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SCIENCE AND SOCIETY INSIGHTS
Sci Soc Insights (2025), 1(1): 41-50
Research Article

Integrated Management of Salt Affected Soils in Pakistan: Organic, Inorganic, and Combined Approaches for Sustainable Agriculture

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Article History: 25-290	Received: 07-Feb-2025	Revised: 11-Mar-2025	Accepted: 15-Mar-2025	Published Online: 2025

Citation: Ain NU, 2025. Integrated management of salt-affected soils in Pakistan: organic, inorganic, and combined approaches for sustainable agriculture. SciSoc Insights 1(1): 41-50.

ABSTRACT

Soil salinity is a critical threat to agricultural productivity worldwide, with particularly severe impacts in arid and semi-arid regions such as Pakistan. Excessive accumulation of soluble salts and exchangeable sodium degrades soil structure, restricts water and nutrient availability, and reduces crop yields. In Pakistan, especially in Punjab and Sindh, millions of hectares of farmland are affected, threatening rural livelihoods and food security. This review synthesizes recent advances in the management of salt-affected soils, focusing on organic approaches (compost, biochar, manure), inorganic amendments (gypsum, sulfur), and integrated strategies that combine both for long-term sustainability. The paper evaluates the effectiveness of these methods in improving soil health, enhancing microbial activity, and restoring productivity, while highlighting successful regional case studies. It also addresses economic feasibility, environmental co-benefits, and institutional challenges to adoption. Finally, it identifies key research gaps and policy priorities to guide researchers, policymakers, and farmers toward scalable, sustainable solutions for reclaiming salt-affected soils in Pakistan.

Keywords: Soil salinity, Agricultural productivity, Pakistan (Punjab, Sindh), Organic and inorganic amendments, Biochar, Soil health, Crop yield, and Sustainable agriculture.

INTRODUCTION

Soil salinity is like a slow-moving disease for farm land creeping in quietly, year after year, until once-productive fields can no longer grow enough to feed the people who depend on them. It's a problem faced across the globe, but it hits hardest in dry and semi-dry regions where water is scarce and evaporation is high. When salts such as sodium, chloride, and sulfates build up in the soil, they change its very nature: the structure collapses, water can't soak in properly, nutrients get locked away from roots, and plants struggle to survive (Monika et al., 2022). The scale of the issue is staggering over 900 million hectares of land worldwide are already salt-affected, and that number is rising fast thanks to unsustainable irrigation, poor drainage, and climate change (Schubert & Qadir, 2024; Sharma et al., 2023).

In South Asia, the challenge is especially urgent. Large-scale irrigation systems, while essential for farming, often make the problem worse when canals leak, drainage is inadequate, or farmers are forced to use poor-quality groundwater. Pakistan offers a striking case. With much of its agriculture relying on the massive Indus Basin Irrigation System, the country now has around 6.67 million hectares of cultivable land suffering from salinity or sodicity (Zia, Khan, & Baig, 1986). Punjab and Sindh are at the epicenter. Here, shallow water tables, canal seepage, and decades of brackish groundwater use have created vast stretches of salt-stressed soil. The result? Falling yields of wheat, rice, cotton, and sugarcane, leading to lost incomes for farming families and growing pressure on the nation's food supply (Rahman Khan et al., 2024).

The roots of the problem are both natural and man-made. Naturally, the region's hot, dry climate and mineral-rich soils make it prone to salinity. But human activities such as over-irrigating fields, failing to line canals, and neglecting drain age push it over the edge. Climate change is turning up the heat, quite literally, by raising temperatures, shifting rainfall patterns, and speeding up evaporation, all of which leave even more salt behind in the soil (Nadeem et al., 2024). In coastal Sindh, seawater intrusion adds another layer of trouble, polluting freshwater aquifers and creating waterlogged, saline soils that are especially hard to restore.

Fig 1: integrated management of salt-Affected soils in Pakistan.

