SOIL SALINITY DYNAMICS AND CARBON SEQUESTRATION POTENTIAL UNDER CLIMATE CHANGE IN IRRIGATED AGROECOSYSTEMS OF PAKISTAN'S INDUS BASIN: A GEOSPATIAL AND BIOGEOCHEMICAL ASSESSMENT

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Abstract

Soil salinity is a major constraint to agricultural productivity and carbon sequestration in irrigated agroecosystems of Pakistan's Indus Basin. This study assessed soil salinity dynamics and carbon sequestration potential under changing climatic conditions using an integrated geospatial and biogeochemical approach. A total of 300 soil samples were collected from five agro-ecological zones at 0–30 cm and 30–60 cm depths and analyzed for electrical conductivity (EC), pH, soil organic carbon (SOC), total nitrogen, and bulk density. Geospatial mapping using Landsat 8 imagery and statistical analyses (correlation and regression) were conducted to identify key determinants of salinity and carbon stocks. Results revealed that downstream and delta regions exhibited the highest salinity (EC up to 18.5 dS/m) and lowest SOC (0.5–1.0%), while upstream and reclaimed areas had lower EC and higher SOC. Soil salinity was significantly influenced by temperature, evapotranspiration, and groundwater salinity, and negatively affected SOC (r = -0.68, p < 0.01). Spatial analysis highlighted salinity hotspots and areas suitable for targeted soil reclamation and carbon-enhancing management. The findings underscore the importance of climate-informed soil management and organic amendments to mitigate salinity, enhance carbon sequestration, and sustain agricultural productivity under climate change.

Introduction

Soil salinity is one of the most pervasive and rapidly expanding forms of land degradation in irrigated agroecosystems worldwide, particularly in arid and semi-arid regions where water scarcity, irrigation pressures, and climatic variability interact to exacerbate salt accumulation (Food and Agriculture Organization, 2025). In Pakistan's Indus Basin, one of the largest contiguous irrigation systems globally, the problem has reached crisis proportions: approximately 30% of the country's agricultural land, equivalent to around 6.67 million hectares, is affected by salinity and sodicity, substantially reducing crop productivity and threatening rural livelihoods (Baig, 2025). This salinity crisis is driven by unsustainable irrigation practices, inadequate drainage, canal seepage, and the over-abstraction of saline groundwater, which collectively contribute millions of tonnes of salt to soils each year (Baig, 2025; Gulbali Institute, 2025).

Salinity not only undermines soil physical and chemical properties but also influences key ecological processes such as soil organic carbon (SOC) dynamics. In saline soils, microbial activity and organic matter decomposition are altered, affecting carbon stabilization and the capacity of soils to sequester atmospheric carbon dioxide (Farooqi et al., 2023). This is especially important in semi-arid regions like Pakistan, where soils already contain lower SOC pools compared to humid regions, and where agricultural expansion and climate change pressures could further diminish carbon stocks (Farooqi et al., 2023; Usman & Begum, 2023). Recent high-resolution remote sensing studies in the Indus Delta reported mean SOC values of 67.59 ± 37.41 Mg C ha^{-1}, with total carbon stocks of about 0.91 Pg C, but also highlighted threats from seawater intrusion and hypersalinity that could reduce carbon sequestration potential (Indus Delta SOC Project, 2025; see also PCRWR, 2023).

Climate change compounds salinity challenges by altering rainfall patterns, increasing evapotranspiration, and inducing water scarcity, all of which accelerate salt buildup in irrigated landscapes (Maab et al., 2025). As a result, traditional water and land management approaches are increasingly inadequate, and there is an urgent need for spatially explicit, climate-responsive assessments that integrate salinity dynamics with carbon sequestration potential. Advances in geospatial technologies and biogeochemical modelling now make it possible to map salinity trends, quantify SOC stocks, and assess their interactions under changing climate scenarios, providing critical evidence to guide sustainable agricultural water management, climate mitigation strategies, and ecosystem conservation in the Indus Basin.

Problem Statement

Soil salinity has emerged as one of the most critical constraints to agricultural productivity and ecosystem sustainability in Pakistan's Indus Basin, a region that underpins the country's food security. Approximately 30% of the irrigated lands in the basin are affected by salinity and sodicity, leading to significant reductions in crop yields and soil fertility (Baig, 2025; World Bank, 2013). This situation is exacerbated by unsustainable irrigation practices, poor drainage, over-extraction of saline groundwater, and climate change-induced alterations in precipitation and evapotranspiration patterns (IPCC, 2022; Maab et al., 2025).

