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Research article

Seasonal Variability in Soil Salinity and its Climatic Drivers in Khulna, Bangladesh

Karno Kumar Mondal[1*], Md. Abdullah Elias Akhter[1], Muhammad Abul Kalam Mallik[2]

[1] Department of Physics, Khulna University of Engineering & Technology, Bangladesh; [2] Bangladesh Meteorological Department, Agargaon-Dhaka, Bangladesh

[*] Correspondence: karno@kuet.ac.bd

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Abstract

Bangladesh is one of the countries in the world most severely affected by soil salinity issues. This research focuses on the seasonal variation in soil salinity and the associated impact of climate change across different sites in the Batiaghata sub-district of Khulna, located in the southwestern coastal belt of Bangladesh. The study encompasses four meteorological seasons: pre-monsoon (March-April-May), monsoon (June-July-August-September), post-monsoon (October-November), and winter (December-January-February). Maximum and minimum electrical conductivity values are employed, collected from the Soil Research Development Institute (SRDI) in Khulna, and which show variations in the pre-monsoon and monsoon seasons. The Normalized Difference Salinity Index (NDSI) is used to detect soil salinity aspects using remote sensing techniques. Satellite-derived NDSI indices, visualised via the ArcGIS template, indicate that soil salinity peaks during the pre-monsoon season, which is consistent with the observed data. The minimum values were recorded in the monsoon season. The highest maximum value of the NDSI indices for the pre-monsoon season was 0.11580, while the lowest maximum value for the monsoon season was 0.06533. Rainfall is the main reason for lower soil salinity in the monsoon season. Conversely, soil salinity increases during the pre-monsoon season due to higher average air temperatures (2m above surface). The broader implication of the study is that it highlights how climate drivers influence soil salinity. It also supports the formulation of targeted climate adaptation and coastal resilience policies. The main focus of the study is on temperature, rainfall and cyclone data; however, this could be considered a limitation, as other elements that also affect soil salinity, such as wind patterns, evapotranspiration and tidal effects are not fully examined. Furthermore, understanding of long-term salinity trends and variability influenced by interannual climatic patterns may be limited due to the use of short-term data.

Keywords: Soil Salinity; Climatic Impression; Variability; Seasonal, Indices.

1. Introduction

Bangladesh faces various natural calamities due to its geological location, with coastal areas being the worst affected by soil salinity, cyclones, storm surges and flooding. In such areas, soil salinity poses major risks to agriculture, and livelihoods, and to ecosystem health, which is a crucial environmental concern. Its low elevation, tidal effects and seasonal freshwater scarcity are characteristics of the Ganges Delta, which includes the coastal region in the southwest of the country. Agricultural interventions related to climate change-related salinity adaptation are vital to guarantee food security in the context of environmental change (Lam *et al.,* 2021).

A recent study found that estimations of the soil salinity in the south-central coast of Bangladesh are far higher than those found in historical records (Bhuyan *et al.,* 2023), with a decrease of 20.96% in suitable land for crops in the coastal areas, and a significant rise in soil salinity between 1990 and 2016 (Morshed *et al.,* 2021). Significant seasonal (dry and wet) variation in soil salinity in the coastal regions of Bhola island, Bangladesh, has been found (Jamil *et al.,* 2020).

Studies have also been conducted on seasonal variation in the many parts in our Earth which indicate that coastal zones are plagued by high saline levels during the dry season and severe drought and flooding during the wet season (Yadav *et al.,* 2019). Soil salinity is positively connected with depth; it is higher in the accreted land of the Noakhali district in Bangladesh than in the non-accreted areas (Das *et al.,* 2020).

In recent decades, soil salinisation has increased due to a combination of natural and man-made processes, such as tidal inundation, rising sea levels, increased evapotranspiration, and reduced upstream freshwater flow. The primary cause of soil salinity is natural events such as periodic flooding, but incorrect and unscientific irrigation practices have also contributed over time. Inappropriate irrigation, soil erosion, dispersion, and engineering issues are some of the factors which contribute to soil salinity. The southwestern coastal district of Satkhira in Bangladesh has particularly suffered from climate change-driven salinity intrusion (Fahim *et al.,* 2023). Excessive rainfall is inversely correlated with soil salinity levels in the Noakhali coastal region of Bangladesh, while rising temperatures have shown positive interaction with the salinity (Kawser *et al.,* 2022).

The soil salinity scenario of the southwest coastal region of Bangladesh offers invaluable insights for mitigation and policy-making in the context of climate-driven issues (Sarkar *et al.,* 2025). Soil salinity is negatively affected by climate change, and significantly hinders crop productivity in coastal areas (Sarkar *et al.,* 2022).

Remote sensing and GIS tools are a precise approach to mapping coastal salinity and addressing climate drivers. A study conducted in China coastal zone which covering 350,000 square kilometers of sea area, shows potential for coastal monitoring and provides a robust framework for sustainable development (Liu *et al.,* 2025). Another study, likewise conducted in China, also provides invaluable insights for the spatial prediction of soil salinity (Zhou *et al.,* 2024). Remote sensing and GIS techniques indicate a high potential for mapping saline areas, with a correlation coefficient (R^2) of 0.73 and RMSE of 0.68 respectively (Thiam *et al.,* 2021). Monitoring soil salinity levels and mapping salinity-affected areas can be achieved using remote sensing, a non-invasive and time-saving technique (Tripathi *et al.,* 2020).

Research has been conducted in the Batiaghata sub-district in Khulna to evaluate variations in soil salinity. The district is facing acute salinity due to salinity intrusion by storm surges and irrigation during cultivation from surface water (Shaibur *et al.,* 2021). There was an increasing tendency from 2008 to 2018 of electrical conductivity in areas where rice was cultivated. Research has revealed that in Bangladesh the spatial distribution of salinity has tended to increase, with approximately 222,300 ha of land newly affected over the last decade (Faisal *et al.,* 2020).