Over the years, farmers and researchers have tested many solutions. Quick-acting chemical amendments like gypsum can replace harmful sodium with calcium, restoring soil structure in a matter of months. Organic approaches such as compost, biochar, and farmyard manure take longer but work more deeply, improving soil health, feeding beneficial microbes, and helping the ground hold water better. Increasingly, experts are turning to integrated strategies that combine these tools with better irrigation scheduling, salt-tolerant crop varieties, and improved drainage systems for results that last (Hayat et al., 2020).

But in Pakistan, solving the salinity crisis isn't just about fixing the soilit's about protecting livelihoods, ensuring food security, and building resilience against a changing climate. Quick fixes alone won't be enough. What's needed are approaches that deliver immediate relief while also safeguarding productivity for future generations, and that are affordable and practical for farmers to adopt. This review looks at the extent of salinity in Pakistan, unpacks its causes, and evaluates organic, inorganic, and combined management strategies. It also highlights the gaps in knowledge and policy that must be addressed if we are to turn degraded, salt-ridden fields back into thriving, fertile farmland.

Objectives

The objectives of this review are to:

(i) Analyze the current extent, drivers, and impacts of soil salinity in Pakistan

(ii) Evaluate the effectiveness of organic, inorganic, and integrated management practices in reclaiming salt-affected soils

(iii) Identify research gaps and policy priorities for sustainable salinity management in the country.

Salinity in Pakistan: Extent, Drivers and Typologies

Pakistan's agricultural landscape is highly vulnerable to salinity due to its geographic and climatic context, as well as the structural limitations of its irrigation infrastructure. Estimates suggest that around 6.67 million hectares of cultivable land are affected by salinity and sodicity, representing nearly one-third of the country's irrigated area (Farooqi, Sabir, Ahmad, Shahbaz, & Smith, 2023). The distribution of salt-affected soils varies across provinces, with Punjab and Sindh experiencing the most severe cases, followed by parts of Khyber Pakhtunkhwa and Balochistan. These soils are typically classified into saline (high electrical conductivity but low exchangeable sodium), sodic (high sodium adsorption ratio and poor structure), and saline sodic types, each requiring distinct reclamation strategies. The primary drivers of salinity include seepage from unlined canals, over-irrigation with low-quality groundwater, inefficient drainage systems, and excessive evaporation rates that concentrate salts in the root zone (Falkenmark, 2013). Climate change exacerbates the problem through altered rainfall patterns, higher temperatures, and increased evapo transpiration, further accelerating secondary salinization processes (Janjua, Hassan, Muhammad, Ahmed, & Ahmed, 2021; Nadeem et al., 2024). In Sindh's coastal belt, seawater intrusion adds another layer of complexity, contaminating freshwater aquifers and degrading productive lands(S. Ahmed, 2024). Field assessments often use indicators such as electrical conductivity of the soil saturation extract (ECe), pH, and sodium adsorption ratio (SAR) to diagnose salinity levels, while satellite-based remote sensing provides broader spatial monitoring across the Indus Basin. Without targeted interventions, the continued expansion of salinity will severely undermine food security and rural livelihoods, making it imperative to adoptsite-specific and integrated management solutions.

Assessment and Monitoring

Understanding how salt accumulates and spreads in soil is the key to fixing it effectively. On the ground, farmers start with simple signs spindly plants, patchy growth, white crusts on the soil. Then they pull out portable EC meters to gauge salinity quickly, though for precision, lab analysis of soil saturation extract (ECe), pH, and sodium adsorption ratio (SAR) is still the gold standard (Ayers & Westcot, 1985). But technology has leaped lately machine-learning models paired with remote sensing now let us map salinity over whole landscapes. A recent review highlights how sites like Kot Addu are being studied using Landsat-derived salinity indices and powerful algorithms such as Random Forest, achieving strong prediction accuracy (Haq, Shahbaz, Asif, Al-Laith, & Alsabban, 2023). GIS combined with spectral indices from Sentinel-2 imagery offers even finer spatiotemporal detail, enabling detection of subtle salinity shifts over (NAWAZ et al.). Electromagnetic Induction (EM38) instruments provide rapid, non-destructive field estimates of ECe across soil depths, offering four-dimensional salinity snapshots in areas under reclamation trials (Mohsin Waqas et al., 2021). On a national level, tools like the Land Information and Management System (LIMS) now compile real-time soil condition, irrigation water quality, and salinity trends for farmer advisories making assessment both timely and actionable (Ahsan et al., 2024). Altogether, merging traditional observations, lab data, and real-time remote sensing creates an effective, layered surveillance system crucial for early warning, planning reclamation efforts, and steering sustainable land management.