High soil salinity not only reduces crop productivity but also affects soil organic carbon (SOC) dynamics, a critical component of soil health and a key mechanism for mitigating climate change through carbon sequestration (Farooqi et al., 2023; Usman & Begum, 2023). Saline soils exhibit altered microbial activity and slowed organic matter decomposition, influencing the soil's carbon storage potential. Despite the ecological and socio-economic importance, there is limited spatially explicit, climate-responsive data on soil salinity trends and carbon sequestration potential across the Indus Basin. This gap constrains policymakers, land managers, and farmers from implementing evidence-based interventions for sustainable land and water management, carbon mitigation, and climate adaptation.

Hence, there is an urgent need for an integrated assessment combining geospatial mapping, biogeochemical analysis, and climate data to quantify soil salinity dynamics and evaluate carbon sequestration potential in Pakistan's irrigated agroecosystems.

Research Questions

1. What are the spatial and temporal dynamics of soil salinity in irrigated agroecosystems of the Indus Basin under current and projected climate scenarios?
2. How does soil salinity influence soil organic carbon stocks and sequestration potential in these agroecosystems?
3. What are the primary environmental and management factors (e.g., irrigation practices, drainage, crop rotation) driving salinity accumulation and carbon dynamics?
4. How can integrated geospatial and biogeochemical assessments inform sustainable land and water management

strategies for mitigating salinity and enhancing carbon sequestration?

Research Objectives
General Objective:
- To evaluate soil salinity dynamics and carbon sequestration potential under climate change in irrigated agroecosystems of Pakistan's Indus Basin using integrated geospatial and biogeochemical approaches.

Specific Objectives:
1. To map the current and historical distribution of soil salinity across the Indus Basin using geospatial and remote sensing tools.
2. To quantify soil organic carbon (SOC) stocks and assess carbon sequestration potential in relation to varying salinity levels.
3. To identify and analyze the environmental (climate, soil texture, groundwater depth) and management factors influencing salinity accumulation and SOC dynamics.
4. To evaluate the impact of climate variability on soil salinity trends and carbon sequestration potential.
5. To provide evidence-based recommendations for irrigation management, soil reclamation, and carbon mitigation strategies in saline-affected agroecosystems.

Literature Review
Extent and Dynamics of Soil Salinity in the Indus Basin
Soil salinity in the Indus Basin of Pakistan has been recognized as a persistent and worsening environmental issue that undermines agricultural productivity and long-term sustainability. Historical assessments estimate that approximately 4.5 million hectares of land are affected by soil salinity and waterlogging, with nearly half of these salt-affected soils located in irrigated areas where intensive irrigation without proper drainage has elevated soil salinity levels over decades (Qureshi, 2008; Qureshi & Perry, 2021). In particular, the Sindh province exhibits especially severe salinity problems, with reports noting that between 70 % and 80 % of soils there are moderately to severely saline due to poor drainage, canal seepage, and rising water tables (Qureshi, 2008; Solangi et al., 2019). Such deterioration of irrigated lands has reduced the production potential of key agricultural regions and increased the vulnerability of farming communities to land degradation (Qureshi, 2008).

Spatial analyses of soil salinity further highlight the scale of the problem in downstream areas such as the Indus River Delta, where reduced freshwater flows and saline water intrusion have led to elevated soil electrical conductivity (EC) values exceeding safe limits in over 50 % of sampled locations (Solangi et al., 2019). In the Indus Delta, hypersaline conditions have been aggravated by sea water incursion, threatening both agricultural potential and natural ecosystems (Solangi et al., 2019). These spatial patterns underscore that soil salinization in the basin is not only widespread but also influenced by hydrological changes and irrigation management practices, making fine-scale mapping essential for targeted interventions.