Some studies have documented the spatial distribution of soil salinity with limited reference to the role of seasonal climatic variability, and have rarely integrated satellite validation (Faisal *et al.,* 2020). However, our study overcomes such limitations by enhancing the remote sensing linkage to seasonal variation, thus providing more comprehensive climatic integration and variation, and by examining the differences between the four meteorological seasons in terms of soil salinity.

The research also suggests policies for a sustainable ecological environment in relation to the crop production sector. We consider temperature, rainfall and cyclone-associated storm surges for comprehensive climatic integration, together with pre-monsoon, monsoon, post-monsoon and winter seasonal variations and tendencies, contributing to the uniqueness of the study. The research aims to assess recent seasonal variability in soil salinity; to evaluate the influence of climatic conditions on such variation; and to establish the relationship between observed soil salinity and satellite-derived indices using remote sensing and GIS technology.

2. Materials and Methods

2.1. Study Area

The research was conducted in Khulna District, located in the coastal region of Bangladesh. The study focuses on six sites within Batiaghata, a sub-district of Khulna. Batiaghata is divided into two parts, western and eastern, by the Kajibacha River. It is bounded by Rupsa, Rampal and Fakirhat upazilas to the east; Dumuria and Paikgaccha upazilas to the west; Kotowali and Sonadanga thanas and Dumuria upazila to the north; and Dakope, Rampal and Paikgachha upazilas to the south. The area of Batiaghata covers 235.32 square kilometers and is situated between latitudes 22° 34' and 22° 46' north and longitudes 89° 24' and 89° 37' east.

According to the 2022 Bangladeshi census, the population of Batiaghata was 171,752, with a population density of 730 per square kilometre, comprising 86,685 males and 85,067 females. The main rivers in Batiaghata upazila are the Kazibachha, Shoilmari, Pasur and Vadra. The annual average maximum and minimum rainfall totals in the region are 172.60 mm and 152.40 mm respectively, with average maximum and minimum temperatures of 31.7°C and 22.3°C. Figure 1 and Table 1 present the selected study sites.

Table 1. Study Site Description.

Upazila	Union	Site Name
Batiaghata	Batiaghata	Krishnanagar_1
		Krishnanagar_2
		Kismat Fultala_1
		Kismat Fultala_2
	Jalma	Fultala_1
		Fultala_2

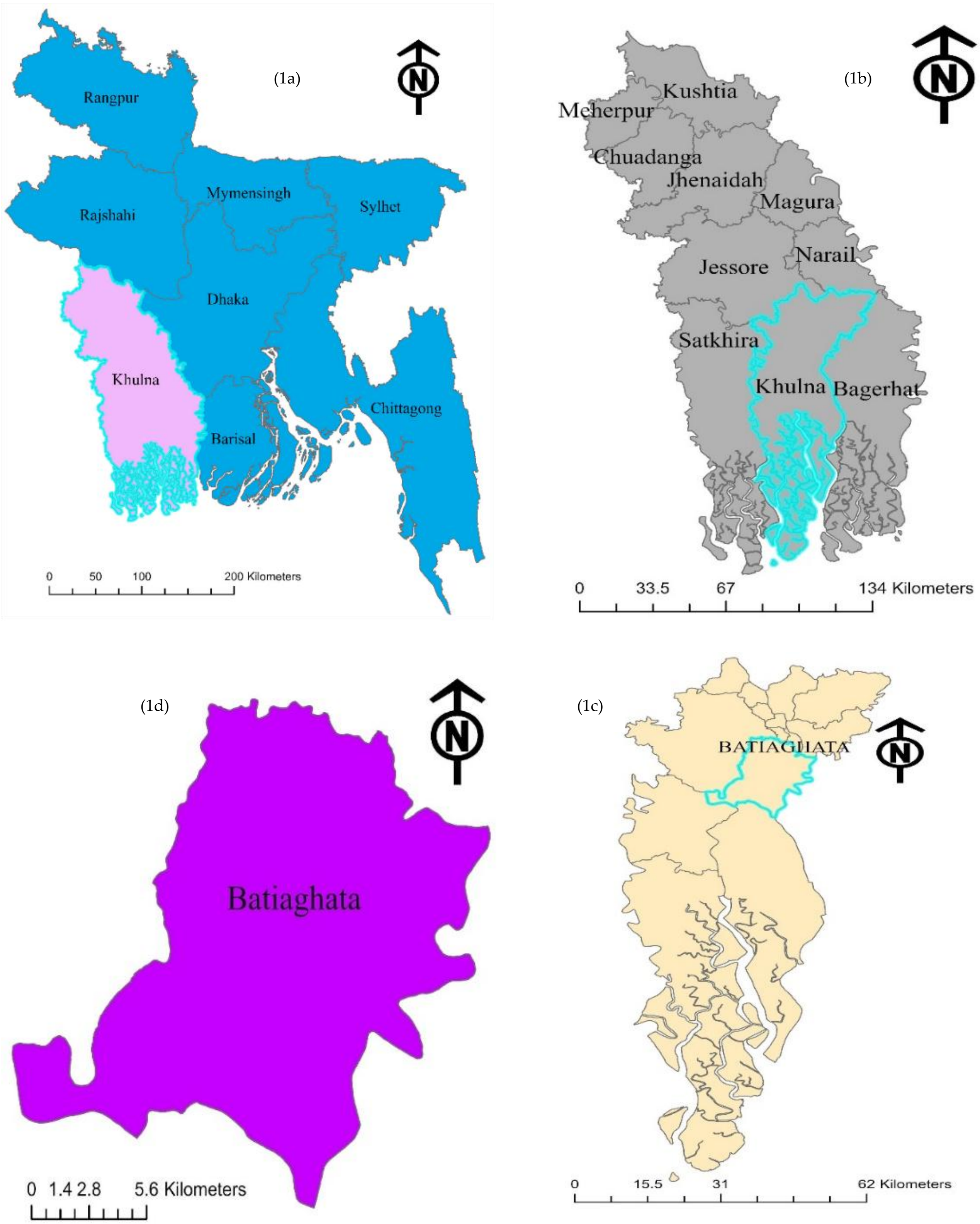

Figure 1. Study Area Map (1a. Bangladesh Divisional Boundary Map; 1b. Khulna Division Map; 1c. Khulna District Map; 1d. Batiaghata Sub-District Map)

