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Soil Salinity in Irrigated Punjab, Pakistan: Drivers, Impacts on Agricultural Productivity, and Integrated Management Strategies

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ABSTRACT

Soil salinity and sodicity are major land-degradation challenges affecting the sustainability of irrigated agriculture in Punjab, Pakistan. The region's semi-arid climate, high evaporative demand, dependence on irrigation, variable groundwater quality, inadequate drainage, and long-term salt accumulation create conditions that can impair soil productivity and crop performance. Salinity reduces plant water uptake through osmotic stress and may cause ion toxicity and nutrient imbalances, whereas sodicity deteriorates soil structure, infiltration, and hydraulic conductivity through excessive exchangeable sodium. These problems frequently coexist, complicating the management of salt-affected soils. This review synthesizes research on the major causes, agricultural consequences, and amelioration strategies relevant to Punjab's irrigated farming systems. Particular attention is given to canal–groundwater conjunctive use, irrigation-water quality assessment, drainage and leaching, gypsum application, organic amendments, salt-tolerant crops, improved fertilizer management, and emerging biological approaches. Research conducted in Punjab demonstrates that combining chemical amendments with organic materials and appropriate water management can improve soil conditions and support rice–wheat production on salt-affected land. Nevertheless, the success of reclamation depends on soil texture, salinity and sodicity severity, groundwater depth, water quality, drainage capacity, and farmers' access to inputs and technical advice. The review advocates a site-specific, integrated management framework supported by regular soil and irrigation-water testing, targeted reclamation, salt-tolerant cropping systems, and long-term monitoring. Coordinated action among researchers, extension services, irrigation agencies, and farmers is essential to reduce salt accumulation, restore degraded land, and strengthen agricultural sustainability and food security in Punjab.

Introduction

Irrigated agriculture is fundamental to food production and rural livelihoods in Punjab, Pakistan. However, crop production in this semi-arid region depends on the reliable supply of irrigation water and the maintenance of soil physical, chemical, and

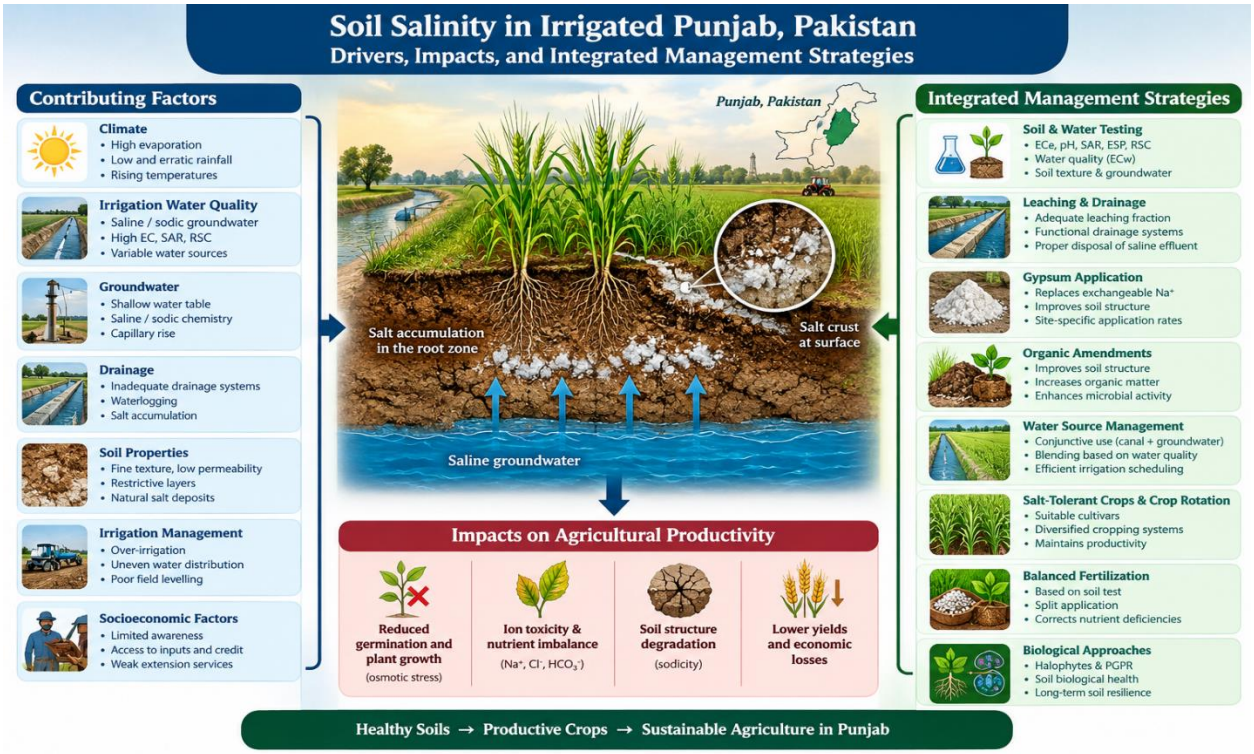
biological properties. Under conditions of high evaporative demand, limited rainfall, and inadequate natural drainage, dissolved salts introduced through irrigation or mobilized from groundwater and soil parent materials may accumulate within the crop root zone. Over time, this accumulation can reduce crop establishment, restrict nutrient acquisition, decrease yields, and accelerate land degradation.

