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Salinity Dynamics: Exploring Causes and Consequences

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Abstract

Salinization significantly affects agricultural productivity and environmental stability. This phenomenon results from a complex interplay of factors including salt precipitation, evaporation, ion exchange, and salt transport. Salinization poses challenges for crop production by diminishing soil fertility and water availability, thereby impacting both local economies and societal well-being. Salts found in affected soils, primarily comprising cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO^{-}_3), as well as potentially toxic elements like aluminum, boron, and selenium, disrupt agriculture, reducing plant growth and yield while threatening human and animal health. This article delves into the causes and consequences of soil salinity and salinization, highlighting natural processes such as fossil salt deposits and geological events. Moreover, anthropogenic activities exacerbate the issue, including deforestation, uncontrolled irrigation practices, excessive groundwater extraction, and the use of chemical fertilizers and sewage effluents. Understanding these causes is crucial in developing sustainable agricultural practices, emphasizing the moderation of fertilizer use, proper drainage systems, and efficient water management, ensuring the preservation of soil health and the ecosystem.

Keywords: Capillary rise, electrical conductivity, low quality water, osmotic potential, primary soil salination, salt precipitation, salt transport, secondary soil salination.

Introduction – Critical Role of Soil Health and Cultural Significance

The condition of soil health is fundamental for sustainable agriculture, exerting a direct influence on crucial aspects such as crop production, nutrient circulation, and overall ecosystem stability (Gaikwad *et al.* 2023). Recognizing soil as a finite resource, non-renewable within human timescales, is essential. Soil, beyond its agricultural significance, holds cultural importance, supporting terrestrial life fundamentally (Gaikwad *et al.* 2023). Soil's limited availability and vulnerability to deterioration from natural and human-induced factors emphasize its irreplaceable value. Healthy soils are indispensable for the growth and sustainability of vegetation, forests, and crop plants globally, ensuring the survival of animals, birds, and humans (FAO, 2015). Salinization, characterized by the accumulation of salts in the soil, presents a visible challenge as a white salt crust on the soil surface, resulting from the evaporation of water containing dissolved salts, especially pronounced in dry regions.

Intensive irrigation in semi-arid and arid areas disrupts the soil's hydrologic balance, escalating salinization risks. Climate change exacerbates this issue, intensifying aridity and stressing water resources globally due to increasing agricultural demands. Irrigated lands, crucial for the world's food supply and significantly more productive than rainfed lands, face the critical challenge of irrigation-induced salinity, impacting crop yield profoundly. Beyond yield concerns, salinization jeopardizes soil quality, disrupting intricate soil ecosystem interactions vital for environmental sustainability, biological productivity, and the well-being of all biotic components. Integrating this understanding into agricultural practices is critical, emphasizing the need for mindful, sustainable approaches to preserve this invaluable resource for current and future generations. The urgency of this approach becomes even more apparent in the face of salinization, emphasizing the immediate need for holistic solutions to safeguard soil health, environmental balance, and the future of agriculture and ecosystems.

- **Impact of Salt-Affected Soils:** Salt-affected soils, characterized by elevated salt content (Goswami and Deka, 2020), pose significant challenges to agriculture. These soils hinder crop production and plant growth due to the accumulation of ions like Na^+, Cl^-, or SO_4^{2-} (Bai *et al.* 2008; WMO 2005). High salt levels reduce soil fertility, leading to problems such as ion toxicity, osmotic stress, and nutrient imbalances, thereby impeding plant growth. Human-induced salinity further exacerbates the problem, affecting 2% of global arid regions and 20% of irrigated farmlands (Sharma and Singh, 2017). This salinization jeopardizes the productivity of irrigated regions, despite their potential for higher yields compared to non-irrigated areas, becoming a significant concern in the context of global agricultural productivity. The alarming trend of human-induced salinity, impacting approximately 15% of cultivated land and expanding at a rate of 0.25 to 0.5 M ha annually on a global scale, necessitates urgent attention (Wicke *et al.* 2011).
- **Salinity Stress and Plant Growth:** Elevated soil salinity induces salinity stress, creating obstacles in plant growth and photosynthesis, especially in sensitive plant species. Various agricultural crops display a range of responses when exposed to salinity stress, as depicted in **Figure 1** (Kundu *et al.* 2022). Salinity stress encompasses osmotic stress, disrupting the water balance in plants, and specific ion effects due to the accumulation of ions like Na^+, Cl^-, or SO_4^{2-} **(Figure 1)**. The extent of salinity's impact on plants varies based on factors such as plant species, genotype, growth phase, soil ionic strength, and the duration of exposure to salinity. Additionally, the specific plant organ exposed to salt plays a pivotal role in determining the severity of damage (Robin *et al.* 2016). Understanding these complexities is vital for developing effective strategies to mitigate the detrimental effects of salinity on plant growth.

