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Strengthening adaptation in coastal Bangladesh: community-based approaches for sustainable agriculture and water management

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Abstract

The coastal region of Bangladesh is significantly influenced by soil and water salinity, which is further exacerbated by the increasing frequency of tropical cyclones and rising sea levels. Understanding the extent of salinity and its challenges is crucial for promoting sustainable agriculture and ensuring access to safe drinking water. Using quantitative (soil and water parameters) and qualitative (focus group discussion and key informant interview) data, we investigated (i) soil and water salinity and soil nutrient contents; and (ii) adaptive practices in agriculture and drinking water management in three sub-districts (Assasuni, Dacope and Morrelganj) in the southwestern coastal region of Bangladesh. Results show that soil salinity levels did not significantly differ among the sub-districts, with Assasuni having slightly higher soil salinity (8.24 dS m^{-1}) compared to Dacope (8.08 dS m^{-1}) and Morrelganj (7.96 dS m^{-1}). Significant differences were observed in the salinity level of pond and canal water among the sub-districts, with Assasuni having the highest levels of salinity in both pond (13.98 dS m^{-1}) and canal water

(77.85 dS m^{-1}), compared to other sub-districts. Soil and water salinity were the major challenges reported by the respondents; however, climate-induced stresses (e.g., untimely precipitation) and outbreaks of pests during droughts have been identified as prominent issues in sustainable agriculture. Rainwater harvesting has been identified as a viable adaptive technique in drinking water management, offering a feasible solution to address water and soil salinity. The study underscores the importance of implementing adaptive practices (e.g., rainwater harvesting) to address water scarcity and salinity issues in the coastal region and promote resilient agricultural systems.

Keywords: Climate change adaptation, drinking water management, resilient agriculture, soil properties, water salinity, adaptive agriculture, coastal Bangladesh

INTRODUCTION

Soil and water salinity in coastal regions have significant global implications, transcending geographical boundaries and affecting various aspects on a global scale[1]. Coastal regions around the world contribute a substantial portion of agricultural production, supplying food both locally and internationally. The salinity significantly threatens global food security by reducing crop yields and compromising the viability of agricultural land[2]. The decline in agricultural productivity in coastal areas can lead to food shortages, price fluctuations, and increased dependence on imports, affecting global food supply chains and potentially leading to broader food insecurity. Soil and water salinity in these regions are closely linked to climate change and rising sea levels[3]. As climate change accelerates, the frequency and intensity of extreme weather events such as storms, cyclones, and floods increase[4,5], resulting in the intrusion of saltwater into freshwater sources and agricultural lands[6]. Understanding the dynamics of the salinity in coastal areas provides valuable insights into the impacts of climate change on vulnerable ecosystems worldwide, helping to inform adaptation and mitigation strategies internationally.

The scarcity of safe drinking water caused by water salinity affects coastal communities across the globe[7]. As seawater infiltrates freshwater sources, including underground aquifers and surface water bodies, access to clean and safe drinking water becomes a significant challenge[8]. This issue is not limited to specific regions but is a global concern, particularly for coastal communities and small island developing states[9,10]. Addressing water scarcity and ensuring access to safe drinking water are critical for achieving global water security goals and promoting public health worldwide[11]. Soil and water salinity align with several Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Climate Action (SDG 13), Life Below Water (SDG 14), and Partnerships for the Goals (SDG 17). Addressing these challenges enhances global efforts towards achieving the SDGs, promoting sustainable development, poverty alleviation, and climate resilience globally.

Coastal areas of Bangladesh are currently struggling with the detrimental effects of soil and water salinity and pollution[12] and frequent droughts, floods, tropical cyclones, and storm surges[9,13]. These natural disasters have significantly affected agricultural land in the coastal regions, reducing arable cropland and posing risks to the socio-economic development of the country[9,14]. Over the past two decades, Bangladesh has experienced the devastating impact of eight major storm surges triggered by tropical cyclones, including Sidr in 2007 and Aila in 2009, affecting nearly 3.45 million people[15]. These cyclone-induced storm surges have been the primary cause of soil salinity in coastal areas, leading to soil contamination. As a result, approximately 37% of arable land along the coast has been affected by varying degrees of soil salinity[6]. The rise in salinity levels in both soil and water has severe consequences for the coastal ecosystem, including adverse effects on crop growth, diminished food security, and increased scarcity of clean drinking water due to the deterioration of freshwater quality[9,16].

Water salinity is a significant concern in coastal Bangladesh due to the intrusion of seawater into underground aquifers and the impact of cyclone-induced storm surges[17]. These factors contribute to the contamination of both underground water sources and freshwater bodies, posing challenges to crop cultivation, drinking water availability, and community well-being[18]. Cyclone-induced storm surges worsen water salinity, contaminating freshwater sources and compromising their usability for irrigation and drinking water. Coastal areas face significant challenges due to the salinity of the land itself. Seawater infiltration into the soil leads to high salt concentrations, hindering plant growth and agricultural productivity. Saline soils have reduced water-holding capacity, causing stunted growth, decreased yields, and crop failure. The scarcity of safe drinking water in the southwestern coastal region of Bangladesh has direct implications for public health, as communities resort to unsafe alternatives such as untreated rainwater or limited treatment options for surface water bodies[18-20].

Ensuring access to safe drinking water is of paramount importance for human health[21], particularly in coastal Bangladesh, where the presence of saline water poses significant health risks. Saline water, contaminated with high levels of salts and other minerals, can have detrimental effects on the well-being of coastal communities. Excessive intake of salt can contribute to hypertension, increasing the risk of heart disease, stroke, and kidney problems[22]. Consuming saline water can lead to gastrointestinal issues, dehydration, and worsening diarrhea, compromising overall health[20]. The scarcity of safe drinking water in coastal Bangladesh results in communities relying on unsafe alternatives such as shallow wells and contaminated surface water bodies[23]. This raises the risk of waterborne diseases such as cholera, dysentery, and typhoid fever[20]. Vulnerable populations, including children, pregnant women, and the elderly, are particularly affected. Children are more susceptible to the adverse effects of consuming saline water due to the sensitivity of their developing bodies to electrolyte imbalances. The lack of access to safe drinking water also hampers proper hygiene practices, further contributing to the spread of waterborne diseases[24].

The coastal regions of Bangladesh, characterized by their low-lying nature and elevations ranging from one to four meters above sea level[4], are highly susceptible to the impacts of rising sea levels, which are projected to exacerbate soil and water salinity in these areas[25,26]. Recent findings from a study conducted in southwest coastal Bangladesh[27] highlight the multifaceted threat of salinity to household food production, negatively affecting livelihoods such as crop cultivation, homestead gardening, livestock rearing, and aquaculture. Over the past decade, Bangladesh has witnessed a decrease in arable cropland, dropping from 65% in 2010 to 59% in 2020. Additionally, there has been a notable increase in fertilizer usage in the soil, indicating a rise from 160 kg ha^{-1} in 2003 to 209 kg ha^{-1} in 2013[28]. Given the rise in soil salinity and decline in soil nutrients and organic carbon content in arable land, adopting sustainable agricultural practices becomes critically important.

Soil and water salinity in coastal Bangladesh have wide-ranging impacts on agricultural productivity, food security, and public health[9,29]. The decline in agricultural output and food security affects both the livelihoods of coastal communities and the socio-economic development of the country[30]. The scarcity of safe drinking water directly affects public health, particularly for vulnerable populations[20]. Many existing studies[6,9,15,16,18] have focused on either soil or water salinity separately rather than considering them as interconnected issues. Additionally, a lack of both qualitative and quantitative studies in these coastal regions hinders a comprehensive understanding of the problem and the development of effective solutions. Further research is needed to address these gaps and adopt a holistic approach considering the interconnected nature of soil and water salinity. A comprehensive analysis incorporating various methodologies can provide valuable insights into the causes, dynamics, and consequences of soil and water salinity in coastal regions, leading to targeted strategies for mitigation.

The distinction of this research from previous studies lies in its focus on conducting a comprehensive analysis of the impacts of soil and water salinity on agricultural practices, food security, and access to safe drinking water in the southwestern coastal region of Bangladesh. While previous studies have examined either soil or water salinity separately[6,9,15,16,18], this investigation aims to address both issues as interconnected factors. Additionally, we seek to bridge the gap between qualitative and quantitative studies by incorporating a holistic approach that considers the interplay between soil and water salinity and the perceptions of farmers and stakeholders. By examining the problem from various angles and utilizing both qualitative and quantitative methodologies, this research provides a more nuanced understanding of the causes, dynamics, and consequences of soil and water salinity in coastal regions, enabling the formulation of targeted strategies for mitigation.

Assessing the soil and water salinity level and understanding how communities in coastal regions of Bangladesh adapt their crop cultivation and water management practices is critical, given the unique challenges they face due to soil and water salinity. To explore these aspects, we have formulated the following three research questions:

(i) What are the levels of soil nutrient content and salinity concentration in the three sub-districts of the southwestern coastal region, and how do they impact agricultural productivity and soil health?

(ii) How do farmers adapt their agricultural practices, including crop selection, irrigation methods, and soil management techniques, to cope with the challenges posed by enhanced soil and water salinity in the salinization-affected croplands, and what are the outcomes in terms of long-term sustainability?

(iii) What techniques and strategies do communities employ to effectively manage water salinity in their drinking water sources, considering factors such as water treatment methods, alternative water sources, community-based water management initiatives, and the socio-economic impacts of water salinity on public health and well-being?

We established the following three objectives to address these challenges:

(i) Assess soil nutrient content and soil and water salinity concentration in three sub-districts in the southwestern coastal region;

(ii) Explore the adaptive agricultural practices in crop cultivation under enhanced soil and water salinity in the salinization-affected croplands;

(iii) Investigate the techniques and strategies communities employ to adapt to water salinity in drinking water management.

