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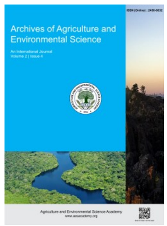

ORIGINAL RESEARCH ARTICLE

Assessment of soil suitability for rice cultivation potential in the coastal region of Bangladesh: A GIS-based approach for Sarankhola Upazila, Bangladesh

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ABSTRACT

Rice is the staple food in Bangladesh. However, soil degradation in coastal land hinders rice production there. This study aims to assess the suitable area for rice production in Sarankhola, a coastal region in Bangladesh. This study uses SRDI's physiochemical and nutrient data as a secondary source. We interpolated these data using Inverse Distance Weighting (IDW) methods and weighed the data using the Suitability Modeler in ArcGIS Pro v3. The findings show that some parameters, like OM, N, P, Cu, and Mn, are close to or within their optimal ranges suggested by SRDI, for rice production in Bangladesh. On the other hand, EC, S, Ca, Mg, and Fe are much higher than their optimal values. The correlation analysis shows strong positive correlations between organic matter and nitrogen (0.97); and Ca and Mg (0.64). Moreover, there is a moderate positive correlation of Soil EC with S (0.43), and K (0.34), respectively. Conversely, a negative correlation was found between soil pH with N (-0.28) and Organic Matter (-0.30), respectively. The spatial distribution of soil physiochemical and nutrients reveals varying suitability for agriculture, with some regions showing optimal conditions while others face significant nutrient deficiencies. The land suitability analysis for rice production reveals that 40–50% of the area, mainly in the Dhansagar and parts of Khontakata unions, is "suitable" for rice cultivation. Meanwhile, 20–30% of Rayenda, Southkhali, and parts of Khontakata are "moderately suitable," necessitating additional inputs. The remaining 30-40%, particularly in Rayenda and Southkhali, are "marginally suitable." The results suggest that Dhansagar and Khontakata unions in Sarankhola are potential areas for rice production naturally, without using hybrid seeds.

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INTRODUCTION

Rice is an important and major cereal crop in Bangladesh owing to its nutritional value, higher yields, and versatile uses (Islam *et al*., 2016). Bangladesh is now self-sufficient in rice production, but this is not for the coastal zone (MoA-FAO, 2013; Tuong *et al*., 2014). During the wet season, farmers produce mostly low -yielding and traditional rice varieties. In the dry season (from January to May), most cultivable lands remain fallow because of varying degrees of salinity in soil and the scarcity of good-quality irrigation water (Karim *et al*., 1990; Mondal, 1997). According to SRDI (2010), the climate change effect will significantly influence Bangladesh's soil salinity levels to be increased. In Bangladesh, coastal areas comprise about 2.5 million ha, which accounts for nearly 25% of the country's total cropland. Of this, around 0.84 million ha are impacted by varied salinity intensities (Karim *et al*., 1990). In addition, nutrient deficiencies, specifically those of N and P, are quite prevalent imposed by salinity. Among the saline soils' micronutrients, Cu and Zn are limited, resulting in a substantial yield reduction (Shelley *et al*., 2016; AL-Huqail *et al.*, 2022). Compared to Bangladesh's other regions, dry-season rice cultivation remains very low in the coastal region, even though it is grown in approximately 83% of the nation's potential rice-cultivating areas (Ali, 2006; BBS, 2020). Thus, the intensification of coastal areas' dry season rice cultivation has attracted noticeable attention from policymakers, occupying about 30% of the nation's total area in these regions (Baten *et al.*, 2015; Islam, 2004).

Consequently, cropland suitability analysis emerges as a crucial step in assuring that the available land resources can be utilized to their full potential for sustainable agricultural production practices (Halder, 2013; Lupia, 2014). The Land Suitability Analysis (LSA) is a spatial multicriteria decision analysis (MCDA) approach (Ferretti & Pomarico, 2013), in which numerous MCDA techniques can be utilized in a GIS setting, e.g., weighted linear combinations (WLC), analytical hierarchy process (AHP), Boolean overlays, ordered weighted averaging, and multiple-objective land allocation (Rikalovic *et al.*, 2014). Several researchers applied the GIS-based Multi-Criteria Decision Approach to develop suitability maps for rice crop production; for instance, over 70% of the total study region in Ethiopia was found to be moderately and highly suitable for rice cultivation, recommending taking more factors like socio-economic conditions, soil fertility, and land use into consideration for future research works (Ayehu & Besufekad, 2015). Similar investigations were carried out in Embu, Mbeere, and Kirinyaga counties in Kenya by Kihoro *et al.* (2013); Morobe province in Papua New Guinea by Samanta *et al.* (2011); and Prachuap Khiri Khan province in Thailand by Hussain *et al.* (2012). Due to Bangladesh's mixed land use pattern, studies on LSA are highly emphasized according to several experts' opinions (Muhsin *et al.*, 2018). GIS and remote sensing techniques have been successfully used in site suitability analysis for salt-tolerant rice varieties like Bina dhan-8 and -10, and BRRI dhan-47, in 20 southern districts of Bangladesh. A total of 4070 mauzas under 65 upazilas of 12 districts, were found suitable for disseminating these varieties (Sinha *et al.*, 2014). In another study by Islam *et al.* (2018), 22.74% of the area as highly suitable, 28.54% as moderately suitable, and 14.86% as marginally suitable have been identified for rice production in three northern districts (Rangpur, Lalmonirhat, and Kurigram) of Bangladesh integrating GIS and MCDA including nine factors such as slope, elevation, land type, topsoil texture, soil pH, flood-prone, rainfall, temperature, and land use. They also suggested producing rice up to marginally suitable land to gain support from insurance.

