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Assessment of Soil Salinity and its Impact on Agricultural Productivity in District Khushab, Pakistan

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ABSTRACT

Salinity of soil is one of the greatest environmental and agricultural problems in arid and semi-arid areas such as District Khushab, Punjab, Pakistan. This research evaluated the geographic areas, intensity and farming implication of the soil salinity and sodicity in twelve representative sites. A series of physico-chemical tests were carried out to assess such parameters as Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Exchangeable Sodium Percentage (ESP), pH, and organic matter content. It has been noted that the salinity level of more than 60 percent of the sites was moderate to severe, and the EC and SAR were between 2.10 and 9.10 dS/m and 7.41 and 19.72. The close positive relationships ($r > 0.90$) between EC, Na^+, SAR, and ESP demonstrate that sodium is the major cause of salinization. Poor soil productivity is further reduced by alkaline pH and low organic matter (below 1 per cent). Based on irrigation water quality, soil texture, and drainage conditions, there was a spatial variation. Locations that had clay texture and could not manage water possessed the most risk of salinity. The results highlight the necessity to have localized salinity monitoring and site-specific land management approaches such as gypsum application, organic amendments, and salty-tolerant cropping. The study offers a basis of sustainable soil and water management in Khushab, and other agro-ecological zones in Pakistan.

Keywords: Soil salinity, SAR, Sodicity, Soil degradation, Khushab, Pakistan, EC,

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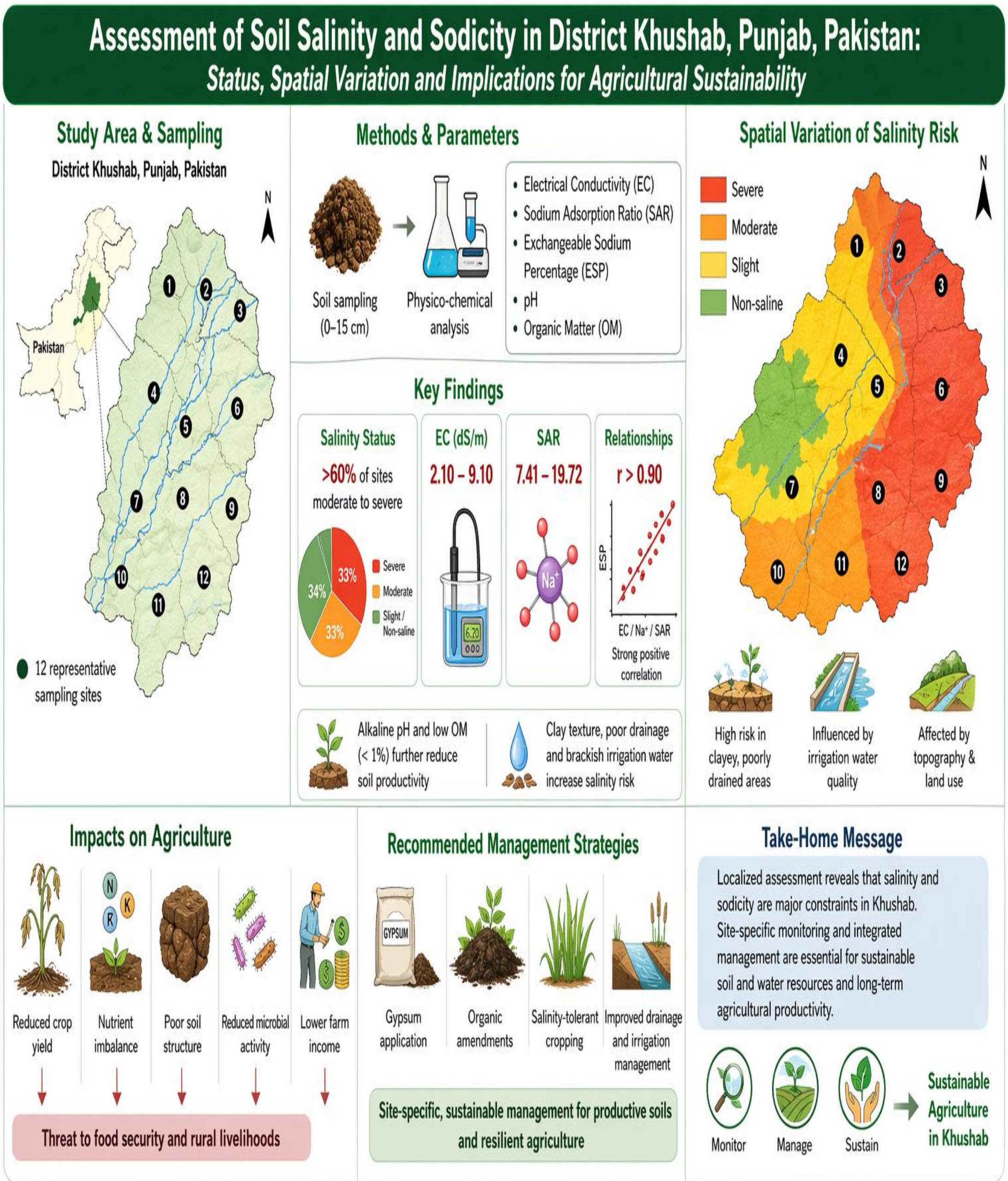
Agricultural sustainability



