

Research article

Soil Physicochemical Alteration Associated with Dolomite Influx Along the India–Bhutan Border

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ABSTRACT

Dolomite, a calcium magnesium carbonate mineral, can adversely affect soil properties when present in excessive amounts. The India-Bhutan border region of West Bengal has experienced substantial declines in the quality and yield of fresh tea leaves, potentially associated with dolomite influx from the neighbouring lower Himalayas through recurrent flooding and the use of river water for irrigation. This study assessed the soil status of the affected area. The overall moisture content of the soil was low, with the lowest average values recorded in riverbeds, followed by the tea plantations. The average value of organic carbon, total nitrogen, available phosphate and potash across the study area were $1.34 \pm 0.98\%$, $0.10 \pm 0.08\%$, 20.27 ± 38.58 ppm and 199.18 ± 270.37 ppm, respectively. The soil pH of the study region varied from 7.85 to 3.91, with an average of 6.16 ± 1.02 . The riverbeds showed average pH 6.94 ± 0.46 , followed by the tea plantations (5.61 ± 0.91) and forest area (5.03 ± 0.53). The quantity of soil calcium carbonate of the area varied between 1% to 14%, with an average of 7.09%, in comparison to $0.4 \pm 0.2\%$ in unaffected areas. The tea plantations near the riverbeds were most affected. Elevated soil pH causes ammonia volatilization reducing the availability of nutrients such as P, N, B, Mn, Cu, Fe and Zn for the tea bushes leading to decline in productivity. Soil reclamation strategies should therefore include the potential use of calcite-solubilising microorganisms, measures to reduce further dolomite influx associated with mining activities, and appropriate hydraulic interventions, including check dams and the management of sediment accumulation in streams and riverbeds. Tea plantations should also consider avoiding river water for irrigation where it contributes to further carbonate accumulation and soil alkalinisation.

Key words:

India-Bhutan border, dolomite, tea plantations, pH, CaCO_3

Citation:

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INTRODUCTION

Bhutan is characterized by rugged mountainous terrain, deep valleys, and an extensive network of rivers and tributaries. Most rivers originate in the northern highlands and flow southward through narrow gorges and ravines before entering the Duars region of West Bengal, India, and ultimately draining into the Brahmaputra River and its adjoining drainage systems in India and Bangladesh. Major rivers of this region include Jaldhaka, Torsha, Raidak, Gadadhar and Manas. These fresh water resources play an important role in sustaining local communities and supporting agricultural activities. India and Bhutan share a 699 km border, of which 183 km lies between Bhutan and

the Indian state of West Bengal. The border region is susceptible to earthquakes and landslides owing to its location within a seismically active zone. Steep slopes, unstable geological formations, intense rainfall, and anthropogenic activities, including deforestation, urbanization, inappropriate land use, and dolomite mining, have collectively increased the region's vulnerability to environmental hazards ([Barman and Choudhury, 2023](#)).

Dolomite is a complex of calcium magnesium carbonate having a chemical formula $\text{CaMg}(\text{CO}_3)_2$. The complex is originally formed by post-depositional alteration of calcium carbonate muds and limestone by magnesium-rich groundwater by the process of diagenesis. The ore is an important raw material for industries like iron and steel, ferroalloys, glass, alloy steels, fertilizer industry, etc. In tea cultivation, where the ideal pH ranges between 4.5 and 5.5 ([Mukherjee et al., 2020](#)), dolomite dust is added to soil as a corrective measure for low pH. It is abundant in Bhutan, where it occurs as bands within the Manas Formation of the Buxa Group in the Lesser Himalayan sequence along the southern foothills, extending from Samtse Dzongkhag in the west to Sarpang Dzongkhag in the east. These deposits are frequently intercalated with limestone, phyllite and quartzite. The total known dolomite reserves in Bhutan have been estimated at approximately 51.33 million tonnes of proven reserves and 15,979 million tonnes of inferred resources ([JICA, 2021](#)). The opencast mining of dolomite in Bhutan has led to the accumulation of dolomitic debris on the riverbeds of the neighbouring plains, resulting in the contamination of groundwater, forests and tea plantations in the region. The consequences of contamination have resulted in shortage of drinking water, rise in soil pH level, respiratory and dermal diseases along with heavy loss in productivity and quality deterioration ([Chakraborty and Dutta, 2013](#)). The deterioration of soil quality in tea garden soil associated with the presence of dolomite in irrigation water has previously been documented by [Sarkar \(2008\)](#) and [Nandi et al. \(2024\)](#). In addition, [Sarkar \(2008\)](#) and [Chamling and Bera, 2020](#) reported health related issues among tea garden workers resulting from the consumption of contaminated river water in the Madarihat Block of Alipurduar District. Moreover, the impact of the dolomite influx along the Indo Bhutan border region of West Bengal on soil physicochemical properties has been documented, including the loss of nearly 5,000 Sal trees (*Shorea robusta*) between 1998 and 2000, as reported by [Sarkar \(2008\)](#). Several studies conducted in this region have emphasized the sociological, geographical, and geological dimensions of fluvial hazards ([Sarkar, 2008](#); [Chakraborty and Dutta, 2013](#); [Talukdar and Das, 2022](#); [Hasanuzzaman et al., 2022](#)). The unavailability of previous research based on the estimation of dolomite induced soil quality alteration in the Indo-Bhutan border region with special reference to tea plantations, natural forest ecosystem and river bed framed the foundation for the present study aiming to explore the present physicochemical status of soil in the study area with special reference to the pH and CaCO_3 deposition.