Bangladesh's rice-dominated agricultural sector is progressively exposed to natural disasters like cyclones, floods, droughts, and salinization, which have immediate and long-term implications on national food security (Alam, 2018). In coastal areas, salinization is one of these disasters, considered a principal constraint to expanding dry-season rice cultivation which might affect the pace of achieving the SDGs targets (Alam, 2018; MoA-FAO, 2013). Studies regarding the site suitability analysis for sustainable rice production in coastal regions of Bangladesh are still very few. The present study aims to fill this critical research gap by identifying the most suitable area for successful rice production in Sharankhola upazila of Bagerhat district, Bangladesh, using GIS and remote sensing techniques. This suitability analysis will provide valuable insights to policymakers and agricultural extensionists in land-use planning, maximizing land use, achieving sustainable agriculture practices, and ensuring food security in the coastal regions of Bangladesh.

MATERIALS AND METHODS

Study area

Sarankhola Upazila is located in the Bagerhat district in the southwestern region of Bangladesh. The absolute location of this study region is 22.3104° N latitude and 89.7910° E longitude, covering 151.23 square kilometers with a specific area of 22.12 square kilometers. It comprises 4 unions (Dhansagar, Kontakata, Rayenda, and Southkhali), 44 villages, and 11 Mouzas. The total population is 110,400. The region encompasses 15,129 hectares of land (Bangladesh National Portal, 2024). It is surrounded by Mathbaria and Patharghata upazilas on the east, Mongla upazila on the west, Morrelganj upazila on the north, and the Bay of Bengal on the south (Figure 1).

Data collection

The soil's physicochemical and nutrient data was collected from the SRDI yearly published book of 2018, which served as a secondary data source for this study. The location of the data points was also georeferenced from the map available in the book (Figure 2). The location-wise data is attached in Table S1.

Data analysis

Interpolation

Spatial interpolation, a key method in geospatial analysis, is useful for estimating continuous spatial environmental variables for efficient decision-making and determining values at un-sampled locations by considering known data points (Yang *et al.*, 2020). Inverse Distance Weighting (IDW) interpolation is a common method used in spatial analysis. It finds cell values by combining a set of sample points that are linearly weighted (Bilonick *et al.*, 1991). Furthermore, IDW interpolation explicitly carries out the assumption that objects closer in proximity are more alike than those farther away (Hodam *et al.*, 2017). In the current study, we implemented IDW using ArcGIS 10.8.2 to predict the location's soil physicochemical parameters and soil nutrient concentration to display the spatial distribution.

Suitability analysis

Parameters for rice suitability

Land for rice suitability is shaped by climate, soil, socio-economic, and technological factors. Optimal temperature and rainfall significantly boost yields (Wang & Li, 2023; Mahato *et al.*, 2024), while soil fertility, texture, and wetness are crucial (Makoi, 2020). Technological tools like remote sensing and GIS