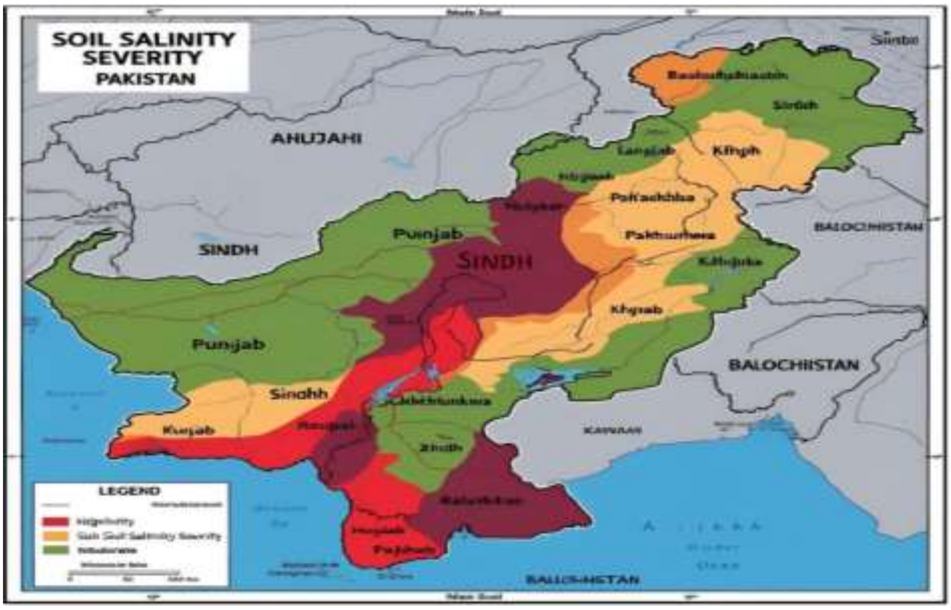

Fig 2: Distribution and severity of soil salinity across Pakistan, high-lighting Punjab and Sindh as the most affected provinces.

Organic Approaches

Organic approaches play a vital role in improving the productivity and resilience of salt-affected soils by enhancing their physical, chemical, and biological properties. Unlike purely chemical amendments, organic inputs provide long-term benefits, supporting soil structure, nutrient cycling, and microbial biodiversity while reducing salt stress in plants.

Organic Amendments

Farmyard manure (FYM) remains one of the most effective organic amendments, as it boosts soil organic matter, improves aggregation, and increases water-holding capacity, thereby alleviating salt-induced osmotic stress (Naz et al., 2023). Compost derived from crop residues, municipal green waste, or agro-industrial by-products supplies essential macro- and micronutrients, lowers electrical conductivity, and promotes beneficial microbial activity (Rasool et al., 2023). Biochar, particularly from rice husk, sugarcane bagasse, and cotton stalks, has shown promise in immobilizing sodium ions, reducing the sodium adsorption ratio, and enhancing nutrient availability under saline conditions (Naddafi et al., 2022). Green manures such as Sesbania and cowpea contribute to organic carbon build-up, increase cation exchange capacity, and foster beneficial soil microbial communities, which improve plant tolerance to salinity (Haq, Shahbaz, Asif, Ouahada, & Hamam, 2023). Vermicompost, rich in humic and fulvic substances, further enhances soil aeration, nutrient cycling, and root development in saline environments.

