INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING,
MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue IV, April 2026

Assessment of Salinity Dynamics of Irrigated and Rain-Fed Soils

Ali Bulama Gambo, Dr. Neha Mumtaz

Civil Engineering, Integral Univesity

DOI: https://doi.org/10.51583/IJLTEMAS.2026.150400030

Received: 09 April 2026; Accepted: 15 April 2026; Published: 04 May 2026

ABSTRACT

This research discusses the salinity cycle of irrigated and rain-fed soils in the Integral University Agricultural Farm, Lucknow, Uttar Pradesh, India. Sustainable agriculture is a significant challenge facing soil salinization especially in arid and semi-arid areas where irrigation activities, climatic fluctuations and poor drainage further leads to the soil piling up the soluble salts in the soil profile. The research will be used to compare the main salinity parameters in two opposite land-use systems, irrigation and rain-fed, in the same agroecological environment. A comparative cross-sectional design was used and systematic sampling of soils was done on the surface layer (0 15 cm). Laboratory tests were conducted in accordance with the standard procedures to establish physicochemical parameters, such as pH, electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-). The values were compared to the internationally accepted FAO salinity classification standards. The results show that there is a significant variation in the salinity levels of rain-fed and irrigated soils. Irrigated soils have a greater salt content as a result of continuous irrigation with groundwater, high evapotranspiration and low drainage. In comparison, rain-fed soils are less salty, and this is affected by seasonal rainfall and natural processes of leaching. The findings indicate the importance of irrigation activities and water quality in influencing the dynamics of soil salinity. This work presents a scientific background of the salinity changes in alluvial soils of the Indo-Gangetic Plains and highlights the fact that site-specific management measures, such as better irrigation, drainage and constant monitoring of the soils are necessary. The results are useful to sustainable land and water management and policy implementation designed to reduce soil erosion and guarantee agricultural productivity in the long term.

Keywords: Soil Salinity, Irrigated and Rain-fed Soils, Electrical Conductivity (EC), Soil Physicochemical Properties, Salinity Dynamics.

INTRODUCTION

The salinization of soils has become one of the most pressing issues for sustainable agricultural systems worldwide, and especially in arid and semi-arid areas, where scarce rainfall and high evapotranspiration rates predispose the development of progressive increases in the concentration of soluble salts in the soil profile. This process not only poses a threat to agronomic productivity, but also to the long-term ecological integrity of the landscapes involved and food security of the populations that are dependent on it. The Food and Agriculture Organization and the Intergovernmental Technical Panel on Soils [1] estimate that some 955 million hectares of land on Earth are at risk due to salinity, 76 million hectares of which have been directly affected by human-induced secondary salinization. The economic impacts of salt-induced land degradation are also very worrying, as the estimated global losses each year exceed USD 27 billion in the direct crop production losses, land devaluation, and spending on remediation efforts [2].

Salinization has two main sources: primary (natural) and secondary (anthropogenic) methods. The main causes of salinization are geochemical effects such as parent rock weathering, mineral dissolution and redistribution, intrusion of seawater into coastal aquifers and aeolian deposition of marine aerosols [3]. The secondary salinization, however, has taken the lead and is growing much faster, with the dominant contribution of irrigated agriculture, which provides almost 40 percent of world food production on only 20 percent of arable land [4]. Repeated irrigation of the soil using irrigation water of poor quality without sufficient drainage to remove accumulated salts beneath the root zone gradually changes the physicochemical characteristics of the soil, destabilizing nutrient availability, water uptake by plants, interactions within the microbial community, and soil structure [5,6].

Eswar et al. [7] thoroughly examined the cause-and-effect relationships between soil salinization and climate change, and they determined the elevated temperatures, unpredictable rainfall, increased reliance on marginal-quality groundwater as the irrigation source, and rising saline water tables as the main risks of the present day. Their estimates showed that climate change alone, with its impact on the rainfall evapotranspiration balance, would increase salt-affected soil areas in arid and semi-arid regions by up to 10 percent by 2050 without any substantial increase in irrigation. Complementary to this, Hassani et al. [8] designed a universal machine learning model to forecast primary soil salinization risk in all climate conditions and all areas in the world to classify the Indo-Gangetic Plains, Mesopotamian lowlands, the North China Plain, and the Murray-Darling Basin as regions of convergent and increasing salinization risk in both RCP4.5.