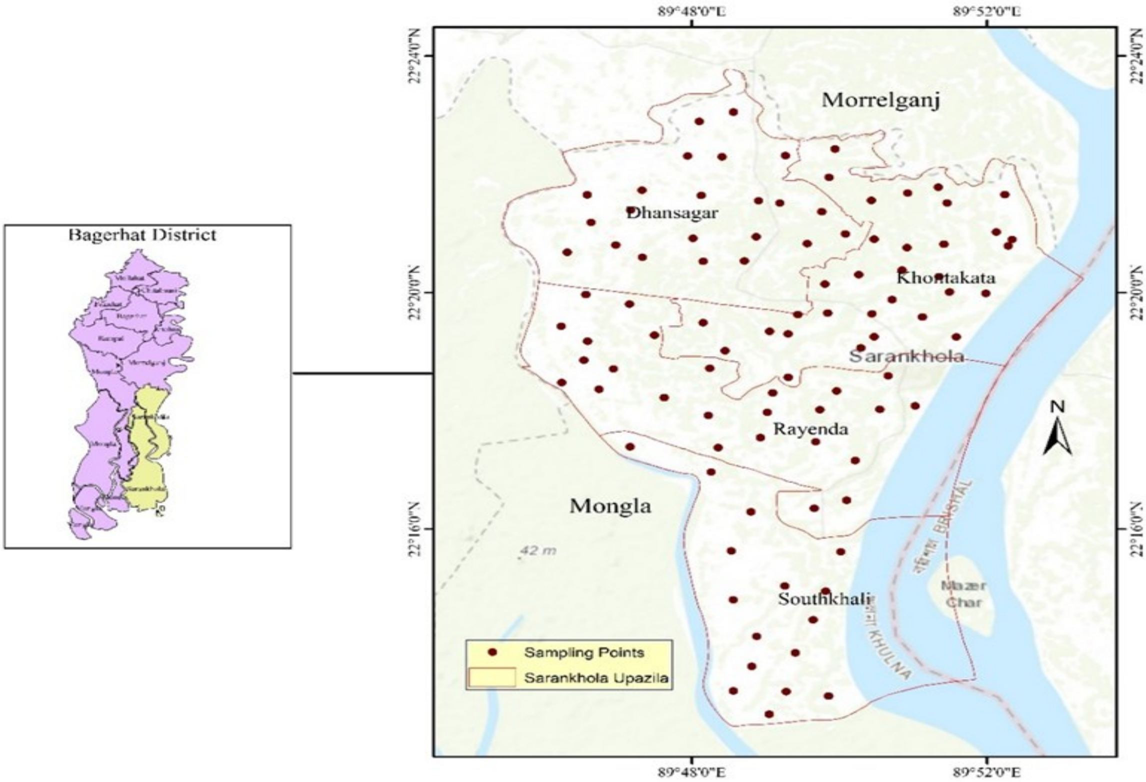

Figure 1. *Study area and sampling points.*

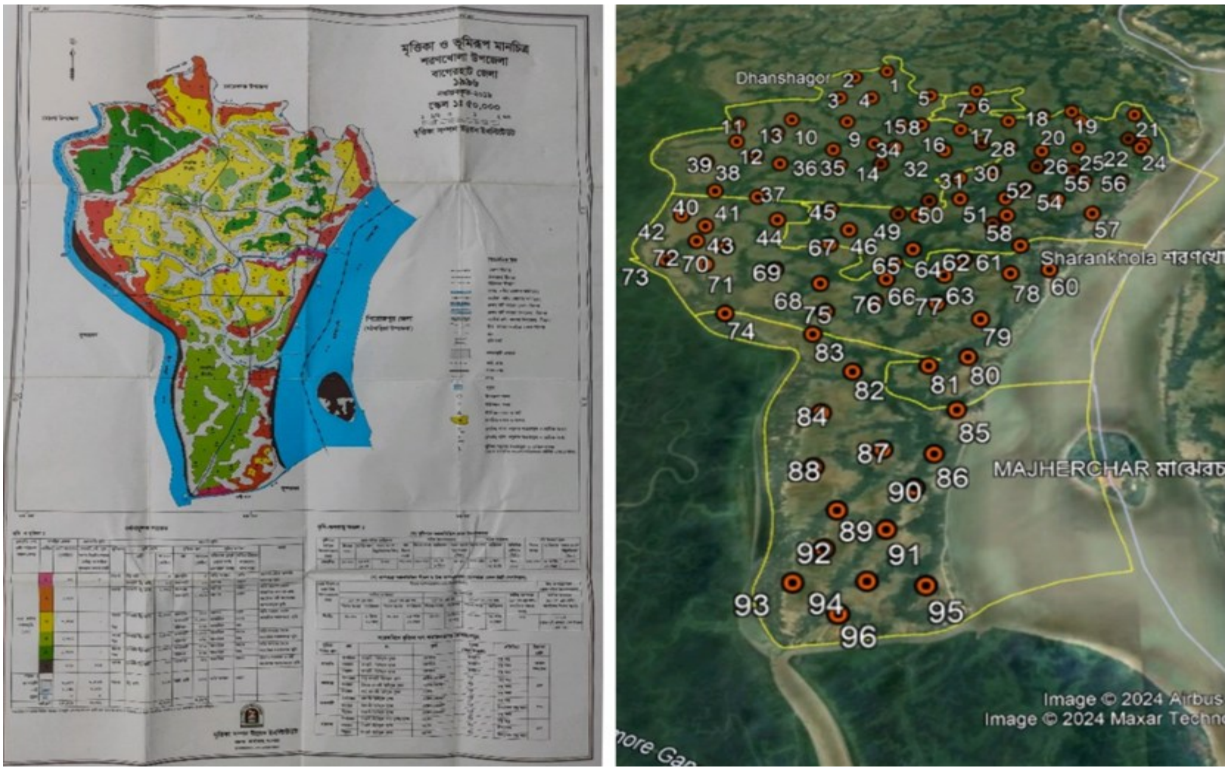

Figure 2. *Georeferenced map - (a) Base map; (b) Georeferenced sampling points.*

further enhance land suitability assessments, improving resource management (Mahato *et al.*, 2024). However, in this study, the rice suitability analysis is conducted based on 14 soil physicochemical and nutrient parameters. The optimum soil pH for rice production in Bangladesh is 6.0-6.5 (FRG, 2012), as low pH levels via high H^+ activity directly inhibit plant growth (Schubert *et al.*, 1990; Koyama *et al.*, 2001). High H^+ concentration triggers oxidative stress in plants, leading to the accumulation of reactive oxygen species (ROS) like hydrogen peroxide (H_2O_2) and superoxide radicals ($O_2^- \bullet$) in plant tissues (Shi Qing-Hua *et al.*, 2006; Liu *et al.*, 2011). The optimum electrical conductivity (EC) level for Bangladeshi soil is between 0 and 4 dS/m (SRDI, 2010), with higher levels indicating potential salinity issues that can limit crop growth and microbial activity, cause structural problems, and lead to sodium toxicity (NRCS, 2011). The soil in Bangladesh should contain at least 2% organic matter (OM) for successful crop production (Islam, 1990), but approximately 54% of 7.6 million hectares is severely deficient,

Table 1. Selected parameters and their optimum level with remarks.

Parameters	Range of the data for this study	Optimum values	Remarks
pH	5.6-6.5	6.0-6.5	Slightly less than optimum level
EC	1.4-34.27	0-4	Far from optimum
OM	1.21-2.06	2	Optimum level
N	0.07-0.12	0.02-0.12	Optimum level
P	3.01-56	6	Far from optimum
S	6.43-198.33	22.51-30.00	Far from optimum
K	0.22-0.92	0.271-0.36	Slightly less than optimum level
Ca	16.27-30.29	4.51-6.00	Far from optimum
Mg	5.37-16.02	1.16-1.50	Far from optimum
Cu	0.98-4.2	0.451-0.60	Far from optimum
Zn	0.46-1.5	1.351-1.80	Below optimum level
Fe	20.11-42.75	9.1-12.00	Far from optimum
Mn	1.38-4.82	2.56-3.00	Slightly less than optimum level
B	0.09-1.45	0.451-0.60	Far from optimum

