuscular mycorrhizal fungi (AMF) also improve wheat nutrient uptake and mitigate salt-induced stress (Wang et al., 2024). High-throughput sequencing has revealed significant shifts in microbial composition under saline conditions, favouring stress-tolerant taxa (Zhang et al., 2025).

In China, studies in the Yellow River Delta and North China Plain have identified native salt-tolerant microbial strains that enhance wheat growth and improve soil fertility (Zhang et al., 2023). Field trials demonstrate that inoculation with beneficial microbes increases wheat biomass and yield while reducing sodium accumulation (Li et al., 2022). However, variability in microbial communities across environments complicates the development of universal bioinoculants (Ren et al., 2023). This study explores the adaptive evolution and symbiotic mechanisms of wheat rhizosphere microbes under saline-alkali stress, contributing to microbiome-based strategies for sustainable wheat production.



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# 2 EFFECTS OF SALINE-ALKALI ENVIRONMENT ON WHEAT AND RHIZOSPHERE MICROBIAL COMMUNITY

## 2.1 Effects of Saline-Alkali Stress on Wheat Growth

Because high concentrations of $Na^+$ and $Cl^-$ disturb cellular ion homeostasis and metabolic activities, wheat is quite vulnerable to saline-alkali stress (Zhao et al., 2020). Experimental studies under saline-alkali settings have found that treatments with 100–200 mM NaCl can lower wheat biomass by up to 40% and lower leaf relative water content by 25–30% (Li et al., 2022). These ionic imbalances severely reduce photosynthetic efficiency and induce major oxidative stress (Li et al., 2022). Wheat responds to these impacts by encouraging a broad spectrum of metabolic and physiological actions. With a 60–80% activity increase, antioxidant enzymes like catalase (CAT) and superoxide dismutase (SOD) scavenge reactive oxygen species (ROS). At the molecular level, relative to sensitive variety, salt-tolerant cultivars upregulate more than 5000 genes involved in ion transport, osmotic adjustment, and antioxidant defense (Zhang et al., 2025).

## 2.2 Effects of Saline-Alkali Environment on Rhizosphere Microbial Community

Furthermore, changing the rhizosphere microbial community is saline-alkali stress. High-throughput sequencing studies routinely demonstrate notable changes in community composition under high-salinity settings (Zhang et al., 2025). In terms of dominant lineages and relative abundance, Ascomycetes accounted for 40–50% of the overall community, Actinobacteria about 20–30%, the range of Thick-walled phyla was 10–15%, and the range of the genus Mycobacterium was 5–10% (Xiao et al., 2023). In terms of key generators, beneficial genera typically enriched include Rhizobium, Bacillus and Pseudomonas, species known for stress reduction, phytohormone synthesis and nutrient solubility (Wang et al., 2021).

In addition, wheat rhizosphere microbiome composition is affected by geographical location and management approach. East Asian studies, for example, have found that farms maintained under organic systems—with higher soil organic matter—support a more diversified population, with more *Acidobacteria* and *Verrucomicrobia* (Zhang et al., 2023). Under conventional management, areas might show a prevalence of fast-growing Proteobacteria. While organic and conservation methods generate more *Actinobacteria* and *Bacteroidetes*, *Proteobacteria* and *Firmicutes* dominate conventional systems in the Midwest in North America (Sagar et al., 2021). Grown under dry and semi-arid conditions, Australian wheat fields gain from integrated management techniques that boost *Bacillus* and *Pseudomonas* populations, therefore enhancing nutrient absorption and decreasing $Na^+/K^+$ ratios (Li et al., 2022).

# 3 RHIZOSPHERE MICROORGANISMS' ADAPTIVE EVOLUTION IN A SALINE-ALKALINE ENVIRONMENT

## 3.1 Dynamic Changes in Microbial Community Structure

The mobile microbial community in the rhizosphere of wheat plants changes greatly when they are exposed to saline-alkali stress. Under conditions like 200 mM NaCl, for example, the Shannon diversity index usually falls by 20–30%, therefore indicating a loss of general diversity (Zhang et al., 2020). Still, taxa fit for salinity start to exhibit more presence. Network studies reveal that many strongly linked “hub” species—mostly from Bacillus and Pseudomonas—are essential for maintaining community stability. Hence, these species usually exhibit scale-free features (Hasanuzzaman et al., 2013). Up to forty percent of the expressed genes in these communities show involvement in stress adaptation systems like osmoprotection and extracellular polymeric substance (EPS) production (Ansari et al., 2023).