Soil salinity is particularly important in irrigated environments because irrigation water inevitably contains dissolved salts. When water is removed through crop transpiration and evaporation, most salts remain in the soil unless sufficient water moves below the root zone and carries them away. Consequently, the long-term salt balance depends on irrigation-water quality, irrigation depth and frequency, rainfall, drainage, groundwater conditions, and crop water use (Ayers & Westcot, 1985; FAO, 1985). In Punjab, the historical expansion of tubewell irrigation has enabled farmers to supplement unreliable canal supplies, but the use of groundwater with unsuitable chemical characteristics can intensify salinity and sodicity risks (Kijne & Kuper, 1995; Smets et al., 1997).

An essential distinction must be made between salinity and sodicity. Salinity refers to excessive soluble salts in the soil solution, whereas sodicity refers to excessive sodium associated with soil exchange sites relative to calcium and magnesium. Saline soils primarily impose osmotic stress and, depending on the ions present, specific-ion toxicity. Sodic soils can exhibit clay dispersion, surface crusting, poor infiltration, restricted aeration, and reduced root penetration. Saline-sodic soils display characteristics of both processes and may require coordinated chemical and hydraulic management.

Research from Pakistan has documented the benefits of gypsum, organic amendments, improved drainage, and suitable crop rotations for reclaiming saline-sodic soils. Field experiments in Punjab have also demonstrated that reclamation can improve crop yields and nitrogen-use efficiency, although outcomes depend on the initial soil condition and the management strategy employed (Zia et al., 2006; Zaka et al., 2018).

Despite substantial research, the challenge remains to translate reclamation technologies into affordable, field-specific practices that farmers can sustain. The purpose of this review is therefore to synthesize the principal factors contributing to soil salinity and sodicity in irrigated Punjab, explain their effects on soil health and crop productivity, evaluate available amelioration approaches, and identify priorities for sustainable management.



Review methodology and scope

This narrative review draws on peer-reviewed research, established soil and irrigation-management publications, research conducted in Punjab, Pakistan, and technical information from the Food and Agriculture Organization of the United Nations and the Punjab Agriculture Department. The literature was selected to cover salinity development, irrigation-water quality, soil reclamation, crop responses, organic amendments, drainage, and socioeconomic constraints to technology adoption.

Priority was given to research with direct relevance to the Indus Basin and Punjab's irrigated cropping systems, supplemented by internationally established principles of salt-affected soil management. The review is qualitative rather than a systematic review or meta-analysis; no new field observations, experimental measurements, or pooled effect estimates were generated. Published findings are interpreted in relation to their original study conditions, and numerical results from individual experiments should not be generalized to all soils in Punjab.