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Introduction

The issue of soil salinity is an emerging environmental problem that has been a huge challenge to agriculture around the world especially in arid and semi arid areas. By 2021, the worldwide land area under salinization is estimated at 833 million hectares with more than 20% of the irrigated lands exhibiting moderate or extreme salt levels (FAO, 2021). Salinity not only lowers agricultural production, but also modifies the soil structure, slows down the activities of microorganisms and the availability of

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nutrients important to agriculture- posing a risk to food security and rural livelihoods. In South Asia, land degradation through salinity is a growing concern according to the United Nations Sustainable Development Goals (SDGs), specifically Goal 2 (Zero Hunger) and Goal 15 (Life on Land) (Wang et al., 2022).

Salty soil is becoming a significant obstacle to sustainable farming practices and environmental protection in South Asia as a result of intensive irrigation, inadequate drainage, and climate-related changes including the decreased rainfall and the increase in the evapotranspiration rate. This is especially susceptible to Pakistan, which has a vast canal irrigation system. Recent estimates indicate that over 6.5 million hectares of a land in Pakistan are salt-affected with most of them being found in the provinces of Punjab and Sindh (Rasheed et al., 2023). This degradation has resulted into extreme reduction of the yield of key food and cash crops like wheat, rice, and cotton. Localized assessment and sustainable management practices are poor in district Khushab, one of the most representative cases of salinity-induced soil degradation, which is found in the middle of Punjab (Ashraf et al., 2020).

The climate in the area is semi-arid, which means that the yearly precipitation is limited (200300 mm), evaporation is high, and the dry season is long. Khushab farmers mostly depend on canal irrigation as well as shallow tube wells with several of them using the brackish groundwater. There is also lack of effective subsurface drainage systems and this further enhances the build of salts in the root zone especially in clay soils. In the long run, it leads to salinization (accumulation of soluble salts) and sodicity (excess of sodium over calcium and magnesium) that undermine the soil fertility and the performance of crops (Iqbal et al., 2023).Also, the salinization in Khushab is spatially heterogeneous, as it is determined by the land use, irrigation processes, soil texture, and topography. Nevertheless, published literature has a tendency to dwell on the wider-scale or remote sensing estimates of the regions or the trends and seldom incorporate on-ground soil sampling and chemical profiling. This means that there exists an acute knowledge gap of localized severity, variability, and causes of soil salinity in Khushab. In the absence of such information, mitigation measures are generic and in most cases, fail to work at the

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farm level.

The proposed study will help to fill this gap by performing a site-specific, physio-chemical analysis of the salinity of soil at 12 representative agricultural sites in District Khushab. The study uses conventional procedures to examine the most vital parameters of the soils, such as Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Exchangeable Sodium Percentage (ESP), pH and organic matter.