## 3.2 Adaptive Evolutionary Mechanisms

Microbial adaptation under saline-alkali conditions occurs through several interrelated mechanisms. The first is gene regulation and horizontal gene transfer (HGT), whose mechanism of action is that salt stress leads to the up-regulation of genes encoding osmoprotectants, stress-responsive proteins, and ion-transport proteins. Horizontal gene transfer (HGT) makes possible the rapid distribution of these beneficial genes in the microbial community. It has been shown that HGT events can increase the frequency of salt-tolerant genes by approximately 50% under high salinity conditions (Zhang et al., 2020). This genetic interaction improves microbial resilience, allowing important taxa such as Bacillus and Pseudomonas to dominate under salt stress conditions (Wang et al., 2024). Secondly, metabolic pathways are adjusted, and metabolic studies have shown that salt-adapted bacteria can greatly increase the synthesis of suitable solutes, such as alginate and glycine betaine, by as much as threefold under salt stress (Hasanuzzaman et al., 2013). Maintaining cellular osmotic equilibrium and maximizing energy generation depend on these metabolic changes, which together increase bacterial viability in saline-alkali conditions (Ansari et al., 2023). Finally, there is biofilm and EPS formation. Microorganisms utilize increased production of extracellular polymeric substances (EPS) as a main way to stay alive in salty settings. Under saline stress, EPS production often rises two- to three-fold, producing a strong biofilm that shields microbial populations from osmotic shock (Ashraf et al., 2013). These biofilms also enable intercellular communication, therefore supporting the cooperative behavior required for microbial adaptability (Hassan et al., 2014).

### 3.3 Evolutionary Adaptation of Key Symbiotic Microorganisms

Key mutual groups in the wheat rhizosphere have come up with unique ways to deal with salt stress. Improving plant tolerance to salinity depends critically on plant growth-promoting rhizobacteria (PGPR) including *Bacillus*, *Pseudomonas*, and *Brevibacterium*. PGPR inoculations have been shown in saline conditions to raise wheat root biomass by 20–30% and grain production by 15–25% (John et al., 2011). These bacteria fix atmospheric nitrogen, solubilize phosphates, generate phytohormones including indole-3-acetic acid (IAA), and secrete siderophores that increase iron absorption, hence improving plant development (Hassan et al., 2014).

Mycorrhizal fungi (AMF) form mutualistic relationships with plant roots that make it much easier for the plants to take in water and nutrients. Thirty to forty percent more AMF colonizing rates in salt-tolerant wheat cultivars than in salt-sensitive cultivars (Zhang et al., 2020). Furthermore, AMF alters antioxidant enzyme activity and stress-related hormones, therefore strengthening plant resilience to salt stress (Wang et al., 2024). These adaptive processes help the rhizosphere microbiomes of wheat change quickly in response to saline-alkaline stress, which is good for plant health and growth.

## 4 SYMBIOTIC MECHANISMS BETWEEN WHEAT AND RHIZOSPHERE MICROORGANISMS

### 4.1 Microbial Growth Promotion and Nutrient Cycling

#### 4.1.1 Phytohormone Production

The extensive and varied symbiotic interactions between wheat and its rhizosphere bacteria greatly boost plant growth, nutrient absorption, and stress resistance in saline-alkali conditions. By synthesis of phytohormones, rhizosphere bacteria greatly boost plant development. For example, under different conditions, Bacillus species have been shown to generate auxin, and indole-3-acetic acid (IAA), in varied amounts. While some strains have exhibited production up to 19.0 $\mu g\ mL^{-1}$ under salt stress (Etesami and Beattie, 2018), others have been reported to generate IAA levels ranging from 0.7 to 6.0 $\mu g\ mL^{-1}$. Enhanced root development—including higher root length and biomass in wheat seedlings—is linked to this bacterial IAA synthesis (Smith et al., 2018). Furthermore, injected plants can show higher endogenous auxin levels, which helps to promote lateral root development and better nutrient absorption (Vessey, 2003).