Source: (FRG, 2012)

necessitating the addition of compost, vermicompost, cow dung, bio-organic fertilizer, or poultry manure to sustain rice production (SRDI, 2010; FRG, 2012). The optimum nitrogen content ranges from 0.02 to 0.12% (Ahsan & Karim, 1988), and deficiency impedes chlorophyll and protein synthesis, reducing photosynthesis and dry matter production in rice (Wang *et al.*, 2020), while excess nitrogen can lead to overgrowth and increased pest and disease susceptibility (Ali *et al.*, 2017). Phosphorus is the second most limiting nutrient after nitrogen for rice, with an optimum level of 6 μg/g, and deficiency results in reduced tillering, stunted growth, and poor development (Portch, 1984; Rice Knowledge Bank Website, 2020). Sulfur, with an optimum content of 22.51-30.00 μg/g (FRG, 2012), is crucial for nitrate uptake and nitrogen metabolism, with deficiency leading to reduced plant growth (Prosser *et al.*, 2001; Abdallah *et al.*, 2010). The optimum potassium content is 0.271-0.36 meq/100 g (FRG, 2012), and deficiency results in decreased potassium concentration in shoots and roots and increased antioxidant enzyme activities (Liu *et al.*, 2013). Calcium should be present at 4.51-6.00 meq/100g (FRG, 2012), with deficiency leading to membrane injury and reduced antioxidant capacity (Van Steveninck, 1965; Tewari *et al.*, 2004; Schmitz-Eiberger *et al.*, 2002; Chao *et al.*, 2009; Paranhos *et al.*, 1999). Magnesium, with an optimum value of 1.16-1.50 meq/100g (FRG, 2012), is essential for root growth and photosynthesis, with deficiency leading to reduced photosynthetic rates (Cakmak *et al.*, 1994; Tränkner *et al.*, 2018). The optimum copper content in soil is 0.451–0.60 μg/g (FRG, 2012), with deficiency resulting in stunted growth and leaf necrosis (Broadley *et al.*, 2012). Zinc content should be 1.351–1.80 μg/g (FRG, 2012), with deficiency impairing rice seedlings' adaptation to anaerobic soil conditions (Moore & Patrick, 1988). Iron content should be 9.1–12.00 μg/g (FRG, 2012), with deficiency severely affecting lowland rice growth and altering phosphate concentrations (Saenchai *et al.*, 2016). Magnesium, with an optimum content of 2.56-3.00 μg/g (FRG, 2012), is often deficient in alkaline soils, restricting plant growth (Behera & Shukla, 2014), while excess levels can be toxic (Migocka & Klobus, 2007). Finally, boron content should be 0.451-0.60 μg/g (FRG, 2012), as insufficient boron decreases crop yield, weakens grain quality, and increases disease susceptibility (Goldbach *et al.*, 2007). Table 1 summarizes the selected parameters, data range, and optimum level for rice production in this study.

Reclassification and ranking

Based on the optimum level and Table 1, the interpolated raster data of 14 selected parameters were reclassified and ranked. The raster data is classified into five levels (optimum, near-optimum, moderate, suboptimal, and poor) with corresponding rankings (5 to 1). Each level has specific criteria and outcomes for rice suitability. The detailed classification and ranking systems are presented in Table 2.

Weighting

Various soil parameters (e.g., pH, EC, OM, etc.) are assigned weights (%) based on their importance in determining rice suitability, as advised by SRDI officers (as an expert opinion) and shown in Table 3. The weight values also align with the existing literature. Like, larger weights are assigned to pH, EC, and nitrogen because of their vital roles in nutrient availability, salinity control, and plant development (Khan *et al.*, 2024). Additionally, potassium and phosphorus are modestly weighted because of their roles in disease resistance and root formation (Kanojia & Sreekesh, 2022). Soil structure and plant health are maintained by organic matter, calcium, and magnesium; iron, zinc, and sulfur are necessary, although in lower amounts (Kanojia & Sreekesh, 2022). Since copper, boron, and manganese are micronutrients needed in trace amounts for rice development, they have lower weights (Duan *et al.*, 2019).

Weighted overlay analysis for soil-suitable land

The suitability modeler in ArcGIS Pro v3 was used to calculate and visualize the land for rice-suitable areas in Sarankhola upazila. It starts with soil physicochemical and nutrient parameter selection, followed by interpolation and reclassification of raster data. A suitability modeler then uses raster insertion and weighted overlay (based on expert opinion and literature review) to calculate suitability levels. The results classify land as highly suitable, moderately suitable, marginally suitable, or poorly suitable for use.

Table 2. Reclassification scheme for the raster data.

Condition	Ranking	Range	Comment
Optimum	5	Optimum level	The condition is ideal and produces the best possible outcome
Near Optimum	4	Slightly less than optimum level	Still very effective
Moderate	3	Not optimum nor poor	The condition is acceptable, but improvements could enhance the outcome
Suboptimal	2	Level below than optimum	Leads to less effective yields
Poor	1	Far from optimum	Yields are significantly compromised

Table 3. Weight for the selected parameters.

Parameters	Weight (%)
pH	10
EC	12
OM	8
N	12
P	9
K	9
S	6
Zn	5
B	4
Ca	8
Mg	7
Cu	3
Fe	5
Mn	2

RESULTS AND DISCUSSION

Descriptive statistics

The pH range is found to be 5.6 to 6.5; the mean pH value was observed to be 5.83±0.23, which is slightly below the optimum range of 6.0-6.5 (Figure 3A). The EC ranges from 1.43 to 34.27 ds/m, with a mean of 10.47±7.32 ds/m (Figure 3B). This is much higher than the ideal range of 0–4 ds/m, which could mean that the soil is too salty. Organic matter (OM) content varies from 1.21% to 2.06%, with a mean of 1.57±0.17% (Figure 3C), which is close to the optimum value of 2%, indicating relatively adequate organic content. The nitrogen (N) concentration varies between 0.07% and 0.12%, with an average of 0.09±0.01% (Figure 3D). This is comfortably within the recommended range of 0.02-0.12%, indicating adequate nitrogen levels. The phosphorus (P) level in the soil ranges from 3.01 to 56.24 µg/g (Figure 3E), with an average of 6.99±6.85 µg/g, which closely matches the optimal value of 6 µg/g. Potassium (K) shows a range of 0.22 to 0.92 meq/100 g soil, with a mean of 0.49±0.15 meq/100 g soil (Figure 3F), slightly above the optimum range of 0.27–0.36 meq/100 g soil, indicating marginally high potassium levels. Sulfur (S) content ranges from 6.43 to 198.33 µg/g soil (Figure 3G), with a mean of 86.08±38.77 µg/g soil, significantly higher than the optimum range of 22.51-30.00 µg/g soil, which may indicate excessive sulfur presence. Zinc (Zn) content varies from 0.46 to 1.5 µg/g soil, with a mean of 0.97±0.24 µg/g soil (Figure 3H), slightly below the optimum range of 1.35-1.80 µg/g soil, suggesting zinc deficiency. Boron (B) content ranges from 0.09 to 1.45 µg/g soil, with a mean of 0.40±0.25 µg/g soil (Figure 3I), which falls within the optimum range of 0.45-0.6 µg/g soil.