Qualitative studies provide insights into the socio-economic and cultural aspects of soil and water salinity. They explore the experiences, perceptions, and coping strategies of local communities in affected areas, identifying specific challenges and local knowledge related to soil and water management. Quantitative studies, on the other hand, gather scientific data on salinity levels, spatial distribution, and contributing factors. Techniques such as ground surveys and laboratory analysis quantify the extent and severity of salinity. This data helps identify the most affected areas, assess impacts on agriculture, water resources, and ecosystems, and monitor changes over time. Combining insights from qualitative studies with quantitative data captures the complexity and multi-dimensional impacts on the environment, agriculture, livelihoods, and public health. The findings inform evidence-based strategies and interventions for policymakers, development agencies, and local communities. These may include improved agricultural practices, water management techniques, coastal ecosystem restoration, and alternative livelihood options. Integrating scientific research with local knowledge and community participation is crucial for designing context-specific and sustainable solutions to address soil and water salinity challenges in coastal Bangladesh.

The scientific novelty of this study lies in its integrated and interdisciplinary approach, encompassing soil and water parameter assessment, adaptive agricultural practices, and community strategies for water management. The findings will contribute to a holistic understanding of the challenges posed by salinization in the southwestern coastal region. These outcomes have practical implications for sustainable agriculture, including developing tailored agricultural practices and improved water resource management strategies. Furthermore, the insights gained can inform policy decisions and community interventions, promoting resilience and sustainable development in salinization-affected regions.

MATERIALS AND METHODS

Study area

The research was conducted in three sub-districts (Assasuni, Dacope, and Morrelganj) in the southwestern coastal region of Bangladesh [Figure 1]. They were purposively selected due to their vulnerability to tropical cyclones, storm surges, and other natural disasters and the recent growing concern of soil and water salinity[31]. This coastal region is characterized by its proximity to the Bay of Bengal and the renowned Sundarbans mangrove forest, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site. The study areas are home to a socio-economically disadvantaged community, which faces hardships but also demonstrates remarkable resilience. The unique geographical features of this region, coupled with its socio-economic context 10], make it a compelling area for research and the development of targeted interventions to address the salinity-related issues faced by the community[29].

We purposively selected six unions (Putikhali and Chingrakhali from the Morrelganj sub-district, Assasuni and Khajra from the Assasuni sub-district, and Sutarkhali and Kamarkholar from the Dacope sub-district) for this study [Figure 1]. Putkhali union spans an area of 22.36 km^2 with a total population of 22,666. The literacy rate in Putkhali is 60%. Chingrakhali union covers an area of 6.67 km^2 and has a population of 29,001. The literacy rate in Chingrakhali is 65%. Khajra union extends over an area of 43.52 km^2 and is home to one river and several canals. Kamarkhola and Suterkhali unions are encompassed by four main rivers: Pashur, Bhadra, Shibsa, and Manki. The southern part of all these unions is encircled by the Mangrove Sundarbans[32]. All three sub-districts experience a mean minimum temperature of 20.8 °C and a mean maximum temperature of 34.3 °C[33]. The annual precipitation in this region is recorded at 1,854 mm[34]. Located in the subtropical zone, April is the warmest month, August is the wettest month, and January is the coldest and driest month[33]. All these sub-districts are highly prone to various natural disasters, including tropical cyclones, floods, river bank erosion, salinity intrusion, and sea-level rise[25,31].

Data collection

Description of variables and their significance

We have considered several variables covering both quantitative (soil nitrogen, phosphorus, potassium and salinity, and water salinity) and qualitative (Focus Group Discussion [FGD], Key Informant Interview [KII], and Household [HH] survey) data from the study area. A thorough summary of the variables, encompassing their definitions, sources of data, and measuring units, has been shown in Table 1. The variables were chosen based on their theoretical significance and relevance to the research objectives. Each

Table 1. Description of the variables studied for quantitative and qualitative data collection

Data type	Variable	Definition	Data source	Measuring unit or mode
Quantitative	Soil nitrogen	Concentration of nitrogen in the soil	Sample collection and laboratory analysis	g kg^{-1}
	Soil phosphorus	Concentration of phosphorus in the soil	Sample collection and laboratory analysis	µg g^{-1}
	Soil potassium	Concentration of potassium in the soil	Sample collection and laboratory analysis	meq 100 g^{-1}
	Soil salinity	Electrical conductivity of soil	Sample collection and laboratory analysis	dS m^{-1}
	Water salinity	Electrical conductivity of water	Sample collection and laboratory analysis	dS m^{-1}
Qualitative	Focus group discussion	Moderated group discussion with a small number of participants	Questionnaire	Filled in questionnaire
	Key informant interview	Interview with individuals who possess specialized knowledge or expertise on a particular subject	Questionnaire	Filled in questionnaire
	Household survey	Obtain information about various aspects of the households	Physical observation	Photograph

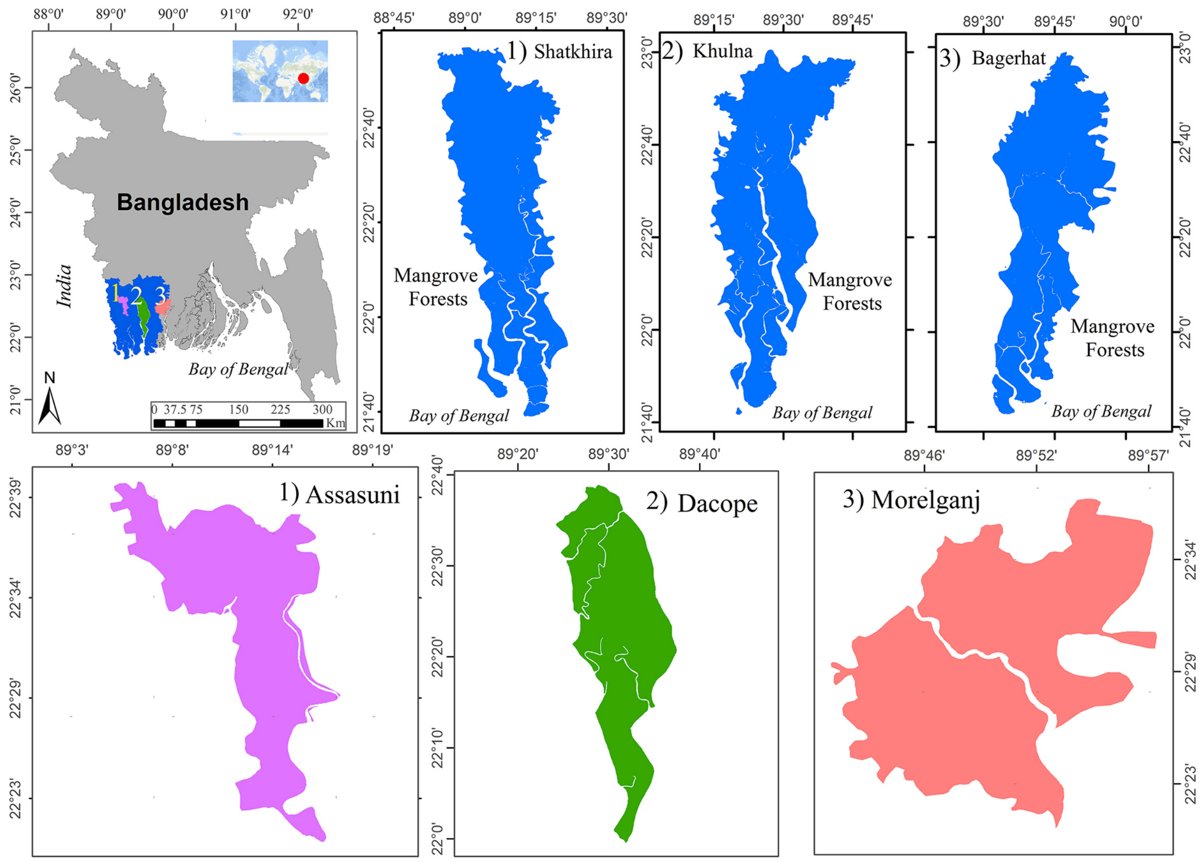

Figure 1. Location of the three sub-districts (Assasuni and Khajra unions in Assasuni, Sutarkhali and Kamarkholar unions in Dacope, and Putikhali and Chingrakhali unions in Morrelganj sub-districts) in the study.

variable is crucial in understanding the relationships and dynamics under investigation. The soil variables (nitrogen, phosphorus, potassium, and salinity) were selected as they are key indicators of soil fertility and salinity levels, directly influencing agricultural productivity. The focus on these variables allows for an assessment of the nutrient status and salinity levels of the soil across different areas. The water salinity variable was included to examine the salinity levels in surface water bodies, such as ponds and canals, which are important water sources for agricultural activities and drinking water in water-scarce conditions. The significance of each variable is rooted in prior studies and scientific literature, which have established their associations with agricultural productivity, nutrient availability, and soil and water salinity. By including these variables, we aim to gain insights into the relationships and potential impacts on agricultural practices and water management strategies.

The inclusion of FGDs in this study is significant for several reasons. They offer a unique opportunity to delve into the perspectives, experiences, and attitudes of participants related to the research topic. By engaging in a moderated group discussion, valuable insights can be gained, shedding light on social, cultural, or contextual factors that influence the phenomenon under investigation. The interactive nature of FGDs fosters rich discussions, allowing for a deeper understanding of the research topic within its specific context. Additionally, they provide access to diverse viewpoints, enabling the exploration of various opinions, experiences, and insights. This diversity contributes to a more comprehensive analysis of the research topic, enhancing the validity and depth of our findings.

KIIs provide access to individuals with specialized knowledge or expertise relevant to the research topic. Engaging in one-on-one interviews with key informants allows researchers to tap into their expert insights, opinions, and experiences, significantly enhancing the depth and credibility of the study. They offer a platform for in-depth exploration of specific aspects of the research topic, enabling researchers to obtain detailed explanations and clarify uncertainties. Key informants often reveal hidden or less apparent factors that influence the variables under study, providing valuable insights into underlying mechanisms or suggesting additional variables that may need consideration. The inclusion of KIIs adds a level of expertise and nuance to the study, enriching the overall analysis.