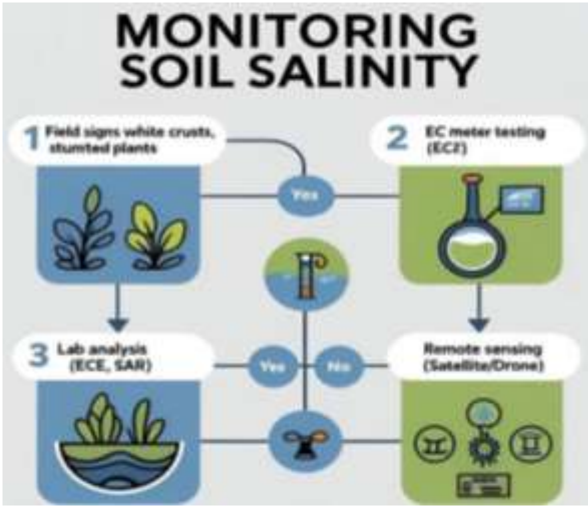

Fig 3: Stepwise process for assessing and monitoring soil salinity using field observations, EC/SAR measurements, and remote sensing technologies.

Mulching and Residue Management

Mulching with crop residues, straw, or other organic materials helps suppress evaporation, reducing the upward movement of salts to the soil surface (Ren et al., 2021). Residue retention also adds organic matter over time, which improves soil porosity and water infiltration rates. These practices are particularly effective in arid and semi-arid regions where high evaporation accelerates surface salinization.

Microbial and Biostimulant Approaches

Salt-tolerant plant growth-promoting rhizo bacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) have emerged as promising bio-based solutions for salinity management. These microbial inoculants improve nutrient uptake, produce stress-alleviating phytohormones, and enhance root growth under saline conditions (Bhat et al., 2020). Biostimulants such as humic acids, seaweed extracts, and amino acid formulations have also been shown to improve plant water use efficiency, chlorophyll synthesis, and antioxidant activity, leading to better crop performance in saline soils (Chatterjee et al.).

Inorganic Approaches

Inorganic approaches are among the most widely adopted strategies for reclaiming salt-affected soils, particularly where rapid improvement in soil structure and crop productivity is required. These methods primarily focus on replacing harmful sodium ions with calcium, improving water movement in the soil profile, and preventing the upward movement of salts.

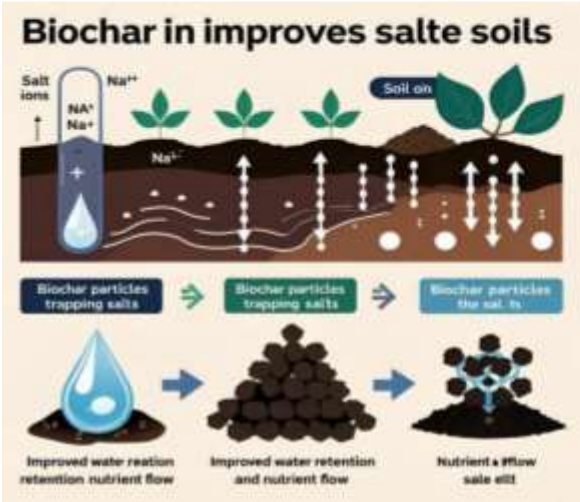

Fig 4: Mechanism by which biochar reduces soil salinity, improves water retention, and enhances nutrient availability

Chemical Amendments

Gypsum ($CaSO_4 \cdot 2H_2O$) remains the most common and cost-effective chemical amendment for saline-sodic soils. It works by supplying soluble calcium that displaces sodium from the soil exchange complex, thereby improving soil aggregation, porosity, and permeability (Mannan, Karim, Higichi, Akter, & Akter, 2024). In calcareous soils, elemental sulfur and sulfuric acid are also used, as they lower soil pH and dissolve native calcium carbonate to release calcium ions (Deshmukh, Kochar, Kaur, & Singh, 2023). Phosphogypsum, a by-product of phosphate fertilizer production, has been explored as a low-cost alternative to natural gypsum, although careful monitoring is needed to avoid potential heavy metal contamination (Farooqi et al., 2023).