Calcium (Ca) levels are significantly high, ranging from 16.27 to 30.29 meq/100g soil (Figure 3J), with a mean of 23.05±3.40 meq/100g soil, far exceeding the optimum range of 4.51-6.00 meq/100g soil. Magnesium (Mg) content ranges from 5.37 to 16.02 meq/100 g soil, with a mean of 9.0±1.98 meq/100 g soil (Figure 3K), which is also much higher than the optimum range of 1.16–1.50 meq/100 g soil. Copper (Cu) levels range from 0.98 to 4.2 µg/g soil, with a mean of 2.54±0.69 µg/g soil (Figure 3L), within the optimum range of 0.45–6.00 µg/g soil. Iron (Fe) content shows a wide range from 20.11 to 42.75 µg/g soil (Figure 3M), with a mean of 29.46±5.08 µg/g soil, which is above the optimum range of 9.1–12.00 µg/g soil. Manganese (Mn) levels range from 1.38 to 4.82 µg/g soil, with a mean of 2.67±0.71 µg/g soil (Figure 3N), within the optimum range of 2.56-3.00 µg/g soil. Overall, some parameters, like OM, N, P, Cu, and Mn, are close to or within their optimal ranges. Other parameters, like EC, S, Ca, Mg, and Fe, are much higher than their optimal values.

Soil physiochemical properties and nutrient levels can be effectively balanced using green and engineering-based remediation techniques (Nouri *et al.*, 2017). Green remediation strategies involve leaching with low-salinity water to control salinity levels and enhance drainage, thereby preventing salt accumulation (Hoffman & Shalhevet, 2007). Leaching and the incorporation of organic matter, such as compost, can mitigate sulfur levels (Iram *et al.*, 2019). To reduce potassium and calcium levels, refrain from using fertilizers that contain these elements and consider the addition of gypsum to improve leaching. Enhancing the calcium-to-magnesium ratio may assist in regulating elevated magnesium levels (Kabir *et al.*, 2024). Enhancing soil aeration via drainage can mitigate excess iron (Huang *et al.*, 2016), while the application of lime is beneficial for acidic soils. Zinc deficiency can be addressed with zinc fertilizers and phytostabilization (Padmavathiamma & Li, 2009). Engineering-based remediation employs precision agriculture through remote sensing and soil sensors to facilitate real-time nutrient monitoring, thereby optimizing the use of fertilizers and water (Sishodia & Ray, 2020). Sustainable practices include controlled-release fertilizers and community engagement through bioremediation (Sharma *et al.*, 2024). Smart irrigation systems and soil data platforms enhance nutrient management and decision-making efficiency (Lakhiar *et al.*, 2024). These methods enhance sustainable soil management through the integration of technology and community engagement.

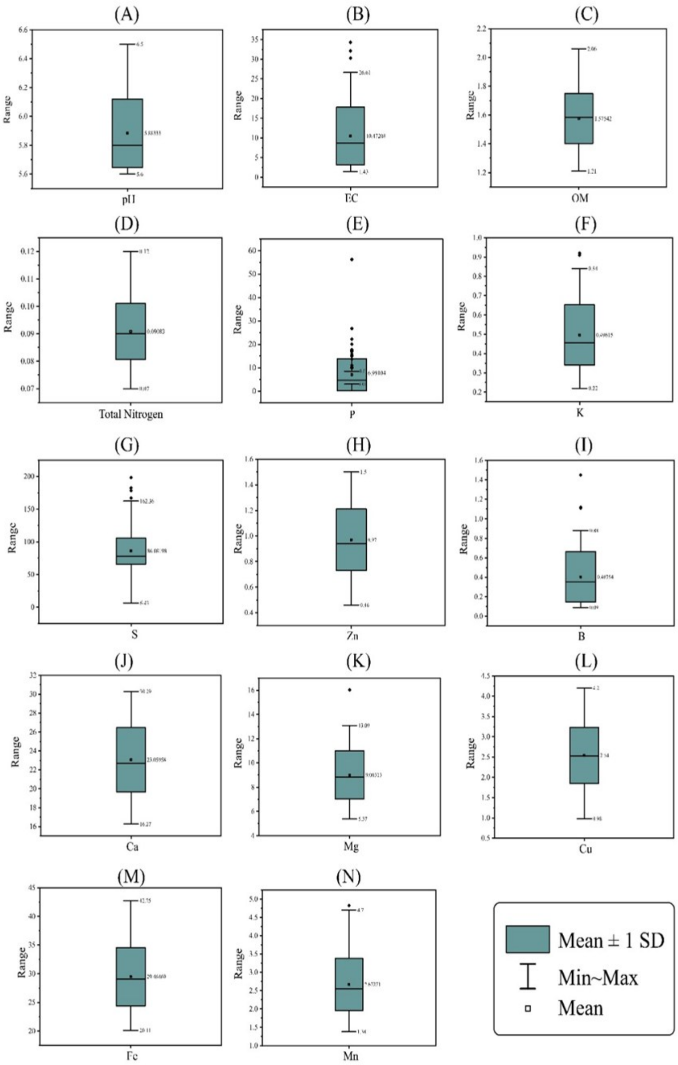

Figure 3. *Descriptive statistics of the collected soil sample's physicochemical parameters and soil nutrients including mean, minimum, and maximum.*