Salinity has a dual mechanism of stress at the plant physiological level as fully explained by Munns and Tester [9] in their two-phase paradigm. The first osmotic step which happens within hours to days of salt exposure, decreases osmotic potential of the soil solution, restricting the uptake of water by plants, triggering stomatal closure, and inhibiting photosynthetic CO_2 assimilation and growth rate. The next ion-specific step the sequential build-up of sodium (Na^+) and chloride (Cl^-) in leaf tissues, enzymatic deactivation, the build-up of reactive oxygen species, membrane instability, and the eventual premature senescence and cell death of leaves are ion-specific stages. Singh et al. [10] also described the mechanistic foundation of chloride toxicity, which is direct impact on photosynthetic electron transport and inactivating of essential enzymes by Cl^-concentrations greater than 100–150 mM in the mesophyl cell of leaves, representing a different and complementary pathway compared to osmotic inhibition. This group of stressors has been found to cause quantifiable yield losses in a broad spectrum of economically valuable crop species, with sensitive crops like beans and carrots showing a significant yield loss at EC values as low as 1.0 dS m^{-1}, and crops with moderate tolerance like wheat (EC threshold 6.0 dS m^{-1}) and maize (EC threshold 1.7 dS m^{-1}) showing a severe decrease in productivity.

The soil salinity is not uniform in space and time but complex dynamics of the interaction of climate variability, soil texture, irrigation management, drainage infrastructure, and groundwater properties. The salinity of soils with shallow underlying saline aquifers, as illustrated by Kumar et al. [11] using multi-decadal analysis of dryland systems across South Asia, is intensely driven by the inter-annual variability of rainfall, with below-normal monsoon years yielding greatly increased post-monsoon EC values when compared to years of normal or above-normal rainfall. Wang et al. [12] also emphasized that the most crucial warning of long-term salinization risk is sub-surface salinity dynamics, which cannot be effectively captured by remote sensing techniques alone, but instead have to be combined with ground-based geophysical and hydro-logical observations, especially in alluvial systems where sub-surface salt buildup can predict surface expression years to decades before the surface.

The Indo-Gangetic Plains of northern India are considered one of the most fertile agroecological zones in the world, but they are also highly susceptible to salinity. Singh et al. [13] used satellite imagery, soil survey data, and field validation to develop a spatially explicit database of salt-affected soils across the Indian subcontinent, finding approximately 6.73 million hectares of salt-affected land in Uttar Pradesh, Haryana, and Rajasthan. These saline and sodic soils are mainly concentrated in alluvial areas. Their discussion explained that the recent expansion of salt-affected regions is driven by the increasing use of tube-well irrigation from shallow salty aquifers, limited sub-surface drainage capacity in flat alluvial landscapes, and the declining quality of groundwater in overexploited aquifers, all conditions that are directly relevant to the current study.

The current research site is the Integral University Agricultural Farm which is run under the Integral Institute of Agricultural Science and Technology (IIAST) in Lucknow, Uttar Pradesh, India (26.956232° N, 81.003817° E). The site is a special comparative site: there are two distinctly different soil management systems, continuously irrigated and only rain-fed, which exist in the same alluvial soilscape, and which are subject to the same macro-climatic and geological conditions. The hot dry summer with evapotranspiration more than 10 times higher than precipitation, a highly concentrated monsoonal season bringing 70–80 percent of annual precipitation, and cool dry winters, create strong seasonal variations in salt levels and some leaching. Corwin [14] has highlighted that within these systems, the massively accelerating climate change is projected to reduce the source of surface water during the dry season to irrigate crops; in turn, decreasing the availability of groundwater in increasingly salinized aquifers, which increases root-zone salt loading per unit of irrigated land. The trend necessitates that the characterization and comparative analysis of baseline salinity and irrigated and rain-fed systems should be done with scientific rigour to inform sustainable land and water management planning.