2.2. Data

Electrical conductivity (EC) data from six sites in Batiaghata were collected from the Soil Research Development Institute (SRDI), at Khulna in Bangladesh (Table 2). Satellite Landsat 8–9 OLI data for the period from January 2023 to December 2023 were downloaded from the USGS Earth Explorer data portal (Table 2). In addition, severe cyclonic storm data were collected from the India Meteorological Department (IMD).

Table 2. Description of the Temporal Range and Resolution of the Data.

SL	Data	Source	Temporal Range	Temporal Resolution
1	Electrical Conductivity	SRDI	2020-2023	Monthly
2	Rainfall & Temperature	BMD	2020-2023	Daily
3	Cyclone	IMD	30 Nov to 6 Dec 2021	*
4	Satellite data	USGS Earth Explorer	2023-2023	Every 16 Days

*The integrated effects of soil salinity on soil due to cyclone are only covered.

2.3. Methodology

The methodology is subdivided into three parts:

(i) Data collection; (ii) Processing and mapping; and (iii) Statistical analysis

Data collection : For the study, climatic driver data (rainfall and temperature) were collected from BMD, cyclone data from IMD, and EC data from SRDI. The data were then processed using Excel software to analyse seasonal variation and trends through regression equations. Subsequently, freely accessible remote sensing data were collected from the Landsat program (https://earthexplorer.usgs.gov/), which involves a series of Earth-observing satellite missions jointly managed by NASA and the US Geological Survey (USGS).

Processing and mapping : Monthly climatic data were obtained from the daily data. From the monthly data, seasonal mean values were computed for the four seasons, pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February), in an Excel template. Additionally, the average EC value was evaluated for the Khulna district from the six sites. The influence of climatic conditions on soil salinity was evaluated using a bar graph. Satellite data extraction, raster calculation, and the creation of cartographic materials were then conducted in the geographic information system (GIS) for the mapping of indices. The seasonal field data of soil salinity and satellite indices were compared to determine the relationship between them based on maximum and minimum values.

Statistical analysis : The coefficient of determination (R^2) was obtained through diagrams, while the significance of the R^2 was assessed using a t-test.

2.4. NDSI Indices

Using remote sensing data, especially Landsat imagery, NDSI demonstrated encouraging results for the assessment of soil salinity. Additionally, NDSI frequently shows a high positive association with electrical conductivity (EC) recorded in the field. Since NDSI performs well in detecting soil salinity in areas with minimal vegetation, and as the study area is a coastal region with low vegetation, it is effective in representing soil salinity in the local context.

NDSI indices were derived by using the formula shown in Table 3 for Landsat 8-9 OLI.

Table 3. Description of the Spectral Indices.

Spectral Indices	Equation	Reference
Normalized difference salinity index (NDSI)	$\frac{R - NIR}{R + NIR}$	Khan et al. (2001)

R (Red) = Band 4 (0.64 – 0.67 µm)

NIR (Near Infrared) = Band 5 (0.85 – 0.88 µm)

3. Results

All of the results are discussed in the following sub-section.

3.1. Seasonal Trend Variation

Soil salinity across the six sites in the coastal district of Khulna exhibits both spatial and seasonal variability. The highest salinity levels were recorded during the pre-monsoon season, while the lowest occurred in the post-monsoon season (Figure 2). As elevated salinity during the pre-monsoon period adversely affects crop production, the use of rainwater irrigation and the adoption of salt-tolerant crop varieties are recommended as effective mitigation strategies to enhance agricultural productivity in the region.