Irrigation and Leaching Management

Leaching with good-quality water is essential to flush excess salts beyond the root zone. Calculating the leaching requirement ensures that sufficient water is applied without causing water logging (Bauder & Brock, 2001). In some regions, blending high-salinity canal water with low-salinity groundwater has proven effective for reducing irrigation water salinity (Jamil et al., 2021). Modern irrigation techniques such as raised-bed planting, surge irrigation, and drip systems can further reduce salt accumulation by minimizing surface evaporation and improving water distribution uniformity (Hayat et al., 2020).

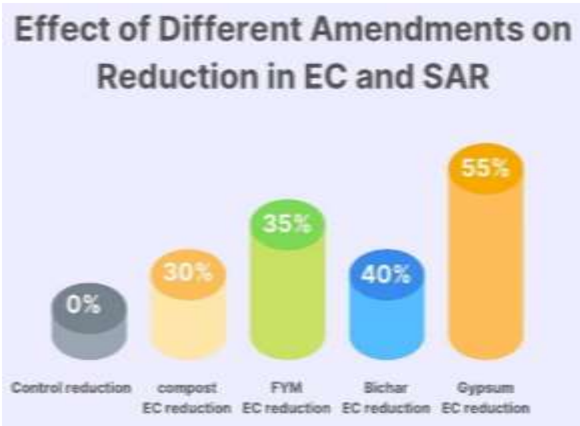

Fig 5: Reduction in electrical conductivity (EC) and sodium adsorption ratio (SAR) achieved by different organic and inorganic amendments.

Drainage and Water Table Control

Efficient drainage is critical for preventing secondary salinization. Surface drainage systems remove excess water from the field, while subsurface pipe drains help lower the water table and prevent capillary rise of salts (Baig, Ashfaq, & Afzal, 2021). Biodrainage, the use of deep-rooted, salt-tolerant trees such as Eucalyptus camaldulensis, has been successfully adopted in some areas as a low-cost, eco-friendly method for lowering water tables and reclaiming saline-water logged soils (Mishra et al., 2024).

Regional Case Studies

Punjab

Punjab is considered the agricultural heart of Pakistan, but decades of continuous irrigation from the Indus Basin canals have created large pockets of saline and sodic soils. In many districts, salts accumulate not only from the quality of irrigation water but also from poor field drainage. Farmers in areas such as Sahiwal and Okara have seen noticeable improvement when gypsum is applied in pelletized form, often in combination with better field leveling(F. Hussain, Afzal, Rehman, & Zaman). Laser land leveling has helped ensure that water is distributed more evenly, reducing patches where salts concentrate and restoring wheat yields in the rice–wheat farming system(Aziz, 2025).

Sindh

Lower Sindh faces one of the most complex salinity problems in the country, as seawater intrusion from the Arabian Sea affects soils along the Indus delta. In districts like Thatta and Badin, water logging from inadequate drainage worsens the situation (Arshad, Sarki, & Khan, 2015). Studies have shown that installing shallow subsurface drains, together with adding biochar and using salt-tolerant rice varieties, can improve both yield and soil health. Recent community-led water management initiatives have also made adoption of these techniques more practical for farmers(Mitchell, Awan, Iqbal, & Punthakey, 2021).

Fig 6: Comparison of organic, inorganic, and combined amendment strategies for salinity management in terms of pros, cons, cost, and effectiveness.