Although much of the world literature is available on soil salinity, a research gap remains in terms of comparative field studies, which have the capacity to simultaneously describe salinity dynamic when the soil and climate are in irrigated and rain-fed conditions. The majority of the literature has analyzed either irrigated or rain-fed salinity alone, which does not allow making strong, location-specific conclusions regarding the relative role of irrigation management in salt accretion [15,16].

This gap is directly addressed by the present study in terms of systematic characterization of the physicochemical parameters of salinity of soil in the two-management systems pH, electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) in both management systems against internationally accepted Food and Agriculture Organization (FAO). The results are expected to offer empirically informed evidence base to guide site-specific salinity management advice and it is expected to add to the overall scientific body of knowledge on irrigated agriculture sustainability in the Indo-Gangetic Plains.

MATERIALS AND METHODS

Study Area

The research study was conducted at the Agricultural Farm of Integral University, which operates under the Integral Institute of Agricultural Science and Technology (IIAST), Lucknow, Uttar Pradesh, India. The study area is geographically located at approximately 26.956232° N latitude and 81.003817° E longitude. The spatial location and extent of the study area are depicted in Figure 1, which presents a Google Earth map of the experimental site.

The study area lies within the Indo-Gangetic Plains, one of the most important agricultural regions of India. This region is characterized by extensive cultivation supported by both rain-fed and irrigated farming systems, making it suitable for investigating soil salinity dynamics under contrasting water management conditions.