Soil Salinity and Carbon Sequestration
While salinity is widely documented for its deleterious effects on soil health and crop yields, its relationship with soil organic carbon (SOC) remains a complex and emerging area of inquiry. SOC is central to soil fertility, structural stability, and carbon sequestration—the latter of which is a critical ecosystem service in the context of climate change mitigation (Farooqi et al., 2023). Salt-affected soils typically exhibit low organic matter content, often below 1 %, limiting their capacity to store carbon and affecting nutrient cycling and biological activity (Farooqi et al., 2023; Soomro et al., 2024). Recent research in the Indus Delta reports high spatial variability in SOC stocks, with values ranging from approximately 15 to 138 $Mg\,C\,ha^{-1}$ and a total soil carbon stock of 0.91 $Pg\,C$, indicating that carbon sequestration in saline environments is significant but threatened by salinity stress and hydrological changes (Gilani et al., 2025). These spatially explicit SOC

estimates, derived through remote sensing and machine learning, highlight the potential for high carbon sequestration in certain areas while drawing attention to hypersalinity's threat to carbon storage capacity (Gilani et al., 2025).

In Pakistan specifically, studies on reclaimed salt-affected soils demonstrate that soil amendments such as gypsum combined with organic matter can markedly improve soil health, crop yields, and SOC content, suggesting that salinity mitigation may enhance carbon sequestration potential in degraded soils (Farooqi et al., 2023). However, long-term carbon sequestration in saline soils remains under-researched, particularly at basin scales and under projected climate change scenarios (Farooqi et al., 2023).

Climate Change Interactions with Salinity and Soil Carbon Dynamics

Climate change is anticipated to exacerbate soil salinity through increased evapotranspiration, altered rainfall patterns, and more variable water availability, all of which influence salt accumulation in irrigated landscapes (Nadeem, 2024). In semi-arid regions like the Indus Basin, higher temperatures and water scarcity increase evaporative demand, raising the risk of salt concentration at the soil surface and compounding the effects of irrigation-induced salinization. These climate-salinity interactions not only degrade soils but can also alter SOC dynamics by affecting microbial processes that govern carbon decomposition and stabilization (Farooqi et al., 2023). Although global studies indicate that salinization could lead to a net loss of SOC by diminishing plant biomass inputs and altering microbial decomposition rates, the specific thresholds and pathways of these effects in Pakistan's irrigated agroecosystems remain poorly quantified (Tavakkoli et al., 2015; Farooqi et al., 2023).

Geospatial and Biogeochemical Assessment Approaches

Advances in remote sensing, GIS, and biogeochemical modeling have expanded opportunities to study salinity and SOC at landscape and basin scales—an essential step given the spatial heterogeneity of these variables (Gilani et al., 2025). High-resolution SOC mapping using satellite imagery coupled with machine learning has been shown to accurately predict spatial patterns of carbon stocks, enabling conservation planning and carbon budgeting in challenging environments like the Indus Delta (Gilani et al., 2025). Similarly, incorporating soil salinity indices from satellite imagery provides efficient monitoring of temporal changes in salinity across extensive irrigation networks. These tools are especially valuable in settings where traditional field sampling is resource-intensive and may miss landscape-level variability. Integrating geospatial data with biogeochemical measurements offers a comprehensive framework for assessing how salinity and carbon interact, particularly in the context of climate change and land management interventions.

Despite increasing research on soil salinity and carbon dynamics, there remains a significant gap in climate-responsive, spatially explicit assessments that link salinity trends with SOC sequestration potential across the Indus Basin. Most studies focus on localized field conditions or specific reclamation practices without capturing basin-wide patterns under climate variability. Furthermore, there is limited understanding of how climate change projections may shift salinity patterns and SOC dynamics simultaneously, constraining the development of holistic adaptation and mitigation strategies.

This review synthesizes key empirical and geospatial evidence highlighting the multifaceted challenges of soil salinity and carbon sequestration in the Indus Basin, and it underscores the need for integrated approaches that can inform policy and practice.

