International Journal of Theoretical & Applied Sciences, **17**(2): 80-99(2025)

ISSN No. (Print): 0975-1718
ISSN No. (Online): 2249-3247

Cloud-Based Geospatial Mapping of Soil Properties Using Google Earth Engine: A Case Study of Koch Bihar District, West Bengal, India

Prasanta Das[1], Nazrul Islam[1]* and Dibyendu Mukhopadhyay[3]
[1]Department of Geography, Cooch Behar Panchanan Barma University, Cooch Behar (West Bengal), India.
[2]Department of Soil Science and Agricultural Chemistry,
Uttar Banga Krishi Viswavidyalaya, Cooch Behar (West Bengal), India.

(Corresponding author: Nazrul Islam)*
(Received 05 May 2025, Revised 27 June 2025, Accepted 19 July 2025)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Soil fertility is a critical component for ensuring sustainable agriculture and food security. This study assesses the spatial variability of soil fertility across Koch Bihar district, West Bengal, using a cloud-based geospatial approach via Google Earth Engine (GEE). The analysis utilized SoilGrids250m data (0–30 cm depth) and Landsat 8 reflectance imagery to extract key physical and chemical parameters, including pH, SOC, nitrogen (N), phosphorus (P), potassium (K), bulk density (BD), CEC, and soil texture (sand, silt, clay). A Fuzzy-AHP-based Soil Fertility Index (SFI) was developed using min–max normalization and expert-weighted indicators in Google Earth Engine. Results revealed that 28.59% of the district falls under high fertility (SFI: 0.61–0.80), 23.11% under moderate (0.41–0.60), and 21.19% under very high fertility (0.81–1.00), together covering ~73% of the region. Sitalkuchi (96.3%), Mathabhanga I (94.1%), and Mekhliganj (82.3%) showed the highest fertile zones, while Sitai, Cooch Behar II and Mathabhanga II have shown considerable portions of land under low to moderate fertility categories.. These spatial disparities underline the need for location-specific nutrient management and crop planning. The findings support policy interventions for precision agriculture, sustainable land use, and informed input allocation. Future research should incorporate time-series monitoring and field-based validation to enhance the accuracy of fertility predictions.

Keywords: Soil Fertility Index, Koch Bihar, Google Earth Engine, Fuzzy AHP, Sustainable Agriculture.

INTRODUCTION

Soil Fertility is a cornerstone of global food security, environmental sustainability, and economic stability, particularly in agrarian regions where agriculture forms the backbone of livelihoods (Brady & Weil 2016). In the Terai zone of West Bengal, India, the district of Koch Bihar exemplifies such a region, with approximately 3,387 km² of land, of which 70.3% is dedicated to farming (Census, 2011). This area, nestled at the Himalayan foothills, supports diverse cropping systems such as rice-jute and rice-oilseed rotations, driven by its subtropical climate and alluvial soils. The significance of soil health in Koch Bihar lies in its direct impact on crop productivity, rural economies, and regional food systems. Understanding the spatial distribution of soil properties—such as texture, organic carbon, and nutrient levels—is critical for optimizing agricultural output and ensuring sustainable land use in the face of increasing environmental pressures, including climate variability and land degradation.

Recent advancements in soil science highlight the role of digital soil mapping (DSM) in transforming traditional soil assessment methods. Studies have demonstrated the efficacy of platforms like Google Earth Engine (GEE) in integrating high-resolution datasets, such as SoilGrids250m, to map soil properties across large areas with improved accuracy (Hengl *et al.*, 2017; Amani *et al.*, 2020). For instance, Gorelick *et al.* (2017); Javidan *et al*. (2024) showcased GEE's application in environmental monitoring, such as key soil characteristics and assessing fertility by merging high-resolution datasets with spatial models and statistical techniques. While Dong *et al*. (2016) used it to delineate rice cultivation patterns in Northeast Asia. However, the application of DSM in soil fertility studies, particularly in alluvial floodplains, remains underexplored (Amani *et al*., 2020). GEE has allowed scientists to track changes in soil fertility over large landscapes, classify areas based on nutrient content, and promote precision agriculture practices (Taghizadeh-Mehrjardi *et al*., 2016). Traditional soil sampling, as noted by Robinson and Metternicht (2006), is resource-intensive and often fails to capture fine-scale variability, limiting its utility for precision agriculture. In the context of West Bengal's Terai region, Mondal *et al*. (2015) reported sandy loam dominance in adjacent floodplains, emphasizing the need for organic amendments, yet comprehensive block-level fertility mapping is scarce. Similarly, Abdel Rahman *et al*. (2021) highlighted soil organic carbon depletion in northern Bangladesh, a region agro-ecologically similar to Koch Bihar, but lacked spatially explicit solutions. These gaps underscore the need for advanced geospatial approaches to address soil fertility variability in heterogeneous landscapes.

Despite its agricultural significance, Koch Bihar faces challenges in maintaining soil health due to spatial variability in soil properties, intensive farming practices, and high rainfall, which exacerbate nutrient leaching and soil compaction. Conventional soil assessment methods are inadequate for capturing the district's diverse soil characteristics, hindering the development of targeted management strategies. The lack of high-resolution, block-level soil fertility data limits the ability to implement precision agriculture, optimize resource use, and mitigate environmental risks like nutrient runoff. This study addresses the critical need for a spatially explicit soil fertility assessment to guide sustainable agricultural practices in Koch Bihar.

The primary aim of this study is to map and evaluate soil fertility across Koch Bihar district by leveraging digital soil mapping and geospatial technologies. Specifically, the study has focused on analyzing key soil properties—namely texture, organic carbon, pH, cation exchange capacity, nitrogen, phosphorus, potassium, and bulk density—within the 0–30 cm soil depth, using the SoilGrids250m dataset and Landsat 8 surface reflectance data. A Soil Fertility Index (SFI) has been developed by applying the Fuzzy Analytic Hierarchy Process (F-AHP) in combination with min-max normalization to classify fertility levels across all 12 administrative blocks of the district.

This study is essential for addressing the pressing need for sustainable agriculture in Koch Bihar, where soil health directly influences economic and food security outcomes. By leveraging GEE and DSM, it provides a cost-effective, scalable framework for high-resolution soil mapping, overcoming the limitations of traditional methods. The resulting SFI maps offer actionable insights for farmers and policymakers, enabling precision agriculture, reducing input costs, and minimizing environmental impacts like eutrophication. The study contributes to the scientific understanding of soil fertility dynamics in alluvial landscapes and supports regional policy formulation for sustainable land use. Its methodology can be adapted to other agro-ecological zones, enhancing its broader relevance.

MATERIAL AND METHODS

A. Study Area

The study area of this research has been identified as Koch Bihar, a northern district of West Bengal, India, which belongs to the Terai region of the Himalayan foothills (Debnath *et al*., 2023; Kundu, 2020) (Fig. 1). It has extended between latitudes 26°32′46″N and 25°57′56″N and longitudes 89°54′36″E and 88°47′40″E, covering an area of approximately 3,387 km², of which 70.3% has been used for cultivation (Census, 2011).

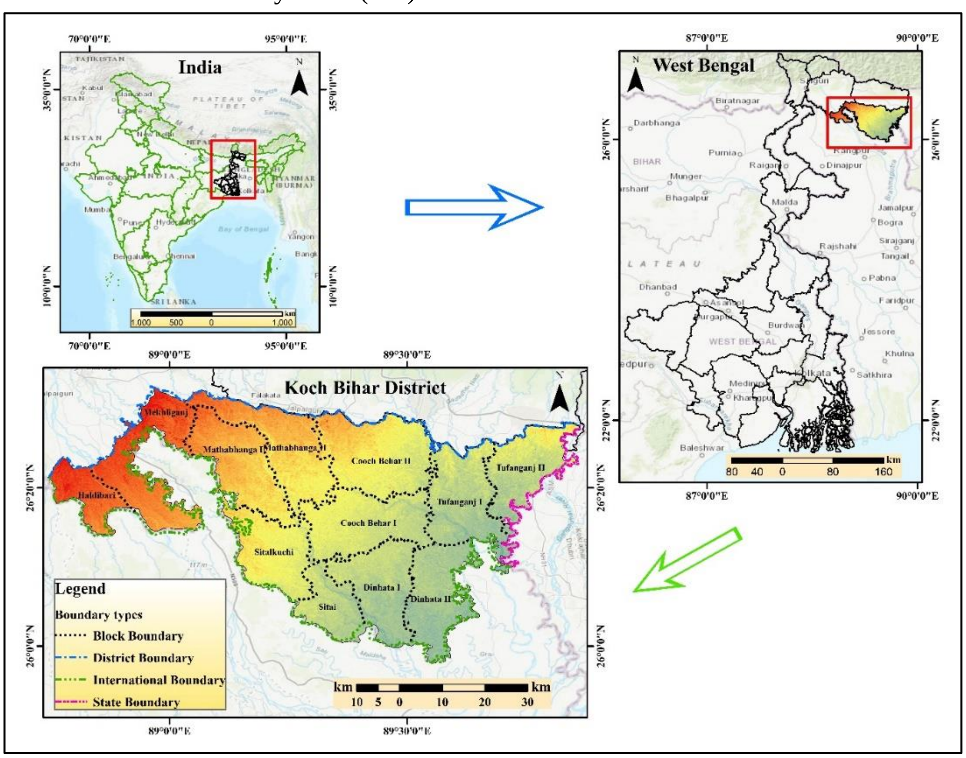

Fig. 1. Koch Bihar district of West Bengal as the study region.

The region has experienced a hot, humid, and subtropical climate, with over 88% of annual rainfall occurring in the months from May to September (Sarkar *et al*., 2021). A flat landscape with a gentle slope and extensive marshy lowlands has characterized it. The soils, formed from Quaternary alluvial deposits, have included silty loam, sandy loam, sandy, and both newer and older alluvium, each exhibiting varying levels of fertility. The local economy has remained predominantly agrarian, with prevailing cropping patterns such as paddy-jute, paddy-oilseeds-jute, paddy-potato-paddy, paddy-tobacco, and a sequential rotation of paddy (Aman)–paddy (Boro)–jute.

B. Database

In the present study, various soil parameters have been analyzed using the SoilGrids250m dataset, which has been developed by ISRIC – World Soil Information. This dataset has been employed to map key soil properties across the Koch Bihar district through the Google Earth Engine (GEE) platform. Soil Grids has provided global estimates for standard soil variables at six depth intervals—0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm, and 100–200 cm—with a spatial resolution of 250 meters. But in this study, 0 to 30 cm merged depth has been considered. The parameters considered in this research have included pH (in H_2O), soil organic carbon (SOC), nitrogen (N), cation exchange capacity (CEC), bulk density (BD), and soil texture fractions (sand, silt, and clay). These data layers have been accessed and processed within the GEE environment, while map layouts have been created using ArcGIS software, enabling efficient spatial analysis and comprehensive visualization of soil characteristics throughout the region. Landsat 8 Tier 1 Surface Reflectance data, provided by USGS and NASA, has been utilized to generate vegetation and soil reflectance indices, which have then been empirically applied to estimate topsoil phosphorus and potassium levels within the study region.

Table 1: Description of the database and sources of the data used.

Dataset Name	Soil Property	Units	Depth Intervals (cm)	Spatial Resolution	Source
SoilGrids250m	pH in H2O	pH units	0-30	250 metres	SoilGrids data now available on Google Earth Engine | ISRIC
SoilGrids250m	Soil Organic Carbon (SOC)	%	0-30	250 metres	
SoilGrids250m	Bulk Density (BD)	g/m³	0-30	250 metres	
SoilGrids250m	Sand Content	%	0-30	250 metres	
SoilGrids250m	Silt Content	%	0-30	250 metres	
SoilGrids250m	Clay Content	%	0-30	250 metres	
SoilGrids250m	CEC	cmol/kg	0-30	250 metres	
SoilGrids250m	Soil Nitrogen	in ppm	0-30	250 metres	
Landsat 8 (OLI)	Phosphorus	mg/kg		30 metres	ee.ImageCollection('LANDSAT/LC08/C02/T1_L2')
Landsat 8 (OLI)	Potassium	mg/kg		30 metres	

Source: Tabulated by the authors

C. Methods

The Google Earth Engine (GEE) has emerged as a powerful, web-based geospatial platform (Javidan *et al*., 2024). It has provided extensive Earth observation data for analyzing environmental and spatial phenomena (Gorelick *et al*., 2017). It has integrated a wide array of satellite imagery along with advanced tools for image analysis and processing (Xiao *et al*., 2020). Researchers have increasingly employed GEE across diverse applications such as delineating rice cultivation patterns in Northeast Asia (Dong *et al*., 2016), monitoring fallow periods in paddy landscapes (Chong *et al*., 2020), and mapping wetland ecosystems (Mahdianpari *et al*., 2018). However, its application in soil science remains comparatively limited (Amani *et al*., 2020). Traditional approaches to estimating soil characteristics over expansive areas have often lacked predictive precision. Moreover, these methods have demanded considerable time, financial resources, and a dense network of uniformly distributed sampling points to be effective (Robinson and Metternicht 2006). In contrast, digital soil mapping (DSM) has been adopted to represent the functional variability of soils more efficiently and to enhance the reliability and spatial resolution of soil information.