Major factors contributing to soil salinity in Punjab

Semi-arid climate and evaporative concentration

Punjab's semi-arid climate promotes salt accumulation when evaporation and plant water use exceed the downward movement of water through the soil profile. Rainfall is seasonal and unevenly distributed, and it may be insufficient to remove salts accumulated during preceding irrigation cycles. During dry periods, capillary movement from shallow groundwater can transport dissolved salts upward. Evaporation then removes water from the surface, leaving salts behind.

The risk is greatest where shallow groundwater, fine-textured soils, poor drainage, and repeated irrigation occur together. However, climate alone does not explain the distribution of salt-affected land; salinity develops through interactions among climate, soil properties, irrigation practices, groundwater chemistry, and drainage conditions (FAO, 1985; Ayers & Westcot, 1985).

Irrigation with saline or sodic groundwater

Groundwater is an important supplementary irrigation resource in Punjab. Its quality varies considerably across locations, depending on geology, aquifer conditions, recharge, and the concentration of dissolved salts. Groundwater may contain elevated concentrations of sodium, chloride, bicarbonate, and carbonate, making it unsuitable for unrestricted irrigation in some circumstances.

Repeated use of saline water introduces salts into the root zone. The risk increases when crop water uptake removes water without an equivalent downward flux to transport salts out of the rooting depth. Water with a high sodium adsorption ratio (SAR) or residual sodium carbonate (RSC) may also reduce infiltration by promoting clay dispersion, particularly when its electrolyte concentration is low.

The Punjab Agriculture Department identifies the use of brackish tubewell water and inadequate water management as important salinity-related concerns. Its Soil Salinity Research Institute recommends combining reclamation measures with the managed utilization of marginal-quality irrigation water and salt-tolerant crops.

Consequently, irrigation-water quality should be evaluated using electrical conductivity (ECw), SAR, RSC, and relevant ion concentrations rather than judged solely by appearance or total dissolved solids.

Inadequate drainage and shallow groundwater

Drainage is fundamental to controlling salinity because it provides an outlet for water carrying dissolved salts away from the root zone. Where drainage is inadequate, excess irrigation or seepage can raise the groundwater table, allowing salts to move upward through capillary flow. The resulting combination of waterlogging and salinity reduces root-zone aeration and creates unfavorable conditions for crop growth.

Historical salinity and waterlogging problems in Pakistan have been associated with inadequate drainage, unlined water channels, irrigation practices, and shortcomings in the maintenance of reclamation infrastructure (Chaudhry, 2001).

Installing drainage without providing a suitable outlet for saline effluent is not a complete solution. Salt-laden drainage water must be collected, managed, reused only where agronomically and environmentally appropriate, or disposed of under a plan that protects downstream soils and water resources.

Inefficient irrigation and uneven water distribution

Poor field levelling, excessive irrigation, inadequate control of water application, and non-uniform distribution can generate contrasting salinity conditions within the same field. Over-irrigated areas may experience shallow groundwater and waterlogging, while under-irrigated areas may lack the water required for effective salt leaching.

Canal water shortages can further increase reliance on tubewell water, including supplies of marginal quality. The effect of this practice depends on the chemistry of both water sources, the proportion in which they are mixed, soil hydraulic properties, and

the availability of drainage. Research in Punjab has shown that irrigation quantity, quality, and frequency influence root-zone salinity and crop water use (Smets et al., 1997).

Soil properties and natural salt accumulation

Soil texture, mineralogy, profile stratification, and hydraulic conductivity influence the movement and accumulation of salts. Fine-textured soils may retain more water and exhibit slow infiltration, particularly where sodicity causes clay dispersion. Conversely, coarse-textured soils often permit faster leaching but may require more frequent irrigation because of lower water-holding capacity.

