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Soil salinity; challenges, mechanisms, and sustainable solution

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Abstract

Soil salinity is a major treat affecting agricultural productivity, environmental sustainability, and food security, particularly in arid and semi-arid regions. It is the accumulation of soluble salts in the soil profile to cause detrimental effects in the growth of the plant, soil structure and microbial activity. Natural and man-made causes lead to occurrence of this phenomenon. As one would expect, soil salinity is caused by weathering of parent rock material, capillary rises of salty ground water, and salt incursion on the coastline. Man-made causes like poor irrigation, ineffective drainage, deforestation, and over application of chemical fertilizers have however led to rapid increase of the rates that have led to the development of salinization as one of the greatest causes of land degradation. Important causes of salt build up in the rooting zone are due to capillary movement of ground water, high evapotranspiration, inadequate leaching and water logging. Such alterations degrade physical and chemical characteristics of the soil, dispersion of soils, loss of permeability, imbalance in nutrients and suppression of microorganisms. Salinity in soil has very serious consequences on plant growth in terms of osmotic stress, ion toxicity and poor nutrient uptake which leads to stunted growth, reduce yield, and in extreme conditions, complete loss of crop. It impacts severely on salt-sensitive crops as well as threatening the incomes of millions of smallholder farmers. In addition, the social-economic effects of salinity comprise of loss of income, migration and augmented reclamation expenses. Mitigation requires the appropriate assessment and monitoring of soil salinity. Traditional soil and water tests (electrical conductivity, SAR, pH) are still a basis, but new tools provide an opportunity to calculate scale and accurate monitoring they may be remote sensing, GIS mapping, and geophysical instruments. The approach to management should combine technological, biological and policy elements of solution. These are enhanced irrigation methods, effective drainage, application of salt tolerant crop varieties, land use planning and soil amendments (e.g., gypsum, organic matter).

Introduction

The phenomenon of soil salinity is becoming a very serious problem on global agricultural systems and environmental sustainability. It is defined by a buildup of soluble salts e.g. sodium, calcium, magnesium, chloride and sulfate to the extent that they inhibit plant growth and degrade soil fertility and negatively affect crop production. This is predominant and particularly common in arid and semi-arid areas where the rate of evaporation is higher than the rate of precipitation resulting into salt accumulation in the root zone (Demo *et al*., 2025). Globally, more than 833 million hectares, accounting for approximately 8.7% of the Earth's land surface, are reported to be affected by salt stress (FAO, 2021). Soil salinity is not something to be ignored because the consequences vary broadly to impact agricultural activities, ecology, and the livelihood of the rural population. The salty soils lessen the supply of water to plants as a result of the osmotic pressure and conditions and the presence of toxicity that degrade plant tissues. It does not only yield poor yields of salt-sensitive crops, but also reduces soil health through the change in soil physical, chemical and biological properties (Ullas *et al*., 2025). Its long term effects are land degradation, decline in agricultural income and more susceptibility to climatic change.

Salinization of soil yields due to a combination of natural factors comprising of weathering of rocks, groundwater intrusion, capillary rise, and anthropogenic factors, including poor methods of irrigation, over-irrigation, the lack of a drainage system, deforestation, and heavy usage of chemical fertilizers (Zhang *et al*., 2025). The secondary salinization has been greatly aggravated by the growth in irrigated farming especially where there is not much control of water and soil. Over the past years, climate change has also worsened salinity problems through changing rainfall patterns, rising temperature and evapotranspiration, rising sea level in the coastal regions causing salt water encroachment into arable farms. Soil salinity is therefore a key obstacle to attainment of food security and sustainment in agriculture. Effective and appropriate management and mitigation practices are necessary to reduce soil salinity and they become attainable through an understanding of the causes, mechanisms, impacts, and the monitoring strategies which are associated with soil salinity. As our land resources become more and more strained to provide food to more and more people than the solution to salinity is not possible but rather, it is necessary. This article will give an in-depth discussion on origin and mechanisms of salinization, the impact it has on soil and crops, how it can be measured and monitored as well as how it can be managed sustainably.

Causes of Soil Salinity

The soil salinity is an accumulation of soluble salts; sodium, potassium, calcium, magnesium, chloride, sulfate, and bicarbonate proportion to the level that harm the development of plants and soil. The causes of soil salinity could be classified under nature and artificially, which are caused by humans which leads to the degradation of farm lands all over the world.