In the present study, a systematic methodology has been employed to map the Soil Fertility Index (SFI) for Koch Bihar district, situated in the Terai-Tista Alluvial Zone of West Bengal, India. The district boundaries have been delineated using shapefiles within the Google Earth Engine (GEE), with the map accurately centred on the study area. Soil parameter data have been obtained from the global SoilGrids250m dataset developed by ISRIC, which has provided standardized predictions for various soil properties across multiple depth intervals. For this analysis, surface-level data (0–30 cm) have been extracted for essential indicators such as sand, silt, clay, bulk density (BD), soil organic carbon (SOC), pH, nitrogen (N), and cation exchange capacity (CEC). These parameters have been normalized to a 0–1 scale using the min–max transformation technique, based on established agronomic thresholds. The ternary soil texture diagram has been generated in R Studio using 500 sample points derived from sand, silt, and clay percentage values extracted from the SoilGrids250m dataset through Google Earth Engine. The soil texture package in R has been used to classify the samples according to USDA standards, allowing for detailed interpretation of soil texture variability across the study region. Fuzzy Analytic Hierarchy Process (F-AHP) weights, derived through a combination of principal component analysis and expert judgment, have been assigned to each parameter to reflect their respective contributions to soil fertility. A weighted sum approach has been adopted to compute a continuous SFI layer, which has subsequently been clipped to the region of interest (ROI) and classified into five distinct fertility categories—ranging from very low to very high—using fuzzy membership thresholds.

RESULTS AND DISCUSSION

A. Soil Texture

Soil texture refers to the relative proportion of the three primary mineral particles—sand, silt, and clay—which together determine key physical properties of soil such as porosity, permeability, water retention, and nutrient availability (Brady & Weil 2010). In the context of Koch Bihar district, where agriculture is a primary livelihood source, understanding soil texture is essential for assessing land suitability, guiding crop choices, and formulating appropriate soil and water management strategies.

B. Sand

Sandy soils, characterized by large particle size and low surface area, generally exhibit poor nutrient- and water-holding capacity, making them inherently low in fertility and requiring frequent irrigation and fertilization to sustain crop productivity (Brady & Weil 2010; Lal, 2004). The distribution of sand content across the blocks of Koch Bihar district reveals significant spatial variation in soil texture, which directly influences fertility, water retention, and crop suitability.

Blocks like Mathabhanga I, Mathabhanga II, and Sitalkuchi exhibit higher sand percentages in Class 5 and Class 4 (above 49.1%), suggesting lighter, well-drained soils that may be less fertile and require more organic matter inputs for sustainable agriculture.

Table 2: Distribution of Sand Content.

Block	Total Area (ha)	Class 1 Area (ha)	%	Class 2 Area (ha)	%	Class 3 Area (ha)	%	Class 4 Area (ha)	%	Class 5 Area (ha)	%
Mekhliganj	30262.50	10725.00	35.44	12612.50	41.68	6825.00	22.55	100.00	0.33	0.00	0.00
Haldibari	14326.47	8756.25	61.12	4787.50	33.42	0.00	0.00	0.00	0.00	0.00	0.00
Mathabhanga I	31015.98	243.75	0.79	825.00	2.66	5175.00	16.68	8456.25	27.26	15506.25	49.99
Mathabhanga II	31594.68	537.50	1.70	2462.50	7.79	6050.00	19.15	12456.25	39.43	7762.50	24.57
Sitalkuchi	265357.75	0.00	0.00	135281.25	50.98	88037.50	33.18	48625.00	18.32	28412.50	10.71
Cooch Behar I	32962.50	1293.75	3.92	14675.00	44.52	8462.50	25.67	7418.75	22.51	112.50	0.34
Cooch Behar II	36587.50	318.75	0.87	12125.00	33.14	18418.75	50.34	5725.00	15.65	0.00	0.00
Tufanganj I	30518.75	668.75	2.19	22587.50	74.01	7262.50	23.80	0.00	0.00	0.00	0.00
Tufanganj II	25793.75	393.75	1.53	9956.25	38.60	12787.50	49.58	1656.25	6.42	0.00	0.00
Dinahata I	26643.75	2343.75	8.80	17812.50	66.85	6343.75	23.81	143.75	0.54	0.00	0.00
Dinahata II	26868.75	206.25	0.77	20443.75	76.09	6218.75	23.14	0.00	0.00	0.00	0.00
Sitai	15788.52	2893.75	18.33	10481.25	66.39	1306.25	8.27	0.00	0.00	0.00	0.00
District Total	335381.25	30025.00	8.95	135281.25	40.34	88037.50	26.25	48625.00	14.50	28412.50	8.47

Source: Calculated by the authors

In contrast, blocks such as Haldibari, Tufanganj I, Dinahata II, and Sitai are dominated by Class 2 sand content (41.15–45.27%), indicating moderately textured soils that are more balanced in terms of aeration and water-holding capacity, which can support a wide range of crops with moderate inputs. Cooch Behar II and Tufanganj II show a strong presence in Class 3 (45.28–49.09%), marking a transitional zone between moderately coarse and moderately fine textures. Interestingly, Sitalkuchi, being the largest in area, has over 50% in Class 2 and substantial portions in Classes 3 to 5, indicating sandy loam to loamy sand conditions. District-wide, the dominance of Class 2 (40.34%) and Class 3 (26.25%) suggests that most soils are moderately sandy, necessitating management strategies that enhance moisture retention and nutrient availability through mulching, composting, and green manuring. Thus, understanding this spatial variation in sand texture is vital for implementing location-specific soil and crop management practices.

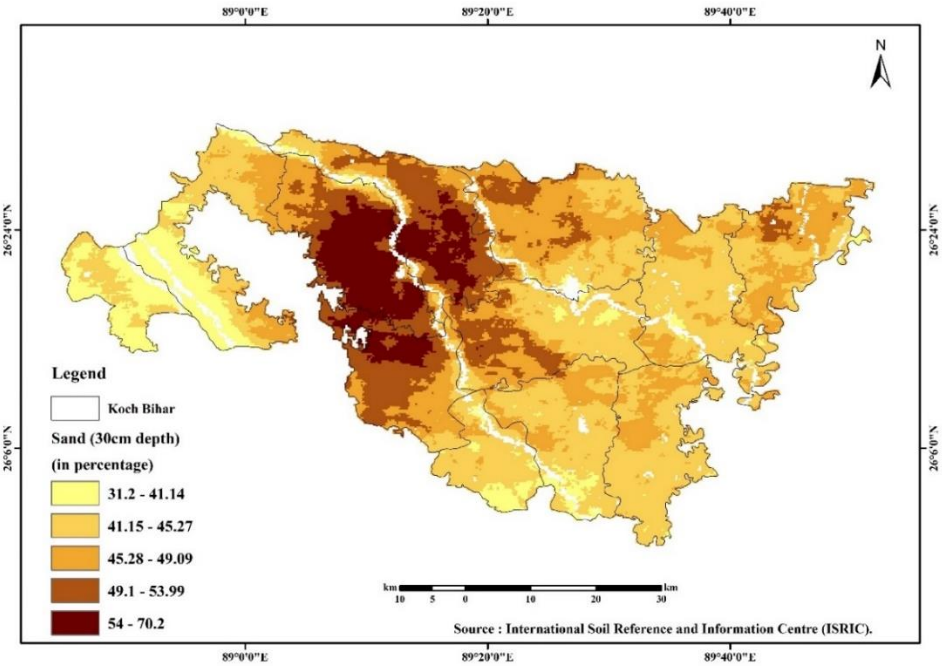

Fig. 2. Percentage of Sand content in the Koch Bihar district.

C. Silt

Silt particles, being intermediate in size and having a relatively high surface area, contribute to better water and nutrient retention than sand, making silty soils more fertile and productive for agriculture, though they can be prone to compaction and erosion (Brady & Weil 2010; Lal, 2004). The spatial distribution of silt content in the soils of Koch Bihar district reveals significant variation across blocks, which has direct implications for soil fertility, water retention, and crop suitability. The majority of the district (35.96%) falls under Class 3 (25.09–28.5%), representing moderately silty soils, followed by Class 4 (28.51–32.04%) at 29.68%, which indicates a slightly higher silt proportion ideal for nutrient and moisture retention.

Table 3: Distribution of Silt Content.

Block	Total Area (ha)	Class 1 Area	Class 1 %	Class 2 Area	Class 2 %	Class 3 Area	Class 3 %	Class 4 Area	Class 4 %	Class 5 Area	Class 5 %
Mekhliganj	30,362.50	0.00	0.00	356.25	1.17	7,918.75	26.08	12,043.75	39.67	9,943.75	32.75
Haldibari	13,543.75	0.00	0.00	0.00	0.00	6.25	0.05	2,143.75	15.83	11,393.75	84.13
Mathabhanga I	30,156.25	14,731.25	48.85	12,418.75	41.18	2,637.50	8.75	418.75	1.39	0.00	0.00
Mathabhanga II	29,268.75	4,387.50	14.99	17,343.75	59.26	6,175.00	21.10	1,362.50	4.66	0.00	0.00
Sitalkuchi	25,756.25	2,456.25	9.54	10,825.00	42.03	10,812.50	41.98	1,662.50	6.45	0.00	0.00
Cooch Behar I	33,162.50	12.50	0.04	3,362.50	10.14	12,081.25	36.44	11,987.50	36.15	4,518.75	13.63
Cooch Behar II	36,687.50	0.00	0.00	4,493.75	12.25	12,887.50	35.13	16,875.00	46.00	2,331.25	6.36
Tufanganj I	30,487.50	0.00	0.00	31.25	0.10	5,306.25	17.41	20,106.25	65.96	5,075.00	16.64
Tufanganj II	25,793.75	0.00	0.00	643.75	2.50	5,775.00	22.38	15,368.75	59.58	3,006.25	11.66
Dinhata I	26,043.75	0.00	0.00	687.50	2.64	21,343.75	81.96	4,468.75	17.15	143.75	0.55
Dinhata II	26,868.75	0.00	0.00	2,537.50	9.44	22,537.50	83.85	1,756.25	6.54	37.50	0.14
Sitai	15,081.25	0.00	0.00	0.00	0.00	8,312.50	55.10	6,368.75	42.22	0.00	0.00
District Total	**330,381.25**	**21,762.50**	**6.59**	**54,106.25**	**16.38**	**118,800.00**	**35.96**	**98,068.75**	**29.68**	**37,643.75**	**11.40**

Source: Calculated by the authors

Notably, blocks like Dinhata I (81.96%), Dinhata II (83.85%), and Sitai (55.10%) have very high representation in Class 3, making them highly productive for intensive agriculture. Tufanganj I (65.96%) and Tufanganj II (59.58%) are predominantly in Class 4, suitable for water-retentive crops. Meanwhile, Class 5 (32.05–40.01%), accounting for 11.4% of the district, is concentrated in Haldibari and Mekhliganj, denoting silty loam soils ideal for cultivation but susceptible to compaction. The least represented is Class 1 (7.75–20.65%), with only 6.59% area, mostly in Mathabhanga I, indicating sandier, less fertile soils with lower moisture retention. Overall, the district's dominance of Classes 3 and 4 suggests that most blocks have well-balanced silty soils conducive to a wide variety of crops, though localized management is required to address the challenges of very high or low silt content.

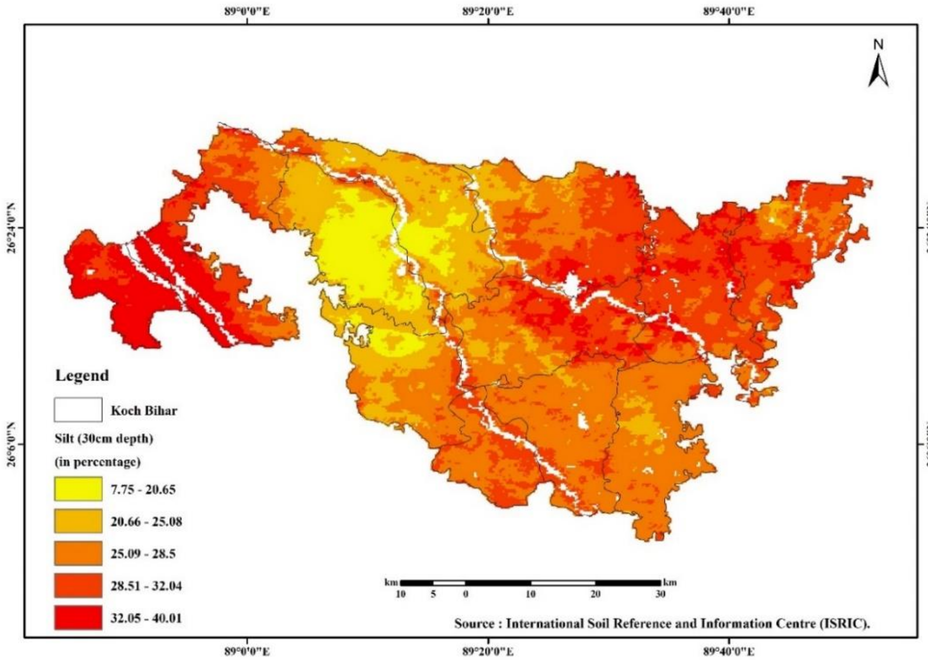

Fig. 3. Silt content in the Koch Bihar district.