Restrictive subsurface layers can impede downward water movement even where surface infiltration appears satisfactory. Natural salts may also be present in soil parent materials or groundwater and can become concentrated through irrigation and evaporation. Therefore, salinity management requires profile-level assessment rather than relying exclusively on surface observations.

Inadequate monitoring and socioeconomic constraints

Soil salinity is often recognized only after poor crop establishment, patchy growth, surface salt crusts, or declining yields become visible. These symptoms may occur after substantial productivity losses have already developed. Without laboratory testing, farmers may apply gypsum unnecessarily, use inappropriate quantities of irrigation water, or select crops that are poorly suited to the soil's salinity level.

A study of gypsum adoption in Punjab found that technology exposure and access to credit influenced adoption, while distance from input markets and soil-testing laboratories reduced the speed of adoption (Sheikh et al., 2022). This demonstrates that reclamation is not solely a technical problem: it also depends on access to information, suitable inputs, financial resources, and dependable advisory services.

Effects of soil salinity and sodicity on agricultural productivity

Osmotic stress and restricted water uptake

Elevated salt concentrations lower the osmotic potential of soil water, making it more difficult for plant roots to absorb water. Plants growing in saline soils may therefore experience physiological drought even when the soil appears moist. Early symptoms include delayed germination, reduced seedling establishment, slower leaf expansion, and reduced biomass accumulation.

As salinity increases, plants must expend additional energy to maintain cellular water balance and ion homeostasis. The resulting reduction in photosynthesis and growth can reduce grain formation and harvestable yield. The magnitude of the effect depends on crop species, cultivar, growth stage, salt composition, and environmental conditions (Munns & Tester, 2008).

Ion toxicity and nutrient imbalance

Excessive sodium and chloride can accumulate in plant tissues and disrupt cellular processes. Salinity may also interfere with potassium and calcium acquisition, while high concentrations of bicarbonate and carbonate in irrigation water can affect nutrient availability and soil chemistry.

Nutrient deficiencies may consequently develop even when the total nutrient concentration in the soil is adequate. However, responses vary with the dominant salts, soil pH, root-zone conditions, and fertilizer management. Fertilizer applications alone cannot correct the underlying salt imbalance and may aggravate salinity if excessive quantities of soluble salts are added without adequate water management.

Soil structural degradation under sodicity

Sodicity can impair the physical properties of clay-rich soils. Excessive exchangeable sodium promotes clay swelling and dispersion under susceptible conditions, reducing aggregate stability, infiltration, and hydraulic conductivity. Surface sealing and crusting can hinder seedling emergence, while poor aeration restricts root development.

These effects create a reinforcing cycle: reduced infiltration limits leaching, retained salts further stress plants, and poor crop growth reduces the economic resources available for reclamation. Field experiments in Punjab have demonstrated that physical interventions, gypsum, and organic amendments can help restore degraded saline-sodic soils when applied under appropriate conditions (Zia et al., 2006; Zaka et al., 2003).

Implications for soil fertility and nutrient-use efficiency

Salt-affected soils can exhibit poor nutrient-use efficiency because restricted root growth, osmotic stress, and ionic competition reduce nutrient uptake. Sodicity may also impair soil structure and the biological processes responsible for nutrient cycling. These effects can complicate nitrogen and phosphorus management in wheat–rice and other intensive cropping systems.

Research on saline-sodic soils in Pakistan found that gypsum amelioration improved crop yield and nitrogen-use efficiency in a rice–wheat rotation, although the yields and efficiency achieved in treated soils remained below those of normal soil (published field experiment, 2017).

This finding highlights an important management principle: soil reclamation and balanced fertilizer management should be implemented together, rather than treating fertilizer deficiency as the sole cause of poor crop performance.

Strategies for amelioration and sustainable management

Soil testing and irrigation-water assessment

The first step in reclamation should be diagnosis. Soil and water testing helps distinguish saline, sodic, and saline-sodic conditions and determines whether leaching, chemical amendments, drainage improvement, or a combination of measures is required.