Balochistan

In Balochistan's arid uplands, the challenge is less about excess water and more about how to manage salts with very limited supplies. Farmers often rely on deficit irrigation schedules, composted crop residues, and partial mulching to keep the soil workable under extreme evaporation rates. Integrating locally sourced gypsum with organic materials has shown promise in restoring infiltration rates and nutrient availability in fields around Pishin and Quetta(Jat Baloch et al., 2021).The combined use of locally sourced gypsum with organic amendments has also been reported to improve infiltration rates, restore nutrient balance, and enhance water retention(A. M. Ali & Salem, 2024).

Fig 7: Visual comparison of saline–sodic land in Punjab before reclamation (high ECe, low yield) and after integrated management (restored soil health and productivity).

Khyber Pakhtunkhwa (KP)

Although salinity is not as widespread in KP as in Punjab or Sindh, there are localized patches of sodic soil in canal-irrigated areas like Swabi and Mardan. Here, smallholder farmers have successfully reduced salt buildup by diversifying crops to include salt-tolerant fodders like barley and Rhodes grass, combined with more precise irrigation scheduling (Haq, Shahbaz, Asif, Al-Laith, et al., 2023). Simple measures such as lining watercourses have helped prevent seepage and slow the spread of salinity (Z. Ullah et al., 2022).

Economics and Adoption

The economic feasibility of soil salinity reclamation practices is a critical factor influencing their adoption by farmers across Pakistan. Studies have consistently shown that while chemical amendments such as gypsum provide rapid soil improvement, their high purchase and transportation costs often limit use among smallholders (A. Ali, 2023). Organic amendments, though slower in effect, are generally more affordable when sourced locally, and their integration into farming systems has demonstrated long-term profitability through improved yields and reduced input dependency (Murtaza, Ahmed, Iqbal, & Deng, 2025). Cost benefit analyses indicate that integrated approaches combining gypsum with farmyard manure, improved irrigation scheduling, and salt-tolerant crops offer the highest economic returns, with benefit cost ratios exceeding 2.0 in certain rice wheat systems (Rehman et al., 2023). However, adoption remains constrained by limited awareness, inadequate access to quality amendments, and lack of institutional support for training and extension (Rafique et al., 2025). Social factors such as risk aversion and reliance on traditional practices further slow the uptake of modern reclamation packages, especially in rural Sindh and Balochistan (Ahmad et al., 2023). Innovative financing schemes, such as subsidized gypsum supply, microcredit for drainage installation, and performance-based incentives, have shown promise in overcoming these barriers, enabling broader adoption and ensuring economic viability for resource-poor farmers (Nafees, 2022).

Environmental Co-benefits and Risks

Reclamation of salt-affected soils offers multiple environmental co-benefits that extend beyond agricultural productivity. The incorporation of organic amendments such as compost, biochar, and green manures not only reduces soil salinity but also enhances carbon sequestration, contributing to climate change mitigation (Alvi et al., 2024). Improved soil structure and enhanced microbial diversity from these practices increase water infiltration and nutrient cycling, thereby supporting long-term ecosystem resilience (Irin & Hasanuzzaman, 2024). Additionally, planting salt-tolerant trees for biodrainage not only lowers the water table but also provides habitats for biodiversity in degraded landscapes (Yadav, Kumar, Singh, & Dagar, 2023). However, certain risks accompany these interventions. The use of untreated municipal waste compost may introduce heavy metals or pathogens into the soil, potentially affecting crop safety and human health (Nawab et al., 2024). Over-application of chemical amendments like gypsum can lead to secondary environmental issues such as sulfate leaching into groundwater (El-Bialy et al., 2025). Moreover, irrigation practices aimed at leaching salts may contribute to water scarcity or downstream salinization if not carefully managed (Nadeem et al., 2024). Therefore, adopting integrated soil management packages that combine organic and inorganic amendments with proper monitoring is essential for maximizing environmental gains while minimizing associated risks (Rehman et al., 2023).