D. Clay

Clay soils, composed of the smallest mineral particles, have a high surface area and cation exchange capacity (CEC), allowing them to retain significant amounts of nutrients and moisture, which enhances fertility—though their poor drainage and potential for compaction can limit plant root development (Singer & Munns 2006; Foth, 1991). The block-wise analysis of clay content in the soils of Koch Bihar district reveals significant spatial variability, influencing soil structure, water retention, and overall fertility. Blocks like Dinahata II (46.80%) and Sitai (45.72%) exhibit the highest percentages of clay in Class 5 (29.19–33.89%), indicating heavy clayey soils with high water-holding capacity, which may pose drainage challenges but are rich in nutrients. Similarly, Dinahata I also shows high clay content in Classes 4 and 5 (79.12% combined), favouring crops that require moisture-retentive soils. On the other hand, blocks like Tufanganj II and Mekhliganj have a higher concentration in Class 3 (25.69–27.35%) and Class 2 (24.01–25.68%), suggesting moderately clayey soils that balance fertility and drainage. Cooch Behar I and II have a strong presence in Classes 2 and 3, indicating favourable soil texture for diversified agriculture.

In contrast, Haldibari and Sitalkuchi have lower clay percentages in higher classes, suggesting relatively lighter soils with quicker drainage, which may need organic amendments for improved moisture retention. Overall, the district demonstrates a mixed soil texture profile, where blocks with higher Class 4 and 5 clay content are more suitable for water-intensive crops, while those with Class 1 and 2 dominance require careful water and nutrient management to sustain productivity. This spatial variation necessitates block-specific land use and soil management strategies for optimal agricultural output.

Table 4: Distribution of Clay Content.

Block	Class 1 Area	Class 1 (%)	Class 2 Area	Class 2 (%)	Class 3 Area	Class 3 (%)	Class 4 Area	Class 4 (%)	Class 5 Area	Class 5 (%)
Mekhliganj	100	0.33%	5,706	18.86%	13,875	45.85%	8,462	27.96%	2,119	7.00%
Haldibari	588	4.34%	4,556	33.64%	7,050	52.05%	1,144	8.45%	206	1.52%
Mathabhanga I	7,606	25.18%	8,000	26.48%	8,488	28.10%	5,038	16.68%	1,075	3.56%
Mathabhanga II	7,519	25.69%	8,294	28.34%	6,350	21.70%	5,350	18.28%	1,756	6.00%
Sitalkuchi	7,469	29.00%	11,425	44.36%	5,162	20.04%	1,394	5.41%	306	1.19%
Cooch Behar I	5,681	17.77%	13,756	43.04%	10,250	32.07%	2,200	6.88%	75	0.23%
Cooch Behar II	8,756	23.93%	17,262	47.18%	8,325	22.75%	1,894	5.18%	350	0.96%
Tufanganj I	5,488	17.98%	8,500	27.85%	11,669	38.23%	4,675	15.32%	188	0.62%
Tufanganj II	10,700	43.16%	9,394	37.89%	2,738	11.04%	1,531	6.17%	431	1.74%
Dinahata I	12	0.05%	1,312	4.92%	4,238	15.91%	10,500	39.41%	10,581	39.71%
Dinahata II	0	0.00%	56	0.21%	2,894	10.77%	11,344	42.22%	12,575	46.80%
Sitai	0	0.00%	262	1.78%	2,056	14.01%	5,650	38.49%	6,712	45.72%

Source: Calculated by the authors

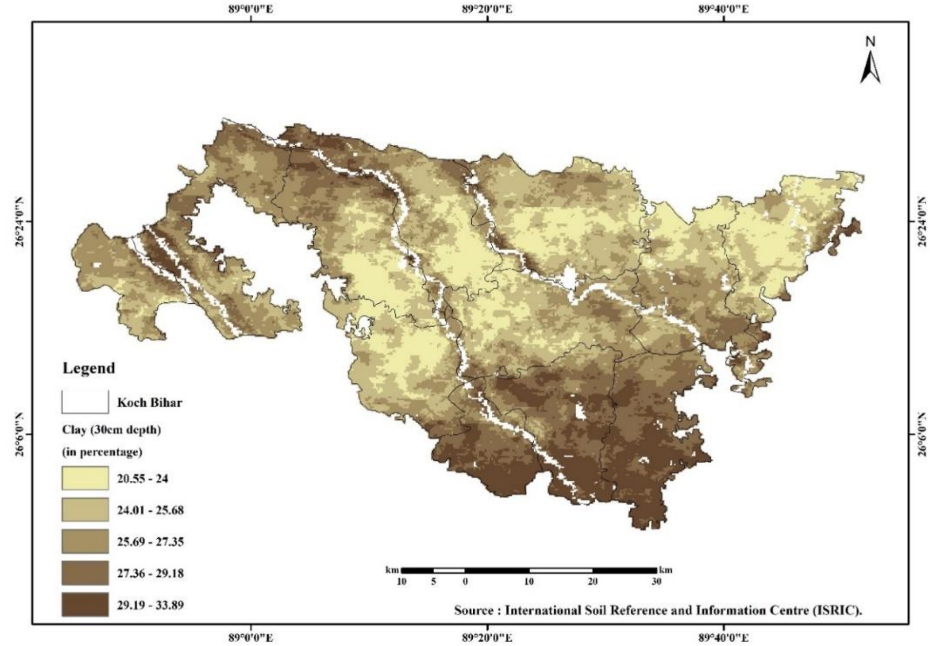

Fig. 4. Clay content in the Koch Bihar district.

E. Soil Textural Class

Soil texture is a key determinant in evaluating soil fertility and crop productivity. A well-balanced mix of sand, silt, and clay signifies good soil structure, which supports optimal plant growth and agricultural productivity (Sağlam and Dengiz 2012; Mallick *et al*., 2023). In the ternary diagram, the area has been divided into regions corresponding to various soil texture classes (e.g., sandy loam, loam, clay loam), as defined by the USDA soil texture triangle (Fig. 5). The blue-shaded region illustrates the spatial distribution of soil samples collected from Koch Bihar District, indicating that the majority of samples belong to the loam and sandy loam categories. This distribution has reflected the diverse nature of the region's alluvial soils. These textures have typically been characterized by a favourable balance of drainage, aeration, and moisture retention, which are essential for promoting healthy root development and efficient nutrient uptake.

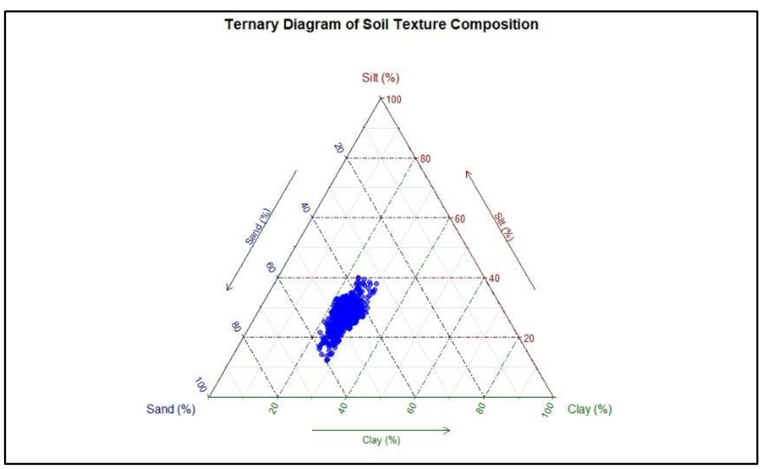

Fig. 5. Ternary diagram showing the distribution of soil texture (Sand, Silt, and Clay).

F. Bulk Density Distribution in Koch Bihar District

Bulk density (BD), a key indicator of soil compaction, porosity, and suitability for agriculture, has been analyzed across the Koch Bihar district and categorized into five classes ranging from very low (122–127.61 g/cm³) to high (134.13–139.67 g/cm³). Very low BD soils, found notably in Sitai (7.77%), Mathabhanga II (5.75%), and Cooch Behar I (5.60%), are loose and porous but prone to erosion and nutrient leaching. Low BD (Class 2) soils, favorable for most crops, dominate in Dinhata I (62.49%), Tufanganj II (47.56%), and Tufanganj I (42.61%), while moderate BD (Class 3), considered optimal for agriculture, is prevalent in Cooch Behar II (47.51%), Sitai (49.98%), and Tufanganj I (50.67%), making these blocks agriculturally productive. Moderately high BD (Class

4), found in Mathabhanga I (47.33%), Sitalkuchi (48.53%), and Mekhliganj (38.63%), suggests early signs of compaction and may require organic amendments. The highest BD values (Class 5), indicating significant compaction, are dominant in Haldibari (55.25%), Mathabhanga I (44.58%), and Mekhliganj (43.42%), where poor root growth and low productivity are likely without soil management interventions. Notably, Tufanganj I, Cooch Behar II, and Sitai emerge as productive zones with favourable BD classes, while Haldibari, Mekhliganj, and Mathabhanga I require urgent decompaction measures. Sitalkuchi and Dinhata II show balanced soil conditions with moderate compaction risk, whereas Mathabhanga II and Cooch Behar I, with higher proportions of Classes 1 and 2, have looser soils suitable for select crops like root vegetables.

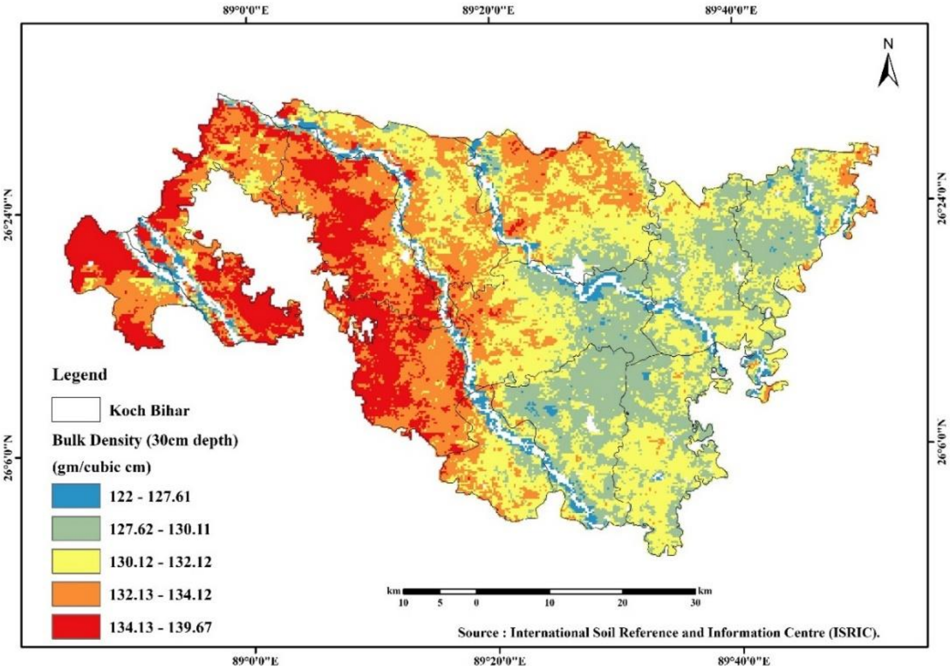

Fig. 6. Spatial distribution of soil bulk density across the study region.

Table 5: Block-wise Bulk Density Distribution (Area & Percentage).