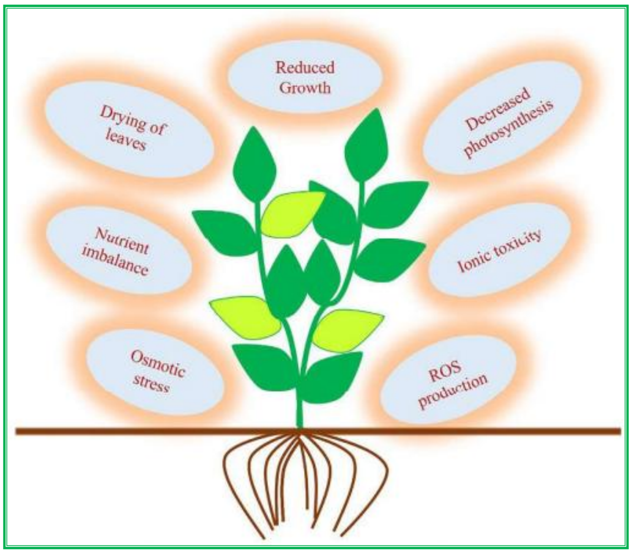

Figure 1: Plant responses to stress caused by salinity

- **Soil Salinity and Soil Salinization:** Soil salinity entails the assessment of salt concentration within the soil, typically quantified in terms of electrical conductivity (EC). Conversely, salinization refers to the accumulation of salts in the soil to a level that detrimentally affects agricultural output, environmental well-being. Furthermore, salinization also has a significant impact on the economic aspects as well as quality of life. This process is intricate, involving factors like salt precipitation, dissolution, evaporation, ion exchange, and salt transport (Kumar and Sharma, 2020). Soils affected by salinity often possess elevated amounts of either neutral soluble salts, exchangeable sodium, or both, resulting from inadequate leaching of essential base-forming cations.

This leads to a range of challenges for crop production, including reduced soil fertility and decreased water availability, which can have significant economic and social implications for affected communities.

- **Types of Soluble Mineral Salts:** The primary soluble mineral salts consist of the cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and the anions (CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO^{-3}). Moreover, hyper-saline soil water may contain elements like aluminum (Al), boron (B), barium (Ba), fluorine (F), lithium (Li), molybdenum (Mo), manganese (Mn), rubidium (Rb), selenium (Se), silica (Si) and strontium (Sr), some of which can be toxic to plants and animals (Kumar and Sharma, 2020). High concentrations of these elements can be harmful to plants and animals, leading to reduced growth and yield, posing threats to human and animal health. Regular monitoring and effective salt level management are vital for ensuring sustainable agricultural land use. This strategy safeguards soil health, agricultural productivity, and environmental safety, preventing adverse impacts on crops, animals, and human communities, thereby fostering long-term agricultural sustainability.
- **Causes of Salinity: Geological Factors and Human Impacts:** Soil salinization, a critical environmental concern, can occur through two primary processes: a) Primary soil salinization, driven by geological factors, and b) Secondary soil salinization, influenced by human activities **(Figure 2)**. Understanding these distinct pathways is essential to mitigate the detrimental impact of salinity on agricultural lands and ecosystems.

a) Primary soil salinization

Natural soil processes can lead to soil salinization which includes;

1. Geological factors in salinization:

- **Fossil salt deposits:** Found in arid regions, these deposits can dissolve and cause salinization when water structures are built over them.
- **Coastal lands salinization:** Occurs due to seawater infiltration and salt-laden sea sprays along coastlines (Rao *et al.* 2012). Sea sprays have the potential to carry salt content reaching 14.2 µg m^{-3}, affecting areas up to 80 km inland or beyond. Coastal areas are vulnerable to progressive salinization from natural events like flooding and tidal surges.
- **Salts release during geological events:** Soluble salts, released during weathering and erosion of rocks and sediments, are carried by surface or groundwater streams. Concentration increases due to factors like limited precipitation and high rates of evaporation.

2. River transport of salts:

- **Downstream salinity:** Rivers carry salts downstream, depositing them with alluvial materials. Weathering of rocks also contributes to salt deposition and subsequent salinization.