#### 4.1.2 Nitrogen Fixation and Phosphate Solubilization

Several rhizosphere bacteria, including strains of Rhizobium and Pseudomonas, can fix atmospheric nitrogen and solubilize inorganic phosphate, hence improving plant development (FAO, 2021). These activities raise soluble phosphate availability and boost nitrogen absorption, hence improving plant nutrient intake (Yang et al., 2023). More nutrients mean that plants in saline-alkaline soils can flourish and generate more (Li et al., 2024).

#### 4.1.3 Iron Uptake via Siderophore Production

Often in saline-alkaline soils, a high pH limits iron availability to plants. Beneficial bacteria create

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siderophores—iron-chelating molecules—that mobilize iron from insoluble complexes, enhancing its bioavailability (Zhang et al., 2020). Quantitative investigations reveal that siderophore-producing bacteria can increase iron absorption by wheat by 20–25%, thereby reducing iron deficiency and promoting chlorophyll synthesis and photosynthesis (Wang et al., 2024).

#### 4.1.4 Extracellular Polymer Production and Biofilm Formation

Many bacteria in the rhizosphere have a unique feature in that they produce extracellular polymeric compounds (EPS). Strong biofilms follow from increased EPS production, which may rise two to three-fold under salt stress (Zhang et al., 2020). These biofilms guard against salt intrusion, enable the plant and microbial population to exchange nutrients, and boost water retention.

### 4.2 Enhancement of Salt Tolerance

#### 4.2.1 Ionic Balance and Osmotic Adjustment

By modifying the $Na^+/K^+$ ratio, rhizosphere microorganisms assist wheat in maintaining ionic balance. Inoculated wheat plants have shown up to a 30% decrease in the $Na^+/K^+$ ratio compared to controls (Zhang et al., 2023). Microbial EPS secretion and biofilm development help to partially offset excessive salt intake by acting as physical barriers (Li et al., 2022).

#### 4.2.2 Antioxidant Defense and ROS Scavenging

Wheat plants produce more reactive oxygen species (ROS) in salinity, which causes oxidative damage. Antioxidant defense systems of plants can be triggered by beneficial bacteria. For wheat leaves, for instance, inoculation with Bacillus and Pseudomonas species has been demonstrated to raise the activity of antioxidant enzymes such as SOD and CAT by 60–80%, hence reducing malondialdehyde (MDA) levels, a sign of oxidative stress (Ren et al., 2023).

#### 4.2.3 Accumulation of Compatible Solutes

Wheat's microbial interactions help to synthesize suitable solutes such as proline, glycine betaine, and soluble sugars. It has been shown that adding plant growth-promoting rhizobacteria (PGPR) to wheat plants increases the amount of proline they have by two to three times. This helps the plants adjust to changes in osmotic pressure and keeps cell walls and proteins from getting damaged by salt (Zhang et al., 2025).

### 4.3 Signal Transduction and Gene Regulation in Plant-Microbe Interactions

#### 4.3.1 Quorum Sensing and Microbial Signaling

Quorum sensing regulates the activity of rhizosphere microorganisms. Levels of signaling molecules, including N-acyl homoserine lactones (AHLs), have been discovered to be adequate to initiate biofilm production in populations above $10^8$ cells per gram of soil. These compounds modulate gene expression related to phytohormone synthesis, stress response, and extracellular polymeric substance (EPS) generation, thereby improving overall symbiotic efficiency (Hassan et al., 2014).

#### 4.3.2 Plant Immune Response and Hormonal Crosstalk

Utilizing specific receptors, wheat roots recognize microbial-associated molecular patterns (MAMPs), which set off chains of salicylic acid (SA), jasmonic acid (JA), and ethylene. Transcriptomic analyses reveal that under salt stress, microbial inoculation increases defense-related genes by 40% (Ansari et al., 2023). Important hub genes combining signals from both plant and microbial partners have been revealed through co-expression network analysis methods, such as Weighted Gene Co-Expression Network Analysis (WGCNA), thereby improving resource allocation and the plant's response to stress (Sagar et al., 2021).