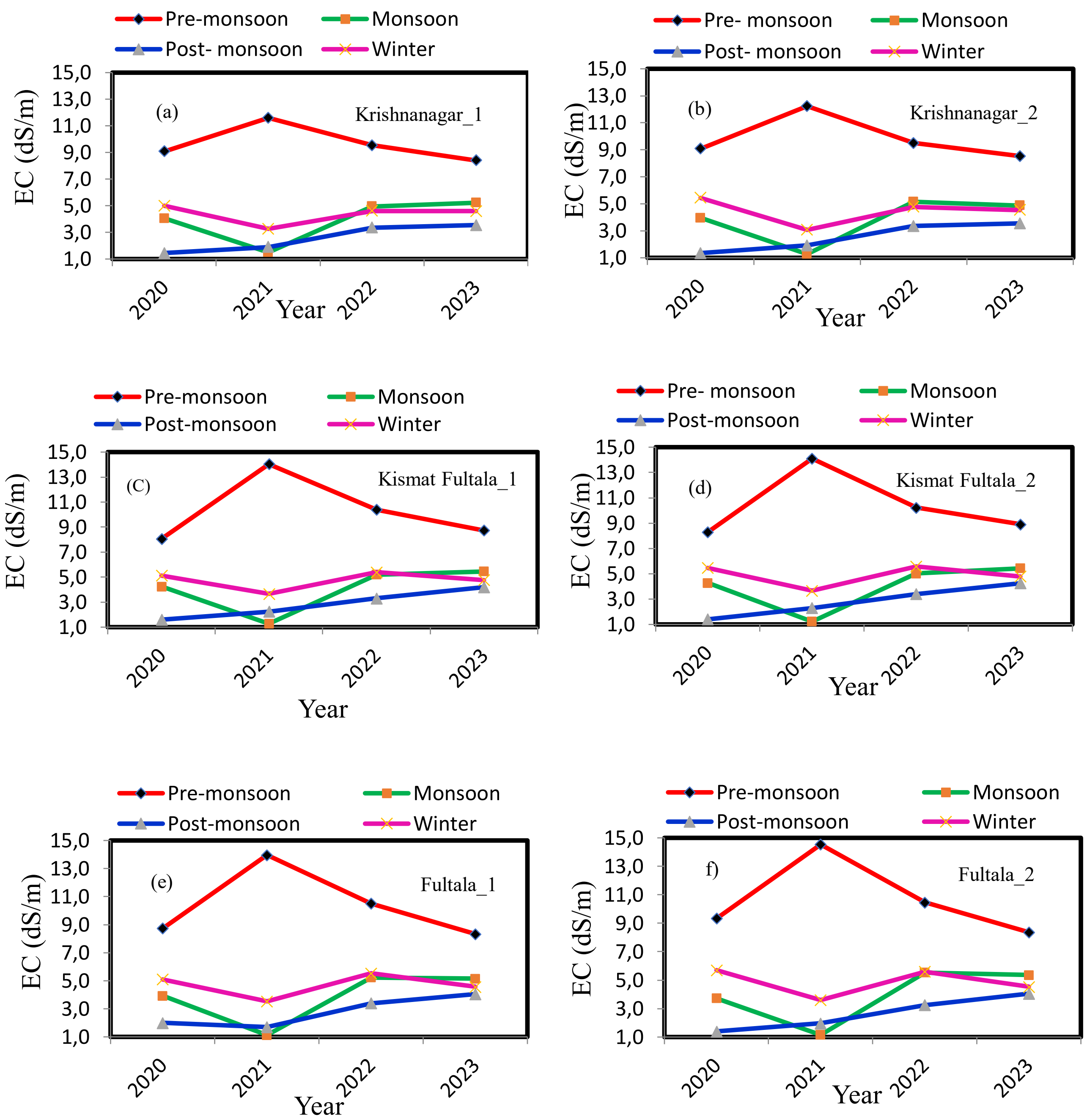

Figure 2. Seasonal Trend Variation in Soil Salinity at the Six Sites in Khulna, 2000–2023.

Table 4. Seasonal Variation in Maximum and Minimum Soil Electrical Conductivity.

SL	Site Name	Maximum (EC dS/m)	Minimum (EC dS/m)	Season		Year	
				Max. Value	Min. Value	Max. Value	Min. Value
1	Krishnanagar_1	11.6	1.5	Pre-monsoon	Post- monsoon	2021	2020
2	Krishnanagar_2	12.2	1.4	Pre-monsoon	Post- monsoon	2021	2020
3	Kismat Fultala_1	14.0	1.3	Pre-monsoon	Monsoon	2021	2021
4	Kismat Fultala_2	14.1	1.2	Pre-monsoon	Monsoon	2021	2021
5	Fultala_1	14.0	1.1	Pre-monsoon	Monsoon	2021	2021
6	Fultala_2	14.5	1.2	Pre-monsoon	Monsoon	2021	2021

In 2021, the highest soil salinity during the pre-monsoon season was observed at Fultala_2 (14.5 dS/m), followed by Fultala_1 and Kismat Fultala_2, while the lowest maximum salinity was recorded at Krishnanagar_1 (11.6 dS/m). These peak values reflect the seasonal salinity buildup prior to the monsoon. In contrast, the lowest soil salinity values occurred during the monsoon and post-monsoon seasons, with the highest minimum level recorded at Krishnanagar_1 (1.5 dS/m in 2020), and the lowest at Fultala_1 (1.1 dS/m in 2021) (see Table 4). These findings highlight a clear seasonal pattern: pre-monsoon salinity levels remain higher than those of any other season, emphasising the strong influence of climatic factors on soil salinity dynamics across all the study sites.

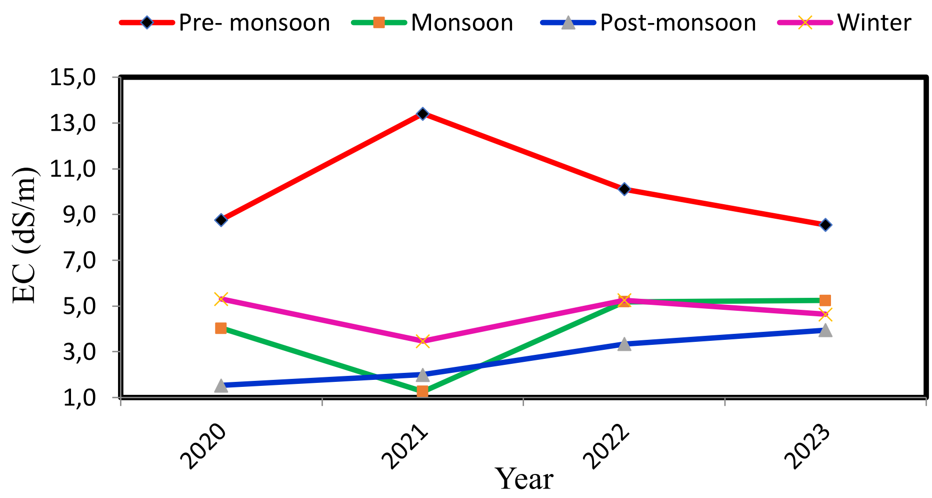

Figure 3. Seasonal Trend Variation of Soil Salinity at Khulna District During 2000–2023.

Figure 3 illustrates the seasonal trend of soil salinity for the Khulna district, aggregated from individual site measurements. The data reveal a consistent pattern, with peak salinity observed during the pre-monsoon season and the lowest levels during the post-monsoon season, mirroring the trends identified at individual sites. This consistency indicates a uniform seasonal salinity pattern across the study area.