Natural Causes

Weathering of parent rocks having salt minerals is one of the main natural causes of soil salinity. These minerals are washed off over a period of time in soil moisture which adds to the content of salt. The other large natural influence lies on the capillary rise of saline groundwater, particularly in arid and semi-arid areas where the rate of evaporation is more than the rate at which rain falls (Demo *et al*., 2025). Such conditions cause water column in the water table to move to the surface by capillarity and evaporated, leaving salts in the root zone. In shores regions, invasion of seawater into freshwater water table and salt spray by sea winds may also cause accumulation of salts in the ground. Moreover, dry weather with low precipitation and high temperature, predisposes a salt build-up due to the natural leachings of salts through rainfall infiltrating are minimized.

Anthropogenic Causes

Soil salinization can be explained by the fact that human activities are becoming one of the main causes of soil salinization. One of the causes is the use of salty or low quality water to irrigate mainly in areas where there are no freshwater sources. Salt accumulation is caused by continuous inappropriate irrigation; by evaporating the water content, it leaves the salts in the land. On the same note, when freshwater is highly irrigated it can also increase the water table thereby pushing the salts nearer the surface leading to salinization caused by evaporation. Another essential factor is poor drainage systems. Without proper drainage, the salty water rises to the zone of roots causing waterlogging and secondary salinization. Slicing and cutting down trees also explains it because the loss of transpiration and danger of the rise of water table leads to salt accumulation (Ullas *et al*., 2025). Excessive use of chemical fertilizers particularly one with sodium salts might lead to development of soil salinity. Also, the natural water balance may also be disturbed due to the land leveling activities as well as the incorrect choice of crops which strengthen the salinization process on prone lands. In short, the salinity of soil is some complicated interaction of natural and anthropogenic factors. Knowledge of these causes is critical in enforcing the correct management measures and making agriculture productivity and soil health in concerned areas to be sustainable.

Processes of Salinization

The accumulation of water-soluble salts in the soil and to a degree that degrades the ability of the soil and plant productivity is referred to as salinization. Knowledge about the mechanisms is important to create effective preventive and management structures. Salinization occurs under interplay of hydrological, geological as well as climatic forces with and besides human activity.

1. Saline Groundwater Capillary Rise

The ascendency of salty ground water through capillaries can also be considered as one of the main salinization processes. Saline aquifers: Water in saline aquifers that has a high water table may rise to the surface of the soil by capillary action particularly in arid and semi-arid zones (Huang *et al*., 2025). Once this water comes to the surface level, it evaporates, and the root zone remains with salts. This is accelerated in case of poor drainage or a lack of it.

2. Climate Conditions and Evapotranspiration

Application of high evapotranspiration rates as a result of hot and dry climatic conditions also contributes substantially to salinization. When the water evaporates off the soil surface or it is transpired by plants, the salt will be left behind and stirred to develop in the top soil. The insufficient rainfalls in those places do not help to wash the salts further into the ground, which worsens the situation (Santhosh *et al*., 2025).

3. Irrigation Practices

Inappropriateness of methods of irrigation contributes to salinization a lot. Over-irrigation with slightly salty water and salty water generally, as well as excessive use of salty water, using salty water that cannot be drained into the ground, causes salt deposits to accumulate in the ground over the years (Lou *et al*., 2025). Irrigation in places where there is no natural leaching (low rainfall, or impermeable subsoil also adds to this salt build up).

4. Unsuitable Drainage and Waterlogging

Inadequate drainage systems prevent proper downward movement of water, leading to waterlogging and a rising water table. When saline groundwater approaches the surface, salt accumulation becomes a serious concern. This often results in secondary salinization, particularly in irrigated regions with waterlogged soils.

5. Weathering and Release of Salt

Naturally, the weathering process of soil minerals and rocks introduces soluble salts in the soil. These salts may end up in dangerous concentrations over time, in the absence of adequate leaching (Demo *et al*., 2025). It is mainly prevalent in ancient alluvial soils and basins of with low drainage.

Effects of soil salinity

Salinity is a major threat to agricultural productivity, ecological sustainability and social-economic development, especially in the arid and semi-arid areas. The buildup of the soluble salts in the root zone disturbs the normal interaction between soil and plants and results in negative impacts on the characteristics of soil, physiology of the plants, and farmers.

1. Effect on soil health

The salinity in soil destroys the soil structure and fertility greatly. Concentrated salt causes dispersion of soil particles decreasing the stability and porosity of the aggregates. This hinders water penetration and aeration thereby making it unfriendly to root growth and presence of microbes. High electrical conductivity (EC) and high pH are some of the characteristics of saline soils and these hamper the availability of nutrients and the balance of the nutrients needed to ensure healthy growth of crops (Dotaniya et al., 2025). The sodic condition of soils may also result in soil crusting and compaction which lowers the ability of soil to be tilled and germination capacity.