Correlation analysis of soil physicochemical parameters and soil nutrients

The Pearson correlation matrix in Table 4 shows the intricate relationships among several soil physicochemical characteristics and soil nutrients. The relationship between OM and N in the soil is strongly positive and significant, with a correlation coefficient (r) of 0.97. This emphasizes the crucial importance of organic matter in retaining nitrogen in the soil. The correlation values of 0.43 and 0.34 suggest a moderately positive association between EC, S, and K, respectively. This implies that soils with higher EC levels typically have greater concentrations of these nutrients. Conversely, both OM and N exhibit negative associations with pH (r = -0.30 and -0.28), indicating that soils with elevated quantities of organic matter and nitrogen tend to have a lower acidity. The same trend was also discovered by Ghode *et al.* (2020). Moreover, a robust positive correlation (r = 0.64) exists between Ca and Mg, suggesting that these two elements are commonly present in soil matrices, also found by Sen and Zaidi (2017) in soil samples in the Eastern Plain Zone of Eastern Uttar Pradesh. The matrix indicates a moderate positive connection (r = 0.24) between Cu and OM. Simultaneously, P demonstrates a negative correlation with EC (r = -0.26), indicating a competitive interaction or separate sources for these elements. The correlation analysis results indicate a significant association between OM and N in the soil samples.

Table 4. Pearson Correlation among soil physicochemical parameters and soil nutrients.

	pH	EC	OM	N	P	K	S	Zn	B	Ca	Mg	Cu	Fe	Mn
pH	1													
EC	0.12	1												
OM	-0.30	-0.17	1											
N	-0.28	-0.18	0.97**	1										
P	0.06	-0.26	-0.03	-0.03	1									
K	-0.19	0.34	0.23	0.18	-0.12	1								
S	-0.13	0.43	-0.15	-0.18	-0.12	0.20	1							
Zn	-0.16	-0.03	0.07	0.05	-0.02	0.09	-0.15	1						
B	0.20	0.40	0.08	0.08	-0.01	0.33	0.10	0.06	1					
Ca	0.14	0.02	0.07	0.06	-0.06	0.12	-0.18	0.19	0.32	1				
Mg	0.25	0.06	-0.28	-0.29	0.02	0.05	-0.12	-0.004	0.09	0.64**				
Cu	-0.15	0.008	0.24	0.24	0.03	-0.05	-0.24	0.15	-0.04	0.14	0.02	1		
Fe	-0.02	0.008	0.067	0.015	0.01	0.19	-0.01	0.14	0.14	0.12	0.06	1.01E-5	1	
Mn	0.09	-0.01	-0.31	-0.30	0.06	-0.04	-0.10	0.02	-0.05	0.13	0.27	-0.01	-0.03	1

2- tailed test of significance is used and correlation is significant at a 0.05 level (**)

Spatial pattern of soil physicochemical properties and nutrients

Figure 4(A) shows five different soil pH levels across the study area. The central and south-eastern parts represent mainly the "optimum" pH level, which is suitable for most crops. In addition, most of the northern part is visualized as "poor," indicating unsuitable for agriculture. In Figure 4(B), the EC is presented as a "near optimal" level from the north-eastern to the southern part, which is suitable for farming. The ''Organic Matter'' level from Figure 4(C) shows most of the portion of the upazila as "Sub-Optimum," which denotes localized areas with lower organic content that may affect soil fertility. According to Figure 4(D), the total nitrogen, which displays a widespread area as "near optimum," seems to have an appropriate nitrogen content. Figure 4(E) exhibits a heterogeneous distribution of phosphorus, where north-central, central, and southern regions are dominated by "near optimum" levels. The potassium in Figure 4(F) is placed as the "near-optimum" level prominently in the south and the "moderate" level in the center. Figures 4(G) and 4(H) for sulfur and zinc, respectively, show "moderate" levels in the central to southern and northeastern regions, indicating adequate but not ideal nutritional levels. The locations with "optimum" levels of Boron from Figure 4(I) are depicted in the north and center and "moderate" levels in the northeast and south zones. In Figure 4(J), calcium has a "poor" category in the northeastern part, signifying a severe shortage, while from northeast to southeast are "moderate" levels. The central area of Figure 4(K) mainly shows "sub-optimum" levels of magnesium, while the majority of the upazila shows "moderate" levels. According to Figure 4(L), the northern and southern regions are marked as "poor" and "suboptimum" levels for copper, respectively. Figure 4(M) demonstrates the iron levels, where the "sub-optimum" and "poor" levels are presented in some places throughout both central and northern regions, and the "poor" level indicates severe iron deficits. In contrast, the manganese level in Figure 4(N) shows "optimum" values across a large portion of the upazila, reasoning manganese levels that are generally adequate.