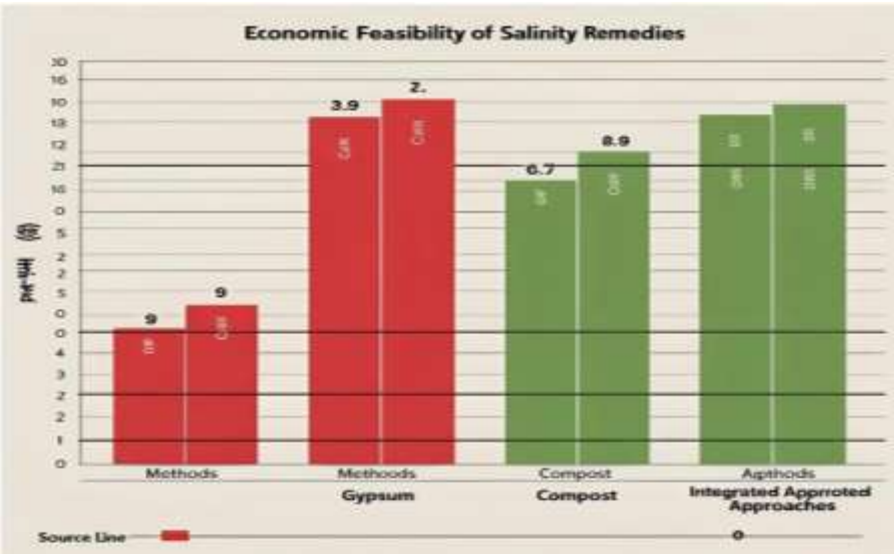

Fig 8: Comparative economic feasibility of various salinity management methods, showing benefit–cost ratios for gypsum, compost, and integrated approaches.

Policy, Institutions, and Extension

The sustainable management of salt-affected soils in Pakistan depends heavily on coherent policy frameworks, effective institutional coordination, and robust extension services. The National Water Policy and the Soil Fertility Enhancement initiatives have provided a baseline for salinity mitigation, yet fragmented implementation and limited inter-agency collaboration often hinder progress (Qureshi & Perry, 2021). Key research bodies such as the Pakistan Agricultural Research Council (PARC) and the National Agricultural Research Centre (NARC) have developed reclamation technologies, but their adoption at the farm level remains slow due to gaps in farmer outreach and insufficient training programs(Mitchell et al., 2021). Provincial soil and water testing laboratories play a pivotal role in diagnosing salinity problems, though many are under-resourced and unable to provide timely services to remote farming communities (Rafique et al., 2025). Strengthening farmer field schools and participatory learning platforms has shown promise in building farmer capacity to adopt integrated reclamation approaches (Mohsin, Mehak, Shafqat, & Luyao, 2024). Public private partnerships, including collaborations with agribusinesses for amendment supply chains, have improved access to affordable gypsum and organic inputs (Mohsin et al., 2024). Moreover, integrating salinity management targets into climate adaptation policies can attract international funding and technical assistance, providing long-term sustainability (Fahad et al., 2024). Digital extension tools, such as mobile-based advisory services and remote sensing alerts, have emerged as cost-effective means of delivering timely recommendations, bridging the gap between research institutions and farmers (Arain, 2025).