Figure 4 demonstrates that electrical conductivity (EC) values consistently peak during the pre-monsoon season across all sites and years. The levels decline from pre-monsoon to monsoon periods, followed by a gradual increase through the post-monsoon and winter seasons, forming a cyclic pattern influenced by climatic factors. The maximum EC values generally demonstrated an upward trend, with the minimum values also indicating a gradual baseline increase in soil salinity, which may pose long-term risks to agricultural sustainability. Increases in the maximum and minimum EC values influence the crop tolerance range, consequently hindering crop productivity.

Table 5. Seasonal Slope (dS m^{-1}/yr) of EC at the Different Sites in Khulna, 2000–2023.

Site/District	Pre-monsoon	Monsoon	Post-monsoon	Winter
Khulna	-0.962	0.7571	0.8566	-0.0234
Krishnanagar_1	-0.4107	0.6975	0.775	0.015
Krishnanagar_2	-0.4393	0.665	0.8035	-0.0993
Kismat Fultala_1	-0.1613	0.7525	0.8865	0.0633
Kismat Fultala_2	-0.2027	0.725	0.966	0.009
Fultala_1	-0.4667	0.7775	0.785	0.04
Fultala_2	-0.6967	0.925	0.9235	-0.1503

AlthThough the highest EC values were observed during the pre-monsoon season (Figure 2), a decreasing trend is evident across all sites during the study period (Table 5). In contrast, increasing trends are observed during the monsoon and post-monsoon seasons. The winter season exhibits both increasing and decreasing trends, depending on the site. The highest rate of increase in soil salinity was recorded at Kismat Fultala_2 during the post-monsoon season (0.966 dSm-1/year), which is statistically significant at the 90% level of significance, while the lowest was also at Kismat Fultala_2 in the winter period (0.09 dSm-1/year). Conversely, the most significant decrease occurred at Fultala_2 in the pre-monsoon season (-0.6967 dSm-1/year), while the smallest decrease was at Krishnanagar_2 during the winter season (-0.0993 dSm-1/year). These trends highlight seasonal and spatial variability in soil salinity dynamics across the study area.

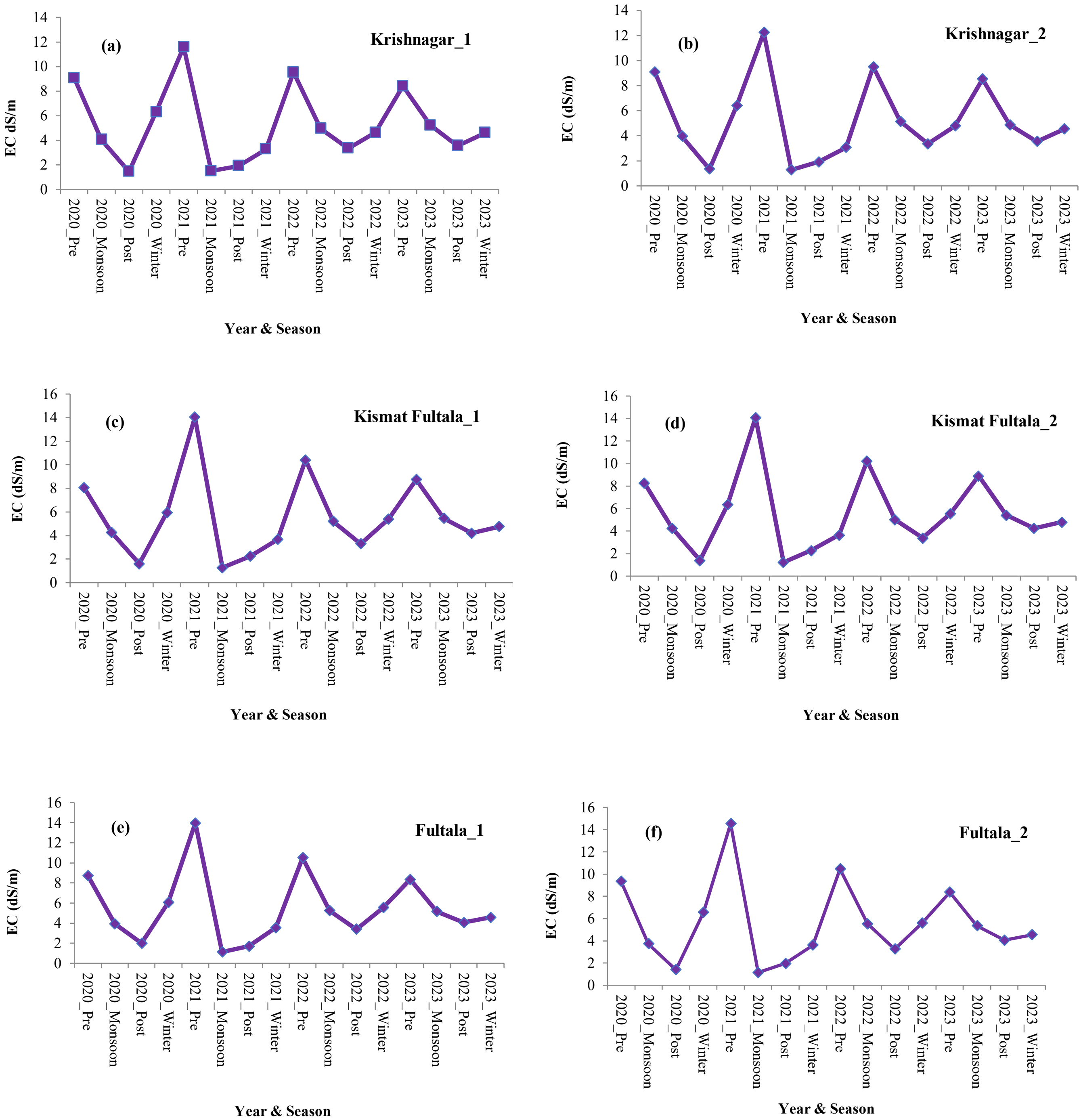

Figure 4. Periodic EC Pattern at Different Sites in Batiaghata, Khulna.