The study also assesses relationships between chemical characteristics and soil structure and fertility and how these characteristics affect the suitability of the soil by correlating these characteristics with salinity severity. Not only does the approach that uses multiple parameters identify the degraded zones but also allows to identify those areas still viable to traditional farming and those that need salinity management approaches to reduce their salinity levels, which provides an addition to the ever-growing body of literature that targets sustainable land management, precision agriculture, and climate-resilient farming. This will not only be important to the local policy makers and the farmers but also to those concerned in the field of research and development agencies that focus on land degradation and a food system that is stressed because of climate variability and unsustainable farm management.

Materials and Methods

Study Area

The location of this study was a District Khushab, Punjab, Pakistan, which is characterized by a variety of agro-ecological setting and rising soil salinity as a result of poor drainage, seepage into the canals, and misuse of the brackish ground water. It has a semi-arid climatic condition that is typified by low rainfall per year, high evaporation levels, and long dry periods. These environmental conditions also add to the salinations of the top soils which adversely impacts the crop production.

In order to determine salinity of the soils of various agricultural areas, twelve representative sampling sites were identified in the district including Khushab city, Jauharabad, Hadali, Noshehra, Jamali, Gunjial, and Quaidabad. Areas with different irrigation patterns, soil types and cropping patterns were selected.

Soil Sampling

A standard soil auger was used to collect soil samples at 0-15 cm deep and surface

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layer because the depth is the one that is critical to seed germination, initial root growth, and acquisition of nutrients. Five subsamples were selected randomly and in a zigzag manner in every site and homogenized into a single composite sample in order to minimize spatial variation.

Samples were put in clean polyethylene bags, and their geographical position was indicated on the bag and then the samples taken to the laboratory for physico-chemical characterization. Air-drying of the samples was followed by a sieve of 2 mm diameter and the sample placed in desiccators until analysis.

Physico-Chemical Analysis

Electrical Conductivity (EC)

EC meter was used on a 1:5 soil-water extract to measure soil EC (dS/m). EC was adopted as the main measure of the severity of salinity of soil.

Total Dissolved Solids (TDS)

The EC values were converted to TDS (mg/L) using the standard conversion:

$TDS=EC\times640$

TDS is the general concentration of the soluble salts in the soil.

Soil pH

The pH of the soil was measured by a calibrated digital pH meter in a 1: 2.5 soil-water suspension. pH was employed to determine the alkalinity of the soil and how it influences nutrient availability.

Exchangeable Cations

Exchangeable cations were calculated in the following way:

Sodium (Na^+) and Potassium (K^+) by flame photometry.

Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) EDTA complexometric titration.

The values were given in milliequivalents per liter (meq/L).

Calcium + Magnesium (Ca+Mg)

Total Ca+Mg was computed as:

$= Ca+Mg=Ca^{2+}+Mg^{2+}(meq/L)$

Sodium Adsorption Ratio (SAR)

SAR measures sodicity and effect of Na^+ on soil structure:

An increase in SAR signifies the possibility of soil dispersion and decrease in

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infiltration.

Exchangeable Sodium Percentage (ESP) reflects the percentage of the market that can be replaced with its substitute products, denoted as the percent of market share that can be vacated in favor of the substitute products. Exchangeable Sodium Percentage (ESP) is the percentage of the market that can be replaced by its substitute products or the percent of market share that can be vacated to favour the substitute products.

Soils were classified with the help of ESP to be normal (<15%) and sodic (>15%).

Organic Matter

The percentage of organic matter was identified as the Walkley-Black wet oxidation method.

Bulk Density

The core method was used to determine bulk density (g/cm3) which is an index of soil compaction and structural state.

Soil Texture

The method of identifying the soil texture was the hydrometer which identified the soil as sandy loam, loam, clay loam and clay.

Statistical Analysis

The obtained data were tabulated in Microsoft Excel to conduct descriptive statistics, comparisons between the sites, trends of correlation, and classification of data by the FAO and USDA salinity criteria. Graphs and tables were created to show differences between sites in EC, pH, SAR, ESP, exchangeable cations.