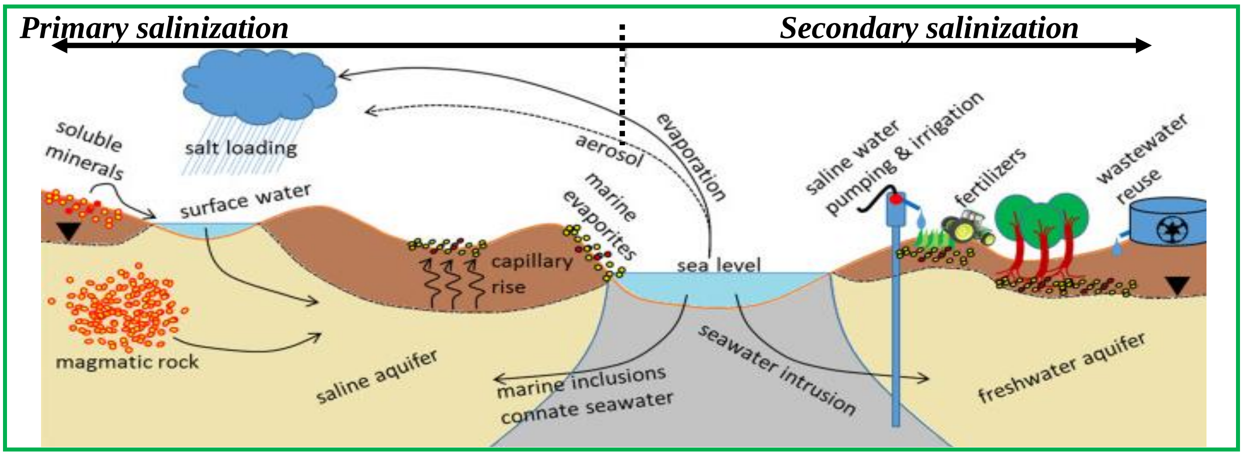

Figure 2: Salinization dynamics: Primary and secondary impacts (adapted from Nachshon and Levy, 2022)

b) Secondary soil salinization

Anthropogenic activities can also contribute to secondary salinization by releasing pollutants that increase soil salinity such as **(Figure 3)**;

- **Saline seepage due to land clearing:** Conversion of natural forests to annual crops reduces evapotranspiration and increases leaching, potentially elevating soil salt concentrations. Low-lying areas with impermeable subsoil layers are especially vulnerable.
- **Impact of irrigation practices:** Uncontrolled use of brackish water, poor drainage, and rising water tables can lead to salinization. Even quality water without proper soil-water-crop management practices can cause salinity. Irrigation with seawater can also contribute to coastal salinization (Rao *et al.*, 2012). Ancient civilizations like Mohenjo-Daro, Mesopotamia, Nile Valley, and Indus Valley fell due to salinity resulting from irrigation. Presently, about 20-33% of the 310 million hectares of globally irrigated land is affected by salinity (Shahid *et al.* 2018).
- **Groundwater extraction and salt accumulation:** Excessive groundwater extraction results in salt deposition when water evaporates, leading to surface salt accumulation.
- **Canal water seepage:** Seepage along canal banks raises the water table, causing salinization. The Indira Gandhi Nahar Priyojna (IGNP) region in India is a notable case affected by this phenomenon.
- **Impact of chemical fertilizers and amendments:** Overuse of fertilizers like gypsum, sulfur, and lime can increase soil salt concentration, disrupting nutrient balance for plant growth and reducing crop productivity. Leaching of these salts into groundwater further pollutes water bodies.
- **Effect of untreated sewage and industrial brine:** Utilizing untreated sewage effluent, sewage sludge, and industrial brine on soil can lead to salinization, posing risks of heavy metal contamination and threatening soil and plant health.