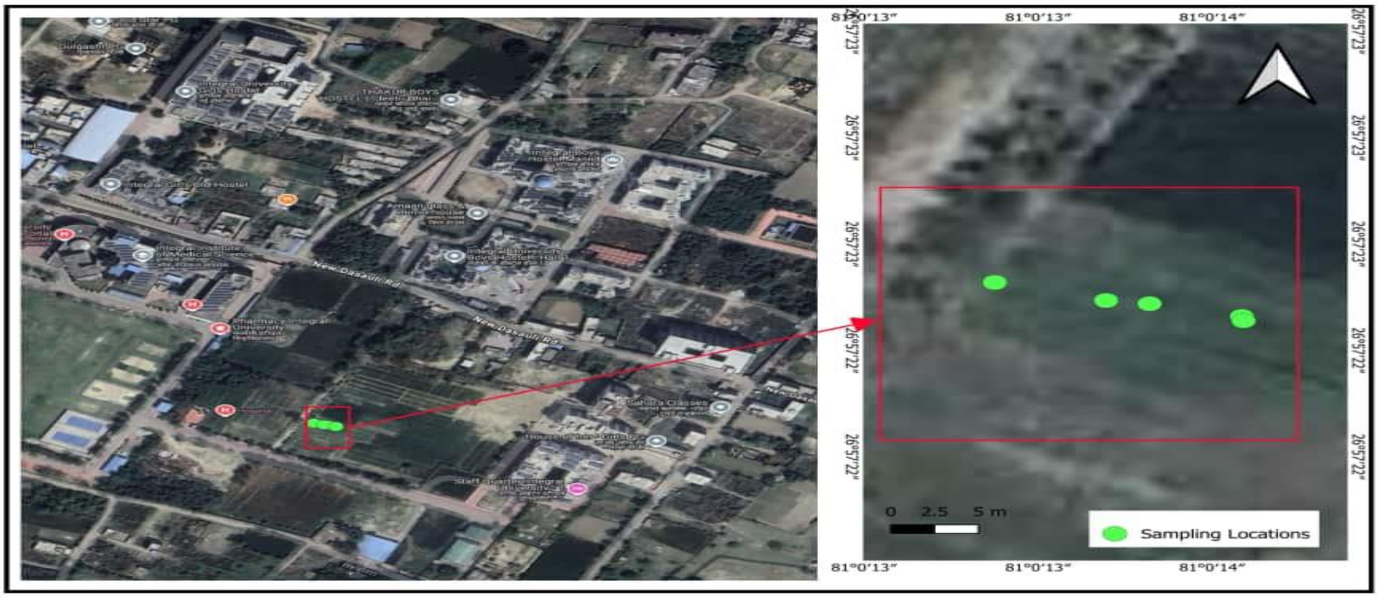

Fig. 1. Google Earth map of the study area

Climate

The climate of the study area is subtropical, with three distinct seasons: summer (March to June), monsoon (July to September), and winter (October to February). Summers are typically hot, with maximum temperatures often exceeding 40°C, while winters are mild to cool, with minimum temperatures occasionally falling below 5°C. The region receives an average annual rainfall of approximately 900–1,000 mm, the majority of which occurs during the southwest monsoon season. Rainfall variability plays a significant role in soil moisture availability and salt leaching processes, particularly in rain-fed agricultural fields.

Soil Characteristics

The soils of the study area are predominantly alluvial in origin, typical of the Indo-Gangetic Plains. They generally range from sandy loam to clay loam in texture, with moderate water-holding capacity and fertility. Due to intensive cultivation and long-term irrigation practices, some areas of the farm exhibit signs of salt accumulation, particularly in low-lying fields and poorly drained sections. These soil characteristics provide a suitable environment for assessing variations in soil salinity under different land-use and irrigation regimes.

Land Use and Cropping Pattern

The Agricultural Farm of Integral University is primarily used for experimental and instructional purposes, with crops cultivated under both irrigated and rain-fed conditions. Major crops grown in the area include cereals, oilseeds, and seasonal crops, following typical regional cropping patterns. The presence of multiple crop types and management practices allows for a comparative assessment of soil salinity behavior across different agricultural systems.

Irrigation and Drainage

Irrigation in the study area is mainly supported by groundwater sources, supplemented by rainfall during the monsoon season. Variations in irrigation frequency, water quality, and field management practices contribute to spatial differences in soil salinity levels. Drainage conditions vary across the farm, with some fields experiencing restricted natural drainage, which can enhance salt accumulation in the root zone.

Experimental Design and Sampling

This study adopts a comparative, cross-sectional field-and-laboratory research design. Surface soil samples were collected from both irrigated and rain-fed plots within the same farm boundary to control for macro-scale climatic and geological variability. Physicochemical analyses were performed on soil extracts to quantify the key salinity and alkalinity parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Chloride (Cl^-), Carbonate (CO_3^{2-}), and Bicarbonate (HCO_3^-). Measured values were compared against FAO irrigation water quality standards and classified according to recognized salinity hazard categories.

Sampling Design

Soil samples were collected from a depth of 0–15 cm, representing the root zone most affected by surface evaporation and irrigation-induced salt accumulation. A random sampling approach was employed to minimize spatial bias and ensure representative coverage of both irrigated and rain-fed zones within the study area.

Fig. 2. Collection of soil samples

Composite Sampling Procedure

At each selected sampling location, multiple soil cores were extracted using clean stainless-steel augers and thoroughly mixed in the field to form a single composite sample. Composite sampling is a widely accepted practice in soil salinity studies as it reduces the influence of micro-scale spatial heterogeneity and enhances the representativeness of derived chemical parameters.

Sample Handling and Preparation

Visible plant residues, stones, and organic debris were manually removed from each composite sample before bagging. Samples were placed in clean, sealed polyethylene bags and labelled with unique site identifiers, land-use type (irrigated / rain-fed), GPS coordinates, sampling depth, and date of collection. All samples were transported to the laboratory within 24 hours of collection and subjected to preliminary air-drying and sieving (2 mm mesh) before analysis.

Laboratory Analysis

Determination of Soil pH

Soil pH was determined to characterize the degree of acidity or alkalinity of the sampled soils. The analysis was conducted using a digital pH meter with a soil-to-water ratio of 1:2.5.

Determination of Electrical Conductivity (EC)

Electrical Conductivity (EC) was measured as a primary quantitative indicator of the total soluble salt concentration in the soil using a conductivity meter after filtration of the soil extract.