2. Effect on Plant Growth

Soil salinity affects plant growth and crop yield most directly. The heavy salt content leads to osmotic pressures, which deprives the plants of the ability to take soil water in any case of wet conditions. This leads to malformation of the plants, wilting and ineffective seed germination. Also, there is ion toxicity (due to excess sodium (Na+) and chloride (Cl)) which disrupts other vital physiological functions like photosynthesis, enzymes and protein production. Other effects of salinity are related to imbalances of nutrients as the absorption of potassium, calcium, and magnesium which are vital to plant health is prevented.

3. Influence on the Agricultural Productivity

Salinity in soil severely affects crop yields and impact is greater on a salt-sensitive crop such as rice, wheat, and pulses. Saline fields may experience losses as much as 100 percent and it varies on the severity and the type of crop. The negative impacts realized long term are: the abdication of the cultivated territory, the decrease in productivity of cultivation, the enhancement of the prices of reclamation and soil amendments.

4. Socio-Economic and Environmental Impact

In highly agricultural regions, the results are extreme on the socio-economic front. The shrinking productivity brings a lack of income in the farmers, food insecurity, and even forced immigration. Deterioration of fertile lands to salty wasteland also leads to biodiversity and ecosystem services depletion, which includes the health of flora and fauna as well as the quality of groundwater (Ds *et al*., 2025). In a nutshell, soil salinity impairs the physical, chemical and biological soundness of the soil, hinders plants growth and negatively affects agricultural yields as well as jeopardizing rural environment and food security. In alleviating its effects, there should be integrated management strategies that include soil science, crop enhancement and water management strategies.

Evaluation and Observation of Soil Salinity

Soil salinity management starts with both proper assessment and monitoring of the problem. The processes form the basis of discovering the magnitude and extent of the salinization and determining the spatial and temporal variation of salinization and how to come up with the right remedial action and best management methods (Zhang et al., 2025). Soil salinity evaluation can comprise field observation methods but also the remote sensing approaches and can be used simultaneously to augment accuracy and precision.

1. Soil Sampling and Laboratory Analytical Test

Soil sampling and laboratory testing is the most direct way of measuring soil salinity. The soil samples are taken in various depths and area particularly in the root zone (0- 90 cm) and tested based on electrical conductivity (EC), pH, sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP). The commonest one is measurement of electrical conductivity of a soil-water extract (typically a 1:2 or saturation paste extract) the electrical conductivity is higher than 4 dS/m denoting salty soils (Lalitha *et al*., 2022). SAR and ESP give a view of sodium risks and sodicity, which is fundamental in finding out the type of salinity issues.

2. Groundwater Analysis

Monitoring of groundwater is critical since salinization is commonly associated with the movement of water. Irrigation water is tested on salinity (EC), total dissolved solids (TDS) and ion concentration. It also involves measuring of the depth and change in prevention of the level of the water table so as to identify the threat of grass-root swell and secondary salinity (Valiallahi *et al*., 2025).

3. The GIS and Remote-Sensing Methods

The modern software such as remote sensing (RS), or geographic information systems (GIS) offer an efficient and massive monitoring strategy. Vegetation stress, soil brightness and moisture anomalies related to salinity can be determined through satellite imagery (e.g, Landsat, Sentinel-2, MODIS). Salinity-afflicted area mapping can be effected using indices such as Soil-adjusted vegetation index (SAVI) and the Normalized Difference Vegetation index (NDVI). With GIS, it is possible to combine soil, climate, and topographic data to produce salinity risk maps and monitor the changes that are incurred over time (El Bahjaouy *et al*., 2025).

4. Geophysical Methods

There is a steadily growing utilization of non-invasive methods of assessing salinity through electromagnetic induction (EMI), and ground-penetrating radar (GPR) (Acharya et al., 2025). The techniques enable high speed to identify salinity levels in the soil profile without the need of sampling over a large area at great depths or in vast sized fields in agriculture.

Conclusion

Soil salinity is a growing problem that seriously affects farming, the environment, and people lives especially in dry and semi-dry regions. When salts accumulate in the soil, they make it hard for plants to grow, reduce soil quality and harm useful microbes. This issue is caused by both natural processes, like the weathering of rocks and rising salty groundwater, and human activities such as poor irrigation, overuse of fertilizers, and cutting down trees. Salinity damages the soil, lowers crop yields and creates serious problems for farmers, including loss of income and food shortages. Over time, it can even lead to people moving away from farming areas and leaving the land. Climate change is making the problem worse through increase in temperatures, less rainfall, and rising sea levels. To deal with this, we need to carefully measure and monitor salinity using both traditional tests and modern tools like satellite images and mapping systems. Managing salinity also means using better irrigation, proper drainage, growing salt-tolerant crops, adding materials like gypsum or organic matter to improve soil and using nature-based solutions like planting trees or cover crops. Overcoming the problem of soil salinity is necessary for protecting our food supply, saving our environment and supporting farmers.

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