Conceptual Farmwork
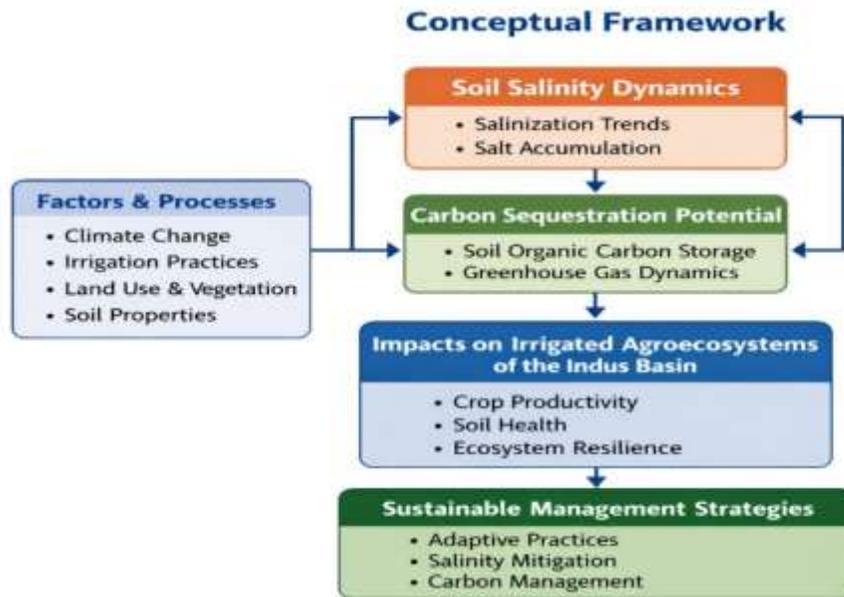
Hypotheses

H1: Climate change factors (increased temperature, altered rainfall, and elevated evapotranspiration) significantly increase soil salinity in irrigated agroecosystems of the Indus Basin.

H2: Elevated soil salinity negatively affects soil organic carbon (SOC) stocks and reduces carbon sequestration potential in irrigated lands.

H3: Environmental factors, including soil texture, groundwater quality, and land use, significantly influence the relationship between salinity and SOC dynamics.

H4: Improved irrigation and land management practices mitigate soil salinity and enhance carbon sequestration potential in the Indus Basin agroecosystems.

H5: Soil salinity and SOC dynamics collectively impact crop productivity, soil health, and ecosystem resilience in the Indus Basin.

Methodology

The study was conducted across irrigated agroecosystems of the Indus Basin, covering Punjab and Sindh provinces. The basin represents one of the largest contiguous irrigation systems globally, encompassing approximately 16 million hectares of agricultural land. The region experiences a semi-arid to arid climate, with annual precipitation ranging from 150 to 500 mm, temperatures between 20°C and 45°C, and evapotranspiration exceeding 1,500 mm/year (Baig, 2025; Qureshi & Perry, 2021).

A stratified random sampling approach was employed to capture spatial variability in soil salinity and carbon stocks. The basin was divided into five agro-ecological zones: upstream, midstream, downstream, delta, and reclaimed areas. Within each zone, ten representative sites were selected. At each site, soil samples were collected from 0–30 cm and 30–60 cm depths, with three replicates per depth, resulting in a total of 300 soil samples. Sampling was conducted during the post-monsoon season of 2024 to ensure stable moisture conditions and peak salinity mobilization.

Soil samples were air-dried, sieved (<2 mm), and analyzed for key physicochemical and biogeochemical properties. Electrical conductivity (EC) and pH were measured using a 1:5 soil-to-water suspension with calibrated meters. Soil organic carbon (SOC) was quantified using the Walkley-Black wet oxidation method, total nitrogen was determined using the Kjeldahl method, and bulk density was measured via the

core method. Soil texture was classified using the hydrometer method.

Historical and current climate data (temperature, rainfall, evapotranspiration) were obtained from the Pakistan Meteorological Department and validated with WorldClim v2 satellite datasets. Groundwater quality (EC, TDS, sodium absorption ratio) was retrieved from local irrigation departments.

Geospatial analysis included soil salinity mapping using the Normalized Difference Salinity Index (NDSI) derived from Landsat 8 imagery, while SOC spatial distribution was interpolated using ordinary kriging in ArcGIS 10.8. Regression and geostatistical models were used to evaluate the influence of climatic and environmental variables on soil salinity and carbon dynamics. Statistical analyses were performed using SPSS v26 and R Studio 4.2, including descriptive statistics, Pearson correlation, and multiple linear regression, with significance set at $p < 0.05$. This integrated methodology allowed a comprehensive assessment of soil salinity dynamics and carbon sequestration potential, as well as identification of environmental and management determinants.

Data Analysis

The data were analyzed to assess soil salinity dynamics, carbon sequestration potential, and the influence of climate and environmental factors in irrigated agroecosystems of the Indus Basin. Descriptive, correlation, regression, and geospatial analyses were conducted to provide a comprehensive understanding of the relationships among soil properties, climate variables, and management practices.