The inclusion of a household survey carries significant implications. Household surveys capture the socio-economic characteristics, demographics, and living conditions of the surveyed households. This context-rich data is invaluable for understanding how these factors interplay with the variables under investigation and can inform policy or intervention strategies. Additionally, findings from these surveys can be generalized to the larger population from which the sample was drawn, increasing the external validity of the study's results. Including a household survey strengthens the study by providing a broader perspective on the research topic.

Soil and water sampling and analysis

We collected a total of 168 soil samples (≥ 24 samples/union) from the agricultural crop field and homestead garden and 124 water samples (≥ 20 samples/union) from surface water bodies (pond and canal) across six unions for the period March-April 2023 [Table 2; Figure 2]. Standard laboratory methods were employed to measure the concentrations of nitrogen, phosphorus, potassium, and electrical conductivity in the soil. Nitrogen levels were determined by treating the soil with sulfuric acid (H_2SO_4). Phosphorus content was assessed by digesting the soil with nitric acid (HNO_3) and perchloric acid ($HClO_4$), followed by colorimetric analysis. Potassium concentrations were measured using hydrochloric acid (HCl) and aqua regia (a mixture of HCl & HNO_3) for soil digestion, followed by atomic absorption spectroscopy. Stringent calibration, quality control measures, and adherence to standard protocols were implemented to ensure accurate and reliable outcomes. To create a soil extract, a soil-to-water ratio of 1:5 was used. The soil samples were mixed with distilled water and allowed to equilibrate for approximately 30 min. During this period, soluble salts dissolved into the water, forming a solution representing the soil salinity. The electrodes of the electrical

Table 2. The participants involved in the focus group discussion and key informant interview within the studied areas

Respondent location	Name of union	Focus group discussion	Key informant interview	Number of water sample	Number of soil sample
Assasuni sub-district	Assasuni	2	4	20	24
	Khajra	3		20	27
Dacope sub-district	Sutarkhali	3	5	22	30
	Kamarkhola	4		21	33
Morelganj sub-district	Putikhali	2	4	20	27
	Chingrakhali	2		21	27
Total		16	13	124	168

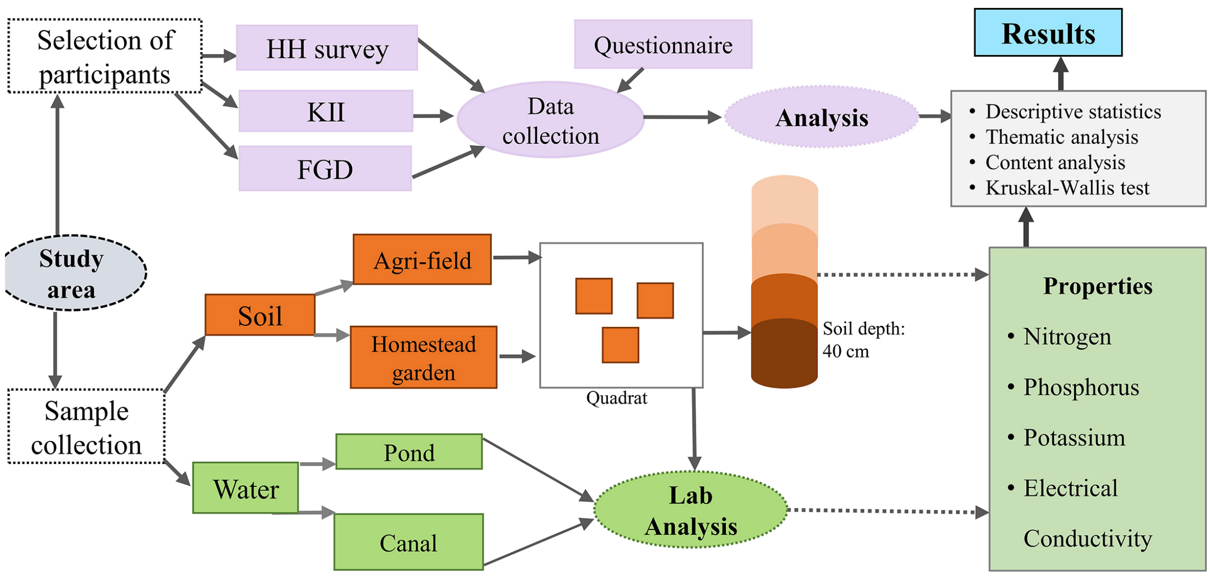

Figure 2. Sampling of the study and quantitative (soil and water salinity and soil nutrient contents: nitrogen, phosphorus, and potassium) and qualitative (FGD: focus group discussion, KII: key informant interview) data collection and processing steps. Household (HH) survey was conducted to observe the homestead agriculture and water management practices (e.g., rainwater harvesting, rain-fed pond, and pond sand filter).

conductivity meter were carefully submerged into the soil extract, and the meter recorded the electrical conductivity of the solution[35].

Focus group discussion and key informant interview

A qualitative method, including FGDs and KIIs, was used to collect information from the households, community, elected representatives, government officials at union and sub-districts level, non-governmental organization (NGO) representatives, fertilizer retailers, teachers, and disaster management committee members for the period April-June 2023. Informed consent was obtained from the participants who attended the FGDs and KIIs and appeared in the photographs.

FGD: FGDs were conducted to facilitate group discussions and obtain qualitative insights into adaptive agricultural practices, water management techniques, and community-based disaster risk reduction initiatives. Participants for the FGDs were selected based on their involvement in agriculture, water management, or community-level decision-making processes, including (i) active farmers who have long experience in farming; (ii) union disaster management committee; (iii) union-level sub-assistant agriculture and health officer; (iv) fertilizer retailer; (v) union parishad member (elected); (vi) business community; (vii) women representative; and (viii) NGO representative. We used a structured questionnaire and conducted 16 FGDs in six unions [Table 2; Figure 3]. The FGDs allowed for exploring shared experiences, perspectives, and local knowledge of soil and water salinity and their adaptive practices. The discussions were transcribed for further analysis.

KII: Thirteen KIIs were conducted with key informants, including local farmers, agricultural experts, health experts, fertilizer businessmen, and community leaders [Table 2; Figure 3]. These interviews aimed to gather detailed information on specific topics of interest, such as innovative agricultural practices, water management infrastructure, and community-based initiatives. They provided a deeper understanding of individual experiences, challenges, and success stories related to adaptation to soil and water salinity, which were transcribed for analysis. A structured questionnaire was used as a guide, covering topics such as adaptive agricultural practices, water salinity management, community-based approaches, challenges faced, awareness levels, and recommendations. The participants in KIIs were purposefully sampled and recruited through professional networks, academic institutions, government agencies, and relevant organizations. Before the interviews, informed consent was obtained from each participant, ensuring confidentiality and voluntary participation.

Data analysis

Soil and water salinity levels and soil nutrient contents in three sub-districts were analyzed in the Kruskal-Wallis test[36]. This test assessed the differences in mean values of soil nitrogen, phosphorus, potassium, and salinity levels among three sub-districts. Likewise, the differences in mean values of pond and canal water salinity among three sub-districts were assessed using the Kruskal-Wallis test[37]. The individual values of water salinity and soil nutrient and salinity were visualized using the geom_point function in R statistical software[38]. Additionally, all the values in their respective sub-districts were depicted in boxplots using the geom_boxplot function. The boxplots depict the distribution of values of soil and water parameters. The line and circle within each box indicate the median and mean values of soil and water parameters. The whiskers extend to the minimum and maximum values, excluding any outliers, which are represented by individual data points outside the whiskers. The P-value obtained by the Kruskal-Wallis test indicates the level of significance in the observed differences in soil and water salinity and soil nutrients across the sub-districts[38]. After detecting significant differences ($P < 0.05$) in soil nutrients and water salinity contents among the sub-districts using the Wilcoxon test[39,40], we proceeded to conduct pairwise comparisons of soil nutrients and water salinity between sub-districts (e.g., Assasuni-Dacope). Additionally, we assessed the differences in soil nutrients and water salinity between each sub-district and the base mean (i.e., the mean soil nutrients and water salinity across the three sub-districts) using the Wilcoxon test[39].

Thematic and content analyses were employed as the analytical approaches to analyze the qualitative data gathered from the FGDs and KIIs[41,42]. The thematic analysis involved identifying patterns, themes, and categories within the data, while content analysis focuses on examining the explicit content and meanings conveyed. In the first step of the analysis, the transcripts of the FGD and KII were carefully reviewed to gain familiarity with the data. This involved reading the data multiple times to immerse oneself in the information and gain an overall understanding of the content. After becoming familiar with the data, the coding process began, involving systematically assigning labels or tags to data segments that represent meaningful units of information. This process helped organize and categorize the data based on common themes. The initial codes were derived from the participant responses, and new codes emerged as the analysis progressed. Next, the coded data were collated and grouped into potential themes. This involved examining similarities and relationships between the codes and identifying overarching patterns. The themes were refined through an iterative process of reviewing the data until a coherent and comprehensive

Figure 3. Collection of data from focus group discussion (A) and key informant interview (B-D) in the southwestern coastal region of Bangladesh. © The Authors 2024.

set of themes was established. Once the themes were identified, the content within each theme was analyzed in-depth. This involved examining the data content within each theme to explore the underlying meanings, interpretations, and insights provided by the participants. Throughout the analysis, rigorous attention was paid to ensure the credibility, reliability, and validity of the findings. This was achieved by maintaining an audit trail of the analytical decisions made, seeking input from multiple authors of the paper to ensure consistency, and employing techniques such as member checking to validate the interpretations with the participants themselves. Finally, we considered two themes in agriculture (Theme-1: challenges in agriculture and Theme-2: resilient agriculture) and two themes in water (Theme-1: drinking water scarcity and Theme-2: drinking water management).