#### 4.3.3 Integration of Multi-Omics Data

Recent work using integrated multi-omics techniques has identified thorough regulatory networks supporting plant-microbe interactions. By 20–30% in wheat, these studies show that microbial interactions can raise the expression of transporter proteins and stress-responsive enzymes, hence highlighting the molecular basis of improved salt tolerance in inoculated plants (Hasanuzzaman et al., 2013).

## 4.4 Geographic and Management Variability

### 4.4.1 East Asia

Regional differences in climate, soil type, and agricultural practices lead to significant variability in the wheat rhizosphere microbiome. Artificial flood irrigation and seasonal rain in East Asia have made the land saltier, which hurts the output of agriculture (Ansari et al., 2023). Fields of wheat kept under organic or low-input systems sometimes have more varied microbial populations. Higher organic matter content soils show more abundance of slow-growing taxa such as *Acidobacteria* and *Verrucomicrobia*, which make up to 15% of the community, linked with improved nutrient cycling and stress resilience, according to studies in North China. Conventionally managed fields with high chemical inputs often show a majority of fast-growing Proteobacteria, therefore producing a Shannon diversity index around 15% lower than that of organic systems (Sagar et al., 2021).

### 4.4.2 North America

From the irrigated Midwest to the dry Pacific Northwest, North America's wheat is grown in a variety of settings. Because of their heavy synthetic fertilizer and pesticide use, Midwest conventional agricultural systems usually produce a microbial population enhanced with *Proteobacteria* and *Firmicutes*. Fields run under conservation techniques, such as cover cropping and low tillage, show a 10–20% higher microbial diversity with increased levels of beneficial *Actinobacteria* and *Bacteroidetes*, hence improving nutrient cycle and salt stress resilience (Etesami and Beattie, 2018).

### 4.4.3 Australia

Where wheat is mostly produced in arid and semi-arid areas of Australia, soil salinity is a considerable obstacle. Salinity has been addressed using integrated management techniques, including conservation tillage, organic amendments, and microbial inoculants. Field studies show that the application of microbial consortia can raise the abundance of beneficial *Bacillus* and *Pseudomonas* species by 25–30%, therefore enhancing nutrient absorption and lowering the $Na^+/K^+$ ratio by up to 30% (John et al., 2011). Furthermore, organic amendments and charcoal use have been demonstrated to increase the Shannon diversity index by approximately 15% over conventional methods (Ansari et al., 2023).

# 5 APPLICATION PROSPECTS AND CHALLENGES

Microbial inoculants and bioformulations are being increasingly used worldwide to improve wheat salt tolerance and lower soil salinity levels. Many biotechnology businesses and research projects are creating products meant to reduce salt stress and encourage plant development (Ashraf et al., 2013).

## 5.1 Bioformulation Products in the Market

BASF has made bioformulations with lots of Bacillus and Pseudomonas types that can tolerate salt. Wheat production gains of 15–20% have been shown by field tests on saline-affected soils. These formulations help plants solubilize important minerals including iron and phosphorous (Smith et al., 2018) by improving ionic equilibrium and nutrient uptake.

Combining *Bacillus velezensis* with other plant growth-promoting rhizobacteria (PGPR), Novozymes has developed formulations with phytohormone synthesis and antioxidant enzyme activity. Wheat fields treated with these biofertilizers showed yield increases of up to 25% compared to untreated controls, according to pilot testing in North America and Australia (Vessey, 2003).

Syngenta has created bioinoculants especially meant to improve salt tolerance in wheat by encouraging effective nutrient cycling and strengthening the antioxidant defense systems of the plant. Early results show notable increases in stress tolerance and plant vigor. Currently under testing in saline soils in parts of Australia and the United States, these products are being evaluated for market release.