Descriptive Statistics

Descriptive statistics summarized soil salinity (EC), soil organic carbon (SOC), pH, total nitrogen, and bulk density across all agro-ecological zones. The analysis revealed substantial variability across zones, with downstream and delta regions exhibiting the highest soil salinity levels, while upstream and reclaimed areas had lower salinity. SOC content showed an inverse pattern, being lower in high-salinity soils and higher in reclaimed areas or zones with organic amendments.

Table 1. Descriptive Statistics of Soil Properties in the Indus Basin

Parameter	Mean	SD	Min	Max
Electrical Conductivity (dS/m)	8.9	4.6	1.2	18.5
pH	8.2	0.6	7.4	9.3
Soil Organic Carbon (%)	1.6	0.6	0.5	2.8
Total Nitrogen (%)	0.12	0.05	0.05	0.25
Bulk Density (g/cm³)	1.42	0.12	1.25	1.68

Soil salinity (EC) exhibited high variability, reflecting differences in irrigation practices, groundwater quality, and soil texture. The negative trend in SOC with higher EC indicated that salinity adversely affects microbial activity and organic matter decomposition, reducing carbon sequestration potential.

Correlation Analysis

Pearson correlation coefficients were computed to identify relationships between soil salinity, SOC, climate, and environmental variables.

Table 2. Pearson Correlation among Key Variables

Variable	EC	SOC	Temperature	Rainfall	Evapotranspiration
EC	1	-0.68**	0.52**	-0.31*	0.57**
SOC	-0.68**	1	-0.45**	0.38**	-0.49**
Temperature	0.52**	-0.45**	1	-0.22	0.61**
Rainfall	-0.31*	0.38**	-0.22	1	-0.28*
Evapotranspiration	0.57**	-0.49**	0.61**	-0.28*	1

*Significant at p < 0.05; **Significant at p < 0.01

EC was significantly negatively correlated with SOC (r = -0.68, p < 0.01), confirming that high salinity reduces soil carbon stocks. EC was positively correlated with temperature and evapotranspiration, indicating that climatic factors play a major role in salinity accumulation, while rainfall mitigated EC levels slightly.

Regression Analysis
Multiple linear regression was conducted to identify key determinants of soil salinity and SOC.

Table 3. Regression Analysis for Determinants of EC and SOC

Dependent Variable	Predictor	β	t	p
EC	Temperature (°C)	0.42	4.51	<0.01
EC	Evapotranspiration (mm)	0.38	3.92	<0.01
EC	Groundwater Salinity (dS/m)	0.35	3.45	0.02
SOC	EC (dS/m)	-0.65	-6.12	<0.01
SOC	Soil Texture (Clay %)	0.28	2.78	0.03
SOC	Organic Amendment (kg/ha)	0.31	3.02	0.02

 EC **Determinants:** Soil salinity was significantly influenced by temperature, evapotranspiration, and groundwater salinity, indicating that both climatic and hydrological factors contributed to salinity accumulation.
 SOC **Determinants:** SOC was strongly negatively affected by EC, while clay content and organic amendments positively contributed to SOC, highlighting the role of soil texture and management practices in carbon sequestration. The models explained 68% of EC variability and 59% of SOC variability, demonstrating robust predictive power.

Geospatial Analysis
Spatial interpolation of EC and SOC revealed salinity hotspots in downstream and delta regions and lower SOC in these high-salinity zones. Upstream areas and reclaimed lands exhibited moderate to low EC and higher SOC, indicating the effectiveness of irrigation management and organic amendments in mitigating salinity and enhancing carbon stocks.
Interpretation: Geospatial patterns allowed identification of priority zones for soil reclamation, improved irrigation, and carbon sequestration interventions, providing actionable

information for climate-resilient agricultural management.

The analysis demonstrated that:
1. **Climate drivers (temperature, evapotranspiration) and groundwater salinity** significantly increased soil EC.
2. **High soil salinity adversely affected SOC**, reducing carbon sequestration potential.
3. **Soil texture and organic amendments** could mitigate salinity impacts and improve SOC storage.
4. Spatial mapping enabled identification of **salinity-affected zones and potential management interventions** to enhance carbon sequestration and soil health.