Theme 1 in agriculture: challenges in agriculture

The first theme, "Challenges in Agriculture", focuses on identifying and understanding the various obstacles and difficulties faced by farmers in the agricultural sector. Through the qualitative data analysis, several key challenges emerged:

Climate change impacts: Participants highlighted the adverse effects of climate change on agriculture, including increased frequency and intensity of extreme weather events, erratic rainfall patterns, and rising temperatures. These changes have disrupted traditional farming practices, affected crop yields, and increased vulnerability to pests and diseases.

Soil degradation: Farmers expressed concerns about soil degradation, including erosion, nutrient depletion, and salinization. The intrusion of saltwater due to sea-level rise and inadequate irrigation practices has increased soil salinity, making it difficult to cultivate crops.

Water scarcity: Participants emphasized the scarcity of water for irrigation purposes, particularly during the dry season. Declining water tables, reduced river flows, and competition for water resources were cited as factors contributing to water scarcity in agricultural areas.

Lack of access to finance and technology: Farmers highlighted the challenges associated with limited access to finance and modern agricultural technologies. Insufficient credit facilities, high costs of inputs, and lack of knowledge about advanced farming techniques hindered their ability to adopt sustainable and productive agricultural practices.

Theme-2 in agriculture: resilient agriculture

The second theme, "Resilient Agriculture", explores the strategies and practices employed by farmers to enhance their resilience and adaptability in the face of agricultural challenges. The analysis revealed the following key aspects:

Crop diversification: Farmers acknowledged the importance of diversifying their crop selection to mitigate risks associated with climate variability and market uncertainties. They explored alternative crops that are better suited to changing climatic conditions, have higher tolerance to salinity, and offer better market prospects.

Water management techniques: Participants emphasized the adoption of efficient water management techniques, such as drip irrigation, rainwater harvesting, and water-saving practices. These approaches aimed to optimize water use, improve irrigation efficiency, and address water scarcity issues.

Organic farming and soil health: Many farmers expressed a shift towards organic farming practices to improve soil health, reduce dependence on chemical inputs, and enhance sustainability. They emphasized using organic fertilizers, crop rotation, and cover cropping to restore soil fertility and combat soil degradation.

Knowledge and skill enhancement: Participants recognized the importance of continuous learning and skill development to adapt to changing agricultural practices. They sought training programs, workshops, and access to agricultural extension services to acquire knowledge on climate-smart practices, modern technologies, and improved farming techniques.

Theme 1 in water: drinking water scarcity

The first theme, "Drinking Water Scarcity", examines the issue of inadequate access to safe and clean drinking water in the studied context. The qualitative data analysis revealed the following key aspects:

Water source contamination: Participants highlighted the contamination of drinking water sources, including groundwater and surface water, due to various factors such as industrial pollution, improper waste disposal, and agricultural runoff. This contamination poses health risks and contributes to the scarcity of safe drinking water.

Inadequate infrastructure: Participants discussed the lack of proper infrastructure for water supply and storage. Insufficient piped water connections, limited reservoirs or tanks, and deteriorating water distribution systems were identified as factors contributing to water scarcity in the area.

Population growth and urbanization: The rapid population growth and urbanization in the studied area were identified as drivers of increased demand for drinking water. The existing water infrastructure and resources could not cope with the growing population, leading to shortages and scarcity.

Climate change impacts: Participants acknowledged the role of climate change in exacerbating water scarcity. Changing rainfall patterns, prolonged droughts, and increased evaporation rates were mentioned as factors affecting water availability and further intensifying the scarcity issue.

Theme-2 in water: drinking water management

The second theme, "Drinking Water Management", focuses on the strategies and practices employed to address the challenges of drinking water scarcity. The analysis identified the following key aspects:

Water conservation and rainwater harvesting: Participants emphasized the importance of water conservation practices to optimize water use and minimize wastage. Rainwater harvesting systems, such as rooftop collection and storage tanks, were highlighted as effective approaches to augment water supply and reduce reliance on external sources.

Water treatment and purification: Participants discussed the implementation of water treatment and purification techniques to ensure the availability of safe drinking water. Methods such as filtration, chlorination, and household water treatment systems addressed water contamination issues.

Community-based initiatives: Participants highlighted the role of community-based initiatives in managing drinking water scarcity. Collaborative efforts, such as community water committees, water-sharing agreements, and collective water resource management, were seen as effective approaches to address water scarcity and ensure equitable access to drinking water.

Policy and governance: Participants emphasized the need for supportive policies and effective governance mechanisms to manage drinking water resources. They called for improved regulation, enforcement of water quality standards, and allocation of resources for infrastructure development and maintenance.

RESULTS AND DISCUSSIONS

Soil and water parameters

Soil nutrients and salinity

Soil nitrogen contents did not significantly differ among the studied sub-districts ($P > 0.05$; Figure 4A); however, significant differences were observed for phosphorus and potassium contents (both $P < 0.001$, Figure 4B and C) in the studied three sub-districts. Results show that the soils of Morrelganj exhibited higher nitrogen and phosphorus levels than the soils of Assasuni and Dacope [Figure 4A]. The mean nitrogen content in Morrelganj was 21.91 g kg^{-1}, while Assasuni and Dacope had mean nitrogen values of 20.92 and 20.30 g kg^{-1}, respectively. Similarly, the soils of Morrelganj showed a higher mean phosphorus content of 15.23 μg g^{-1}, whereas the soils of Dacope and Assasuni exhibited mean phosphorus values of 13.95 and 13.41 μg g^{-1}, respectively [Figure 4B]. Conversely, the soils of Dacope demonstrated higher potassium levels (0.216 meq 100 g^{-1}) compared to the soils of Assasuni (0.206 meq 100 g^{-1}) and Morrelganj (0.196 meq 100 g^{-1}) [Figure 4C]. Soil salinity levels among these sub-districts did not significantly differ ($P > 0.05$, Figure 4D). Assasuni had a slightly higher soil salinity, as indicated by its mean electrical conductivity of 8.237 dS m^{-1}, whereas Dacope and Morrelganj had mean electrical conductivity values of 8.076 and 7.956 dS m^{-1}, respectively [Figure 4D].

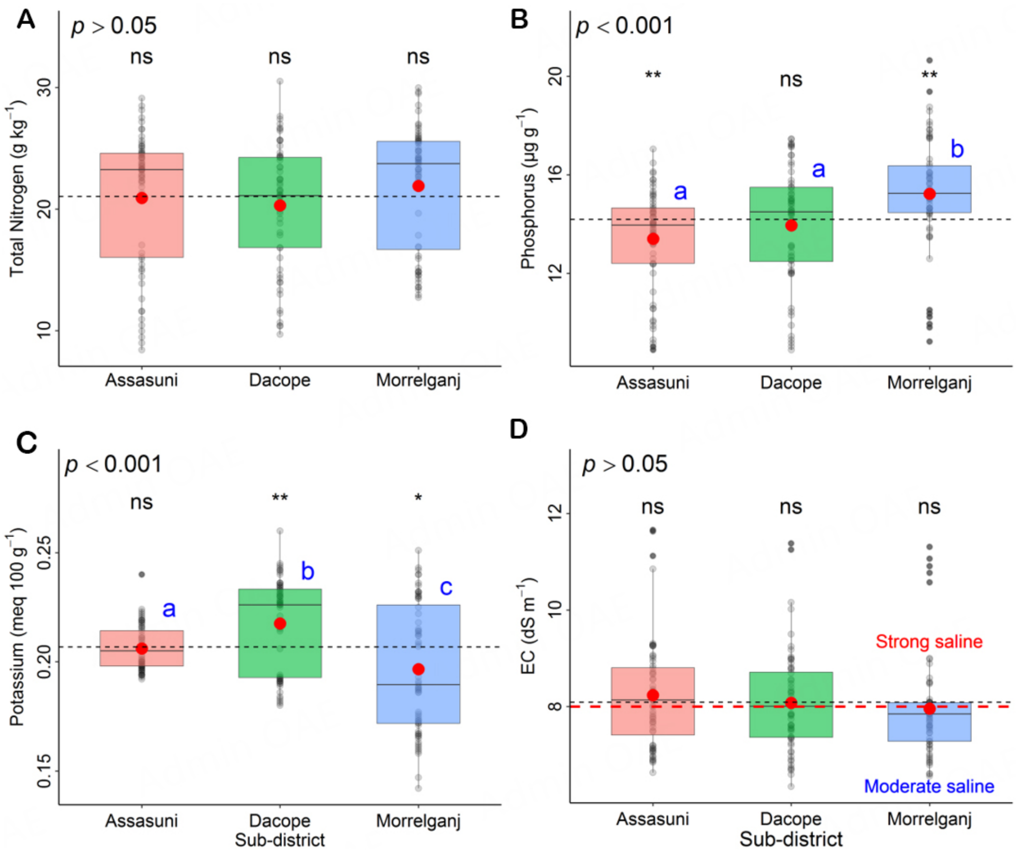

Figure 4. Spatial variation of soil parameters in three sub-districts. The boxplots illustrate the distribution of soil (A) total nitrogen, (B) phosphorus, (C) potassium, and (D) electrical conductivity. The median and mean values of these parameters are represented by a solid line and a red circle within each box, respectively. The whiskers extend to the minimum and maximum values, excluding any outliers, which are displayed as individual data points outside the whiskers. The *P*-value obtained from the Kruskal-Wallis test indicates the level of significance in the observed variations of soil nutrient and salinity levels among the different sub-districts. The letters (a, b, and c) on the boxes indicate the significant differences in pairwise comparisons (e.g., Assasuni-Dacope) of soil nutrients and salinity. Asterisks (* and **) above the boxes signify the significance ($P < 0.05$ and $P < 0.001$) of the differences in the studied variables in each sub-district compared to their base mean (i.e., mean values of all sub-districts), which were derived using the Wilcoxon test, whereas the symbol "ns" represents the differences are insignificant. The dashed lines within the plots indicate the mean values of the studied variables in three sub-districts.