Estimation of Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) were estimated to quantify the aggregate mass concentration of dissolved salts in the soil extract using the empirical relation:

$$\text{TDS (mg L}^{-1}\text{)} = \text{EC (dS m}^{-1}\text{)} \times 550$$

Determination of Chloride (Cl^-)

Chloride concentration was determined using the Mohr argentometric titration method.

Determination of Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^-)

Carbonate and bicarbonate concentrations were determined using the double-indicator titration method.

Standards and Classification

All laboratory procedures and analytical methods were conducted in conformity with the relevant Indian Standard (IS) codes issued by the Bureau of Indian Standards (BIS). Measured values were compared against FAO irrigation water quality standards and classified according to recognized salinity hazard categories.

Instrumentation

All soil preparation, physicochemical testing, and analytical procedures were performed in the Environmental Engineering Laboratory of the Civil Engineering Department, Integral University. Instruments used included digital pH meters, conductivity meters, analytical balances, filtration apparatus, and titration equipment.

Quality Assurance and Quality Control (QA/QC)

A rigorous quality assurance and quality control framework was maintained to ensure accuracy, precision, and reproducibility of results. Calibration of instruments was carried out using standard solutions, and all measurements were performed in duplicate. Any measurement deviating beyond acceptable limits was repeated.

Data Analysis

Measured parameters were compared between irrigated and rain-fed soils and evaluated against FAO classification thresholds to assess salinity status and potential impacts on agricultural productivity.

RESULTS

Overview

This section presents the results of the physicochemical analysis of irrigated and rain-fed soils based on FAO standards. The parameters analyzed include pH, electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-). The results provide a comparative understanding of salinity and alkalinity conditions in the two soil systems.

Soil Reaction (pH)

Table 1 Soil pH values and FAO classification

Soil Type	pH	FAO Range	Salinity Class	Interpretation
Irrigated	8.3	6.5–8.5	Normal	Suitable for most crops
Rain-fed	8.5	6.5–8.5	Upper limit	Risk of reduced nutrient availability

Source: Laboratory analysis (2026); FAO classification

The results show that both soils fall within the acceptable FAO range. However, the rain-fed soil lies at the upper limit, indicating a tendency toward alkalinity. The irrigated soil, although slightly lower, also exhibits alkaline characteristics. This suggests that both soil systems may gradually shift toward higher alkalinity if not properly managed.

Electrical Conductivity (EC)

Table 2 Electrical conductivity and salinity classification

Soil Type	EC (dS m^{-1})	FAO Range	Salinity Class	Interpretation
Irrigated	8.9	8–16	Strongly saline	Severe salinity
Rain-fed	7.5	4–8	Moderately saline	Yield reduction likely

Source: Laboratory analysis (2026); FAO classification

The EC values indicate significant salinity in both soils. Irrigated soils fall within the strongly saline category, while rain-fed soils are moderately saline and close to the threshold of strong salinity. This pattern highlights a clear difference in salinity intensity between the two systems.

Total Dissolved Solids (TDS)

Table 3 Total dissolved solids and classification

Soil Type	TDS (mg L^{-1})	FAO Range	Classification	Interpretation
Irrigated	4895	>2000	Unfit	Unsuitable
Rain-fed	4125	>2000	Unfit	High salinity hazard

Source: Laboratory analysis (2026); FAO classification

The TDS values in both soils exceed FAO permissible limits, indicating very high levels of dissolved salts. The irrigated soil shows a slightly higher value, suggesting greater accumulation of salts compared to the rain-fed system.

Chloride (Cl^-)

Table 4 Chloride concentration

Soil Type	Cl^- (meq L^{-1})	FAO Range	Classification	Interpretation
Irrigated	6	4–10	Some restriction	Moderate risk
Rain-fed	4	<4	Safe (borderline)	Near restriction

Source: Laboratory analysis (2026); FAO classification

Chloride levels are higher in irrigated soils than in rain-fed soils. While irrigated soils fall within the moderate restriction category, rain-fed soils remain at the borderline of safe limits, indicating relatively lower salt accumulation.