Results

Descriptive Statistics of Soil Parameters

The mean EC (5.63 dS/m) indicates moderate salinity across Khushab. High standard deviation in Na^+ and SAR indicates major spatial variation in sodicity. pH values show overall alkaline soil conditions, consistent with salinity hazards. Organic matter is low (<1%), reducing nutrient availability and soil structure.

The descriptive statistics show that there is significant variation in salinity in soils among the 12 sampling sites of District Khushab. The EC value was between 2.10 and 9.10 dS/m with a mean of 5.63 dS/m as a result of which a majority of the

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sites were in the moderately saline to highly saline category. This is also evident in TDS values that indicated a great variation ranging between 1340 and 5600 mg/L, which proved that dissolved salts were present in large amounts. The average pH of the soil was always alkaline (8.18) that is characteristic of the salt-influenced areas in arid and semi-arid climate. Sodium was the most changeable cation with a mean of 28.66 meq/L and a large standard deviation implying localized sodium deposition. ESP and SAR also recorded high values, a fact that means sodicity is a significant challenge to the soil structure and agricultural output. The amounts of organic matter were relatively low at all sites (<1%), which is typical of salty environments that inhibit the activity of microorganisms and decomposition. In general, the descriptive statistics affirm that saltiness and sodicity are significant soil limitations in the District Khushab (Table 1).

Table 1: ***Descriptive Statistics of Physico-Chemical Parameters***

Parameter	Minimum	Maximum	Mean	Std. Deviation
EC (dS/m)	2.10	9.10	5.63	2.18
TDS (mg/L)	1340	5600	3418.33	1311.46
pH	7.40	9.00	8.18	0.46
Na^+ (meq/L)	12.00	50.00	28.66	12.02
K^+ (meq/L)	0.42	1.10	0.70	0.22
Ca^{2+} (meq/L)	2.30	3.90	3.05	0.46
Mg^{2+} (meq/L)	2.00	3.50	2.71	0.49
Ca+Mg (meq/L)	4.30	7.40	5.76	1.03
SAR	7.41	19.72	13.05	3.61
ESP (%)	12.00	26.50	18.40	4.25
Organic Matter (%)	0.45	1.01	0.69	0.18

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Parameter	Minimum	Maximum	Mean	Std. Deviation
Bulk Density (g/cm^3)	1.38	1.46	1.41	0.02

Site-Wise Soil Salinity Classification

Sites 8 and 9 show the highest salinity and sodicity, making them unsuitable for most crops. Sites 1, 2 and 7 are relatively safe for agriculture. Mid-range EC (4–7 dS/m) across many sites suggests Khushab is undergoing salinization expansion.

The site-wise analysis reveals that there is an evident spatial difference in salinity intensity throughout the district. Site 7, site 2 and site 1 have comparatively low EC, SAR, and ESP value and therefore belong to the non-saline to slightly saline group, which is more favorable to conventional cropping. Conversely, the sites 8 and 9 have very high EC, Na + and sodacity indices, which qualify them as some of the worst impacted salt locations. Their elevated pH also indicates that it is in a strong alkaline environment which is harmful to the availability of nutrients. The observed mid-range EC and SAR levels at site 4, 5, 6, 10, 11, and 12 are moderately to highly saline. These areas of transition have high chances of additional salinization particularly in case there are still irrigation practices that are improper or poor drainage. In general, the classification shows that, despite the fact that there are still some pockets in Khushab that are agriculturally viable, much of the district is going through the higher levels of soil degradation as a result of salinity and sodicity (Table 2).

Table 2: ***Site-Wise Comparison of EC, pH, Na^+, SAR and ESP***

Site	EC (dS/m)	pH	Na^+	SAR	ESP (%)	Salinity Class
Site 1	2.10	7.4	12	7.41	12.0	Non-saline to Slight
Site 2	3.40	7.8	18	9.74	14.0	Slight
Site 3	4.70	8.1	24	11.21	16.0	Moderate
Site 4	5.90	8.3	31	13.94	19.0	Moderate–High