Water salinity

The salinity measurements of pond and canal water in Assasuni, Dacope, and Morrelganj sub-districts revealed significant differences (both $P < 0.001$, Figure 5). When considering pond water salinity, the measurements indicate notable variations among the three sub-districts. Pond water in Assasuni recorded the highest salinity level with 13.98 dS m^{-1}, followed by Dacope with 13.75 dS m^{-1}, and Morrelganj had a slightly lower value of 13.26 dS m^{-1} [Figure 5A]. Likewise, the measurements of canal water salinity revealed significant differences among Assasuni, Dacope, and Morrelganj [Figure 5B]. Assasuni exhibited the highest recorded salinity level (77.85 dS m^{-1}), followed by Dacope (72.78 dS m^{-1}), while Morrelganj has the lowest measurement of canal water salinity (67.95 dS m^{-1}).

The coastal areas of Bangladesh often face challenges related to low soil nutrient levels. The combination of factors such as high salinity, frequent tidal inundation, and limited availability of organic matter contributes to the poor nutrient status of the soil. Several studies in other coastal regions reported differential patterns of soil nutrient contents. For example, Hossin *et al.* reported soil potassium content between 0.16 and

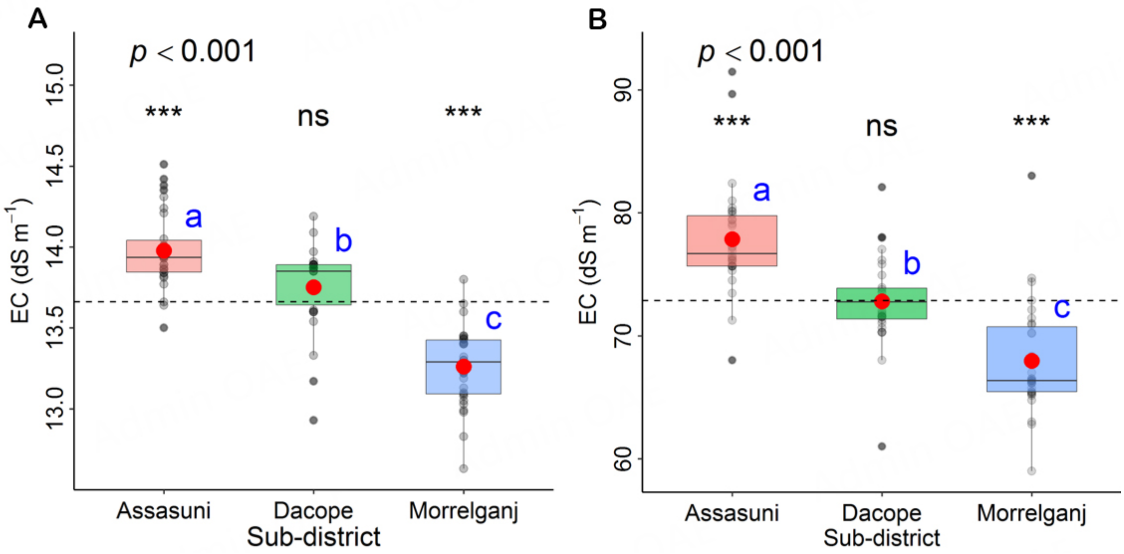

Figure 5. Spatial variation of water salinity (dS m^{-1}) in three sub-districts. The boxplots illustrate the distribution of electrical conductivity in (A) pond water and (B) canal water. The median and mean values of these parameters are represented by a solid line and a red circle within each box, respectively. The whiskers extend to the minimum and maximum values, excluding any outliers, which are displayed as individual data points outside the whiskers. The *P*-value obtained from the Kruskal-Wallis test indicates the level of significance in the observed variations of water salinity levels among the different sub-districts. The letters (a, b, and c) on the boxes indicate the significant differences in pairwise comparisons (e.g., Assasuni-Dacope) of water salinity. Asterisks (* and **) above the boxes signify the significance ($P < 0.05$ and $P < 0.001$) of the differences in the studied variables in each sub-district compared to their base mean (i.e., mean values of all sub-districts), which were derived using the Wilcoxon test, whereas the symbol "ns" represents the differences are insignificant. The dashed lines within the plots represent the mean values of water salinity in three sub-districts.

0.27 meq 100 g^{-1} and phosphorus content between 17.02 and 33.09 mg kg^{-1} in Patuakhali district[43]. Our study findings of soil potassium (mean potassium content was 0.206 meq 100 g^{-1} in Assasuni, 0.216 meq 100 g^{-1} in Dacope, and 0.196 meq 100 g^{-1} in Morrelganj sub-districts) and phosphorus content (mean phosphorus content was 13.41 µg g^{-1} in Assasuni, 13.95 µg g^{-1} in Dacope, and 15.23 µg g^{-1} in Morrelganj sub-districts) in all our sub-districts are consistent with the findings of Hossain *et al.*[44]. Another study in the south-central coastal region also found lower phosphorus (8.32-27.93 µg g^{-1}) content in agricultural soil[45], which supports our findings of lower soil nutrient content in the coastal region. The lower soil nutrient contents could be attributed to increasing soil salinity and frequent tidal inundation of agricultural soils. Frequent tidal inundation experienced in coastal areas leads to the leaching of nutrients from the soil. The tidal water carries away essential nutrients, gradually depleting the soil's nutrient content. This continuous flushing of nutrients exacerbates the already low nutrient levels in the soil.

The combination of high salinity, limited organic matter, and the leaching effect of tidal inundation creates a challenging environment for agriculture in coastal Bangladesh. Addressing these issues requires comprehensive approaches that focus on improving soil fertility through appropriate soil management practices, such as using organic amendments, crop rotation, and efficient irrigation systems. Additionally, the implementation of strategies for mitigating salinity intrusion and managing tidal inundation can help alleviate the nutrient depletion in the coastal agricultural soils.

Due to its extensive low-lying coastal region and frequent exposure to tropical storms, Bangladesh is highly vulnerable to the ingress of saltwater[19] and sea level rise[24]. Saltwater intrusion has detrimental effects on terrestrial environments, increasing salinity levels in both soil and surface water[46]. In a recent study conducted in the southwestern coastal regions of Bangladesh, Lam *et al.* reported that soil salinity in

Bagerhat and Satkhira ranged from moderate to very strong saline (4-32 dS m^{-1}), while in Khulna, it ranged from slightly to moderately saline (2-8 dS m^{-1}) in the year 2015[27]. In our study, we observed higher soil salinity levels in some agricultural fields and homestead gardens compared to the previous study by Lam *et al.*[27]. One possible explanation for this difference is that our soil samples were collected during the dry period (April), whereas Lam *et al.* collected their samples in June[27]. The presence of precipitation, especially during June when the monsoon starts, could reduce salt concentrations in the soil. Rainwater infiltrates the soil, aiding in the dispersion and leaching of salts downward, thereby reducing their overall concentration in the soil profile. The absence of significant rainfall during the dry period when our samples were collected may have resulted in limited leaching of salts, leading to higher soil salinity levels.

The higher levels of soil salinity observed in our study indicate the severity of saltwater intrusion in the coastal areas of Bangladesh. This poses significant challenges for agriculture and horticulture practices, as high salinity negatively affects plant growth and productivity[27]. Sustainable soil and water management strategies are crucial to mitigate the impacts of saltwater intrusion, such as implementing proper drainage systems, using salt-tolerant crop varieties, and adopting efficient irrigation practices. Understanding the dynamics of soil salinity and its temporal variations is essential for developing effective adaptation and mitigation measures in the face of climate change-induced sea-level rise and associated saltwater intrusion. Further research is needed to explore the long-term trends and spatial patterns of soil salinity in coastal Bangladesh, considering different seasons and climatic variations. Such knowledge will contribute to developing targeted and site-specific strategies to enhance agricultural productivity and resilience in the coastal regions.

Challenges and resilience in sustainable agriculture

Mitigation measures

Mitigating soil and water salinization requires a multifaceted approach combining both preventive and remedial measures. One key strategy is improving irrigation practices to minimize the accumulation of salts in the soil. This can be achieved through techniques such as controlled or deficit irrigation, which provide water in quantities that match the plant's needs, reducing excess water that can lead to salt buildup. Implementing efficient drainage systems is another vital step to prevent waterlogging and facilitate the removal of excess salts from the soil. Additionally, promoting organic matter content and soil structure through the application of organic amendments and crop residue management can enhance soil health and reduce the impacts of salinity. Furthermore, adopting salt-tolerant crop varieties and employing appropriate crop rotation systems can help minimize crop vulnerability to salinity. Proper land management practices, such as contour plowing and terracing, can also prevent erosion and minimize the transport of salts to water bodies. Finally, public awareness campaigns and educational programs that highlight the importance of sustainable agricultural practices and the detrimental effects of salinization can play a crucial role in encouraging farmers and stakeholders to adopt these mitigation measures. By combining these strategies, we can effectively reduce soil and water salinization and ensure the long-term productivity and sustainability of agricultural systems.

Challenges in crop cultivation (agriculture: theme 1)

Farmers in the southwestern coastal region have employed specific methods for cultivating crops. For instance, paddy cultivation has been prevalent in all six unions. Before the intrusion of saline water, farmers had cultivated paddy and other crops. However, after two catastrophic disasters (cyclones Sidr 2007 and Aila 2009), the agricultural patterns have shifted. For example, winter crop cultivation is severely affected by the emergence of salinity. These coastal areas have been experiencing increased salinity levels, affecting the productivity of agricultural lands. Moreover, the availability of irrigation water has become a pressing issue, significantly influencing crop cultivation. Despite abundant water in rivers and canals, farmers struggled with irrigation water because of the high salt content in water. The challenges in crop cultivation associated with soil and water salinity have been documented from FGD and KII findings, and the most highlighted findings are reported below.