3.2. Impacts of Climatic Conditions

Rainfall reduces soil salinity by diluting salt concentrations through leaching, while high evaporation increases it by removing soil moisture and leaving salts behind. In Bangladesh, rainfall is highest during the monsoon season and lowest in winter. Figure 5 (a–d) illustrates the relationship between soil salinity and climatic parameters, namely rainfall and temperature, for the Khulna region. Excessive rainfall contributes to reduced soil salinity in the monsoon season. In contrast, the lower rainfall during the post-monsoon and winter seasons leads to increased salinity in winter, peaking in the pre-monsoon season, due to continued moisture deficit. Elevated average temperatures during the pre-monsoon season further intensify evaporation, exacerbating salinity levels. Conversely, lower average temperatures correlate with reduced salinity. These findings suggest a strong inverse relationship between rainfall and soil salinity, and a positive correlation between temperature and salinity, indicating the significant influence of climatic factors on soil salinity dynamics in coastal Bangladesh.

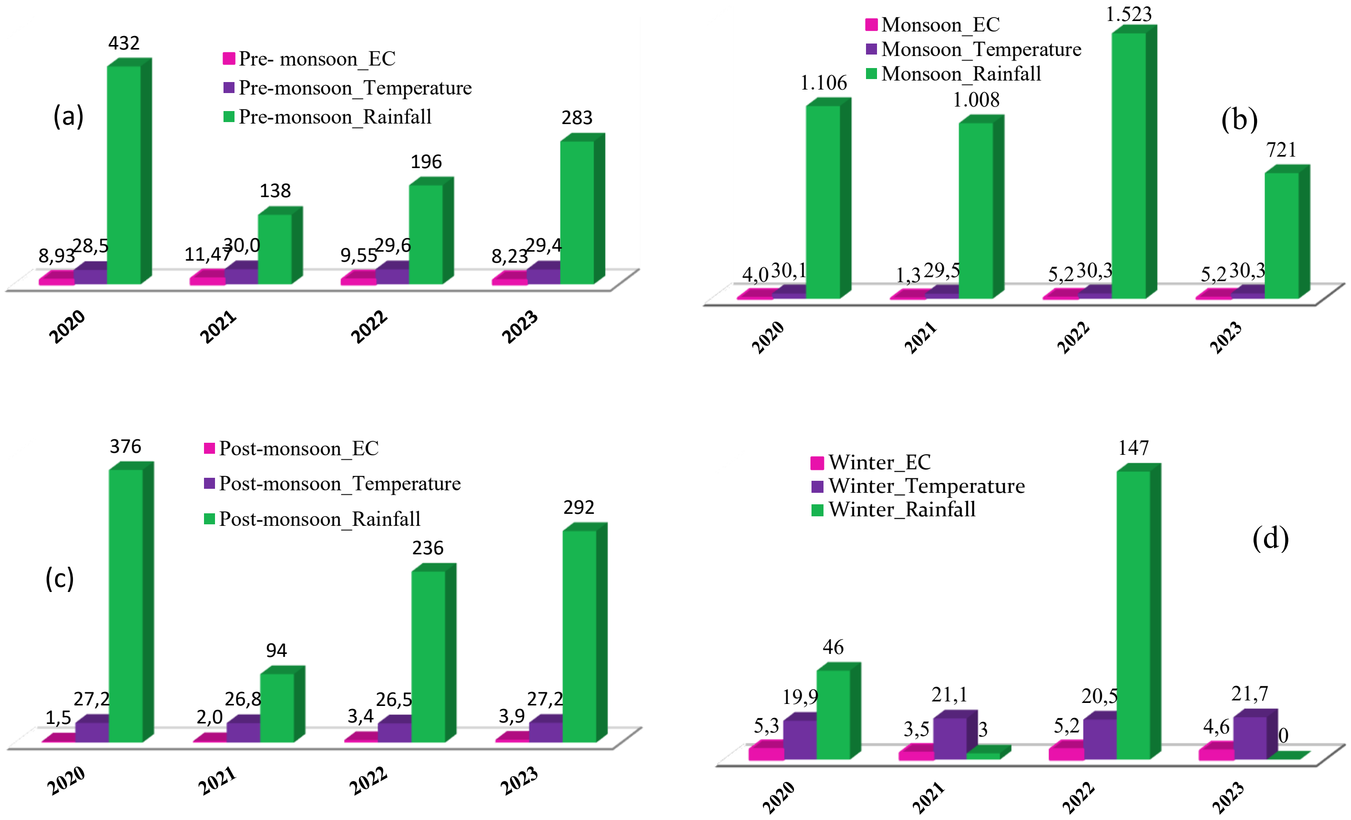

Figure 5. Relationship Between EC (dS m⁻¹), Temperature (°C) and Rainfall (mm).

Khulna faced a tropical cyclone from 30 November to 6 December, 2021, namely JAWAD (Table 6). Storm surges, commonly associated with such events, transport saline water inland, leading to increased soil salinity through salt deposition. The impact of tropical cyclones on soil salinity is clearly illustrated in Figure 6. Following the cyclone event referred to above, soil salinity exhibited an exceptional increase in December 2021 compared to the same month in previous and subsequent years.

Table 6. Description of Tropical Cyclone JAWAD.

Jawad: 30 November to 6 December 6, 2021	
Region:	Bay of Bengal
Wind speed:	Max. 65 km/h
Saffir-Simpson scale:	Tropical depression
Affected region :	Khulna

This indicates a sustained influence of storm surge events on long-term soil salinisation in coastal areas. Specifically, EC levels sharply increased in December 2021, suggesting that a notable event had occurred during this transition period compared to other years. This event may have been associated with the storm surge of tropical cyclone JAWAD.