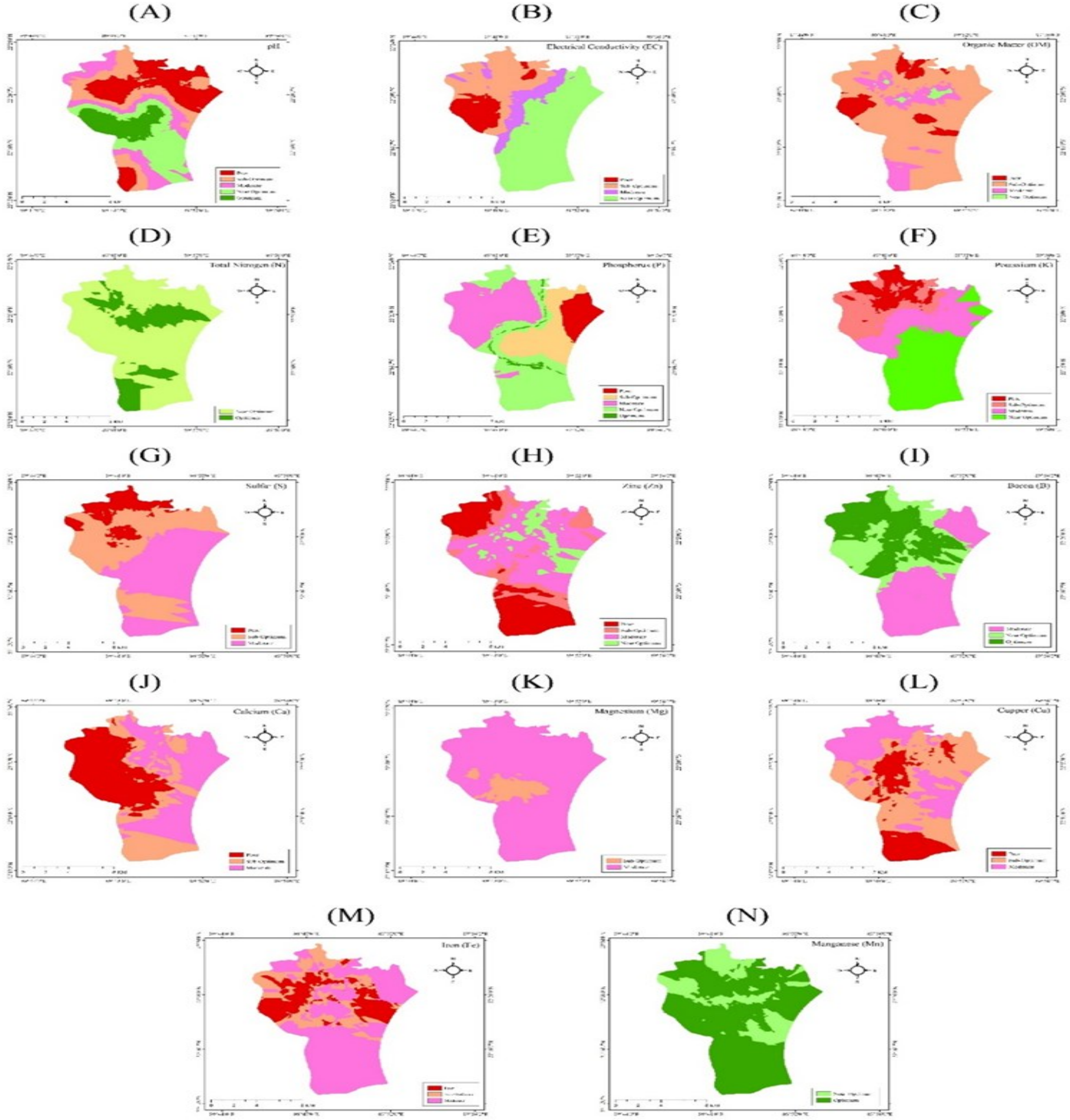

Figure 4. *Spatial distribution of soil physiochemical and nutrient levels in Sarankhola Upazila where dark green indicates optimum values, light green denotes near-optimum levels, light purple represents moderate levels, pink shows suboptimal levels, and red indicates poor levels.*