While talking with the FGD participants, most expressed their sufferings in crop cultivation during 1.5 decades. The participants in the Assasuni union stated that:

"*Previously, we had an adequate water supply for irrigation from both the canal and the pond. However, in 2007, saltwater intrusion occurred, impacting our croplands with salinity. Despite the challenges, we managed to recover from the initial impacts. Unfortunately, our locality was subsequently hit by another cyclone named Aila in 2009, which brought saltwater and further exacerbated the salinity levels in the soil.*"

Similar experiences have been reported in another FGD in the Putikhali union in the Morrelganj sub-district, where farmers stated that:

"*Due to the excessive salinity in both the soil and water, farmers made a shift from traditional agriculture to shrimp farming as a means of livelihood. Following the 2009 cyclone, paddy cultivation became impossible for 4-5 years. To address this challenge, the government and NGOs stepped in to promote resilient agriculture by providing salt-tolerant paddy varieties (e.g., BRRI 52) and alternative crops (e.g., sesame, sunflower, and watermelon). However, initially, farmers faced economic losses as the production from these salt-tolerant crops was lower than expected. Despite the support and availability of resilient crop varieties, the transition to alternative crops required adjustments and learning for the farmers.*"

Farmers cultivating salinity-resilient crops face the challenge of low soil fertility. To compensate, they use high doses of fertilizers and pesticides, increasing production costs. However, this practice has negative environmental and health implications. Excessive use of these chemicals leads to water contamination, soil degradation, and the accumulation of residues in crops, posing risks to human health. During an FGD in Sutarkhali union, situated in the Dacope sub-district, the participants shared similar experiences and expressed their concerns regarding the other challenges they encountered in agriculture.

"*Smallholder farmers in our region have observed that to maintain optimal production levels, it is necessary to apply high doses of fertilizers. Additionally, we have noticed that each year, there is a growing need for increased pesticide application to combat pests effectively. The situation has worsened as pest attacks during the early stages of seedling growth have become more frequent, requiring multiple applications of pesticides throughout the season. This has resulted in additional costs and challenges for farmers to ensure crop protection and yield stability.*"

While the majority of participants in most FGDs attributed their challenges in agricultural production to soil and water salinity, shortage of irrigation water, crop failure, and increased use of fertilizers and pesticides, some also emphasized the emergence of climate-induced stresses as significant factors in recent times. These participants highlighted that climate-related factors, such as unpredictable weather patterns, prolonged droughts, and increased frequency of extreme events such as storms and cyclones, have become more prominent and pose additional obstacles to agricultural productivity. For example, the participants in an FGD in the Kamarkhola union of Dacope sub-district reported that:

"*Farmers in our region have experienced a shift in rainfall patterns, with reduced rainfall occurring during critical periods and excessive rainfall when it is unnecessary. This irregularity in rainfall has had adverse effects on crop production. During the harvest period, excessive rainfall leads to crop losses due to waterlogging and damage to mature crops. On the other hand, during the growing season, water scarcity becomes a significant challenge, affecting crop growth and development. Moreover, droughts have become more frequent, resulting in higher seedling mortality rates and disrupting (prolonging) the flowering process. These drought conditions further exacerbate the difficulties faced by farmers, impacting the overall productivity of their crops.*"

We categorized KII findings regarding the most concerning issues associated with agricultural production into four broad classes (extreme, severe, moderate, and mild challenges) [Table 3]. The challenges are categorized into different factors such as soil salinity, water salinity, irrigation water, soil fertility, pest outbreaks, sea level rise, droughts, heatwaves, hailstorms, cyclones/storm surges, untimely rainfall, limited rain in the growing season, unwillingness to adapt, and lack of input support.

Results showed that all the locations experienced extreme soil salinity, water salinity, pest outbreaks, sea level rise, cyclones/storm surges, untimely rainfall, and limited rain in the growing season. The availability of irrigation water was reported as extreme in Assasuni, Khajra, Sutarkhali, and Kamarkhola, while it was severe in Putikhali and Chingrakhali. This highlighted the critical issue of accessing sufficient irrigation water for agricultural purposes in those areas. Soil fertility emerged as a severe challenge in Putikhali and Chingrakhali, suggesting the need for targeted soil management and improvement strategies to address this particular concern. The presence of moderate droughts and heatwaves across all the locations underscored the adverse effects of these climate stressors on crop production and agricultural systems. Mild challenges, such as hailstorms, unwillingness to adapt to new practices, and lack of input support, were observed across multiple locations, indicating areas requiring further attention and interventions [Table 3].

To address the challenges reported by FGD and KII respondents, prioritizing the cultivation of crops resilient to soil salinity, water salinity, and pest attacks is crucial. These factors have significantly affected agricultural productivity in the studied areas. The government of Bangladesh has implemented interventions to address these challenges and promote resilience in the agricultural sector. The Department of Agriculture Extension, along with universities, research organizations, and NGOs, has introduced various interventions. Farmers are now cultivating saline-tolerant crops such as sunflower, sesame, watermelon, and cucumber, which better withstand the challenges in coastal communities.

The evidence provided by the FGD and KII respondents highlights the impact of salinity and other biological and environmental challenges on agricultural crop cultivation in the region. The traditional cultivation of paddy has been significantly affected by the untimely precipitation and water shortages during the growing season, decreasing crop production. Several studies conducted in coastal regions of Bangladesh, including Hoque *et al*. and Aziz *et al*., have reported similar findings, emphasizing the detrimental effects of soil and water salinity[47,48]. These previous studies demonstrate that the coastal region, including the southwestern coastal belt, is highly vulnerable to sea level rise, salinity, climate-induced shocks (e.g., drought and heatwave), and outbreaks of pests. Additionally, Prodhan *et al*. documented severe to extreme droughts during the paddy (Boro rice) growing season, further exacerbating the challenges posed by soil and water salinity[49]. These increasingly intense droughts and salinity-related issues significantly affect crop production in many coastal districts, rendering the livelihoods of local communities vulnerable[50]. In response to these challenges, the government is actively working to enhance agricultural production by promoting resilient crop seeds[51]. However, it is important to recognize that addressing the agricultural

Table 3. The ranking of the challenges in agriculture reported from the key informant interview (KII) findings conducted in three exposed sub-districts in southwestern coastal Bangladesh

Challenges	Assasuni	Khajra	Sutarkhali	Kamarkhola	Putikhali	Chingrakhali
Soil salinity	****	****	****	****	****	****
Water salinity	****	****	****	****	****	****
Irrigation water	****	****	****	****	***	***
Soil fertility	***	***	***	***	***	***
Pest outbreak	****	****	****	****	***	***
Sea level rise	****	****	****	***	***	***
Droughts	**	**	**	**	***	***
Heatwave	**	**	**	**	**	**
Hailstorm	**	**	*	*	*	*
Cyclone/storm surge	****	****	****	***	***	***
Untimely rainfall	****	****	****	****	****	****
Limited rain in growing season	****	****	****	****	***	***
Unwilling to adapt	*	*	**	**	*	*
Lack of input support	*	*	*	*	*	*

The intensity of each challenge is indicated on a scale from Extreme to Mild. The number of asterisks (*) next to each variable in the respective union represents the severity level, with **** indicating extreme, *** indicating severe, ** indicating moderate, and * indicating mild.

challenges in coastal areas requires a multifaceted approach. In addition to promoting resilient crop seeds, other strategies should also be considered, such as improved water management practices, implementing appropriate irrigation techniques, and developing sustainable soil management strategies. Furthermore, integrating climate-smart agriculture practices, such as agroforestry, crop rotation, and conservation agriculture, can enhance the resilience of coastal agricultural systems. Climate-adaptive agriculture is viewed as a viable option in Bangladesh to mitigate the escalating magnitude of water and soil salinity, which is discussed in the following theme (Agriculture: Theme-2).

Resilient agriculture (agriculture: theme-2)

The implementation of resilient agriculture practices is crucial in ensuring production stability and fostering sustainable agricultural practices, especially in response to the salinity[52] and the growing impact of climate-induced shocks[53]. The insights provided by the FGD and KII respondents in our study highlight various climate-adaptive agricultural measures that farmers have adopted in recent years. These measures encompass cultivating crops that are adaptive to soil and water salinity, resilient to drought and heat, adopting efficient irrigation methods, diversifying crop varieties, and enhancing soil health. These adaptive strategies aim to mitigate the adverse effects of climate change and promote agricultural resilience under increased soil and water salinity.

During an FGD in the Assasuni sub-district, a participant who is actively engaged in cultivating salt-tolerant crops shared his experience. He stated that:

"*We have been experiencing a series of natural disasters, which forced us to adopt new technologies to cope with changing conditions. To address these difficulties, the government's Department of Agriculture Extension has provided support to the farming communities. Capacity-building training and participation in climate field schools, where crop demonstration fields are set up, have been instrumental in enhancing our resilience. Additionally, marginalized farmers have received heat- and saline-tolerant seeds from the agriculture department, leading to the increased popularity of climate-resilient crops like watermelon, mustard, sunflower, and salt-tolerant rice varieties. We have also adopted measures to meet irrigation needs, such as digging small* *ponds in croplands for harvesting rainwater, utilizing harvested rainwater, application of vermicompost (organic fertilizer), and implementing pest control strategies using pheromone traps*."

Farmers can effectively mitigate the adverse effects of soil and water salinity on agriculture by embracing climate-resilient practices and technologies. The focus on climate-adaptive agriculture not only protects crop yields and ensures food security but also strengthens the resilience of farming communities during ongoing climate challenges[54]. While the farmers in our study areas, as highlighted by FGD participants in the Khajra union of Assasuni sub-district, have shared various climate-adaptive agricultural techniques, further research is necessary to explore and identify resilient crop varieties.