Sub-Region	Total Area (ha)	122–127.61 (ha)	(%)	127.62–130.11 (ha)	(%)	130.12–132.12 (ha)	(%)	132.13–134.12 (ha)	(%)	134.13–139.67 (ha)	(%)
Mekhliganj	30,268.75	1,175.00	3.88%	1,400.00	4.63%	2,856.25	9.44%	11,693.75	38.63%	13,143.75	43.42%
Haldibari	13,506.25	362.50	2.68%	387.50	2.87%	975.00	7.22%	4,318.75	31.98%	7,462.50	55.25%
Mathabhanga I	30,187.50	450.00	1.49%	475.00	1.57%	1,518.75	5.03%	14,287.50	47.33%	13,456.25	44.58%
Mathabhanga II	29,250.00	1,681.25	5.75%	1,575.00	5.38%	13,268.75	45.36%	11,625.00	39.74%	1,100.00	3.76%
Sitalkuchi	25,768.75	262.50	1.02%	531.25	2.06%	12,400.00	48.12%	12,506.25	48.53%	70.00	0.27%
Cooch Behar I	31,931.25	1,787.50	5.60%	10,531.25	32.98%	13,643.75	42.73%	5,756.25	18.03%	212.50	0.67%
Cooch Behar II	36,650.00	1,168.75	3.19%	4,881.25	13.32%	17,412.50	47.51%	12,625.00	34.45%	562.50	1.53%
Tufanganj I	30,612.50	1,368.75	4.47%	13,043.75	42.61%	15,512.50	50.67%	687.50	2.25%	0.00	0.00%
Tufanganj II	24,731.25	1,000.00	4.04%	11,762.50	47.56%	10,097.50	40.83%	1,887.50	7.63%	43.75	0.18%
Dinhata I	26,643.75	1,293.75	4.86%	16,650.00	62.49%	8,237.50	30.92%	462.50	1.74%	0.00	0.00%
Dinhata II	26,912.50	300.00	1.11%	11,981.25	44.52%	14,937.50	55.50%	293.75	1.09%	0.00	0.00%
Sitai	14,643.75	1,137.50	7.77%	3,743.75	25.57%	7,318.75	49.98%	4,162.50	28.43%	281.25	1.92%

Source: Calculated by the authors

G. Soil Organic Carbon distribution in Koch Bihar district

Soil Organic Carbon (SOC) is a key indicator of soil quality, productivity, and ecosystem health. It influences nutrient availability, water retention, microbial activity, and overall crop sustainability. The distribution of Soil Organic Carbon (SOC) within the top 0–30 cm of soil in Koch Bihar district reveals significant spatial disparities in soil quality and fertility. SOC, a crucial determinant of soil health, affects nutrient cycling, moisture retention, and microbial activity. The analysis classifies SOC into five categories, with Class 1 (14.1–17.62 g/kg) indicating very low SOC and dominating large swathes of the district, especially in Mathabhanga I (83.27%), Mathabhanga II (72.79%), Mekhliganj (69.68%), Tufanganj II (69.04%), Sitai (64.17%), and Tufanganj I (65.39%), reflecting severe organic matter depletion and poor soil health, necessitating urgent interventions like composting, mulching, and conservation agriculture. Class 2 (17.63–24.28 g/kg), reflecting low to moderate SOC, is prevalent in Koch Bihar I (60.48%), Dinhata II (64.33%), Dinhata I (43.88%), and Sitalkuchi (41.83%), indicating transitional soils that could benefit from moderate organic enrichment to boost fertility. Class 3 (24.29–30.93 g/kg), signifying moderate SOC, is limited but present in small patches in Mekhliganj (3.62%), Mathabhanga II (3.23%), and Sitai (4.03%), indicating relatively stable yet vulnerable soils. Class 4 (30.94–33.7 g/kg), denoting moderately high SOC, appears in Mathabhanga II (3.57%), Mekhliganj (3.93%), and Tufanganj I (2.51%), representing more resilient and nutrient-rich soils where practices like crop rotation and minimal tillage can help preserve carbon levels. Class 5 (33.71–46.13 g/kg), indicating high - SOC and the most fertile category, is extremely rare and observed only in small patches of Dinhata II (0.52%), Cooch Behar I (0.72%), Tufanganj I (0.80%), and Sitai (0.87%), highlighting ecologically critical zones that require protection through sustainable practices like agroforestry and cover cropping. Thus, the SOC distribution directs the need for intensive soil health restoration in most parts of the district, while conserving the limited high-carbon areas for long-term agricultural sustainability.

Table 6: Block-wise SOC Distribution (Area & Percentage).

Sub-Region	Total Area (ha)	Class 1 (14.1–17.62)	%	Class 2 (17.63–24.28)	%	Class 3 (24.29–30.93)	%	Class 4 (30.94–33.7)	%	Class 5 (33.71–46.13)	%
Mekhliganj	33,862.50	23,593.75	69.68%	7,337.50	21.67%	1,225.00	3.62%	1,331.25	3.93%	375.00	1.11%
Haldibari	15,012.50	7,431.25	49.50%	6,781.25	45.17%	225.00	1.50%	493.75	3.29%	81.25	0.54%
Mathabhanga I	33,800.00	28,143.75	83.27%	4,456.25	13.18%	656.25	1.94%	531.25	1.57%	12.50	0.04%
Mathabhanga II	32,868.75	23,925.00	72.79%	6,543.75	19.91%	1,062.50	3.23%	1,175.00	3.57%	162.50	0.49%
Sitalkuchi	28,818.75	16,087.50	55.82%	12,056.25	41.83%	325.00	1.13%	268.75	0.93%	81.25	0.28%
Cooch Behar I	35,737.50	12,750.00	35.68%	21,612.50	60.48%	225.00	0.63%	893.75	2.50%	256.25	0.72%
Cooch Behar II	40,881.25	26,106.25	63.86%	13,425.00	32.84%	368.75	0.90%	762.50	1.87%	218.75	0.54%
Tufanganj I	34,162.50	22,337.50	65.39%	10,281.25	30.10%	412.50	1.21%	856.25	2.51%	275.00	0.80%
Tufanganj II	27,618.75	19,068.75	69.04%	7,718.75	27.95%	568.75	2.06%	237.50	0.86%	25.00	0.09%
Dinhata I	29,643.75	15,562.50	52.50%	13,006.25	43.88%	331.25	1.12%	550.00	1.86%	193.75	0.65%
Dinhata II	29,993.75	10,387.50	34.63%	19,293.75	64.33%	37.50	0.13%	118.75	0.40%	156.25	0.52%
Sitai	16,450.00	10,556.25	64.17%	4,437.50	26.98%	662.50	4.03%	650.00	3.95%	143.75	0.87%

Source: Calculated by the authors

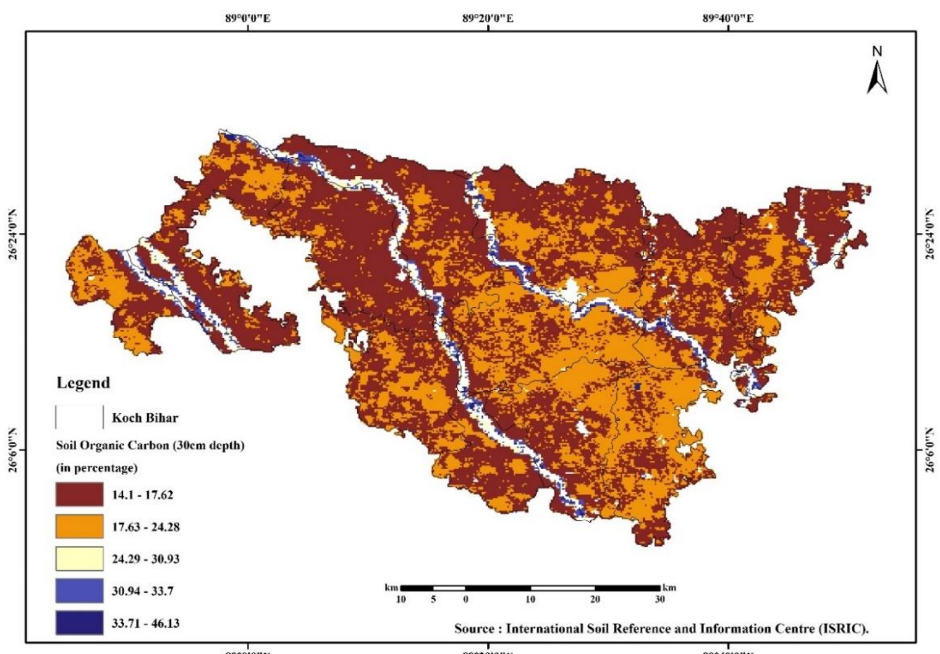

Fig. 7. Spatial distribution of Soil Organic Carbon across the study region.

H. Cation Exchange Capacity **(***CEC***)** *distribution in Koch Bihar District*

The Cation Exchange Capacity (CEC) distribution across the Koch Bihar district provides crucial insight into the soil's ability to retain and supply essential nutrients, thereby serving as a key indicator of soil fertility and guiding block-level agricultural planning and nutrient management strategies. The Cation Exchange Capacity (CEC) distribution across the Koch Bihar district provides crucial insight into the soil's ability to retain and supply essential nutrients, thereby serving as a key indicator of soil fertility and guiding block-level agricultural planning and nutrient management strategies. Cation Exchange Capacity (CEC), a key indicator of soil fertility and nutrient-holding capacity, has been assessed across the 12 blocks of Koch Bihar district and categorized into five classes, ranging from very low (142.67–170.4) to very high (195.62–234.5). Soils in Class 1 (very low CEC) are the least fertile and are most prevalent in Mathabhanga II (24.13%), Mekhliganj (19.81%), and Sitai (19.5%), indicating areas that require regular fertilization and organic matter amendments. Class 2 (low CEC) covers 21.57% of the district and is significantly represented in Sitai (36.85%), Mekhliganj (32.62%), and Cooch Behar II (31.75%), reflecting moderately fertile soils that benefit from balanced nutrient management strategies. Class 3 (moderate CEC) is the most widespread, occupying 37.42% of the district area and is dominant in Cooch Behar I (53.13%), Dinhata I (51.38%), and Tufanganj I (46.55%).

Table 7: Block-wise CEC Distribution (Area & Percentage).

Sub-Region	Total Area (ha)	142.67–170.4 (ha)	(%)	170.41–179.4 (ha)	(%)	179.41–186.24 (ha)	(%)	186.25–195.61 (ha)	(%)	195.62–234.5 (ha)	(%)
Mekhliganj	30,262.50	5,993.75	19.81%	9,868.75	32.62%	6,512.50	21.52%	4,481.25	14.81%	3,406.25	11.25%
Haldibari	13,543.75	356.25	2.63%	1,375.00	10.15%	2,287.50	16.89%	6,625.00	48.93%	2,900.00	21.41%
Mathabhanga I	30,206.25	3,512.50	11.63%	7,393.75	24.49%	10,562.50	34.96%	8,206.25	27.17%	531.25	1.76%
Mathabhanga II	29,268.75	7,062.50	24.13%	4,656.25	15.91%	9,612.50	32.83%	7,787.50	26.61%	150.00	0.51%
Sitalkuchi	25,756.25	937.50	3.64%	8,125.00	31.54%	11,243.75	43.67%	3,993.75	15.51%	1,456.25	5.65%
Cooch Behar I	31,962.50	1,175.00	3.68%	6,562.50	20.53%	16,987.50	53.13%	6,837.50	21.39%	400.00	1.25%
Cooch Behar II	36,587.50	4,500.00	12.30%	11,618.75	31.75%	14,400.00	39.35%	5,656.25	15.46%	412.50	1.13%
Tufanganj I	30,518.75	1,218.75	3.99%	4,325.00	14.17%	14,200.00	46.55%	10,112.50	33.13%	662.50	2.17%
Tufanganj II	24,793.75	1,568.75	6.33%	4,693.75	18.93%	10,993.75	44.34%	6,962.50	28.08%	575.00	2.32%
Dinhata I	26,643.75	818.75	3.07%	4,300.00	16.15%	13,687.50	51.38%	7,487.50	28.11%	350.00	1.31%
Dinhata II	26,868.75	43.75	0.16%	425.00	1.58%	5,931.25	22.08%	17,831.25	66.37%	2,637.50	9.82%
Sitai	14,681.25	2,862.50	19.50%	5,412.50	36.85%	4,400.00	29.96%	1,443.75	9.83%	562.50	3.83%
District Total	**330,381.25**	31,531.25	9.55%	71,262.50	21.57%	123,625.00	37.42%	89,406.25	27.06%	14,556.25	4.41%

Source: Calculated by the authors

These soils are well-balanced and suitable for diverse crops with minimal need for external inputs. Class 4 (high CEC) accounts for 27.06% of the district and is prominent in Dinhata II (66.37%), Haldibari (48.93%), and Tufanganj I (33.13%), indicating fertile soils ideal for intensive agricultural practices. Class 5 (very high CEC), though limited to 4.41% of the area, denotes highly nutrient-retentive soils, mainly found in Haldibari (21.41%), Mekhliganj (11.25%), and Dinhata II (9.82%). These soils are extremely fertile but may require careful water management to prevent waterlogging, especially in heavy-textured areas. Overall, Dinhata II and Haldibari emerge as the most fertile zones, with over 70% of their area in the high and very high CEC classes. Cooch Behar I and Sitalkuchi show strong representation in Class 3, suggesting moderate fertility levels suitable for general cropping. Conversely, Mathabhanga II, Mekhliganj, and Sitai, dominated by Classes 1 and 2, indicate poorer soil fertility and require targeted improvements through composting, green manuring, and judicious fertilizer use. This spatial variability in CEC highlights the importance of block-specific soil fertility management and crop planning to ensure long-term agricultural sustainability in the district.

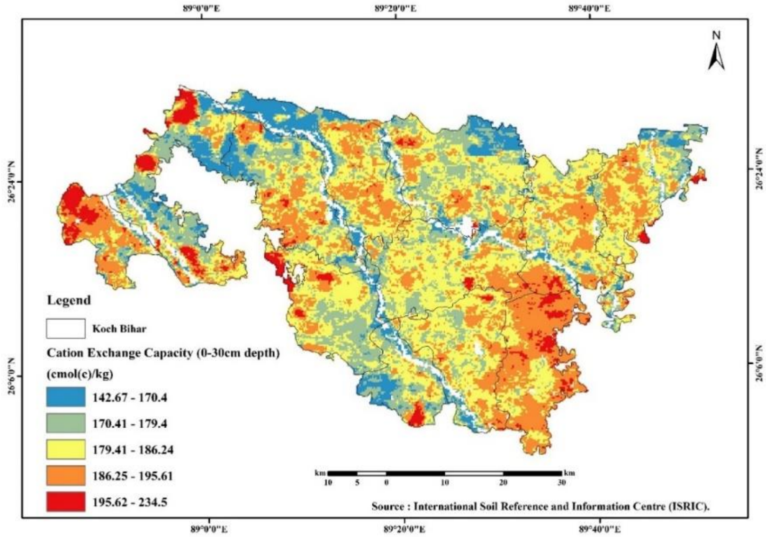

Fig. 8. Spatial distribution of Cation Exchange Capacity across the study region.