Table 1. Recommended diagnostic parameters

Parameter	Significance for management
Soil electrical conductivity of saturation extract (ECe)	Assesses root-zone salinity
Soil pH	Helps identify alkaline conditions and possible sodicity-related problems
Exchangeable sodium percentage (ESP)	Quantifies sodium occupying soil exchange sites
Soil or water sodium adsorption ratio (SAR)	Assesses sodium-related risks to soil structure
Residual sodium carbonate (RSC)	Evaluates carbonate and bicarbonate hazards in irrigation water
Water EC (ECw)	Indicates total dissolved ionic salinity
Soil texture and hydraulic conductivity	Determine infiltration and leaching potential
Groundwater depth and chemistry	Help assess waterlogging and upward salt movement

Soil ECe should be interpreted alongside SAR or ESP, pH, soil texture, and the distribution of salts with depth. A high pH alone does not reliably diagnose sodicity, and ECe thresholds should be interpreted in relation to crop tolerance and the measurement method (Ayers & Westcot, 1985; Richards, 1954).

Leaching and drainage management

Leaching removes soluble salts by moving water through the soil profile and below the effective root zone. Its success depends on sufficient water infiltration, adequate downward movement, and a functioning drainage pathway. Leaching without drainage may raise the water table and redistribute salts rather than remove them from the field.

FAO guidance identifies leaching as a principal method for reclaiming saline soils, provided the displaced salts can be transported away from the root zone.

The following measures are recommended:

- Level fields to improve uniform water distribution and avoid local accumulation.
- Apply irrigation according to soil moisture, crop demand, and water quality.
- Provide a suitable leaching fraction where water supplies and drainage permit.
- Maintain surface drains or subsurface drainage systems where required.
- Monitor groundwater depth and salinity to detect secondary salinization.
- Avoid uncontrolled disposal of saline drainage effluent into freshwater channels or neighboring agricultural land.

Leaching requirements should be calculated for the specific soil, irrigation water, crop, and drainage conditions. Applying additional water without considering its quality and the capacity of the drainage system can worsen the problem.

Gypsum application for sodic and saline-sodic soils

Gypsum ($CaSO_4 \cdot 2H_2O$) is a widely used amendment for sodic soils. It supplies soluble calcium, which can replace exchangeable sodium on soil colloids. The displaced sodium must subsequently be leached from the root zone.

Gypsum is not universally required for all saline soils. Where soluble salts are excessive but soil sodicity and infiltration are not problematic, leaching with suitable water may be sufficient. In saline-sodic soils, gypsum requirements depend on exchangeable sodium, soil texture, soil depth, amendment purity, and the chemical composition of the irrigation water (Abrol et al., 1988; FAO, 1985).

The appropriate application rate should be determined using a laboratory-measured gypsum requirement (GR), adjusted for amendment purity and the depth of soil to be reclaimed. Applying a blanket rate without testing can increase costs while failing to correct the underlying problem.

Evidence from Punjab supports the practical value of gypsum. Zia et al. (2006) evaluated physical and chemical reclamation practices at two saline-sodic sites, while subsequent rice–wheat research demonstrated improvements in soil properties, yield, and nitrogen-use efficiency following gypsum application.

Economic considerations are equally important. A Punjab study of farm households reported that gypsum adoption was associated with improved yields and identified access to credit, extension, and input markets as important factors in adoption (Sheikh et al., 2022).

Organic amendments and integrated reclamation

Farmyard manure, compost, crop residues, green manure, and selected industrial organic by-products can complement chemical reclamation. Their benefits may include improved aggregate stability, greater soil organic matter, enhanced biological activity, and improved infiltration. These effects depend on amendment quality, decomposition, soil conditions, and the quantity and composition of salts introduced with the amendment.