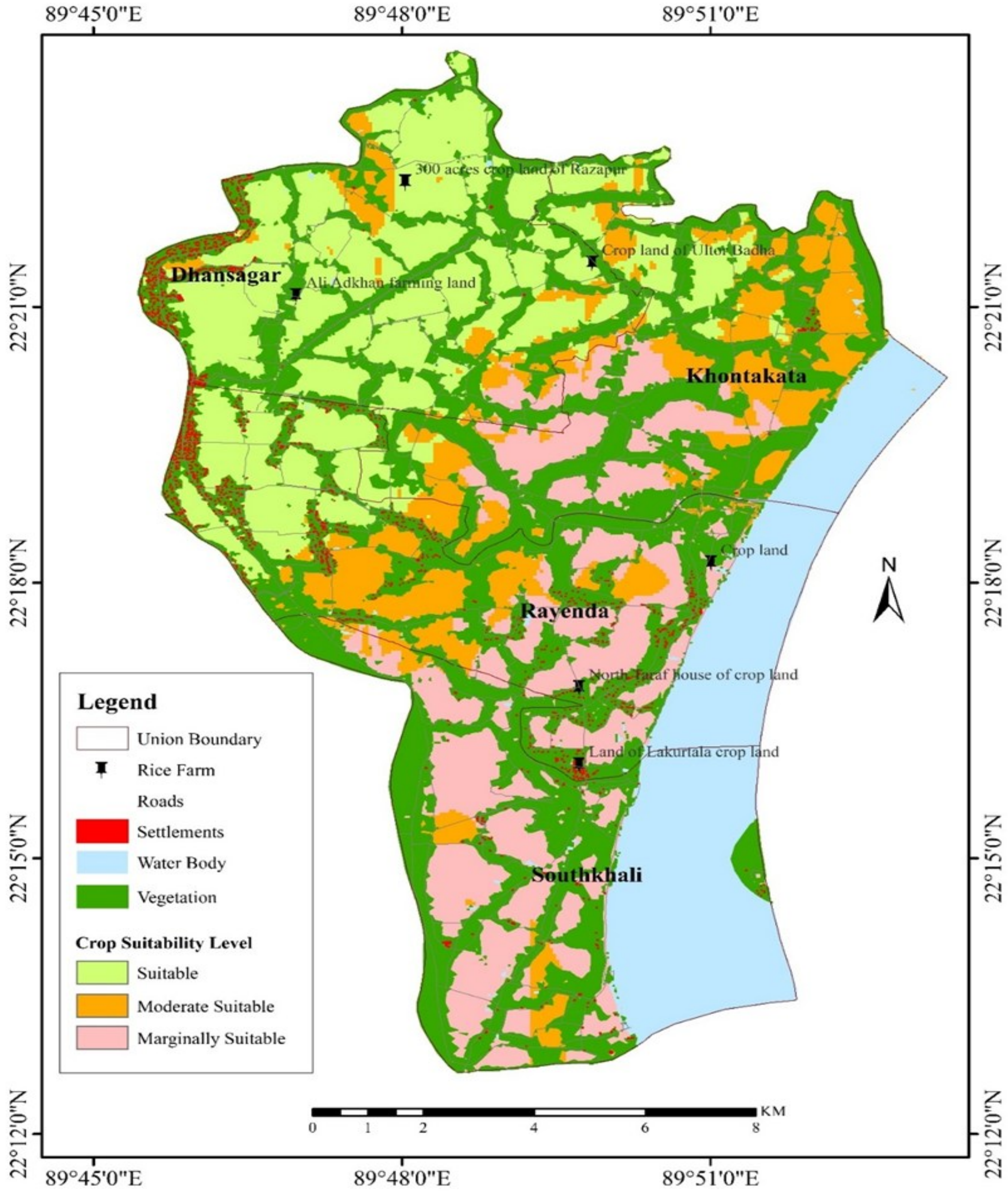

Figure 5. *Union-wise rice suitability based on selected soil parameters.*

Soil suitability for rice production in the study area

Land suitability analysis for rice production in Sarankhola Upazila indicates a diverse agricultural environment in Figure 5. Approximately 40–50% of the upazila fall into the "Suitable" category, suggesting optimum conditions for rice growing, mainly in the northern and western regions such as Dhansagar and parts of Khontakata. These sites have favorable soil, water availability, and terrain, making them excellent for high-yield rice growing. Meanwhile, 20-30% of the upazila is designated as "Moderately Suitable," with such sections being in Rayenda, Southkhali, and parts of Khontakata. Although some areas can support rice farming, they may require extra inputs or adjustments, such as better water management or soil amendments, to attain peak yields. The remaining 30-40% of the upazila, especially in Rayenda and Southkhali, is classified as "Marginally Suitable." These places suffer more major hurdles, such as low soil quality, salt problems, and insufficient drainage, making rice farming less desirable. Surprisingly, some current farms are located in these moderately or marginally suitable places, demonstrating the importance of factors such as previous land usage, local adaptability, and economic restrictions in farming decisions (Aboye *et al.*, 2024; Behairy *et al.*, 2022). These farms also highlight possible limits in the suitability model, underscoring the importance of on-site verification to ensure the model appropriately reflects real-world conditions. Overall, while Sarankhola Upazila has several places that are ideal for rice cultivation, a large percentage of them need focused interventions or adaptation techniques to improve agricultural performance.

Conclusion

The study examined the physicochemical parameters and nutrient composition of soil samples collected from Sarankhola Upazila. The pH range observed was slightly acidic, ranging from 5.6 to 6.5, with a mean of 5.83±0.23. This falls below the optimal range of 6.0-6.5. The electrical conductivity was found to be considerably high (mean 10.47±7.32 ds/m), suggesting the presence of potential salinity concerns. The levels of organic matter and nitrogen were found to be at or close to the optimal range. However, it was observed that electrical conductivity, sulfur, calcium, magnesium, and iron levels were above their optimal ranges, indicating an excess of these nutrients. An analysis of the Pearson correlation indicated a significant positive relationship (r = 0.97) between organic matter and nitrogen, highlighting the importance of organic matter in nitrogen retention. There were moderate correlations observed between EC and sulfur (r = 0.43) and potassium (r = 0.34). The strong correlation (r = 0.64) observed between calcium and magnesium indicates a likely co-occurrence of these elements in the soil. Negative correlations were observed between pH and both organic matter (r = -0.30) and nitrogen (r = -0.28), indicating that higher levels of these components are associated with lower acidity. The spatial analysis showed that pH levels were optimal in central and southeastern areas, while EC levels were near-optimal across much of the upazila. The presence of insufficient organic matter in various regions has had a negative impact on soil fertility. Nitrogen and phosphorus levels were near optimal, but sulfur and zinc levels were only moderate. Calcium and magnesium were predominantly moderate to suboptimal, with some areas showing severe deficiencies. Iron levels were suboptimal, while manganese levels were generally adequate across the upazila. Land suitability analysis revealed that 40–50% of Sarankhola Upazila is "suitable" for rice cultivation, mainly in the northern and western regions. Around 20 to 30% of the area is "moderately suitable," requiring additional inputs for optimal yields. The remaining 30–40% are "Marginally Suitable" due to issues like low soil quality and salinity, underscoring the need for targeted interventions such as improved water management and soil amendments to enhance agricultural productivity. These results suggest that future research should focus on refining land suitability models, incorporating more localized data, and testing the effectiveness of tailored agricultural practices in improving marginal lands.

DECLARATIONS

Author contribution statement

Conceptualization: M.A.H., M.A.K., M.K.H. and M.A.H.M.J.; Methodology: M.A.H., M.A.K., M.S.K.; Software and validation: M.A.H., M.O.F.M. and M.K.H.; Formal analysis and Investigation: M.A.H., M.A.K., M.K.H., M.S.K., and M.O.F.M.; Resources: M.A.K.; Data curation: M.A.K.; Writing-original draft preparation: M.A.H., M.A.K., M.K.H., M.S.K., and M.O.F.M.; Review and editing: M.A.K., and M.A.H.M.J; Supervision: M.A.H.M.J. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Ethics approval

This study did not involve any animal or human participant and thus ethical approval was not applicable.

Consent for publication

All co-authors gave their consent to publish.

Data Availability

The data used to support the findings of this study are included in the article.

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