I. Soil pH distribution in Koch Bihar District

Soil pH is one of the most critical indicators of soil health, fertility, and crop suitability. It influences the availability of essential nutrients, microbial activity, and overall soil-plant interactions. The spatial distribution of soil pH in Koch Bihar district reveals significant variability, influencing crop suitability and overall soil fertility. Soil pH, a key determinant of nutrient availability and microbial activity, has been classified into five categories ranging from strongly acidic (Class 1: pH 5.20–5.46) to near neutral (Class 5: pH 5.81–6.13). Class 1, representing strongly acidic soils, covers about 6.89% of the district but is concentrated in blocks like Cooch Behar II (20.32%), Tufanganj II (22.06%), and Tufanganj I (11.55%), where nutrient availability may be impaired and aluminium toxicity is likely, necessitating liming for correction. Class 2 soils (pH 5.47–5.6), moderately strongly acidic, occupy 13.38% of the district, with high presence in Cooch Behar II (36.85%), Dinhata I (26.79%), and Cooch Behar I (17.81%), still requiring amendments for optimal productivity. Class 3 (pH 5.61–5.7), moderately acidic and the most widespread class (27.69%), dominates in Tufanganj I (51.53%), Dinhata II (46.10%), and Tufanganj II (45.84%); these soils can be improved with light liming and appropriate crop selection. Slightly acidic soils (Class 4: pH 5.71–5.8), ideal for most crops, cover 28.16% of the district and are dominant in Mathabhanga I (49.37%), Sitai (53.86%), Mathabhanga II (47.14%), and Mekhliganj (42.95%), indicating regions with strong agricultural potential. Class 5 soils (pH 5.81–6.13), near neutral and most favourable for diverse cropping systems, account for 23.98% of the area, with high presence in Sitalkuchi (77.87%), Haldibari (65.21%), and Mathabhanga I (43.93%), requiring minimal pH correction. Overall, while many blocks lie in the moderately to slightly acidic range—suitable for most crops with minimal interventions—areas such as Cooch Behar II and Tufanganj II require targeted soil amendments to improve soil health. This pH distribution reflects the influence of high rainfall and alluvial parent materials, reinforcing the importance of block-specific soil and crop management strategies for sustainable agriculture in Koch Bihar.

Table 8: Block-wise pH Distribution (Area & Percentage).

Sub-Region	Total Area (ha)	Class 1 (5.2–5.46) ha	%	Class 2 (5.47–5.6) ha	%	Class 3 (5.61–5.7) ha	%	Class 4 (5.71–5.8) ha	%	Class 5 (5.81–6.13) ha	%
Mekhliganj	30,262.5	0	0%	262.5	0.87%	4,037.5	13.34%	12,993.75	42.95%	12,968.75	42.84%
Haldibari	13,543.75	0	0%	0	0%	50	0.37%	4,662.5	34.42%	8,831.25	65.21%
Mathabhanga I	30,206.25	6.25	0.02%	118.75	0.39%	1,900	6.29%	14,912.5	49.37%	13,268.75	43.93%
Mathabhanga II	29,268.75	1,575	5.38%	3,318.75	11.34%	6,868.75	23.47%	13,800	47.14%	3,706.25	12.66%
Sitalkuchi	25,756.25	0	0%	25	0.10%	425	1.65%	5,250	20.38%	20,056.25	77.87%
Cooch Behar I	31,962.5	2,650	8.29%	5,693.75	17.81%	11,718.75	36.66%	9,518.75	29.78%	2,381.25	7.45%
Cooch Behar II	36,587.5	7,437.5	20.32%	13,481.25	36.85%	12,556.25	34.31%	2,062.5	5.63%	1,050	2.87%
Tufanganj I	30,518.75	3,525	11.55%	6,175	20.24%	15,725	51.53%	3,468.75	11.37%	1,625	5.32%
Tufanganj II	24,793.75	5,468.75	22.06%	3,650	14.72%	11,362.5	45.84%	2,718.75	10.97%	1,593.75	6.42%
Dinhata I	26,637.5	1,018.75	3.83%	7,137.5	26.79%	11,837.5	44.45%	5,012.5	18.82%	1,637.5	6.15%
Dinhata II	26,875	287.5	1.07%	3,287.5	12.23%	12,393.75	46.10%	8,025	29.85%	2,875	10.69%
Sitai	14,643.75	18.75	0.13%	43.75	0.30%	981.25	6.70%	7,887.5	53.86%	5,750	39.26%
District Total	**330,000**	22,743.75	6.89%	44,162.5	13.38%	91,375	27.69%	92,925	28.16%	79,175	23.98%

Source: Calculated by the authors

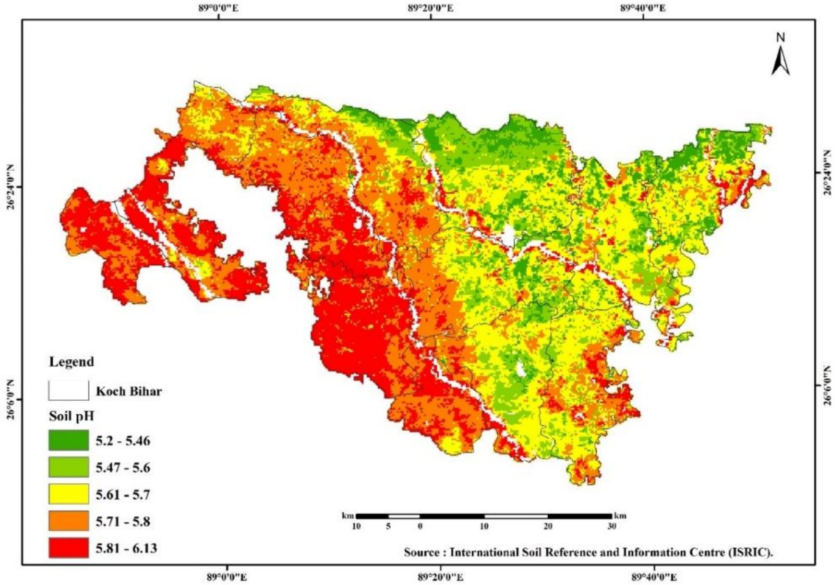

Fig. 9. Spatial distribution of soil pH across the study region.

J. Soil Nitrogen Distribution in Koch Bihar District

Nitrogen (N) is a critical macronutrient for plant growth, and its availability in the soil significantly influences agricultural productivity. The nitrogen availability across Koch Bihar district reveals a wide spatial variation in soil fertility, classified into five categories ranging from very low to very high (1,066.83–7,927.33 kg/ha). Class 1 (very low nitrogen) dominates large portions of the district, particularly in Mathabhanga I (77.4%), Haldibari (83.6%), Mekhliganj (63.9%), Sitai (63.3%), and Mathabhanga II (45.4%), indicating severe nitrogen deficiency and poor soil fertility that demand urgent interventions such as nitrogen-based fertilization, legume cultivation, and green manuring. Class 2 (low to moderate nitrogen) is significant in Mathabhanga II (46.4%), Cooch Behar I (47%), and Dinhata I (58.8%), suggesting moderate limitations that can be managed through integrated nutrient management practices to sustain productivity. Class 3 (moderate to high nitrogen), ideal for most crops, is dominant in Tufanganj I (76.6%), Dinhata II (87.7%), Tufanganj II (64.8%), and Cooch Behar II (37.8%), reflecting fertile soils with good agricultural potential for sustainable or organic farming systems. Class 4 (high nitrogen) is moderately represented in Cooch Behar I (14.7%), Tufanganj I (16.7%), and Cooch Behar II (13.0%), where careful nitrogen budgeting is necessary to prevent over-fertilization and leaching. Class 5 (very high nitrogen), though limited, is observed in Cooch Behar I (9.7%), Cooch Behar II (9.7%), and Tufanganj I (2.7%), indicating highly fertile but environmentally sensitive soils that require close monitoring to avoid nitrate pollution and eutrophication. Overall, while around 30% of the district still suffers from nitrogen deficiency (Classes 1 and 2), other regions like Tufanganj I, Dinhata II, and Cooch Behar II emerge as nutrient-rich zones ideal for intensive or high-value cropping.

Table 9: Block-wise Nitrogen Distribution (Area & Percentage).

Sub-Region	Total Area (ha)	Class 1 (1066.83–1927.76)	%	Class 2 (1927.77–2546.55)	%	Class 3 (2546.56–3568.9)	%	Class 4 (3568.91–4779.57)	%	Class 5 (4779.58–7927.33)	%
Mekhliganj	30,262.5	19,337.5	63.92%	9,387.5	31.01%	1,537.5	5.08%	0	0.00%	0	0.00%
Haldibari	13,543.75	11,325	83.61%	2,206.25	16.29%	12.5	0.09%	0	0.00%	0	0.00%
Mathabhanga I	30,187.5	23,362.5	77.40%	3,562.5	11.80%	2,687.5	8.90%	587.5	1.95%	6.25	0.02%
Mathabhanga II	29,268.75	13,281.25	45.38%	13,593.75	46.44%	2,106.25	7.20%	281.25	0.96%	6.25	0.02%
Sitalkuchi	25,756.25	11,100	43.09%	7,131.25	27.69%	7,050	27.38%	475	1.84%	0	0.00%
Cooch Behar I	31,962.5	0	0.00%	15,006.25	46.95%	9,156.25	28.64%	4,687.5	14.67%	3,112.5	9.74%
Cooch Behar II	36,650	5,468.75	14.92%	8,943.75	24.40%	13,843.75	37.77%	4,781.25	13.05%	3,550	9.69%
Tufanganj I	30,518.75	0	0.00%	1,231.25	4.03%	23,393.75	76.64%	5,081.25	16.65%	812.5	2.66%
Tufanganj II	24,793.75	0	0.00%	4,693.75	18.93%	16,062.5	64.79%	3,100	12.50%	937.5	3.78%
Dinhata I	26,643.75	1,131.25	4.25%	15,650	58.75%	9,662.5	36.27%	193.75	0.73%	6.25	0.02%
Dinhata II	26,925	0	0.00%	2,581.25	9.59%	23,625	87.74%	662.5	2.46%	0	0.00%
Sitai	14,662.5	9,281.25	63.29%	5,168.75	35.26%	212.5	1.45%	18.75	0.13%	0	0.00%

Source: Calculated by the authors

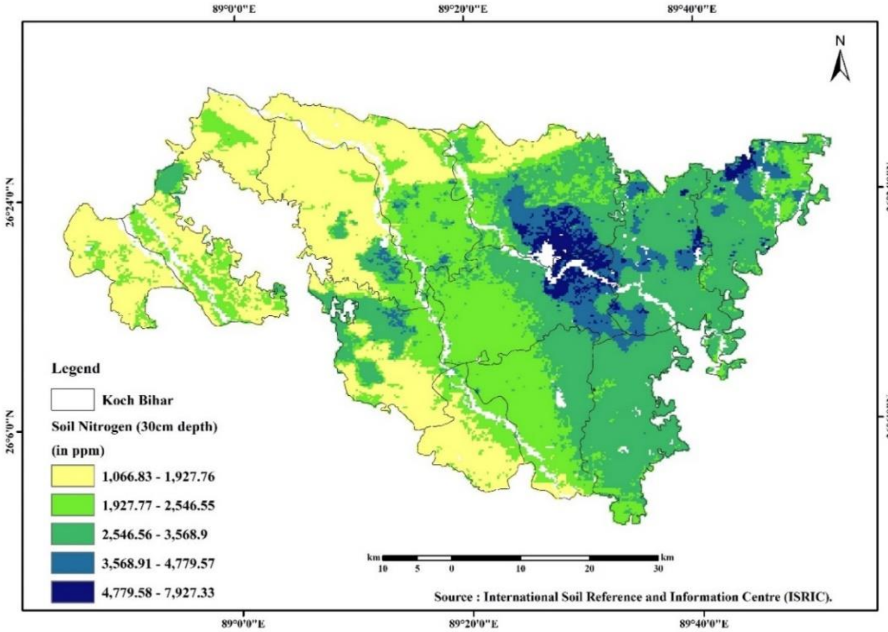

Fig. 10. Spatial distribution of soil Nitrogen across the study region.

K. Phosphorus distribution in Koch Bihar District

Phosphorus (P) is a vital macronutrient essential for plant growth, playing a key role in energy transfer, root development, and crop maturity. Its availability in the soil directly influences agricultural productivity and sustainability.

Table 10: Block-wise Phosphorus Distribution (Area & Percentage).