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Site	EC (dS/m)	pH	Na^+	SAR	ESP (%)	Salinity Class
Site 5	7.20	8.6	39	15.58	21.0	High
Site 6	6.10	7.9	27	12.40	17.3	Moderate
Site 7	3.00	7.6	15	8.47	13.0	Slight
Site 8	8.40	8.7	46	18.55	25.0	Severe
Site 9	9.10	9.0	50	19.72	26.5	Severe
Site 10	6.90	8.2	34	14.92	20.3	High
Site 11	5.20	8.0	28	12.88	17.8	Moderate
Site 12	4.00	7.9	20	10.92	15.0	Moderate

Correlation between Soil Parameters

Very strong positive correlation between EC and Na^+ (r = 0.953) indicates that rising salinity is primarily sodium-driven. SAR and ESP show exceptionally high correlation (r = 0.980), meaning sodicity increases proportionally with sodium buildup. pH correlates moderately with EC and Na^+ , confirming that saline areas are also alkaline.

The correlation analysis shows significant and strong relationships between important key soil salinity indicators. Sodium concentration has a very high positive correlation with electrical conductivity (EC) (r = 0.953), meaning that sodium is the major contributor of total salt content in the soils. On the same note, SAR and ESP show the highest correlation in the matrix (r = 0.980), as would be anticipated since the two parameters would grow in relation to the increase in exchangeable sodium. The correlation of soil pH with EC, Na + and SAR also show moderately high values, which support the notion that the intensity of alkaline reactions increases in soils where salts gather over time. These trends indicate that salinity and sodicity caused by sodium are twin processes that influence the soil chemistry of Khushab and the management of sodium accumulation will be critical in enhancing soil health and productivity (Table 3).

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Table 3: ***Pearson Correlation Matrix***

Parameter	**EC**	**pH**	**Na^+**	**SAR**	**ESP**
EC	1	.812	.953	.905	.898
pH	.812	1	.772	.788	.801
Na^+	.953	.772	1	.960	.943
SAR	.905	.788	.960	1	.980
ESP	.898	.801	.943	.980	1

Organic Matter and Soil Structure Analysis

Organic matter remains below 1% in most sites, insufficient for crop fertility. Higher bulk density in Sites 8 and 9 reflects soil compaction due to sodicity. Clay soils accumulate more salts, explaining severe salinity at Sites 8 and 9.

There is a consistent low amount of organic matter content in the district, all sites of which are below 1% which is typical of salinity stressed soils. Reduced organic matter decreases the aggregate stability, water infiltration, and nutrient retention that increases the negative impact of salinity. The values of the bulk densities are not very wide, and even higher densities appear in the clay-rich and highly sodic locations (8 and 9). This occurs in all sodic soils in which the dispersed clay particles cause compaction and decreased porosity. The surface of soils also takes the center stage of salinity: the finer the particles of the soil, the more salts it retains, which is why the EC and sodium values are higher at those sites. Sandy loam sites on the other hand experience less accumulation of salt because of enhanced drainage and leaching potential. These associations indicate the level at which physical and chemical properties interact to determine the level of soil degradation in Khushab (Table 4).

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Table 4: ***Organic Matter and Bulk Density***

Organic Matter (%)	Bulk Density (g/cm³)	Texture
0.45	1.42	Sandy Loam
0.52	1.40	Sandy Loam
0.60	1.39	Loam
0.71	1.41	Loam
0.80	1.43	Clay Loam
0.68	1.40	Loam
0.49	1.38	Sandy Loam
0.92	1.44	Clay
1.01	1.46	Clay
0.77	1.42	Clay Loam
0.66	1.39	Loam
0.58	1.40	Sandy Loam

Discussion

The results of the present study have given strong indications that soil sodicity and salinity are a major and extensive constraints to sustainable agriculture in District Khushab. The physio-chemical examination of twelve representative locations indicates that Salinity intensity is highly variable as the Electrical Conductivity (EC) varies between 2.10 and 9.10 dS/m and Sodium Adsorption Ratio (SAR) reaches a high of 19.72. When these values are calculated in terms of FAO and USDA standards, several locations come under the moderate and severe salinity and sodicity range, therefore, validating the fact that significant areas of the Khushab agricultural land are at risk.