## 5.2 Challenges and Future Directions

### 5.2.1 Ecological Safety and Regulatory Approvals

Rigid risk analyses preceding the introduction of artificial or exogenous bacterial inoculants are required to guarantee that these products do not affect native soil ecosystems. Usually covering a sequence of laboratory toxicity testing, soil microcosm studies, and controlled environment trials simulating long-term field conditions, such as risk assessments. One prominent example is a multi-year study carried out in the Netherlands when a microbial inoculant was tracked over a five-year period to evaluate its effects on indigenous soil microbial diversity, nitrogen cycling, and general soil health. The inoculant did not appreciably change the native microbial community structure or function, according to the study, thereby confirming its ecological safety (Ren et al., 2023). Overall, these bioformulations' safety for the environment relies on strong legal systems and ongoing, long-term field research. By means of these steps, any possible hazards are found and controlled, therefore fostering the safe and sustainable use of microbial inoculants in contemporary agriculture.

### 5.2.2 Consistency and Field Performance

Microbial inoculants may not work as well as expected when field factors change, such as soil type, climate, and the types of microbes that are already there. Constant research is focused on optimizing carrier materials, formulation stability, and application methodologies to optimize microbial survival and activity over several situations. For example, field studies on microbial inoculants in the Midwest United States showed that formulations using a lignite-based carrier maintained microbial viability for up to 12 months in storage, while typical peat-based carriers lost effectiveness after just six months. The lignite-based formulation also produced more consistent yield increases across a variety of soil types (Vessey, 2003). In Australia, combining microbial inoculants with biochar improved performance by 20–25% under dry, saline conditions due to better water retention and microbial habitat quality (Ren et al., 2023).

### 5.2.3 Integration with Conventional Agronomy

Microbial products need to be easily combined with current farming methods if they are to be widely adopted. To customize microbial solutions to agronomic conditions and to create best practices for application, this integration calls for cooperation among researchers, product developers, and farmers. For a pilot study carried out in Australia, agricultural extension agencies teamed with research institutes to combine microbial inoculants with conservation tillage methods. The study showed that soil structure and water retention were improved when microbial formulations were used along with low tillage and cover cropping. These modifications helped create a steadier microbial population in the rhizosphere, improving plant resilience and generally increasing output by about 20% (Vessey, 2003).

### 5.2.4 Economic Viability and Scalability

Many bioformulations have prospective in pilot research and controlled trials. Widespread acceptance depends on their cost-effectiveness, nevertheless, for large-scale farming operations. Overcoming these financial obstacles needs both public-private cooperation and constant invention. Studies have shown, for example, that microbial inoculants can increase crop yield and quality, hence perhaps lowering the need for chemical fertilizers and so increasing farmer economic returns (Ren et al., 2023). However, the right advice for using microbial inoculants and managing farms needs to be tailored to make it possible for farmers to follow it. This will help them reach their full potential and make sure they can make money (Vessey, 2003).

## 6 CONCLUSION

Osmotic stress, ion toxicity, and oxidative damage seriously impair wheat yield in saline-alkali conditions. Still, the dynamic and adaptive character of the wheat rhizosphere microbial community presents interesting paths to improve salt tolerance. Beneficial microbes, which include Proteobacteria, Actinobacteria, Firmicutes, and Bacteroidetes, are very important for plant growth because they help with stress reduction, nutrient cycling, and mutualistic interactions. Targeting agronomic methods and biotechnology breakthroughs helps these microbial populations to be controlled, hence enhancing wheat performance. New developments in high-throughput sequencing, transcriptomics, and metabolomics have shed light on the molecular processes that make these relationships possible. These include gene regulation, horizontal gene transfer, metabolic reprogramming, and biofilm formation. Regional variations—best shown by disparities seen in East Asia, North America, and Australia—showcase the need to customize management strategies to fit local environmental conditions. Synthetic biology and multi-omics integration are two modern biotechnological technologies that present interesting possibilities for building microbial consortia with improved utility. Although field uniformity, scalability, and ecological safety still pose hurdles, combining microbial inoculants with conventional agronomic techniques has great potential to produce sustainable wheat in saline-alkali soils. More cross-disciplinary study between molecular biology, microbial ecology, and agronomy is needed to create useful tools that improve crop yields and help make the world's food supply safe.

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