Block	Total Area (ha)	Class 1 (-20.11 – 6.45 ha)	%	Class 2 (6.46 – 15.15 ha)	%	Class 3 (15.16 – 22.02 ha)	%	Class 4 (22.03 – 27.06 ha)	%	Class 5 (27.07 – 38.28 ha)	%
Mekhliganj	32,493.96	758.7	2.33	4,093.2	12.59	8,344.71	25.68	12,584.43	38.73	6,712.92	20.66
Haldibari	18,326.47	8.64	0.05	804.33	4.39	8,119.26	44.30	4,615.56	25.18	778.68	4.25
Mathabhanga I	31,016.43	300.33	0.97	1,570.59	5.06	9,922.5	31.99	12,966.57	41.81	6,256.44	20.17
Mathabhanga II	31,597.69	681.12	2.15	2,565.63	8.12	9,370.08	29.65	11,314.35	35.81	7,664.31	24.26
Sitalkuchi	26,995.69	132.57	0.49	924.21	3.42	8,831.25	32.71	11,109.33	41.16	4,998.33	18.52
Cooch Behar I	33,605.19	382.68	1.14	1,291.5	3.84	10,873.62	32.36	12,905.55	38.40	8,151.84	24.26
Cooch Behar II	38,298.77	315.27	0.82	1,612.53	4.21	12,134.61	31.68	14,583.51	38.08	9,752.85	25.46
Tufanganj I	32,174.64	400.95	1.25	1,911.33	5.94	11,276.19	35.05	10,579.59	32.89	8,006.58	24.89
Tufanganj II	27,553.79	182.43	0.66	931.05	3.38	8,367.93	30.37	7,860.87	28.52	8,211.51	29.79
Dinhata I	27,638.91	430.2	1.56	1,429.29	5.17	9,924.84	35.91	10,511.91	38.04	5,342.67	19.33
Dinhata II	27,088.95	26.01	0.10	305.73	1.13	9,821.88	36.26	10,903.14	40.25	6,031.17	22.26
Sitai	15,788.79	477	3.02	1,837.26	11.64	5,833.8	36.94	5,110.11	32.37	2,530.62	16.02
District Total	**236,625.36**	**4,112.82**	1.74	**19,357.65**	8.18	**113,215.05**	47.86	**125,558.73**	53.07	**74,699.01**	31.57

Source: Calculated by the authors

Unlike nitrogen, phosphorus is relatively immobile in soil, and its deficiency can significantly reduce crop yields, while excessive accumulation may lead to environmental concerns like eutrophication. The block-wise distribution of phosphorus in the soils of Koch Bihar district reveals a predominantly phosphorus-rich environment, with the majority of the area falling under Class 3 (15.16–22.02 kg/ha, 47.86%) and Class 4 (22.03–27.06 kg/ha, 53.07%), indicating sufficient to high phosphorus availability suitable for most crops. Class 5 (27.07–38.28 kg/ha), representing very high phosphorus levels, also covers a significant 31.57% of the area, especially in Cooch Behar II (25.46%), Tufanganj II (29.79%), and Mathabhanga II (24.26%), suggesting fertile soils with potential risk of nutrient runoff if not managed properly. Class 1 (very low phosphorus) is minimal (1.74%) but locally significant in Sitai (3.02%) and Mekhliganj (2.33%), indicating areas needing phosphorus enrichment. Class 2 (low phosphorus) covers 8.18% and is relatively more prominent in Sitai (11.64%), Mathabhanga II (8.12%), and Mekhliganj (12.59%), requiring moderate supplementation. As a whole, the district displays a strong phosphorus fertility status, particularly in blocks like Mathabhanga I, Dinhata II, Cooch Behar II, and Sitalkuchi, which show high to very high phosphorus levels ideal for high-value cropping, while a few localized zones require strategic nutrient inputs to address deficiency and maintain environmental balance.

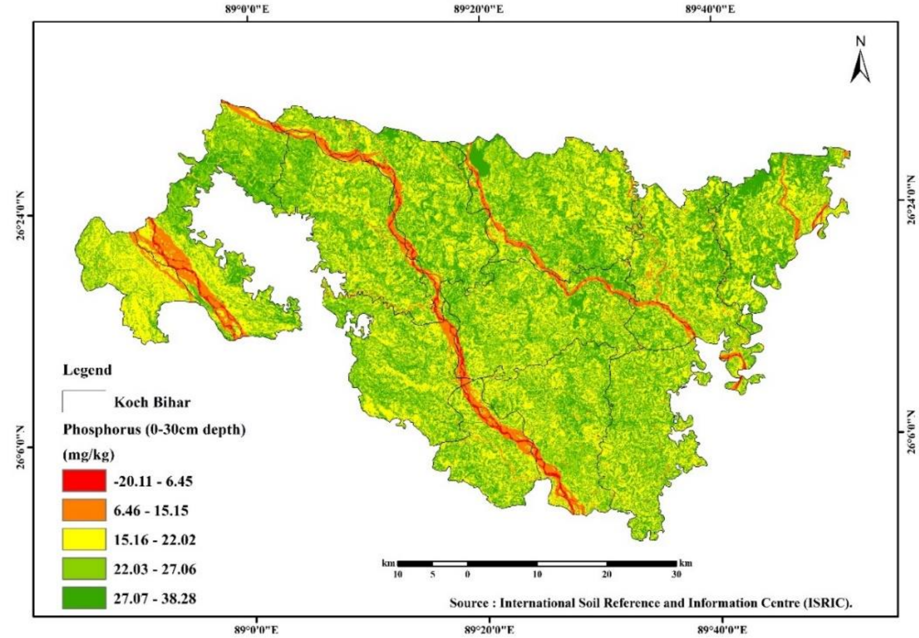

Fig. 11. Spatial distribution of soil Phosphorus across the study region.

L. Potassium distribution in Koch Bihar District

Potassium (K) is one of the essential macronutrients required for healthy plant development, alongside nitrogen and phosphorus. It plays a key role in regulating numerous physiological processes, including enzyme activation, water uptake, photosynthesis, protein synthesis, and enhancing resistance against pests and diseases. Although it does not become part of plant structures, potassium significantly improves crop resilience, root strength, and yield quality, making it a crucial element for sustainable farming systems. In the Koch Bihar district, the spatial distribution of soil potassium demonstrates considerable variability, categorized into five classes. These range from very low (Class 1: 86.67–92.39 kg/ha) to very high availability (Class 5: 108.5–177.9 kg/ha). District-wide data reveal that Class 3, representing moderate potassium availability, is the most dominant (33.84%), followed by Class 2 (26.76%) and Class 4 (20.29%). Only smaller areas fall under Class 1 (7.46%) and Class 5 (11.66%). Class 1 areas, characterized by critically low potassium, are most concentrated in Sitai (15.45%), Mekhliganj (15.51%), and Mathabhanga II (10.74%), signalling an urgent need for nutrient enrichment. Class 2, indicating low to moderate potassium, is most prevalent in Haldibari (48.26%), Sitai (30.44%), and Tufanganj I (29.14%), suggesting the need for consistent potassium input. Conversely, Class 3 dominates productive zones such as Dinhata II (37.09%), Dinhata I (34.28%), and both Cooch Behar I (34.59%) and II (34.44%), indicating balanced potassium levels ideal for most crops. Moderately high levels in Class 4 are prominent in Dinhata II, Mathabhanga I, and Cooch Behar I. Class 5, which can support high yields but needs careful nutrient balancing, is notably high in Tufanganj II (21.31%) and parts of Koch Bihar.

Table 11: Block-wise Consolidated Potassium Distribution (Area & Percentage).

Block	Total Area (ha)	Class 1 (86.67–92.39)	%	Class 2 (92.4–98.12)	%	Class 3 (98.13–103.13)	%	Class 4 (103.14–108.49)	%	Class 5 (108.5–177.9)	%
Mekhliganj	32,493.33	5041.17	15.51	6326.28	19.47	11014.20	33.90	6666.03	20.52	3445.65	10.60
Haldibari	14,326.47	999.81	6.98	6913.53	48.26	4675.41	32.63	1591.74	11.11	145.98	1.02
Mathabhanga I	31,015.98	1972.17	6.36	7446.78	24.01	12135.60	39.13	6525.00	21.04	2936.43	9.47
Mathabhanga II	31,594.68	3394.71	10.74	7448.94	23.58	9993.87	31.63	6644.43	21.03	4112.73	13.02
Sitalkuchi	25,995.51	1132.38	4.36	6751.08	25.97	10511.46	40.44	5234.31	20.14	2366.28	9.10
Cooch Behar I	33,605.19	1769.94	5.27	8559.81	25.47	11624.13	34.59	7431.48	22.11	4219.83	12.56
Cooch Behar II	38,398.41	2036.70	5.30	9518.76	24.79	13223.25	34.44	8149.23	21.22	5470.47	14.25
Tufanganj I	32,174.64	2568.96	7.98	9374.49	29.14	9187.65	28.56	6563.97	20.40	4479.57	13.92
Tufanganj II	25,553.43	1224.72	4.79	6910.92	27.04	6974.64	27.29	4996.71	19.55	5446.44	21.31
Dinhata I	27,638.46	2025.81	7.33	7995.78	28.93	9475.65	34.28	5700.06	20.62	2441.16	8.83
Dinhata II	27,087.93	411.66	1.52	7792.02	28.77	10047.87	37.09	5904.99	21.80	2931.39	10.82
Sitai	15,788.52	2439.00	15.45	4806.00	30.44	4685.58	29.68	2691.72	17.05	1166.22	7.39
District Total	**336943.35**	**25122.78**	**7.46**	**90152.82**	**26.76**	**114012.54**	**33.84**	**68355.00**	**20.29**	**39300.21**	**11.66**

Source: Calculated by the authors

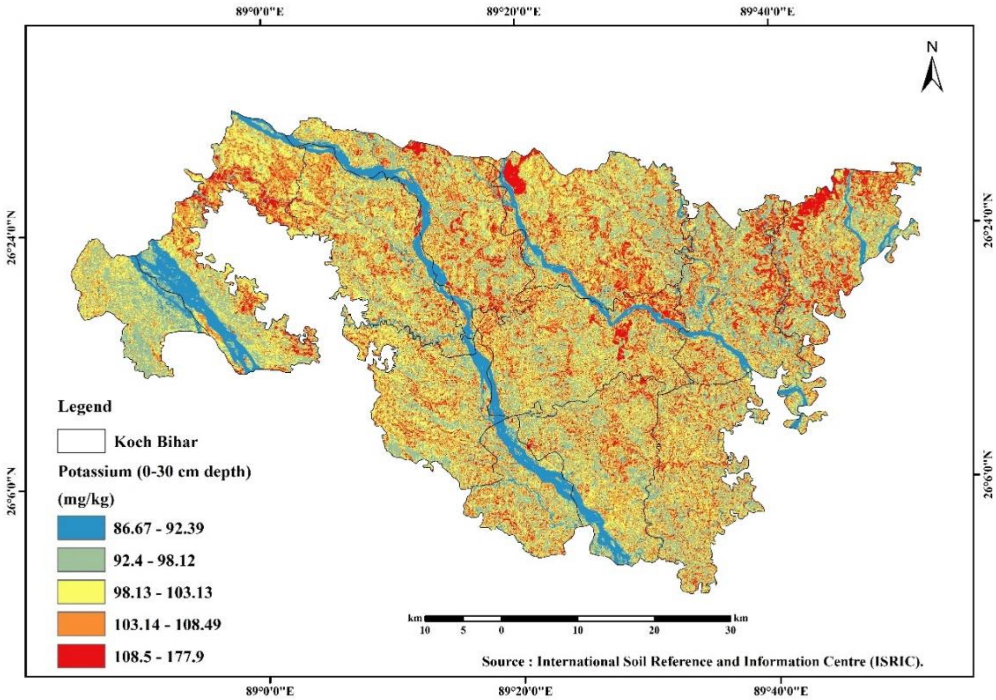

Fig. 12. Spatial distribution of soil Potassium across the study region.

M. Soil Fertility Map

Soil fertility has been defined as the soil's ability to supply essential nutrients to plants in adequate quantities and appropriate proportions to support optimal growth, reproduction, and yield. The Soil Fertility Index (SFI) has been classified into five categories: very low (0.00–0.20), low (0.21–0.40), moderate (0.41–0.60), high (0.61–0.80), and very high (0.81–1.00) (Mallick *et al*., 2023). In the present study, most of the area has fallen under the high fertility category, corresponding to Class 4 (28.59%), followed by moderately fertile areas (Class 3, 23.11%) and very high fertility areas (Class 5, 21.19%). These three classes together have constituted approximately 73% of the district, indicating a predominantly fertile agricultural landscape. In this area, higher bulk density, loamy soil texture, adequate quantity of N, P, K and balanced pH and CEC have been found. Worldwide, various research article says that these soil properties (soil physical and chemical) are very much essential for soil fertility as well as crop productivity (Bostani *et al*., 2025; Mallick *et al*., 2023; Abdel Rahman *et al*., 2021; Tunçay *et al*., 2021; Şenol *et al*., 2020). Loamy soil texture has higher soil fertility than clay texture (Khadem *et al*., 2021). Blocks such as Mekhliganj, Mathabhanga I, and Sitalkuchi have exhibited exceptional soil fertility. Sitalkuchi, in particular, has had around 96.3% of its area under high to very high fertility, reflecting its remarkable agricultural potential. Similarly, Mekhliganj has shown over 82% of its area falling within Classes 4 and 5, while Mathabhanga I has held more than 94% in the same classes, making these blocks highly suitable for crop intensification with minimal fertilizer input. Conversely, blocks like Cooch Behar II, and Mathabhanga II have shown considerable portions of land under low to moderate fertility categories. Sitai has had only 4.18% of its area under high fertility classes, with the majority falling within low and moderate zones. Haldibari has demonstrated a negligible area under moderate fertility (0.03%), relying heavily on high and very high fertility zones to sustain its agricultural output.