Among the most noticeable is the positive correlation between EC and sodium concentration (Na+), SAR, and Exchangeable Sodium Percentage (ESP) were quite

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impressive with the diameters of correlation exceeding 0.90 in the Pearson correlation matrix. This indicates that salinity in Khushab is mainly sodium-based which is not only enhancing osmotic pressure, but also influences the structural strength of the soil. Excess sodium replaces calcium and magnesium to facilitate the dispersion of clay particles thereby causing low aggregate stability, crusting of the surface, and infiltration (Farooq et al., 2022). This is also aided by the higher values of bulk density in the sites that were of higher salinity especially Sites 8 and 9 which also had clay texture. These values have a tendency in line with the world observations that sodic soils, particularly those of fine texture, are associated with lower porosity and increased compaction to be less productive in conventional farming (Shahbaz et al., 2023).

The soil PH used in the sites was an average of 8.18 which is an alkaline environment as salt may cause. Higher PH may have a great impact on solubility of nutrients like phosphorus, iron and zinc thus limiting their potentially further to plants. This is in line with the findings of Rasheed et al. (2023), who also found that, alkaline soils in salty conditions inhibit the efficiency of nutrient uptake and augment crop stress. This directly affects crop production in Khushab, especially the production of such sensitive crops as rice, pulses, and vegetables, which are less resistant to salinity as well as to high pH conditions (Naseer et al., 2022).

The other significant dimension is the low organic matter content of all sites which is between 0.45 and 1.01. This is a result of the lack of fertility of soil and low biological activity since organic matters play an important role in the population of microbes, nutrient cycles and soil architecture. Absence of organic matter is especially detrimental in salty soils where already the microbial diversity is restricted by osmotic and ionic stress. One of the most useful ways to make salt-affected soils more resilient, according to Ashraf et al. (2020), is by improving the level of organic matter, which has the ability to buffer the pH, enhance the cation exchange capacity, and facilitate the formation of aggregates.

Geographically, the difference in EC, SAR, and ESP of the 12 sites indicates the effects of local management practices, quality of groundwater, and irrigation systems. As an example, in Sites 1, 2, and 7, EC and SAR values were rather low,

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and they also belonged to the range of saline slight. Sandy loam textures also defined these sites and made the leaching of salts easier and salt lessening. Sites 8 and 9, on the other hand, displayed greatest amounts of EC, Na+, SAR, and ESP with clay textures and a great bulk density. This data indicates that the soil texture is a crucial factor in the retention of salt and that heavier soils are more susceptible to degradation as time goes by unless properly handled.

The position of water management cannot be overestimated. Farmers in most regions of Khushab use shallow tube wells which tap into brackish aquifers, which in effect causes salt accretion over the years. In the absence of proper drainage or flushing systems, the salts pile up in the root zone especially during dry season. This supports the findings of Iqbal et al. (2023) who stressed the necessity of overseeing groundwater quality and controlling the depth and the distribution of tube wells in Khushab and other districts.

The results are also reminiscent of the criticism in the world literature about the feedback between salinity, low productivity and the land abandonment. With the increase in salinity and loss of yield, farmers must either decrease the amount of inputs (e.g., fertilizers, certified seeds) applied or quit farming on this land completely. This brings about a cycle of self-degradation, poverty, and decreased food security (Garcica et al., 2021). This is a very threatening development in Khushab because this area depends on agriculture as a major source of income and livelihood.

As a management, it is possible to suggest a number of interventions. On the one hand, it is a worldwide recognized fact that the application of gypsum is effective as it substitutes the exchangeable sodium with calcium to enhance the soil structure and reduce sodicity. Second, organic additions of compost, farm yard manure and green manure may enhance the activities of microbes and water retention. Third, salt tolerant varieties of crops, especially wheat, cotton, and barley, can be introduced to provide an immediate solution as long-term remediation of the soil takes place. Finally, better irrigation timing, along with the creation of field drains, would be useful to move the accumulated salts and avoid the occurrence of waterlogging.

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Besides, correlation analysis undertaken in the paper offers a predictive analytical basis to predictive soil quality monitoring. The linkages between EC, SAR and ESP are high enough to give rise to an inkling that periodic EC measurements were a potential cost-effective early warning system in case of increasing sodicity and possible loss of productivity. This understanding can be applied to the extension services as it will enable them to better direct their interventions and to put the available resources into the areas at risk.