Carbonate (CO_3^{2-})

Table 5 Carbonate concentration

Soil Type	CO_3^{2-} (meq L^{-1})	FAO Range	Classification	Interpretation
Irrigated	0.5	<1.5	Slight concern	Minimal effect
Rain-fed	1.1	<1.5	Slight concern	Slight contribution

Source: Laboratory analysis (2026); FAO classification

Carbonate concentrations are low in both soils and fall within acceptable limits. The slightly higher values in rain-fed soils indicate a minor contribution to alkalinity.

Bicarbonate (HCO_3^-)

Table 6 Bicarbonate concentration

Soil Type	HCO_3^- (meq L^{-1})	FAO Range	Classification	Interpretation
Irrigated	2.0	1.5–2.5	Moderate	Nutrient risk
Rain-fed	2.5	1.5–2.5	Upper limit	Alkalinity risk

Source: Laboratory analysis (2026); FAO classification

Both soils fall within the moderate range of bicarbonate concentration. The rain-fed soil reaches the upper limit, indicating a higher tendency toward alkalinity compared to irrigated soils.

SUMMARY OF RESULTS

Table 7 Summary of soil salinity parameters

Parameter	Unit	Irrigated Soil	Rain-fed Soil	Classification
pH	—	8.3	8.5	Normal–alkaline
EC	dS m^{-1}	8.9	7.5	Strong–moderate
TDS	mg L^{-1}	4895	4125	Unfit
Cl^-	meq L^{-1}	6	4	Moderate–safe
CO_3^{2-}	meq L^{-1}	0.5	1.1	Low
HCO_3^-	meq L^{-1}	2.0	2.5	Moderate

The results collectively indicate that both soils are affected by salinity, with irrigated soils showing relatively higher salt accumulation compared to rain-fed soils.

DISCUSSION

The pH values obtained in this study (8.3–8.5) indicate that both irrigated and rain-fed soils are moderately alkaline and lie at the upper limit of the acceptable range for agricultural soils. This suggests a tendency toward reduced nutrient availability and potential long-term soil degradation. Similar alkaline conditions have been reported in irrigated agricultural systems where bicarbonates and basic cations accumulate due to continuous application of groundwater [1,2]. The slightly higher pH observed in irrigated soils reflects the influence of irrigation water quality and limited drainage, which promote salt accumulation. In contrast, rain-fed soils exhibit marginally lower pH values due to natural leaching processes during rainfall. However, the persistence of alkaline conditions in both soils indicates that inherent soil properties and climatic factors also play a significant role. Elevated pH levels, particularly above 8.0, are known to reduce the availability of essential micronutrients such as iron, zinc, and manganese, thereby affecting crop productivity [3].

The electrical conductivity (EC) values (8.9 dS m^{-1} in irrigated soils and 7.5 dS m^{-1} in rain-fed soils) reveal significant salinity stress in both systems, with irrigated soils falling within the strongly saline category and rain-fed soils within the moderately saline range. These findings are consistent with previous studies demonstrating that continuous irrigation with mineral-rich groundwater leads to salt accumulation in the root zone [4,5]. The higher EC observed in irrigated soils can be attributed to evapotranspiration and inadequate drainage, which concentrate salts near the soil surface. Although rain-fed soils benefit from seasonal rainfall that facilitates partial leaching of salts, the observed values indicate that natural processes alone are insufficient to prevent salinity buildup. High EC levels impose osmotic stress on plants, limiting their ability to absorb water and ultimately reducing crop yield, particularly in salt-sensitive species [6].

The total dissolved solids (TDS) values further confirm the presence of excessive salinity in both soils, with recorded values of 4895 mg L^{-1} and 4125 mg L^{-1} for irrigated and rain-fed soils, respectively. These values far exceed FAO permissible limits and are indicative of severe salinity conditions. Similar trends have been reported in irrigated agricultural regions where groundwater contributes significantly to dissolved salt accumulation [7]. Elevated TDS increases the osmotic potential of the soil solution, thereby reducing water availability to plants and creating conditions analogous to physiological drought. This can severely impair plant growth and productivity, even in the presence of adequate soil moisture.