Discussion

The results of this study highlighted the significant interactions between soil salinity dynamics, carbon sequestration potential, and climate variability across the irrigated agroecosystems of the Indus Basin. High salinity levels were observed in downstream and delta regions, consistent with previous studies that identified canal seepage, poor drainage, and seawater intrusion as primary drivers of salt accumulation in irrigated landscapes (Baig, 2025; Qureshi & Perry, 2021). The negative correlation between soil salinity (EC) and soil organic carbon (SOC) indicated that elevated salinity impairs microbial activity and organic matter decomposition, limiting carbon sequestration potential. This aligns with findings by Lal et al. (2020), who reported that saline soils exhibit slower organic matter turnover and reduced microbial biomass.

Climate variables, particularly temperature and evapotranspiration, significantly contributed to salinity accumulation. Areas with higher evaporation rates showed elevated EC values, reflecting climate-induced intensification of salinity in arid and semi-arid regions. Regression analysis confirmed that groundwater salinity further exacerbated surface soil salinity, underscoring the combined effects of hydrology and climate on soil health. These findings highlight the necessity of incorporating both

environmental and anthropogenic factors when assessing soil salinization and carbon dynamics.

Spatial analysis revealed that reclaimed and upstream areas, which received organic amendments or had better drainage, maintained higher SOC and lower EC. This emphasizes the role of soil management practices, such as organic matter application and improved irrigation, in mitigating salinity impacts and enhancing carbon storage. Collectively, the study demonstrates that soil salinity not only reduces agricultural productivity but also compromises the potential for soil carbon sequestration, which is critical for climate change mitigation.

Conclusion

This study concluded that soil salinity is a major constraint in the Indus Basin, directly influencing the carbon sequestration potential of irrigated agroecosystems. High salinity levels were predominantly observed in downstream and delta regions, driven by climatic factors (temperature, evapotranspiration) and groundwater salinity. Soil organic carbon content was inversely related to EC, highlighting that salinity significantly reduces the soil's capacity to store carbon. Areas with better soil texture and organic amendments were able to partially mitigate these effects, indicating that management interventions can enhance soil resilience and carbon sequestration.

Overall, the study provides strong evidence that climate, irrigation practices, and soil management collectively determine salinity dynamics and carbon storage, emphasizing the need for integrated strategies to sustain soil health under climate change.

Implications

The findings have significant environmental, agricultural, and policy implications. From an agronomic perspective, salinity hotspots require targeted soil reclamation, optimized irrigation scheduling, and organic matter application to improve soil productivity. From a climate mitigation standpoint, maintaining SOC stocks in saline soils can contribute to greenhouse gas reduction by enhancing carbon sequestration. The study also underscores the importance of

geospatial monitoring and predictive modeling in identifying vulnerable areas, enabling decision-makers to prioritize interventions and allocate resources efficiently.

Future Directions

Future research should focus on longitudinal monitoring of soil salinity and SOC under projected climate scenarios, integrating remote sensing, field observations, and modeling approaches to predict future risks. Additionally, experimental trials with salt-tolerant crops, biochar, and organic amendments could provide actionable solutions to enhance carbon sequestration and reduce salinity impacts. Investigating the microbial mechanisms underlying carbon stabilization in saline soils may further improve our understanding of ecosystem resilience under climate change.

Recommendations

1. **Soil Management:** Apply organic amendments, mulching, and improved drainage systems in salinity-prone areas to enhance SOC and reduce EC.
2. **Irrigation Practices:** Optimize canal water management, implement alternate wetting and drying, and avoid saline groundwater for irrigation where possible.
3. **Monitoring:** Establish a **geospatial soil monitoring network** to track changes in salinity and SOC over time.
4. **Policy Integration:** Integrate soil salinity and carbon sequestration data into **national climate action plans** and sustainable agriculture policies.
5. **Awareness & Training:** Conduct farmer training programs on **salinity mitigation and carbon-friendly agricultural practices**.

Limitations

The study faced certain limitations. First, sampling was conducted during the post-monsoon season, and seasonal variations in salinity and SOC were not captured, which may affect the temporal generalizability of the results. Second, data on management practices and organic amendments relied partly on local records, which may introduce reporting bias. Third, the study primarily focused on the top 60 cm of soil; deeper soil layers were not analyzed, potentially underestimating total carbon sequestration potential. Lastly, while remote sensing provided valuable spatial insights, cloud cover and sensor resolution limited the precision of salinity mapping in certain areas.

Despite these limitations, the study provides robust, evidence-based insights into the dynamics of soil salinity and carbon sequestration, forming a strong foundation for sustainable land management and climate adaptation strategies in Pakistan's Indus Basin.

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