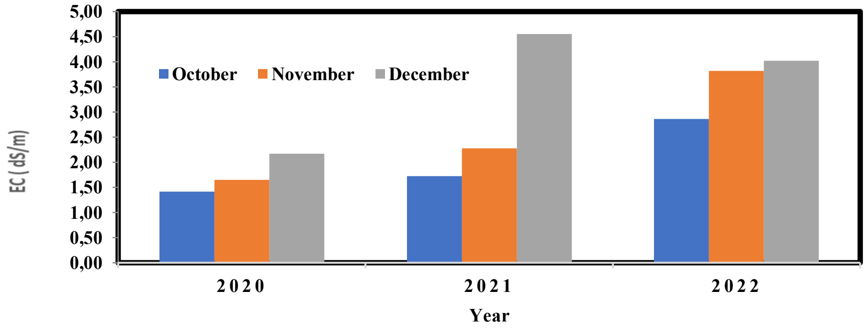

Figure 6. Monthly Variation (October to December) in Soil Salinity Between 2020 and 2022.

3.3. Relationship between Observed Data and Satellite Output

Standard deviation is a fundamental statistical metric that quantifies the degree of dispersion or variability of data points relative to the mean of a dataset. A higher standard deviation indicates a broader spread of values, suggesting that the data points are more widely distributed. In contrast, a lower standard deviation signifies that the data are more tightly clustered around the mean. The values of NDSI, which are computed using spectral reflectance data, normally fall between -1 and +1. Higher salinity is correlated with positive NDSI levels, and lower levels with negative values. Positive and negative values are produced because they arehigher and lower than the reference value respectively. In this study, NDSI values were calibrated to match field-measured electrical conductivity (EC) data to enhance the accuracy of salinity detection. Satellite-derived NDSI values were processed and visualised using ArcGIS, as shown in Figure 7 (a–d).

The highest NDSI values were observed during the pre-monsoon season, aligning with EC data obtained from SRDI, Khulna (Table 7 and Figure 8). A clear seasonal cyclic variation is evident in Figures 7 (a–d) and 8, showing strong correlation with ground data, except for some inconsistency during the monsoon season. This ambiguity may have occurred due to the comparisons being made between the direct field observation values and the maximum and minimum values of the satellite data, which incorporate high spatial resolution.

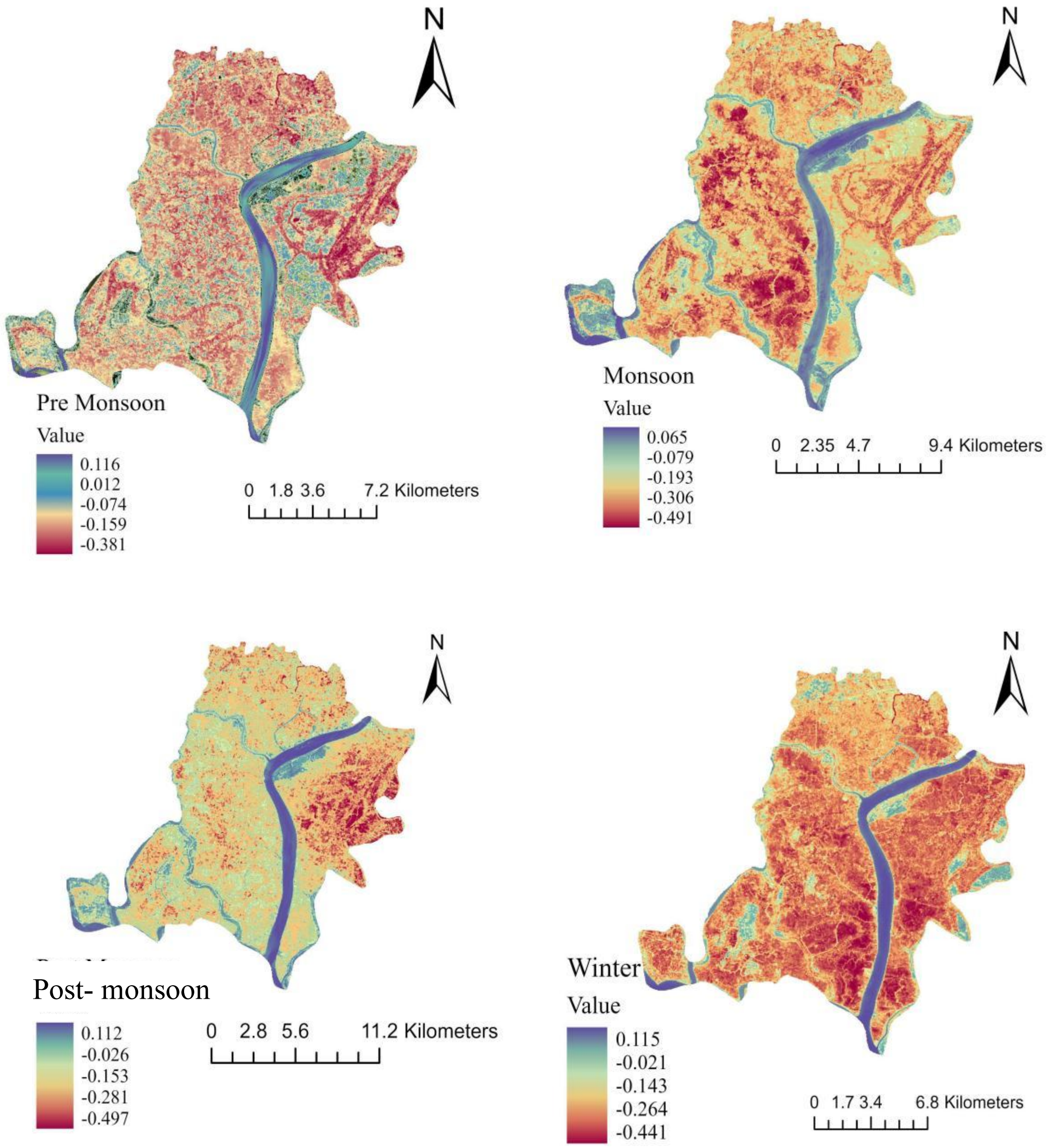

Figure 7. NDSI Indices of Soil Salinity Based on Season.