Organic materials should not automatically be considered substitutes for gypsum in strongly sodic soils. Where exchangeable sodium is high, an adequate calcium source and a mechanism for removing displaced sodium may still be necessary.

A field study in Punjab investigated gypsum and compost combinations in a rice–wheat cropping system, demonstrating the relevance of integrated approaches for reclaiming salt-affected land (Zaka et al., 2018). Other Punjab research has evaluated organic materials alongside reduced gypsum application and documented the potential for combining chemical and agronomic interventions (Zaka et al., 2003).

A practical integrated approach may include:

1. Testing soil salinity, sodicity, and gypsum requirement.
2. Applying gypsum or another suitable calcium amendment where indicated.
3. Incorporating mature compost or farmyard manure according to soil condition and availability.
4. Improving infiltration through appropriate tillage where compaction or surface sealing is limiting water movement.
5. Leaching displaced salts where adequate drainage exists.
6. Monitoring changes in ECe, pH, SAR or ESP, organic matter, and crop yield.

The economic value of this approach should be assessed using input costs, crop response, residual benefits, and the expected duration of reclamation.

Conjunctive use of canal and groundwater

Conjunctive use involves managing canal water and groundwater together to meet crop-water requirements while limiting salt accumulation. Where groundwater is marginal in quality, blending it with canal water or alternating irrigation sources may reduce the salt and sodium load compared with continuous use of the poorer-quality source.

The suitability of blending depends on the EC, SAR, RSC, and ionic composition of both sources. Blending should therefore be supported by water analysis and crop-specific recommendations rather than fixed mixing ratios.

Field experiments in the Indus Basin evaluated saline-sodic water, freshwater, gypsum, and farmyard manure in rice–wheat systems. The findings support combining water-source management with appropriate soil amendments and crop selection rather than relying on poor-quality groundwater alone (Murtaza et al., 2009).

Salt-tolerant crops and adapted cropping systems

Where complete reclamation is uneconomic or water resources are limited, adaptation may be more practical than attempting immediate removal of all salts. Crop selection should account for both salinity tolerance and the local market, climate, irrigation supply, and rotation.

Wheat and rice remain important crops in Punjab, but their performance on salt-affected soils depends on cultivar, growth stage, soil salinity, and management. Salt-tolerant cultivars, suitable forage crops, and selected alternative crops can help maintain productive use of affected land.

The Punjab Agriculture Department's Soil Salinity Research Institute identifies salt-tolerant crop development, improved crop-production technology, and the economic utilization of salt-affected land as important research priorities. Its published achievements include screening and evaluation of crops and management practices for affected soils.

Crop tolerance does not eliminate the need for salt management. Salt-tolerant plants may sustain production under conditions that severely limit sensitive crops, but salts can continue accumulating if irrigation inputs exceed salt removal. Crop adaptation should therefore complement, not replace, sound water and drainage management.

Balanced fertilization and soil organic matter management

Salt-affected soils require nutrient management that accounts for restricted root growth, altered nutrient availability, and the salt contribution of fertilizers. Fertilizer recommendations should be based on soil tests and realistic yield targets, with appropriate timing and placement to improve crop uptake.

Useful practices include:

- Applying nitrogen in split doses matched to crop demand.
- Avoiding excessive fertilizer concentrations near germinating seeds and young roots.
- Correcting confirmed deficiencies of phosphorus, potassium, zinc, and other nutrients.
- Incorporating suitable organic materials to support soil structure and biological activity.
- Evaluating fertilizer response after accounting for salinity and sodicity constraints.

Gypsum and balanced fertilizer management can act synergistically where sodicity limits root development and nutrient uptake. However, additional fertilizer cannot compensate for severe waterlogging, poor infiltration, or high root-zone salinity.