To summarize, the sources verify that the problem of soil salinity and sodicity is common and growing in District Khushab. Their effects are complex and touch on the chemical, physical and biological properties of soil and consequently, diminishing crop feasibility and land productivity. The spatial variability is high based on the range of findings of the sites and therefore, a one-size-fits-all solution is not likely to work. On the contrary, site-specific management plans grounded on site-specific diagnostics are the key to sustainable agricultural development in the area. This paper presents a repeatable experimental design to understand the salinity of the soil and emphasizes the necessity to implement concerted efforts between farmers and researchers and policymakers.

Conclusion

This work represents a thorough and spatially specific evaluation of the salinity in the soil and the implications of the same to agriculture in the District Khushab. The results clearly show that the salinity and sodicity are common in most of the agricultural land in the district and this is caused by the high concentration of sodium and poor drainage. The electrical conductivity, SAR and ESP values of various locations were higher than the critical values and would have moved these soils into saline-sodic category and could not support most conventional crops without some intervention. A close relationship of other important salinity indicators supports the main hypothesis that sodium plays a key role in reducing soil chemical and physical characteristics.

Moreover, the low levels of organic matters and the constant alkalinity of the pH in the study indicates further limitations on fertility to add to the effects of salinity of crops. The study of spatial variability showed that soil texture and

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irrigation method have great impacts on salt accumulation with clay soil and regions relying on brackish groundwater being the most impacted. The EC and SAR values were highest in Sites 8 and 9 and should be given priority to be reclaimed.

To sum up, the research establishes that soil salinity in Khushab is an endemic and dynamic challenge to the agricultural productivity, food security and rural livelihoods. The arable land in large areas will become irretrievable without timely and localized interventions. The information produced in this area can be useful in the process of informing soil healing procedures, extension, and sustainable agriculture within the area.

Future Recommendations

Based on the findings of this study, the following recommendations are proposed to mitigate soil salinity and enhance sustainable agriculture in District Khushab:

1. **Site-Specific Reclamation**

Apply gypsum or other calcium-rich soil amendments in high-salinity and sodicity zones, particularly in Sites 8 and 9, to replace exchangeable sodium and improve soil structure.

2. **Organic Matter Enhancement**

Promote the application of farmyard manure, compost, and green manures to improve microbial activity, water retention, and soil nutrient status.

3. **Irrigation Water Management**

Monitor groundwater quality regularly and discourage the use of brackish tube wells. Encourage the use of canal water where feasible and implement conjunctive water use strategies.

4. **Installation of Field Drains**

Improve surface and sub-surface drainage infrastructure to prevent waterlogging and facilitate salt leaching, especially in low-lying clay-dominant areas.

5. **Crop Diversification with Salt-Tolerant Varieties**

Introduce salt-tolerant cultivars of wheat, barley, and fodder crops in moderately to severely affected areas to ensure continued land use and productivity.

6. **Soil Monitoring and Early Warning Systems**

Establish a district-level salinity monitoring program using EC sensors and GIS-

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based mapping to detect early-stage salinization and guide farmer decisions.

7. **Capacity Building and Farmer Training**

Organize awareness campaigns, training workshops, and field demonstrations to educate farmers about salinity risks, soil health management, and best practices.

8. **Policy Support and Incentives**

Advocate for inclusion of Khushab in national soil rehabilitation programs and provide subsidies or incentives for the adoption of salinity management technologies. Future studies should include temporal monitoring to assess how seasonal changes and farming practices influence salinity dynamics over time. Integration with remote sensing and modeling tools would also help upscale findings and guide regional-level planning.

Declarations

Consent for publication

All subjects gave their "informed consent" for the publication of details within the text ("informed consent") to be published in the above Journal and Article. Written "informed consent" was obtained from all authors for the publication of this manuscript.

Availability of data and materials

The data generated are provided within the manuscript and will be available from author at reasonable request

Competing Interest

All authors declare that there are no competing interests.

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