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Rhizosphere Microbiome Remodeling Enhances Salt-Alkali Tolerance in Proso Millet (*Panicum miliaceum* L.)

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Abstract Saline-alkaline stress is gradually becoming a major factor limiting agricultural productivity because it simultaneously causes osmotic stress, ion toxicity, nutrient precipitation, and high-pH damage within the same soil environment. Under this background, proso millet (*Panicum miliaceum* L.) has gained renewed attention. This study integrates current evidence on how proso millet achieves tolerance under saline-alkaline conditions through coordinated strategies at the morphological, physiological, biochemical, and molecular levels, and further discusses how rhizosphere microbiome reshaping strengthens these response mechanisms. The saline-alkaline tolerance of proso millet depends on the integrated coordination of root structural plasticity, osmotic adjustment, Na+/K+ homeostasis, antioxidant defense, and cell wall remodeling mechanisms.

The study also analyzes grain metabolic reprogramming in proso millet under saline-alkaline stress, including changes in the composition of amino acids, phenolic acids, flavonoids, organic acids, and antioxidant compounds, and discusses their potential significance for nutritional quality and functional food development. Finally, the study evaluates the application potential of proso millet in saline-alkaline land utilization, ecological restoration, low-input agriculture, and diversified food and feed systems. Rhizosphere microbiome reshaping is not a secondary result of saline-alkaline tolerance in proso millet, but rather a key component of the tolerance formation process itself, and it represents an important future research direction for breeding, microbiome engineering, and the design of climate-adaptive cropping systems.

Keywords Proso millet (*Panicum miliaceum* L.); Saline-alkali stress; Rhizosphere microbiome; Ion homeostasis; Antioxidant defense; Functional metabolites; Climate-resilient agriculture

1 Introduction

Soil salinization and alkalization have become major limiting factors in global agricultural production, especially in arid, semi-arid, and irrigated agricultural regions. The global area of saline soils has reached about 17 million km² and continues to expand under the influence of climate change, improper irrigation practices, and poor drainage conditions (Hassani et al., 2021). The main problem of saline-alkaline soils is the combined stress of salt and high pH. Salt stress reduces soil water potential and causes ion toxicity, while alkaline conditions decrease nutrient availability, disturb membrane transport, and inhibit root function. These effects finally lead to lower seed germination, unstable crop yield, and reduced land-use efficiency (Li and Yang, 2023). Saline-alkaline agriculture is not only an issue of soil management, but also an important topic related to crop structure adjustment and agricultural resilience.

Under this background, minor cereals with strong stress resistance have received increasing attention again. Compared with major staple crops that highly depend on resource input, minor cereals usually show better drought resistance, tolerance to poor soil conditions, and stronger adaptability to environmental stress. They can also maintain relatively stable yields on marginal land (Mudnakudu-Nagaraju et al., 2025). Proso millet is a typical example. It has a short growth period and low water requirement, and it also contains high nutritional value, including rich bioactive compounds, a low glycemic index, and gluten-free characteristics. Therefore, it is considered a potential crop for adapting to climate change and promoting agricultural diversification.