In contrast, Tufanganj I and II, Dinhata I and II, and Cooch Behar I have presented a more balanced fertility profile. In these blocks, moderate to high fertility has dominated, although low fertility pockets have persisted, calling for block-specific nutrient management practices. The central and northeastern parts of the district, particularly Cooch Behar I and II, have shown mixed fertility patterns, necessitating diverse and localized agronomic interventions. The area where the course soil texture, a minimal amount of soil macro nutrients like N, P, K, less amount of soil organic carbon and acidic soil have been found, there fertility of the have soil fertility as well as crop productivity and plant growth (Azadi *et al*., 2023). Also, while denitrification, surface runoff, and leaching processes resulted the low nitrogen in soil (Nayak *et al*., 2021). Overall, the SFI map and data have revealed that while a significant portion of Cooch Behar has been endowed with highly fertile soils suitable for sustainable agriculture, certain areas have required targeted nutrient management strategies to optimize productivity across the entire region.

Table 12: Block-wise distribution of Soil Fertility in Koch Bihar District.

Block	Total Area (ha)	Class 1 (0.73–0.74)	%	Class 2 (0.75–0.75)	%	Class 3 (0.76–0.75)	%	Class 4 (0.76–0.75)	%	Class 5 (0.76–0.77)	%
Mekhliganj	29,459.25	0.00	0.00	485.73	0.15	4,549.41	1.41	13,029.48	4.05	11,394.63	3.54
Haldibari	13,265.18	0.00	0.00	0.00	0.00	108.36	0.03	6,167.61	1.92	6,989.58	2.17
Mathabhanga I	29,783.61	6.93	0.00	116.82	0.04	1,634.13	0.51	15,114.51	4.70	12,911.22	4.01
Mathabhanga II	28,618.29	1,489.41	0.46	3,406.50	1.06	6,667.11	2.07	13,780.80	4.28	3,274.47	1.02
Sitalkuchi	25,626.15	5.85	0.00	34.56	0.01	447.84	0.14	6,064.92	1.88	19,072.98	5.93
Cooch Behar I	37,516.01	2,918.97	0.91	8,803.26	2.74	8,724.78	2.71	9,338.58	2.90	1,731.42	0.54
Cooch Behar II	36,100.38	8,198.55	2.55	17,047.98	5.30	8,036.55	2.50	2,057.40	0.64	660.60	0.21
Tufanganj I	29,939.85	3,862.62	1.20	11,966.40	3.72	9,768.15	3.04	3,218.22	1.00	1,124.46	0.35
Tufanganj II	24,322.95	5,976.72	1.86	5,591.07	1.74	9,991.17	3.10	1,517.94	0.47	1,246.05	0.39
Dinhata I	26,121.33	985.50	0.31	6,869.34	2.13	11,694.87	3.63	5,034.69	1.56	1,536.93	0.48
Dinhata II	26,633.70	270.45	0.08	3,053.70	0.95	11,841.84	3.68	8,554.14	2.66	2,913.57	0.91
Sitai	14,414.76	4.50	0.00	36.00	0.01	905.04	0.28	8,120.88	2.52	5,348.34	1.66
District Total	**3,21,801.46**	**23,719.50**	**7.37**	**57,411.36**	**17.84**	**74,369.25**	**23.11**	**91,999.17**	**28.59**	**68,204.25**	**21.19**

Source: Calculated by the authors

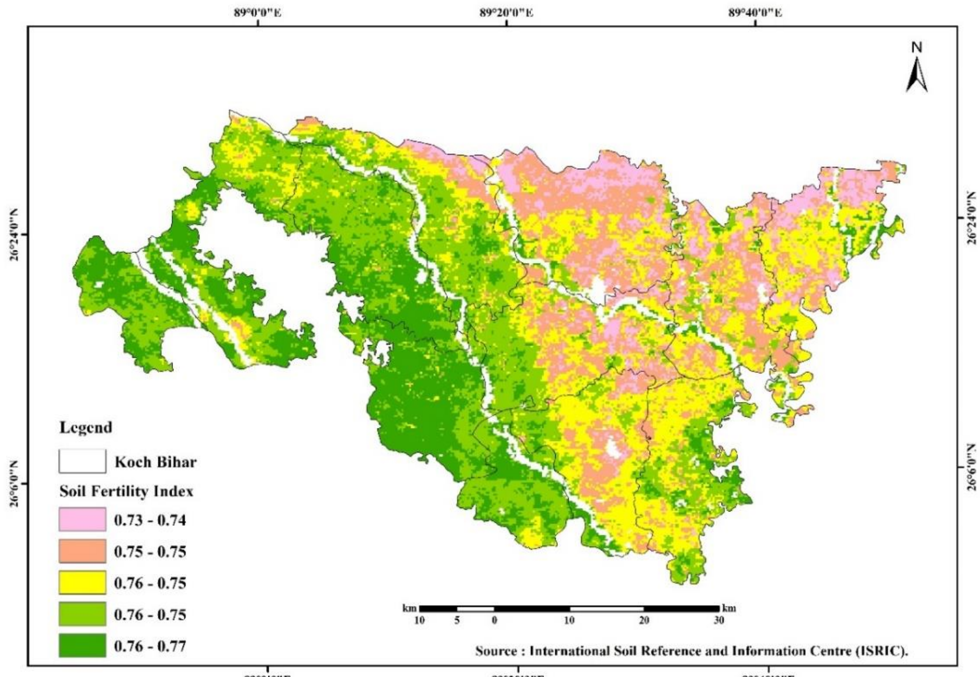

Fig. 13. Spatial distribution of Soil Fertility Index across the study region.

DISCUSSION

The spatial heterogeneity of soil physical and chemical characteristics across Koch Bihar district illustrates the influence of fluvial deposition, climatic variability, and differing land management practices. Comparable trends in soil texture have been noted in adjacent floodplain regions. For example, Mondal *et al*. (2015) observed predominance of sandy loam to loam textures in the North 24 Parganas district of West Bengal, attributing it to cyclic fluvial deposition by the Hooghly River, which mirrors our finding of loam and sandy loam dominance in Koch Bihar soils. Likewise, research by Sahu *et al*. (2012) in Assam's Brahmaputra floodplains recorded moderately sandy soils, advocating organic amendments to improve water retention—an approach consistent with our proposed strategies, including mulching and green manuring. Similarly, Singh *et al*. (2024) reported textural variation ranging from fine sandy loams to clayey loams in Haryana's Kaithal and Karnal districts, emphasizing the necessity for location-specific soil management to optimize moisture and nutrient retention under similar alluvial conditions.

In this study, soil parameters including pH, SOC, nitrogen, CEC, bulk density, and particle size fractions within the 0–30 cm depth were extracted and standardized using the SoilGrids250m dataset via the Google Earth Engine platform. This method enabled consistent spatial analysis while reducing the cost and effort associated with field surveys. Phosphorus and potassium were estimated using vegetation indices derived from Landsat 8 imagery, particularly NDVI and red/NIR ratios, highlighting the potential of satellite-based tools for supporting large-scale soil assessments. This complements findings by Singh *et al*. (2024), who used detailed field sampling and laboratory techniques such as wet oxidation for SOC and alkaline permanganate for nitrogen, reinforcing the importance of combining laboratory and remote sensing methods for robust soil fertility evaluation.

Bulk density (BD) patterns in our study, with moderate BD classes dominating agriculturally productive zones (e.g., Tufanganj I, Sitai), resonate with findings from Ghosh and Jana (2016), who reported optimal BD values (1.2–1.4 g/cm³) for paddy cultivation in the Teesta floodplain. Their work underscored the importance of maintaining moderate compaction through periodic tillage and organic incorporation, which corroborates our recommendation for targeted decompaction in blocks exhibiting high bulk density (e.g., Haldibari, Mathabhanga I). Similarly, Singh *et al.* (2024) in the Indo Gangetic plains emphasized that excessively low BD can exacerbate erosion risks—a cautionary note for management in areas like Sitai and Mathabhanga II, where very low BD classes are prevalent. A considerable decline in Soil Organic Carbon (SOC) was identified, particularly across Mathabhanga I and II, reflecting trends documented by Hossain *et al*. (2016); Begum *et al*. (2018) in the rice-wheat dominated floodplains of northern Bangladesh. Also, the results align with the work done by Dhamak *et al*. (2014); Srinidhi *et al*. (2020); Narsaiah *et al*. (2018); Kadam *et al.* (2022). Singh *et al*. (2024) also found that most sampled sites in Haryana had medium SOC levels, with deficiencies linked to fertility decline and yield reductions. They found that practices such as residue retention and cover cropping could raise SOC stocks by up to 20% over five years. Our identification of small high SOC pockets (Class 4 and 5) in Dinhata II and Cooch Behar I offers valuable reference sites for implementing and monitoring conservation agriculture measures, in line with Datta and Verma's (2017) recommendations for alluvial soils.

The spatial distribution of Cation Exchange Capacity (CEC) revealed high fertility in blocks such as Dinhata II and Haldibari. This mirrors the findings of Karim *et al.* (2014), who reported that older, fine-textured alluvial soils in the Brahmaputra-Meghna basin exhibit elevated exchange capacities. Our identification of high CEC zones coincides with their assessment, affirming the cropping potential of these areas. On the contrary, regions like Mathabhanga II and Mekhliganj showed lower CEC, similar to results by Bhattacharya *et al*. (2013) in the lower Ganges plain. In those settings, green manuring practices were found to enhance organic matter and CEC, a recommendation that complements our findings.

Soil pH patterns in Koch Bihar, with a shift from strongly acidic in the western blocks (Cooch Behar II, Tufanganj II) to near-neutral in Sitalkuchi and Haldibari, align with the pH gradients documented by Hossen *et al*. (2015) in the Brahmaputra floodplain. They attributed acidity in upland flat areas to leaching under high rainfall, and recommended liming based on buffer pH tests. Our block-specific liming recommendations are therefore well supported by established practices in similar humid, alluvial contexts.

The nutrient availability trends—nitrogen deficiency in Mathabhanga and Haldibari versus high N, P, K in Tufanganj and Dinhata blocks—mirror the variability reported by Mukherjee *et al.* (2019) for the Ganga-Brahmaputra delta, where fertilizer application rates were calibrated to block-level soil tests to optimize yield and minimize environmental impacts. Similarly, Yadav *et al*. (2021); Kokode *et al*. (2023) have stated that N deficiency results from topsoil erosion, which strips away organic matter essential for retention. P availability often decreases as calcium binds with it under optimal pH, while organic matter helps maintain a conducive environment for nutrient uptake. Their integrated nutrient management framework, combining organic and inorganic sources, provides a practical model for addressing the substantial N and K deficits we identified in certain blocks.

As a whole, the consistency of our findings with those from adjacent alluvial landscapes underscores the regional coherence of soil formation and fertility patterns in northeastern India and Bangladesh. These parallels validate our methodological approach and reinforce the relevance of adopting best management practices—such as conservation tillage, targeted liming, organic amendments, and precision fertilization—tailored to the unique soil profiles of each block. Future work should focus on long-term monitoring of management interventions to quantify improvements in SOC, CEC, and bulk density, as demonstrated by longitudinal studies in similar settings (e.g., Gajbhiye *et al*., 2011), thereby ensuring sustainable intensification of agriculture in the Koch Bihar district.

CONCLUSIONS

This study has successfully demonstrated the integration of remote sensing and geospatial technologies—specifically Google Earth Engine (GEE)—in mapping and assessing soil fertility across the Koch Bihar district, West Bengal. By leveraging the high-resolution SoilGrids250m dataset and empirical estimations from Landsat 8 surface reflectance data, key soil parameters such as pH, SOC, BD, texture, nitrogen, CEC, phosphorus, and potassium have been spatially analyzed over a merged topsoil depth of 0–30 cm. The adoption of digital soil mapping (DSM) techniques, supported by Fuzzy AHP weighting and min–max normalization, has enabled the creation of a continuous Soil Fertility Index (SFI) surface, which has been classified into five distinct fertility classes. The results have revealed a predominantly fertile landscape, with approximately 73% of the district falling under moderate to very high fertility zones. Blocks like Sitalkuchi, Mekhliganj, and Mathabhanga-I have shown remarkably high fertility, making them suitable for intensive agriculture with minimal fertilizer input.

