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Review Article

Salt Tolerance in Rice Cultivars under Indian Soil Conditions: Current Insights and Future Prospects

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Abstract: Soil salinity is a critical abiotic stress limiting rice production in India, particularly in coastal belts and irrigated landscapes prone to secondary salinization. Rice (Oryza sativa L.) is among the most salt-sensitive cereals, with salinity causing osmotic and ionic stress, oxidative damage, and large yield penalties. This case study synthesizes advances in understanding physiological, biochemical, and molecular mechanisms of salt tolerance [22,23,29]; summarizes Indian breeding achievements including Saltol-introgressed lines and CSR series [3,13,18,30]; and outlines agronomic and microbiome-based strategies suited to Indian soils [5, 28]. We highlight future prospects in genome editing, high-throughput phenotyping, and climate-smart breeding [9,14,27] to ensure resilient rice production in salt-affected areas.

Keywords: Rice (Oryza sativa), Soil salinity, Salt tolerance, Marker-assisted selection, CSR rice varieties.

Introduction

Rice underpins food and livelihood security for hundreds of millions of Indians. However, salinity affects an estimated 6-7 million hectares of Indian farmland [6,20], with hotspots in coastal West Bengal, Odisha, Andhra Pradesh, Tamil Nadu, Gujarat, and sodic tracts of Uttar Pradesh and Haryana [17,28]. Salinity constrains germination, tillering, flowering, and grain filling, primarily via osmotic stress and Na^+/Cl^- toxicity that disrupt nutrient balance and photosynthesis [25]. Given the sensitivity of rice at seedling and reproductive stages, breeding and management for salt tolerance remain national priorities [3,14].

Physiological and Biochemical Responses to Salinity

Salinity first imposes an osmotic phase that reduces water uptake, followed by an ionic phase characterized by Na^+ and Cl^- accumulation in shoots [25,22]. Tolerant genotypes typically maintain a higher K^+/Na^+ ratio, restrict Na^+ loading to the xylem, and enhance vacuolar sequestration through NHX antiporters [12,26]. Biochemical acclimation includes osmolyte accumulation (proline, glycine betaine, soluble sugars) and robust antioxidant systems (SOD, CAT, APX) that mitigate ROS [21]. Photosynthetic performance is preserved through sustained stomatal conductance, chlorophyll stability, and protection of photosystem II [29].

Molecular Mechanisms and Genetic Basis

Salt tolerance in rice is polygenic. The major-effect QTL Saltol on chromosome 1 explains a substantial fraction of seedling-stage Na^+/K^+ homeostasis and has been introgressed into elite varieties via marker-assisted backcrossing [2,11,18]. Key transporters such as HKT1;5 mediate Na^+ retrieval from the xylem [12,26], while SOS1 and NHX1 contribute to efflux and vacuolar sequestration [22]. Transcriptional regulators (DREB/CBF, NAC, bZIP, MYB) orchestrate stress-inducible networks [1,16]; Ca^{2+} signaling, CDPKs, and MAPKs integrate perception to response [9]. Multi-omics (genomics, transcriptomics, proteomics, metabolomics) and GWAS are uncovering novel alleles [9, 23], and CRISPR/Cas is enabling precise edits in candidate genes [14,27].

Salt-Tolerant Cultivars and Breeding in India

Landraces such as Pokkali (Kerala) and Nona Bokra (Bengal) have been foundational donors [10,11]. The ICAR-CSSRI-led CSR series (e.g., CSR 10, CSR 27, CSR 36, CSR 56, CSR 60) target sodic/saline tracts of north India [3,30].

Saltol has been introgressed into widely grown varieties (IR64, Swarna, Pusa Basmati backgrounds) [18], and combinations with Sub1 for submergence (e.g., Swarna-Sub1+Saltol) address compound stresses in coastal deltas [15]. Collaborations among ICAR, IRRI, and State Agricultural Universities continue to expand pipelines for region-specific release [13].

Agronomic and Soil–Water Management Strategies

Reclamation and management practices complement genetics: gypsum for sodic soils [17], organic amendments to improve structure and microbial activity [5], freshwater flushing and controlled irrigation to leach salts [28], and raised-bed or alternate wetting-and-drying practices where feasible [28]. Balanced nutrition (especially K and Zn), seed priming [7], and use of salt-tolerant plant growth–promoting rhizobacteria (PGPR) further improve establishment and yield stability under salinity [5].

Future Prospects

Priority areas include pyramiding of multiple QTLs/genes [18,23], genome editing for transporter optimization [14,27], deployment of high-throughput phenotyping (imaging, drones) [9], and harnessing plant-microbiome interactions for eco-friendly resilience [5]. Climate-smart breeding that stacks salinity tolerance with submergence, drought, and heat tolerance is essential for coastal and inland salinity mosaics [15,29]. Farmer-participatory selection and robust seed systems will accelerate adoption [3].

Conclusion

Soil salinity represents one of the most persistent and complex abiotic stresses threatening rice production in India. With over 6.7 million hectares of saline and sodic soils [6], the problem spans diverse agro-ecological zones. The multifaceted impact of salinity involving osmotic imbalance, ionic toxicity, nutrient deficiency, and oxidative stress severely limits plant growth and yield potential [22,25]. Over the past three decades, significant progress has been made through the development of salt-tolerant rice cultivars, both by utilizing traditional landraces such as Pokkali and Nona Bokra [10,11] and by integrating modern breeding tools like marker-assisted selection (MAS) [3,18]. The successful introgression of Saltol into popular Indian rice varieties (e.g., IR64, Swarna, Pusa Basmati) [18] has provided farmers with more resilient options. Additionally, advances in understanding mechanisms such as ionic homeostasis, osmotic adjustment, and antioxidant defense offer a solid foundation for future molecular and biotechnological interventions [22,29].

Despite these advances, adoption of salt-tolerant cultivars remains uneven due to limited seed dissemination and region-specific adaptability issues [13]. Climate change is further exacerbating salinity problems through sea-level rise and irregular rainfall [20]. The future of sustainable rice production will depend on genomic innovations [14,27], microbiome exploitation [5], integrated soil and water management [17,28], and strong policy and farmer-support systems [3].

Ultimately, solving the problem of salinity in rice cultivation is both a scientific and socio-economic necessity for India, where millions of smallholder farmers rely on rice as their staple crop and livelihood [6]. The integration of traditional breeding wisdom, molecular biology, and field-level agronomic management, supported by institutional frameworks, will be crucial for ensuring food security under worsening soil degradation and climate change.

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