Several adaptation technologies have been recorded from the KII respondents in all studied unions. The most mentioned adaptive technologies surrounding resilient agriculture are sack-based crop cultivation, polythene mulching, construction of small ditches in the crop field, cultivation of resilient crops (e.g., sunflower, sesame, watermelon, and mustard) and paddy (Aman dhan), vegetable cultivation on the raised bed along pond embankment, multiple crops, shallow-rooted crops, and application of vermicompost. For example, a KII respondent in the Dacope sub-district stated that:

"*Salinity is still considered the most destructive factor in agriculture in Sutarkhali and Kamarkhola. Our department is focused on soil health recovery and actively encourages farmers to utilize vermicompost to improve soil health, as it has been proven to reduce soil salinity. Some farmers are adopting this technology; however, progress is slow due to its higher market price compared to commercial inorganic fertilizers. We are trying to raise awareness among farmers by establishing demonstration fields and organizing farmers' field schools. Despite the slow progress, this technology is gaining attention in other salinization-affected regions of the country*."

According to a KII respondent in the Assasuni sub-district, "*the dynamic nature of climate change requires continuous efforts to develop crops that can thrive in changing environmental conditions, specifically addressing the challenges posed by soil and water salinity*". The respondent emphasized that "*farmers are facing issues related to salinity in both soil and water resources, which significantly impact agricultural productivity. In response to this challenge, the agriculture department and universities have been actively involved in inventing new varieties of climate-friendly crops that can tolerate salinity. Bangladesh's government has already introduced several high-yielding and salinity- and heat-tolerant crop varieties, such as BRRI 52, sunflower, and soybean, to address the soil and water salinity issues. These initiatives aim to support farmers in adapting to the changing climate conditions and mitigating the adverse effects of salinity on agricultural production*".

The insights shared by participants in the FGD and KII underscore the significant impact of various challenges on crop cultivation in our study region (Agriculture Theme 1). These findings highlight the vulnerability of agricultural systems to changing climatic conditions, particularly the challenges posed by soil and water salinity. They emphasize the urgent need for adaptation measures to address these issues. The adoption of sustainable practices, such as rainwater harvesting for irrigation, application of organic fertilizer, cultivation on raised crop beds and the use of Pheromone traps for pest control, exemplifies the resilience and adaptability of farming communities in responding to the changing climate, including the salinity issue. These practices not only tackle water scarcity challenges but also contribute to environmental conservation and the promotion of sustainable agriculture. The efforts of the Bangladesh government in inventing high-yielding and climate-resilient crops, such as BINA 7, BRRI 71, and BRRI 56 paddy, maize, sunflower, and soybean, are particularly noteworthy[53]. These varieties have been specifically developed to tackle the challenges posed by climate change, including extreme temperatures, salinity, and pest outbreaks.

The findings in Agriculture Theme-2 underscore the importance of resilient agriculture as a response to the adverse impacts of salinity and climate-induced shocks on crop production, particularly concerning soil and water salinity. By developing and promoting climate-friendly crop varieties that can tolerate salinity, farmers can enhance their resilience and adaptability to changing climatic conditions[55]. These climate-adaptive crops offer potential solutions to mitigate the negative effects of salinity, water scarcity, and pest infestations associated with climate variability[52,56]. The active involvement of the agriculture department and universities in inventing and disseminating climate-resilient crop varieties showcases their proactive stance in addressing climate change and its impact on soil and water salinity issues in the agricultural sector[57]. This focus on climate-adaptive agriculture not only ensures food security and maintains agricultural productivity but also supports the resilience and livelihoods of farmers, paving the way for a more sustainable and resilient future.

By developing and promoting climate-resilient crop varieties, farmers can reduce their dependence on traditional crop varieties vulnerable to salinity and other climatic stresses[58]. By adopting climate-resilient crop varieties, farmers can diversify their agricultural practices and reduce the risks associated with salinity intrusion and climate variability[42]. Furthermore, the involvement of the agriculture department and universities in the research and dissemination of climate-resilient crop varieties ensures that farmers have access to the necessary knowledge and resources to implement these adaptive strategies. This collaborative effort between researchers, extension workers, and farmers enables the effective transfer of technology and best practices, allowing for the widespread adoption of climate-adaptive agriculture[59]. In addition to enhancing agricultural productivity and food security, climate-adaptive agriculture contributes to the overall resilience of farming communities. By reducing the vulnerability of farmers to salinity and climate-induced shocks, resilient agriculture safeguards livelihoods and strengthens the socio-economic fabric of rural communities. Moreover, the adoption of climate-resilient crop varieties promotes sustainable resource management and contributes to the conservation of soil and water resources.

Scarcity and management of drinking water

Drinking water scarcity (water: theme-1)

The salinity of groundwater in coastal areas of Bangladesh, including the intrusion of saltwater during cyclones Aila and Sidr, results from multiple factors, including natural disasters and human activities. The saltwater intrusion during cyclones in 2007 and 2009 brought intense storm surges and high tidal waves that caused saltwater intrusion into freshwater bodies and underground aquifers. During cyclonic events, the force of water and surges pushes saline water from the sea or tidal rivers inland, contaminating previously freshwater resources. Saltwater intrusion also occurs in coastal regions outside of cyclones due to proximity to the sea and tidal rivers. Rising sea levels, reduced river flows, and excessive groundwater extraction contribute to the movement of saltwater inland. This infiltration replaces freshwater in aquifers, leading to saline groundwater. The drinking water salinity issue has been stated by all the respondents in KIIs and FGDs. An elderly respondent in an FGD in Chingrakhali union in Morrelganj sub-district expressed that:

"*As a woman, access to clean drinking water is not just a basic necessity but also a vital aspect of our well-being. Unfortunately, many women, including myself, face significant challenges in obtaining safe and freshwater for ourselves and our families. The struggle to find clean drinking water affects our daily lives, health, and even our ability to care for our loved ones. The scarcity of freshwater resources forces us to make difficult choices, often resorting to consuming saline water or relying on alternative, potentially unsafe sources. This puts us at risk of dehydration, and health complications and exposes us to waterborne diseases.*

Additionally, the time and effort spent searching for water means less time for education, work, and personal development".

This reported expression in the Morrelganj sub-district is also consistent with the findings of another FGD in the Dacope sub-districts, where an elected representative in the Sutarkhali union stated that:

"*Since childhood, our family never had to worry about drinking water. We had a deep tube well that provided safe drinking water, and we never imagined the challenges we would face later on. For the past 14 years, our family has been struggling to access clean drinking water. We used to drink untreated water, and for around 4-5 months each year, we were forced to consume salty water from ponds and canals. As a result, we have been suffering from waterborne diseases*".

The intrusion of saltwater into freshwater bodies directly affected the salinity of groundwater. As the saline water infiltrated the aquifers, it mixed with the existing freshwater reserves, increasing the salt content of the groundwater. This rendered the groundwater unsuitable for drinking and domestic purposes. Additionally, the consumption of saline water could lead to health issues such as hypertension, kidney diseases, and mineral imbalances. The impact of salty drinking water consumption is very severe for children and pregnant women. This has been reported by a health professional in Assasuni sub-district, who stated that:

"*Unsafe drinking water poses a significant threat to the health and well-being of pregnant women, leading to an increased risk of premature birth. The lack of access to clean and potable water exposes expectant mothers to various contaminants and pathogens that can have detrimental effects on both the mother and the developing fetus*".

The impact of unsafe drinking water on human health has been extensively studied and documented[20,30,44]. These studies align with the findings from our FGD and KII. For example, research conducted in the southwest coastal region of Bangladesh has revealed that increased salinity in drinking water enhances waterborne diseases, including gastrointestinal issues, hypertension, diarrhea, malnutrition, and skin diseases[30]. Another recent study conducted in coastal Bangladesh[44] reported that the majority of primary schools in the coastal region have unsafe drinking water sources, and the intrusion of salinity poses a major public health concern due to the presence of indicator bacteria that can cause waterborne diseases. Additionally, the probability of suffering from water-related diseases in salinization-affected regions has been found to be higher than in non-salinization-affected regions[20]. These findings strongly support the concerns expressed by our respondents in the FGDs and KIIs regarding the prevalence of waterborne diseases resulting from the consumption of unsafe and salty water. The presence of salinity in drinking water sources can compromise water quality and increase the risk of various waterborne diseases. The ingestion of contaminated water can lead to gastrointestinal infections, diarrheal diseases, malnutrition, and skin ailments, among other health issues. The vulnerability to these diseases is further amplified in areas where salinity intrusion is prevalent. Addressing the issue of unsafe drinking water and salinity-related health risks requires concerted efforts. It involves implementing appropriate water treatment and purification methods to ensure the provision of safe drinking water to affected communities. Additionally, promoting awareness and education about safe water practices, such as proper hygiene and using water treatment methods at the household level, can contribute to reducing the incidence of waterborne diseases.

Drinking water management (water: theme-2)

Ensuring safe drinking water in coastal regions is of paramount importance due to the economic vulnerability and susceptibility to multiple disasters faced by the communities living in these areas[60].

Coastal regions are often characterized by high levels of poverty, limited access to resources, and dependence on climate-sensitive sectors such as agriculture and fishing. As a result, the impacts of inadequate access to safe drinking water are particularly severe and further exacerbate the challenges faced by these communities. In such vulnerable contexts, ensuring access to safe drinking water becomes a crucial component of disaster risk reduction and resilience-building efforts. It helps prevent waterborne diseases and reduces the burden on healthcare systems during and after disasters. Access to safe water also supports the overall well-being and productivity of community members, allowing them to recover and rebuild their lives more effectively.