Chloride concentrations were found to be higher in irrigated soils (6 meq L^{-1}) compared to rain-fed soils (4 meq L^{-1}), placing irrigated soils within the moderate restriction category and rain-fed soils at the borderline of safe limits. This pattern is consistent with earlier studies indicating that chloride accumulates in soils due to repeated application of saline irrigation water [8]. In rain-fed systems, periodic rainfall contributes to the dilution and downward movement of chloride ions, thereby reducing their concentration at the surface. However, excessive chloride can be toxic to plants, particularly sensitive crops, as it interferes with physiological processes such as photosynthesis and nutrient uptake.

Carbonate concentrations in both soils were relatively low (0.5–1.1 meq L^{-1}) and fall within acceptable limits, indicating minimal immediate risk. However, carbonates contribute to overall soil alkalinity and may influence nutrient availability and soil chemical balance [9]. The slightly higher carbonate levels observed in rain-fed soils may be associated with natural soil processes, including the weathering of carbonate-rich parent materials and reduced dissolution under non-irrigated conditions.

Bicarbonate concentrations (2.0–2.5 meq L^{-1}) fall within the moderate concern range and represent an important factor influencing soil chemical behavior. Elevated bicarbonate levels can lead to the precipitation of calcium and magnesium, thereby increasing the relative dominance of sodium in the soil. This process promotes the development of sodicity, which adversely affects soil structure, reduces permeability, and limits aeration [10]. The slightly higher bicarbonate concentration observed in rain-fed soils suggests that natural mineral weathering processes also contribute to alkalinity, in addition to irrigation-related effects.

Overall, the results clearly demonstrate that both irrigated and rain-fed soils are affected by salinity and alkalinity, with irrigated soils showing more severe conditions due to continuous groundwater irrigation and limited drainage. While rain-fed soils benefit from natural leaching processes, they still exhibit elevated salinity levels, indicating that climatic and soil factors also play a role. These findings highlight the need for improved irrigation management, effective drainage systems, and regular soil monitoring to mitigate salinity risks and ensure sustainable agricultural productivity in the study area.

CONCLUSION

This study assessed the salinity dynamics of irrigated and rain-fed soils at the Integral University Agricultural Farm located in the Indo-Gangetic Plains. The analysis of key physicochemical parameters pH, electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) provided a comprehensive understanding of soil salinity and alkalinity under different water management systems.

The results indicate that both irrigated and rain-fed soils are affected by salinity and alkalinity, although the intensity varies between the two systems. Soil pH values (8.3–8.5) confirm moderately alkaline conditions, with irrigated soils showing a greater tendency toward alkalinity. This suggests a potential decline in nutrient availability and long-term soil quality if not properly managed.

Electrical conductivity values further highlight the severity of salinity, with irrigated soils (8.9 dS m^{-1}) classified as strongly saline and rain-fed soils (7.5 dS m^{-1}) as moderately saline but approaching the threshold of strong salinity. Similarly, TDS values in both soils exceed FAO permissible limits, confirming the presence of high dissolved salt concentrations capable of inducing osmotic stress and reducing plant water uptake and crop productivity.

Chloride concentrations indicate moderate restriction in irrigated soils and borderline safety in rain-fed soils, suggesting a higher risk of chloride toxicity under irrigation. Carbonate levels remain low and do not pose an immediate concern; however, bicarbonate concentrations (2.0–2.5 meq L^{-1}) indicate a moderate risk of sodicity development. This may lead to soil structural degradation, reduced permeability, and impaired aeration over time.

Overall, the study demonstrates that irrigated soils exhibit higher salinity and ionic accumulation compared to rain-fed soils, primarily due to continuous groundwater irrigation and limited drainage. Although rainfall contributes to partial leaching in rain-fed systems, it is insufficient to prevent salinity buildup.