Research Gaps and Future Directions

Despite significant advances in understanding the management of salt-affected soils, several gaps remain that limit large-scale, long-term reclamation success. Most studies in Pakistan focus on short-term field trials, often less than two years, which fail to capture the sustained effects of organic and inorganic amendments on soil health and crop productivity (Mahmood et al., 2024). Limited research exists on the economic feasibility of integrated management practices across diverse agroecological zones, creating uncertainty for policymakers and farmers alike (Fahad et al., 2024; M. H. Khan, 2022). There is also a lack of region-specific salinity thresholds that account for variations in soil texture, groundwater quality, and cropping systems, leading to generalized recommendations that may not be suitable for all areas (F. Ahmed, Shakeel, Ahmad, & Kaur, 2025). Furthermore, very few studies incorporate precision agriculture tools such as sensor-based irrigation scheduling or machine learning models for salinity prediction, despite their potential to enhance resource efficiency (M. A. Khan et al., 2024; Sultan, Imran, Ahmad, & Grichar, 2024). Climate change projections, particularly shifts in rainfall patterns and temperature extremes, are rarely integrated into reclamation models, leaving future planning vulnerable to emerging stressors (M. I. Hussain, Akhtar, Qureshi, & Gallacher, 2021). Research on sustainable amendment sourcing, such as the safe use of industrial by-products or treated wastewater, remains minimal despite its importance for circular economy approaches (A. Ullah, Hussain, Qamar, Ali, & Rehman, 2024; Chandra et al., 2023). Strengthening collaborative, multi-institutional projects with long-term monitoring, farmer participation, and advanced remote sensing will be critical in developing resilient, scalable, and economically viable solutions for Pakistan's salt-affected landscapes (Amin & Tariq, 2024).

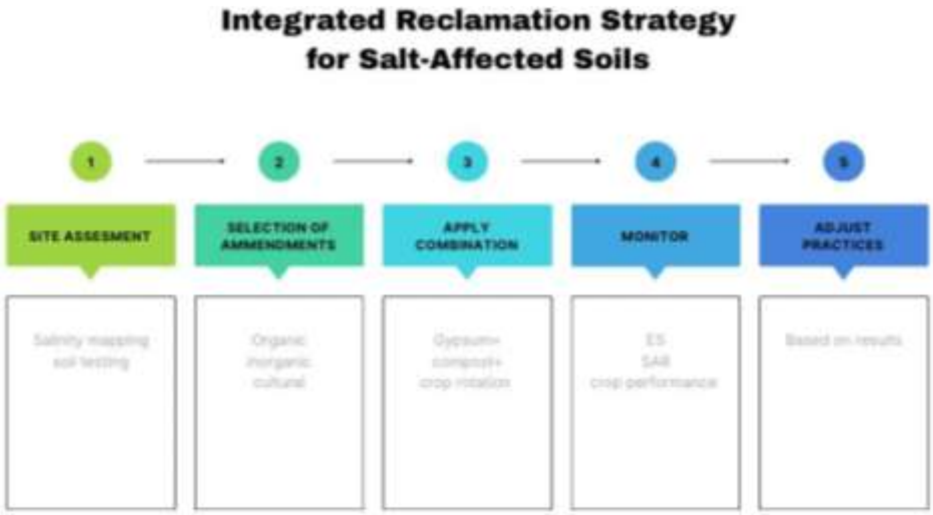

Fig 9: Stepwise integrated reclamation strategy for salt-affected soils, from site assessment to adaptive management.

CONCLUSION

Soil salinity poses a persistent and growing challenge to Pakistan's agricultural systems, undermining productivity, food security, and rural livelihoods. This review shows that while chemical amendments such as gypsum offer rapid improvements, their effectiveness is maximized when combined with organic inputs, improved irrigation management, and drainage solutions. Regional case studies demonstrate that integrated approaches can restore soil health, enhance crop yields, and provide environmental benefits such as carbon sequestration and biodiversity support. However, widespread adoption is hindered by high input costs, limited farmer awareness, and institutional gaps in extension services. Addressing these barriers will require coordinated policy action, targeted subsidies, and stronger public private partnerships to ensure affordable access to amendments and training. Looking ahead, scaling up sustainable reclamation practices will depend on long-term research, region-specific management packages, and the integration of precision agriculture tools for monitoring and decision-making. By aligning science, policy, and farmer participation, Pakistan can transform salt-affected lands from degraded areas into resilient, productive agricultural landscapes.

Funding: This study did not get any financial support from any organization.

Acknowledgement: None Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Not applicable

Ethics Statement: Not applicable

Author's Contribution: Noor-ul-ain conceived the idea and the review scheme and drafted the manuscript.

Generative AI Statements: The authors confirm that no generative-AI tools (including Deep Seek) were used in the writing or preparation of this manuscript.

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