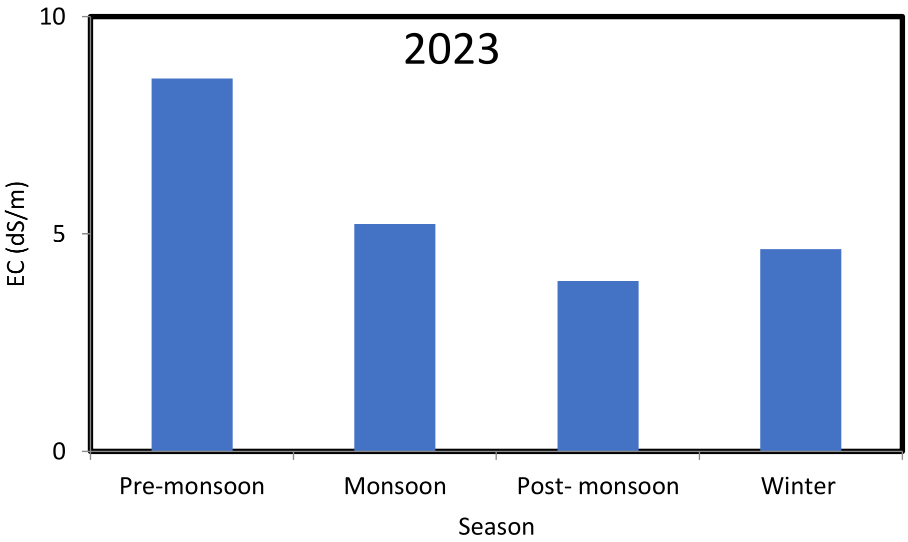

Figure 8. Seasonal Soil Salinity from Observed Data.

Table 7. Description of the NDSI Indices for the Study Area.

S.L.	Year	Season	Max	Min	Mean	STD
1	2023	Pre -monsoon	0.11580	-0.38070	-0.10360	0.06868
2		Monsoon	0.06533	-0.49134	-0.23324	0.10370
3		Post -monsoon	0.11166	-0.49668	-0.17257	0.10468
4		Winter	0.11483	-0.44125	0.22551	0.11212

4. Discussion

The highest maximum NDSI value during the pre-monsoon season was 0.11580, which corresponds to the observational data obtained from SRDI, Khulna. In contrast, the lowest minimum value, 0.06533, was recorded during the monsoon season, while notably low NDSI values were observed in both the monsoon and post-monsoon periods. Rainfall exhibited a negative correlation with NDSI, whereas temperature and cyclonic events showed positive correlations. The fall in soil salinity during the post-monsoon and winter seasons can be primarily attributed to increased monsoonal precipitation and lower evapotranspiration rates. In contrast, elevated soil salinity in the pre-monsoon season results from higher ambient temperatures and storm surges, which enhance salt accumulation within the soil profile. High rainfall is inversely correlated, with inundation due to cyclones being positively correlated with soil salinity level in the Noakhali coastal area of Bangladesh (Kawser *et al.*, 2022). This study also observed a strong inverse relationship between excessive rainfall and soil salinity throughout the seasons. Climate change, or rising air temperatures, causes more water to evaporate and more salt to be present in the soil (Corwin *et al*., 2021). Our study is also consistent with previous research on temperature, as well as other climate drivers that are used in the study. According to the study findings, the south-western region of Bangladesh are more vulnerable to saline intrusion than other regions because of greater storm surge impacts, lower elevation, and different land use patterns (Akter *et al.*, 2025). The cropland of the Indian Sundarbans is experiencing a significant change in soil salinity due to cyclone-induced flooding, with coastal areas tending to have very high soil salinity (Barui *et al.*, 2025). The findings align with this observation. The study demonstrates that soil salinity in the region exhibits significant seasonal variability, largely influenced by climatic parameters. Climatic factors, particularly rainfall and temperature, were found to contribute substantially to the observed fluctuations in soil salinity. However, the study was conducted within a limited spatial scope, specifically in Batiaghata Upazila, a sub-district of Khulna, Bangladesh, over the period 2020–2023. Further research is recommended in other regions of Bangladesh to validate spatial variability and encourage policymakers to implement targeted measures to mitigate the impacts of soil salinity on agriculture, thereby supporting long-term food security.

5. Conclusion

The electrical conductivity was highest during the pre-monsoon season and lowest during the post-monsoon season across all individual sites and in the aggregated data. These results are consistent with satellite-derived indices. The observed seasonal variability in soil salinity, derived from both satellite data and field measurements, aligns with the study objectives. Furthermore, the findings provide a clear interpretation of soil salinity dynamics in relation to climatic drivers.

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Author Contributions

Conceptualization: Mondal, K. K., Akhter, M. A. E; **methodology**: Mondal, K. K., Akhter, M. A. E; **investigation**: Mondal, K. K., Akhter, M. A. E; **writing—original draft preparation**: Mondal, K. K., Akhter, M. A. E; **writing—review and editing**: Mondal, K. K., Md. Akhter, M. A. E., & Mallik, M. A. K.; **visualization**: Mondal, K. K., Akhter, M. A. E. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The Authors declare no conflict of interest.

Data availability

Data will be made available on request to the corresponding author.

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