In conclusion, the soils in the study area can be characterized as saline-alkaline, posing a significant constraint to sustainable agricultural productivity. Effective management strategies, including improved irrigation practices, proper drainage systems, and regular soil monitoring, are essential to mitigate salinity risks and ensure long-term soil health.

REFERENCES

1. Food and Agriculture Organization of the United Nations (FAO), & Intergovernmental Technical Panel on Soils (ITPS). (2021). Global assessment of soil salinization. FAO. https://doi.org/10.4060/cb7247en
2. Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., Drechsel, P., & Noble, A. D. (2014). Economics of salt-induced land degradation and restoration. Natural Resources Forum, 38(4), 282–295. https://doi.org/10.1111/1477-8947.12054
3. Ondrasek, G., Rengel, Z., & Veres, S. (2011). Soil salinisation and salt stress in crop production. In Abiotic stress in plants: Mechanisms and adaptations. InTech. https://doi.org/10.5772/22248
4. Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation — A global inventory. Hydrology and Earth System Sciences, 14(10), 1863–1880. https://doi.org/10.5194/hess-14-1863-2010
5. Litalien, A., & Zeeb, B. (2020). Curing the earth: Anthropogenic soil salinization and plant-based strategies for sustainable desalination. Science of the Total Environment, 698, 134235. https://doi.org/10.1016/j.scitotenv.2019.134235
6. Sahab, S., Suhani, I., Srivastava, V., Chauhan, P. S., Singh, R. P., & Prasad, V. (2021). Soil salinity risk assessment and management strategies. Science of the Total Environment, 764, 144164. https://doi.org/10.1016/j.scitotenv.2020.144164

7. Eswar, D., Karuppusamy, R., & Chellamuthu, S. (2021). Drivers of soil salinity and their correlation with climate change. Current Opinion in Environmental Sustainability, 50, 310–318. https://doi.org/10.1016/j.cosust.2021.04.003
8. Hassani, A., Azapagic, A., & Shokri, N. (2021). Global predictions of primary soil salinization under climate change. Nature Communications, 12, 6663. https://doi.org/10.1038/s41467-021-27188-2
9. Tester, M., & Munns, R. (2008). Mechanisms of salinity tolerance. Annual Review of Plant Biology, 59, 651–681. https://doi.org/10.1146/annurev.arplant.59.032607.092911
10. Singh, R., Mishra, A., Gupta, S., & Kumar, V. (2023). Chloride toxicity in crops and its management. Environmental and Experimental Botany, 204, 105089. https://doi.org/10.1016/j.envexpbot.2022.105089
11. Kumar, M., Raghavan, S., & Tiwari, A. K. (2020). Salinity dynamics in South Asian dryland systems. Journal of Hydrology, 582, 124478. https://doi.org/10.1016/j.jhydrol.2019.124478
12. Wang, F., Shi, Z., Biswas, B., Yang, S., & Ding, J. (2024). Advances in soil salinity assessment using remote sensing and machine learning. Remote Sensing, 16(2), 278. https://doi.org/10.3390/rs16020278
13. Singh, S. K., Bhatt, S. C., Chand, T., & Upadhyay, A. K. (2020). Distribution of salt-affected soils in the Indo-Gangetic Plains. Journal of the Indian Society of Soil Science, 68(3), 312–323. https://doi.org/10.5958/0974-0228.2020.00038.5
14. Corwin, D. L. (2021). Climate change impacts on soil salinity. European Journal of Soil Science, 72(2), 842–862. https://doi.org/10.1111/ejss.13010
15. Gelu, G., Molla, E., & Taddesse, G. (2025). Salinity distribution in semi-arid regions. Agricultural Water Management, 291, 108713. https://doi.org/10.1016/j.agwat.2024.108713
16. Sarkar, S. K., Islam, M. A., Kabir, M. H., & Islam, M. T. (2024). Root-zone soil salinity observatory in coastal Bangladesh. Science of the Total Environment, 912, 168865. https://doi.org/10.1016/j.scitotenv.2023.168865