Biological approaches and emerging technologies

Biological approaches include salt-tolerant plant species, halophytes, microbial inoculants, and selected phytoremediation strategies. Plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungi may improve nutrient acquisition, osmotic adjustment, antioxidant responses, and plant tolerance to salinity. Their effectiveness, however, varies with crop genotype, microbial strain, soil conditions, and management (Etesami & Beattie, 2018; Mitigating the impact of soil salinity, 2023).

Phytoremediation and halophyte-based systems may provide options for selected degraded lands, especially where conventional cropping is uneconomic. Nevertheless, biological approaches alone are unlikely to reclaim strongly saline-sodic agricultural soils rapidly because they do not necessarily provide the calcium needed to replace exchangeable sodium or the drainage required to export accumulated salts.

Emerging approaches should therefore be evaluated through replicated field trials that measure soil ECe, SAR or ESP, crop yield, water use, nutrient-use efficiency, and economic returns. Recent reviews emphasize the complementary roles of prevention, reclamation, adaptation, soil organic matter management, and biological interventions.

Research gaps and future priorities

Although Punjab has a substantial history of salinity research, several gaps limit the development of effective, scalable management strategies.

First, updated spatial assessments are needed. Soil salinity and sodicity should be mapped at field and district scales using standardized soil sampling, laboratory measurements, groundwater observations, and remote-sensing indicators. Satellite-derived salinity indices require ground validation because bare soil, moisture, texture, and vegetation cover can produce similar spectral responses.

Second, soil and irrigation-water quality should be evaluated together. Many assessments focus on soil salinity without adequately quantifying the contribution of irrigation sources and shallow groundwater. Integrated monitoring should include ECe, pH, SAR or ESP, ECw, RSC, water-table depth, and drainage conditions.

Third, long-term field trials are required. Reclamation research should compare gypsum alone with gypsum–organic amendment combinations, improved drainage, adapted cropping systems, and suitable irrigation-water management. Trials should extend across contrasting soil textures and degrees of salinity to identify where each intervention is most effective.

Fourth, economic feasibility requires greater attention. The cost of gypsum, transport, labor, irrigation, and drainage can discourage adoption, particularly among farmers with limited capital. Research should quantify benefit–cost ratios, yield stability, time required for reclamation, and the residual benefits of amendments.

Fifth, nutrient management under salinity needs further investigation. Research should assess nitrogen-use efficiency, phosphorus availability, potassium and micronutrient uptake, soil organic carbon, and biological indicators during reclamation. These measurements would clarify whether improvements in crop performance arise from salt removal, structural recovery, better nutrient acquisition, or their combined effects.

Finally, extension services should deliver field-specific recommendations through soil-testing laboratories, farmer demonstrations, and accessible advisory systems. Such services should prioritize early detection and prevention rather than relying exclusively on reclamation after severe productivity losses have occurred.

Conclusion

Soil salinity and sodicity are interconnected constraints to the sustainability of irrigated agriculture in Punjab, Pakistan. Their development is driven by interactions among semi-arid climatic conditions, irrigation-water quality, groundwater depth and chemistry, inadequate drainage, soil properties, and agricultural management practices. Salinity reduces the ability of crops to extract water and can cause ion toxicity and nutrient imbalance, whereas sodicity can degrade soil structure and restrict infiltration, aeration, and root growth.

No single intervention can address every salt-affected soil. Soluble salts can often be removed through leaching where sufficient suitable water and drainage are available. Sodic and saline-sodic soils may require gypsum or another appropriate calcium amendment, followed by effective leaching. Organic amendments, improved irrigation management, balanced fertilization, salt-tolerant crops, and selected biological approaches can complement these measures.

The most effective long-term strategy is a diagnosis-based, integrated approach combining soil and water testing, appropriate reclamation, functioning drainage, adapted cropping systems, and continuing monitoring. Wider adoption will depend on affordable inputs, reliable extension services, accessible soil-testing facilities, and coordination among farmers, researchers, and government agencies. Implementing these measures can help preserve soil productivity, improve water and nutrient-use efficiency, and strengthen the resilience of Punjab's irrigated agricultural systems.

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