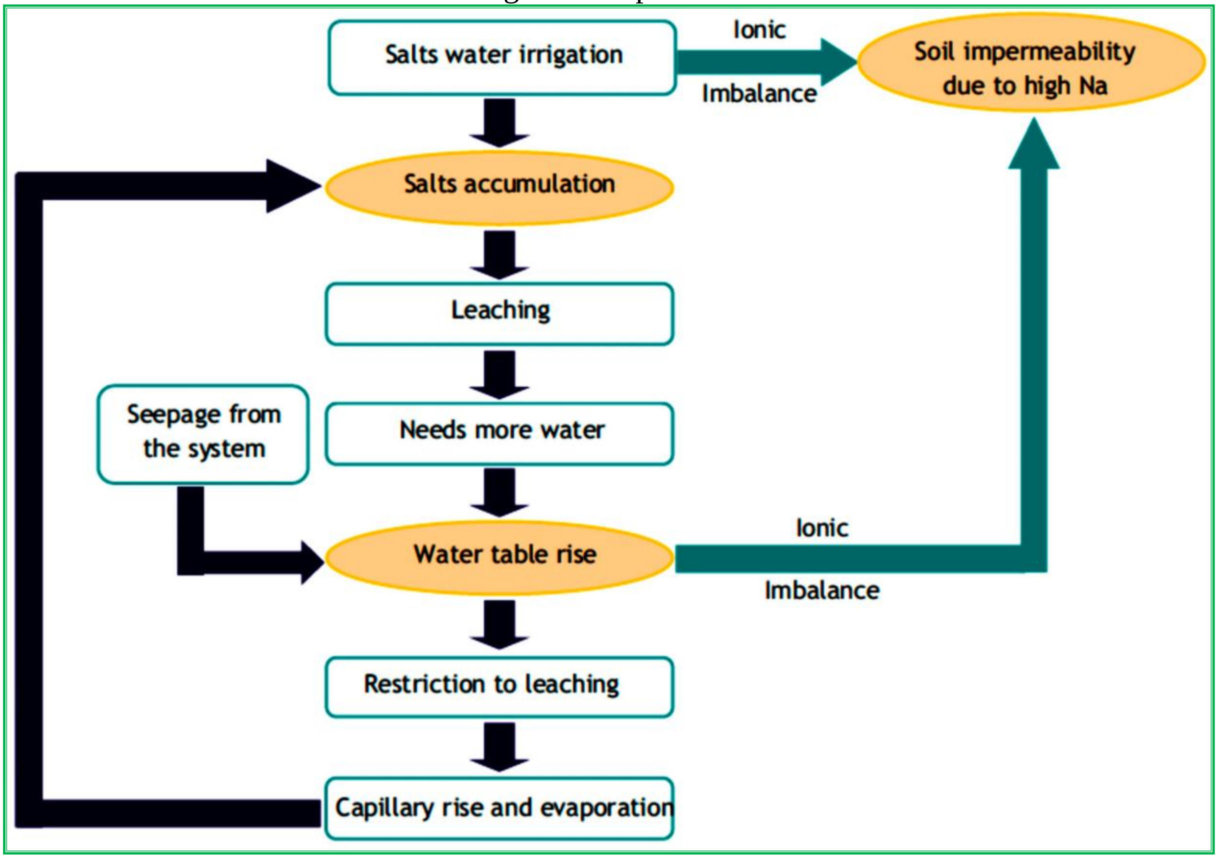

Figure 3: A secondary salinization cycle (adapted from Daba and Qureshi, 2021)

- **Future Perspectives and Implications:** The insights provided in this article emphasize the urgency of research and development efforts aimed at improving soil quality and enhancing crop productivity in salt-affected areas. These efforts are crucial not only for the sustenance of agriculture but also for addressing challenges posed by water scarcity and climate change. By comprehensively understanding the intricate relationship between soil health, salinity stress, and plant growth, scientists and agricultural practitioners can pave the way for sustainable agricultural practices, ensuring food security and environmental conservation in the face of evolving challenges.

Conclusion

Soil salinization poses a significant threat to India's food security, driven by a complex interplay of natural and human-induced factors. Primary salinization, arising from processes like weathering, geological events, saltwater intrusion, hydrological processes, and salt deposition from rainfall, stems from natural sources. In contrast, secondary salinization is human-induced, primarily due to improper irrigation practices, including the use of saline water and excessive fertilizer application, exacerbating the issue in dry regions with limited water supply. Modern agriculture compounds the problem, consuming substantial amounts of water, often solute-rich, leading to a disruption in the delicate balance between saltwater and freshwater. Socio-economic and political factors further complicate the problem, accelerating soil salinization. The consequences are dire, including reduced crop yields, disrupted ecosystems, and threats to human health. Sustainable solutions, such as prudent water management, judicious fertilizer use, and active community engagement, are essential to address this urgent issue. Amidst climate change and water scarcity, understanding and managing soil salinity are pivotal for ensuring both food security and environmental sustainability. Collaborative efforts among scientists, policymakers, farmers, and communities are crucial in preserving soil health and fostering a sustainable future, necessitating a comprehensive approach to mitigate the impacts of soil salinization on agriculture, ecosystems, and human well-being.

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