In contrast, Sitai, Mathabhanga II, and parts of Cooch Behar II have been characterized by lower fertility due to suboptimal soil texture, reduced macro-nutrient levels, and acidic pH conditions. These findings have reinforced the critical role of soil physical and chemical properties—such as texture, organic carbon, pH, and nutrient content—in defining soil fertility and agricultural potential. This research has underscored the efficiency of GEE as a scalable and cost-effective platform for regional soil assessment, especially in heterogeneous landscapes like the Himalayan foothills. The digital SFI maps produced have provided a robust spatial framework for identifying nutrient-deficient zones, enabling site-specific nutrient management strategies. In sum, while Koch Bihar has possessed a strong agronomic base due to its fertile soils, targeted interventions are needed in low-fertility pockets to ensure balanced and sustainable agricultural development. These insights have paved the way for precision farming and informed land-use planning, contributing to long-term soil health and productivity in the region.

RECOMMENDATIONS

The study recommends block-specific soil management strategies in Koch Bihar, informed by spatial variability in fertility. Low-fertility zones like Sitai and Mathabhanga II require integrated nutrient management and organic amendments to boost SOC and nitrogen. Acidic soils in Tufanganj I and Cooch Behar II need liming. High bulk density areas demand conservation tillage, while phosphorus and potassium management must be localized. Conservation agriculture and farmer training on precision tools should be promoted, along with water management in sandy and clay-rich soils. Adoption of these interventions will enhance soil health, crop productivity, and long-term sustainability across the district’s diverse agro-ecological blocks.

FUTURE SCOPE

Future studies should focus on long-term soil monitoring, deeper horizon analysis, and climate-resilient practices. Integrating higher-resolution satellite data, machine learning models, and socioeconomic assessments will refine DSM outputs. Scaling the approach to other Koch Bihar districts and linking Soil Fertility Index maps with crop suitability models can guide regional agricultural planning and promote sustainable intensification across similar floodplain agroecosystems.

Acknowledgements. The first author gratefully acknowledges the financial support received from the University Grants Commission (UGC), Government of India, under the National Fellowship for Scheduled Caste (NFSC) scheme. This fellowship has significantly contributed to the successful completion of the present research work. The authors also acknowledge the Department of Geography, Cooch Behar Panchanan Barma University, for academic support, the use of the Google Earth Engine platform, and other relevant secondary data sources. Special thanks to Dr. Nazrul Islam (Supervisor) and Professor Dibyendu Mukhopadhyay (Co-Supervisor) for their valuable guidance.

Conflict of Interest. None.

REFERENCES

Abdel Rahman, M. A., Hegab, R. H. and Yossif, T. M. (2021). Soil fertility assessment for optimal agricultural use using remote sensing and GIS technologies. *Applied Geomatics*, *13*, 605-618.

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M. & Brisco, B. (2020). Google Earth Engine cloud computing platform for remote sensing big data applications: A comprehensive review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350.

Azadi, A., Zareian, G. & Shakeri, S. (2023). Digital mapping of soil fertility for some agricultural lands by using fuzzy-AHP (FAHP) techniques and GIS in highly calcareous soil, in Southwest Iran. *Communications in Soil Science and Plant Analysis*, *54*, 2885-2897.

Begum, K., Kuhnert, M., Yeluripati, J., Ogle, S., Parton, W., Kader, M. A. & Smith, P. (2018). Model-based regional estimates of soil organic carbon sequestration and greenhouse gas mitigation potentials from rice croplands in Bangladesh. *Land*, *7*(3), 82.

Bhattacharya, T., Pal, D. K., Mandal, C. & Velayutham, M. (2013). Organic carbon stock and soil fertility in the lower Ganges plain. Geoderma, 193-194, 144–154.

Bostani, A., Mohebbi Tafreshi, A. & Bijeh Keshavarzi, M. H. (2025). Assessment of soil fertility and nutrient distribution for enhanced soil health and field management through an innovative approach. *Agrosystems, Geosciences and Environment*, *8*(2), e70088.

Brady, N. C. & Weil, R. R. (2010). Elements of the nature and properties of soils (3rd ed.). Pearson Education.

Brady, N. C. & Weil, R. R. (2016). The nature and properties of soils. Columbus. EUA Pearson Education.

Chong, L. U. O., Qiang, F. U., Hai-xiang, G. U. A. N., Qiang, Y. E. & Fan-chang, K. O. N. G. (2020). Mapping the fallowed area of paddy fields on Sanjiang Plain of Northeast China to assist water security assessments. *Journal of Integrative Agriculture*, *19*(7), 1885-1896.

Datta, M., & Verma, J. P. (2017). Soil organic carbon dynamics in alluvial soils under rice-wheat cropping systems. *Journal of Soil Science and Plant Nutrition*, *17*(4), 892–905.

Debnath, M., Islam, N., Roy, P. B., Ray, S., Sarkar, B. & Roy, R. (2023). Role of Migration in Urbanisation in the Himalayan Foothill Region of West Bengal, India: A Geospatial Analysis. *Urbanization*, *8*(2), 164-187.

Dhamak, A. L., Meshram, N. A. & Waikar, S. L. (2014). Identification of Major Soil Nutritional Constraints in Vertisol, Inseptisol and Entisol from Ambajogai Tehsil of Beed District. *Journal of Research in Agriculture and Animal Science*, (10), 35-39.

Dong, J., Xiao, X., Menarguez, M. A., Zhang, G., Qin, Y., Thau, D. & Moore III, B. (2016). Mapping paddy rice planting area in northeastern Asia with Landsat 8 images, phenology-based algorithm and Google Earth Engine. *Remote Sensing of Environment*, 185, 142-154.

Foth, H. D. (1991). Fundamentals of soil science (No. Ed. 8, pp. xv+-360).

Gajbhiye, K. S., Mandal, C., & Bhattacharyya, T. (2011). Soil fertility and productivity under long-term nutrient management in Vertisols. *Indian Journal of Fertilisers*, *7*(3), 12–22.

Ghosh, S. & Jana, P. K. (2016). Soil physical properties and rice yield in Teesta floodplain soils. Journal of the Indian Society of Soil Science, *64*(2), 132–140.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote sensing of Environment*, *202*, 18-27.

Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., & Kempen, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. *PLoS one*, *12*(2), e0169748.

Hossain, M. S., Hossain, A., Sarkar, M. A. R., Jahiruddin, M., da Silva, J. A. T. & Hossain, M. I. (2016). Productivity and soil fertility of the rice–wheat system in the High Ganges River Floodplain of Bangladesh is influenced by the inclusion of legumes and manure. *Agriculture, Ecosystems & Environment*, *218*, 40-52.

Hossen, M. A. M., Lira, S. A., Mia, M. Y. & Rahman, A. K. M. M. (2015). Soil nutrient status of Brahmaputra floodplain area in Tangail sadar upazila for agricultural uses. *Journal of Environmental Science and Natural Resources*, *8*(2), 11-14.

Javidan, R., Rahmati, O., Soleimanpour, S. M. & Mohammadi, F. (2024). Soil properties mapping using the Google Earth Engine platform. In Remote Sensing of Soil and Land Surface Processes (pp. 385-398). Elsevier.

Kadam, D. M., Waghmare, M. S., Lingayat, N. R., Goswami, H. G., Chavan, N. S. & Kumawat, H. (2022). Soil fertility assessment of Entisol and Vertisol orders from Ausa Tehsil of Latur District. *Biological Forum – An International Journal*, *14*(3), 90–94.

Karim, M. R., Rahman, M. M. & Islam, M. S. (2014). Cation exchange capacity and soil fertility in the Brahmaputra-Meghna basin. Soil Science and Plant Nutrition, *60*(5), 678–689.

Khadem, A., Raiesi, F., Besharati, H. & Khalaj, M. A. (2021). The effects of biochar on soil nutrient status, microbial activity and carbon sequestration potential in two calcareous soils. *Biochar*, *3*, 105-116.

Kokode, N., Bangar, K. S., Kumhare, A., Kumar, K. & Tekam, Y. (2023). Study on soil fertility status of Kalapipal Tehsil of Shajapur District, Madhya Pradesh. *Biological Forum – An International Journal*, *15*(11), 62–70.

Kundu, P. (2020). Assessment of wetlands to evaluate the aquatic environment: A case study in Floodplain of the Himalayan foothill region. *SN Applied Sciences*, *2*(8), 1373.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change & food security. *Science*, *304*(5677), 1623-1627.

Mahdianpari, M., Salehi, B., Mohammadimanesh, F., Homayouni, S. & Gill, E. (2018). The first wetland inventory map of Newfoundland at a spatial resolution of 10 m using Sentinel-1 and Sentinel-2 data on the Google Earth Engine cloud computing platform. *Remote Sensing*, *11*(1), 43.

Mallick, K., Sahana, M. & Chatterjee, S. (2023). Comparing Delphi–fuzzy AHP and fuzzy logic membership in soil fertility assessment: a study of an active Ganga Delta in Sundarban Biosphere Reserve, India. *Environmental Science and Pollution Research*, *30*, 116688-116714.

Mondal, S., Chakravarty, D. & Bandyopadhyay, S. (2015). Soil texture and nutrient status in the Hooghly floodplain. *Journal of the Indian Society of Soil Science*, *63*(3), 245–253.

Mukherjee, A., Saha, D. & Ray, P. K. (2019). Nutrient management in the Ganga-Brahmaputra delta: Challenges and opportunities. *Agricultural Water Management*, *214*, 67–78.

Narsaiah, E., Ramprakash, T., Chandinipatnaik, M., Vishnuvardhan, D. R. & Bhupalraj, G. (2018). Soil physical, physico-chemical properties of Mulugu Division soils of Warangal District, India. International *Journal of Current Microbiology and Applied Sciences*, *7*(6), 2735–2748.

Nayak, S. B., Balaguravaiah, D., Ramana, K. V., Giridharakrishna, T., Munirathnam, P. & Ravindra Reddy, B. (2021). Assessment of soil fertility through geospatial techniques in Kurnool Division of Andhra Pradesh. *Biological Forum – An International Journal*, *13*(3b), 255–259.

Robinson, T. P. & Metternicht, G. (2006). Testing the performance of spatial interpolation techniques for mapping soil properties. *Computers and Electronics in Agriculture*, *50*(2), 97-108.

Sağlam, M. & Dengiz, O. (2012). Influence of selected land use types and soil texture interactions on some soil physical characteristics in an alluvial land. *International Journal of Agronomy and Plant Production*, *3*(11), 508–513.

Sahu, G. C., Mishra, P. & Dhal, B. (2012). Soil physical properties and crop productivity in the Brahmaputra floodplain. *Journal of Agricultural Physics*, *12*(1), 45–52.

Sarkar, B., Das, P., Islam, N., Basak, A., Debnath, M. & Roy, R. (2022). Land suitability analysis for paddy crop using GIS-based F-AHP (F-AHP) method in Koch Bihar district, West Bengal. *Geocarto International*, *37*, 8952-8978.

Şenol, H., Alaboz, P., Demir, S. & Dengiz, O. (2020). Computational intelligence applied to soil quality index using GIS and geostatistical approaches in a semi-arid ecosystem. *Arabian Journal of Geosciences, 13*, 1235.

Singer, M. J. & Munns, D. N. (2006). Soils: An introduction (6th ed.). Pearson Prentice Hall.

Singh, C., Roohi, Kumar, A., Gandhi, V., Lalita, Madaan, S., Saini, S., Mahaveer, Jain, A., Kumar, R. & Sumit. (2024). Soil quality and productivity assessment for bridging the rice yield gaps in farmers' fields. *Biological Forum – An International Journal*, *16*(5), 114–117.

Srinidhi, P., Singh, Y. V., Sharma, P. K., Singh, R. K., Latare, A. M., Srinath, I. & Yogesh, Y. C. (2020). Physicochemical analysis of soils in Madanapalle block, Chittor district of Andhra Pradesh. *International Journal of Chemical Studies*, *8*(3), 154–158.

Taghizadeh-Mehrjardi, R., Nabiollahi, K. & Kerry, R. (2016). Digital mapping of soil organic carbon at multiple depths using different data mining techniques in Baneh region, Iran. *Geoderma*, *266*, 98-110.

Tunçay, T., Kılıç, Ş., Dedeoğlu, M., Dengiz, O., Başkan, O. & Bayramin, I. (2021). Assessing soil fertility index based on remote sensing and GIS techniques with field validation in a semi-arid agricultural ecosystem. *Journal of Arid Environments*, *190*, 104525.

Yadav, T. C., Singh, Y. P., Singh, A., Yadav, S. S., Jakhar, S. R. & Choubey, D. (2021). GIS-based Soil Fertility Maps of Chambal Division of Madhya Pradesh, India. *Biological Forum – An International Journal*, *13*(3), 111-117.

How to cite this article: Prasanta Das, Nazrul Islam and Dibyendu Mukhopadhyay (2025). Cloud-Based Geospatial Mapping of Soil Properties Using Google Earth Engine**:** A Case Study of Koch Bihar District, West Bengal, India. *International Journal of Theoretical & Applied Sciences*, *17*(2): 80–99.