Rainwater harvesting has emerged as a crucial practice in coastal Bangladesh[61], where the availability of safe drinking water is limited due to the salinity of groundwater and surface water sources. Coastal communities have increasingly recognized the benefits of capturing and storing rainwater as an alternative and reliable source of freshwater[60]. In areas where groundwater is saline, relying on traditional sources, such as wells and tube wells, becomes impractical for meeting drinking water needs. Rainwater harvesting provides a viable solution by allowing communities to collect and store rainwater during the monsoon season when precipitation is abundant. The collected rainwater can then be used for various purposes, including drinking, cooking, and domestic use. One of the primary advantages of rainwater harvesting in coastal Bangladesh is that rainwater is naturally fresh and free from the high salt content found in groundwater and surface water bodies. By capturing it directly, communities can bypass the need for costly and energy-intensive desalination processes. Rainwater is typically low in mineral content and requires minimal treatment to make it suitable for drinking and other household uses. Rainwater harvesting also promotes self-sufficiency and resilience in coastal communities. By capturing and storing it, communities become less reliant on external water sources and are better equipped to withstand water scarcity or emergencies. The collected rainwater can be used for irrigation, which is essential for sustaining agricultural activities in saline-affected coastal regions. By utilizing rainwater for irrigation, farmers can reduce their reliance on saline groundwater and surface water, improving crop yields and overall agricultural productivity. However, it is crucial to consider potential challenges and limitations associated with rainwater harvesting in coastal areas. Rainfall patterns and water availability can vary significantly throughout the year, which may necessitate the construction of larger storage capacities to ensure a reliable water supply during dry periods. Additionally, regular maintenance and cleaning of collection systems are necessary to prevent sediment buildup and potential contamination.

As our studied region has been struggling with safe drinking water for over 16 years, communities have adopted various adaptive technologies to manage their drinking water. Rainwater harvesting is the most adopted technique reported by all the respondents in every FGD across the six unions [Figure 6]. For example, participants in an FGD in Sutarkhali union under the Dacope sub-district stated that:

"*We collect rainwater during the monsoon season and drink it for our water needs. Additionally, we preserve rainwater in rainwater harvesting tanks for later use. At the community level, we re-excavate our pond to preserve rainwater. This pond water is used for domestic purposes and, to some extent, for irrigation. During the dry season, we also rely on pond water for consumption*".

Despite the viability of rainwater in addressing the salinity problem and meeting the drinking water demand, the harvested water cannot support households for an extended period throughout the year. This limitation arises from the smaller size of the storage tank, which can only sustain water supply for a few weeks to a few months. Given that many communities in the coastal region are economically disadvantaged, they cannot afford to purchase larger tanks with capacities, for example, of 2,000 liters. This has also been

Figure 6. Drinking water sources: rainwater harvesting (A and B), rain-fed pond (C), and pond sand filter (D) in the studied unions in the southwestern coastal region of Bangladesh. © The Authors 2024.

observed in our physical observation at the community level [Figure 6]. The statement by a participant in an FGD in the Khajra union of Assasuni sub-district was even shocking, who stated that:

"*After we run out of harvested rainwater, we rely on pond water for drinking without treating it. Our method involves keeping the water in a pot overnight, allowing the suspended solids to settle at the bottom. We then separate the freshwater from the top, which we drink*".

At the outset of the salinity problems, certain community-based water treatment techniques were implemented. However, over time, these methods proved to be unsustainable. For instance, the pond sand filter system was introduced in 2010. In the initial years, it was considered practicable. However, as time passed, the equipment used in this adaptive technique was found to malfunction due to improper maintenance and excessive salt content in the water. Additionally, it requires continuous maintenance, which challenges the community. An NGO representative (KII respondent) who has been working in the coastal region for over a decade shared his experience regarding drinking water management in the affected area. She stated that:

"*I have been involved with several NGOs in this region, providing various forms of support to the community. For instance, we initiated the excavation of a water reservoir to cater to the community's needs. Subsequently, we constructed a pond sand filter to treat the water. Initially, this technique proved highly effective in supplying drinking water to the community. However, as time went on, saline water infiltrated the water reservoir, resulting in the salinization of the soil within*".

To address these challenges, comprehensive strategies are needed. These strategies may include implementing infrastructure projects to improve water supply systems[5], promoting water treatment and purification methods at the community level, and establishing early warning systems to mitigate the risks associated with water contamination during disasters. It is also essential to prioritize capacity-building and awareness-raising activities to educate communities about safe drinking water practices, hygiene, and the management of waterborne diseases. Collaboration among government agencies, NGOs, local communities, and development partners is vital for the success of initiatives to ensure safe drinking water in coastal regions. This collaboration allows for the pooling of resources, expertise, and knowledge to develop context-specific solutions that address the unique challenges these communities face.

Several studies also assessed the (i) feasibility and acceptability of rainwater in the coastal region[13,62]; (ii) quality of harvested rainwater[23,63]; and (iii) people's perception in adopting rainwater harvesting techniques[60,64]. These study findings support our FGD and KII findings. For example, rainwater harvesters in public institutions have been found effective for supplying drinking water to the community[13]); strong governmental assistance is needed to promote rainwater harvesting systems[62]; physical and chemical parameters of harvested rainwater met drinking water standards[63]. Taken together, these findings support the observations made during the FGDs and KIIs regarding the potential of rainwater harvesting as a solution to address the water-related challenges in the coastal region. The feasibility and acceptability of rainwater harvesting systems, along with the assurance of water quality, underscore its potential as a sustainable alternative for meeting drinking water needs in coastal communities. To promote the adoption of rainwater harvesting, strong governmental support and assistance are crucial. This can include policy frameworks, financial incentives, and capacity-building programs to facilitate the implementation and maintenance of rainwater harvesting systems. Furthermore, community engagement and awareness campaigns can play a vital role in creating a positive perception and encouraging the uptake of rainwater harvesting techniques.

Limitations

This study has several limitations. Firstly, it only focused on a limited number of sub-districts, which may not represent the entire region or provide a comprehensive understanding of the variability in nutrient and salinity levels. It did not investigate the underlying factors contributing to the observed differences in nutrient and salinity levels, such as land management practices or proximity to water sources. Moreover, the research relied on a single sampling period, which may not capture seasonal variations in soil and water conditions.

CONCLUSION

The salinity issue in the coastal region of Bangladesh, exacerbated by factors such as rising sea levels and frequent tropical cyclones, poses significant challenges to lives and livelihoods. Gaining a comprehensive understanding of the magnitude of salinity and its consequences is crucial for successfully implementing strategies for fostering sustainable agriculture and ensuring the availability of safe drinking water. Based on the analysis of soil and water parameters and FGD and KII data, our study focused on soil and water salinity, soil nutrient contents, and adaptive practices in agriculture and drinking water management in the southwestern coastal region of Bangladesh. Significant differences were observed for phosphorus and potassium contents among the studied sub-districts. Morrelganj had higher nitrogen (21.91 g kg^{-1}) and phosphorus (15.23 μg g^{-1}) than Assasuni and Dacope. Dacope had higher potassium levels (0.216 meq 100 g^{-1}) than Assasuni and Morrelganj. Soil salinity levels did not significantly differ among the sub-districts, with Assasuni having slightly higher salinity (8.237 dS m^{-1}) than Dacope and Morrelganj. The findings of our study reveal that both soil and water salinity levels in the southwestern coastal region of Bangladesh exceeded the tolerable limits for agricultural crop cultivation and human consumption.

Furthermore, the salinity levels observed in the water sources (ponds and canals) were also found to surpass the acceptable thresholds for human consumption. These findings highlight the urgent need for effective mitigation strategies to address the challenges posed by high soil and water salinity. Rainwater harvesting has been identified as a feasible and effective solution to address the challenges of high soil and water salinity. The findings of KII and FGD highlight the feasibility of stress-resilient agriculture crops in adapting to soil salinity and addressing the challenges it poses. Several adaptive techniques, including vermicomposting, shallow-rooted crops, mulching, and rainwater harvesting in rain-fed ponds, have also been practiced in combating soil salinity. Farmers can enhance soil fertility, improve water management, and promote sustainable agricultural practices through these adaptive measures. Continued research, knowledge sharing, and stakeholder involvement are crucial for their successful implementation. In conclusion, the findings of this study emphasize the practical implications of adopting stress-resilient crops and implementing adaptive measures to address soil salinity, promoting sustainable agriculture and resilience in the face of salinity-related challenges.

Future studies should consider additional factors influencing nutrient and salinity levels, such as land management practices, hydrological dynamics, and climate change impacts. Incorporating a qualitative approach, including interviews or surveys with farmers and stakeholders, could provide valuable insights into the socio-economic implications of nutrient and salinity variations. Moreover, investigating the impact of these variations on crop productivity, water availability, and ecosystem health would further enhance our understanding of the agricultural and environmental consequences.

From a policy perspective, the findings of this study have significant implications for sustainable development, particularly concerning SDG targets. Target 2.4 aims to ensure sustainable food production systems and implement resilient agricultural practices. The observed variations in nutrient and salinity levels emphasize the need for context-specific interventions, such as tailored nutrient management practices, improved irrigation techniques, and sustainable land use planning. These measures can enhance agricultural productivity, reduce environmental impacts, and ensure food security (SDG 2). The adaptive agricultural practices identified align with SDG 15, promoting sustainable land management and resilient agricultural practices that contribute to the terrestrial ecosystem preservation. Our investigation into community strategies for managing water salinity directly relates to SDG 6, ensuring access to clean drinking water. Integrating our research into the SDGs highlights the broader implications of our work in addressing global sustainability challenges.

DECLARATIONS

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Authors' contributions

Conceptualization, data collection, data processing, software, writing-original draft: Shapna KJ
Conceptualization, methodology, writing-review & editing, supervision, funding acquisition, project administration: Li J
Methodology, writing-review & editing: Kabir MH, Salam MA, Khandker S
Conceptualization, methodology, data collection, software, formal analysis, writing-original draft, writing-review & editing, supervision, funding acquisition, project administration: Hossain ML

Availability of data and materials

The quantitative data (soil nutrient, water, and soil salinity) can be obtained from the corresponding author (lokmanbbd@gmail.com). The qualitative data is incorporated within the manuscript.

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Conflict of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Our study received ethical approval from the Review Board of the Center for Coastal Development (CCD), with the reference number CCD/extRes/2022/11(19). We strictly followed the ethical guidelines set forth in the World Medical Association Declaration of Helsinki regarding the inclusion of human subjects. Prior to their participation in the FGDs and KIIs, all participants were provided with comprehensive information regarding the study's objectives.

Consent for publication

Informed consent was obtained from the participants for the publication of their pictures.

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