MATERIAL AND METHODS

Study area

The study area comprised riverbeds, tea plantations, and other biotopes along the Indian side of the India–Bhutan border, extending from Bindu in the west (27° 06'N and 88° 52'E; 2000ft asl) to Jayanti in the east (26° 74'N and 89° 61'E; 377ft asl) across the districts of Kalimpong, Jalpaiguri and Alipurduar, West Bengal, India. The study area was divided into five geographical grids (Grid 1–5) on the basis of latitude and longitude (Grid 1: 26°50'–27°00'N and 88° 40'–88° 90'E; Grid 2: 26° 00'–26° 50'N and 89°00'–89° 50'E; Grid 3: 26° 50'–27° 00'N and 89° 00'–89° 50'E; Grid 4: 26° 50'–27° 00'N and 89° 50'–90° 00'E; Grid 5: 27° 00'–27° 50'N and 88° 50'–89° 00'E). In addition to the geographical grids, the sampling sites were grouped into five clusters (Clusters 1–5) according to their spatial proximity. Detailed information on the sampling sites will be provided upon request.

Collection and preparation of soil samples

A total of 310 composite soil samples were collected from 14 riverbeds, 14 tea plantations, and three natural forest sites. Each sample was a mixture of five pre-samples (100 gm each) in equal proportion collected in a zigzag pattern at a distance of hundred meters from the other during January to February, 2023. Consequently, a total of 1,550 sub-sampling points were surveyed. The samples were collected in clean polyethylene bags and transported to the laboratory in an insulated ice box. Pebbles, roots, and other visible debris were removed manually before analysis. Soil moisture was determined in fresh samples, after which the samples were air-dried and prepared for subsequent physicochemical analysis.

Quantification of soil moisture

The moisture content in the soil samples was quantified following the protocol of [Mukherjee et al. \(2020\)](#). Fresh soil samples were weighed (W1) and their dry weight (W2) was taken after 48 hours of drying at 110° C. The difference in weight was expressed as a percentage of moisture content.

Soil nutritional status

Organic carbon (OC), organic matter (OM) and total nitrogen (N) were determined using the methods described by [Walkley and Black \(1934\)](#) and [Jackson \(1973\)](#), respectively. The estimation of available phosphorus (phosphate) (P) was done using the spectrophotometer-based protocol of [Bray and Kurtz \(1945\)](#), whereas available potassium (K) was determined by flame photometry following [Chapman and Pratt \(1961\)](#).

Quantification of pH and CaCO₃

Air-dried and sieved soil samples were mixed in neutral water (1:2.5; W:V) and mechanically shaken for 30 minutes prior to pH determination with a calibrated pH meter following the methodology of [Mukherjee et al. \(2020\)](#). The area was heavily infested by dolomite dust. Therefore, the quantification of CaCO₃ was essential and it was conducted using the rapid titration method of [Puri \(1930\)](#), as modified by [Tamilselvi et al. \(2025\)](#).

Nutrient index (NI)

The fertility status of the study soils was assessed using a nutrient index (NI) calculated from the measured values of pH, OC, N, P, and K according to the method of [Ramamoorthy and Bajaj \(1969\)](#):

$$NI = [(LX1) + (MX2) + (HX3)] / \text{Total Number of soil samples}$$

where, L denotes the number of soil samples with low status, M denotes the number of soil samples with medium status, H denotes the number of soil samples with high status ([Ramamoorthy and Bajaj, 1969](#)). The reference value for the calculation was based on the recommended value provided by the Tea Board of India.

Statistical analysis

The results of the experiments were analysed using Microsoft Excel 2007 and PAST (version 4).

RESULTS AND DISCUSSION

Study area

The research work was conducted in the sub-Himalayan region of West Bengal, India, encompassing tea plantations, natural forests, and riverbeds across the Indo-Bhutan border districts of Kalimpong, Jalpaiguri, and Alipurduar. The study area extended from approximately 26°30' to 27°00' N and 88°50' to 90°00' E, with elevations ranging from 90 to 1,750 m above sea level ([Figure 1](#)). The Kalimpong district is part of the lower Himalayas, whereas the Jalpaiguri and Alipurduar districts, locally named “Dooars” (meaning door), serve as a gateway to Bhutan. Geographically, the Dooars region lies on the foothills and adjoining plains of the Himalayas and is blessed with the mountain ranges of eastern Himalayas standing in the backdrop, forests with rich biodiversity and swift flowing rivers and streams originating from the hills of Bhutan dissecting the region into small terrestrial blocks. As already stated in the materials and methods section, the study area was divided into five topographic grids (Grid 1 to Grid 5) and five clusters (Cluster 1 to Cluster 5) on the basis of geographical proximity for better understanding.

The study area is affected by the deposition of dolomite-bearing sediments and dust transported from the neighboring Bhutan Himalaya through the regional river system. [Figure 2](#) illustrates the principal features of the affected landscape and soil profile, including dolomite deposits in the study area. The deposited dolomite severely influences the ecosystem by increasing pH but reducing the soil water retention capacity, water table, mineral availability, biodiversity, etc. ([Bolan et al., 2023](#)).

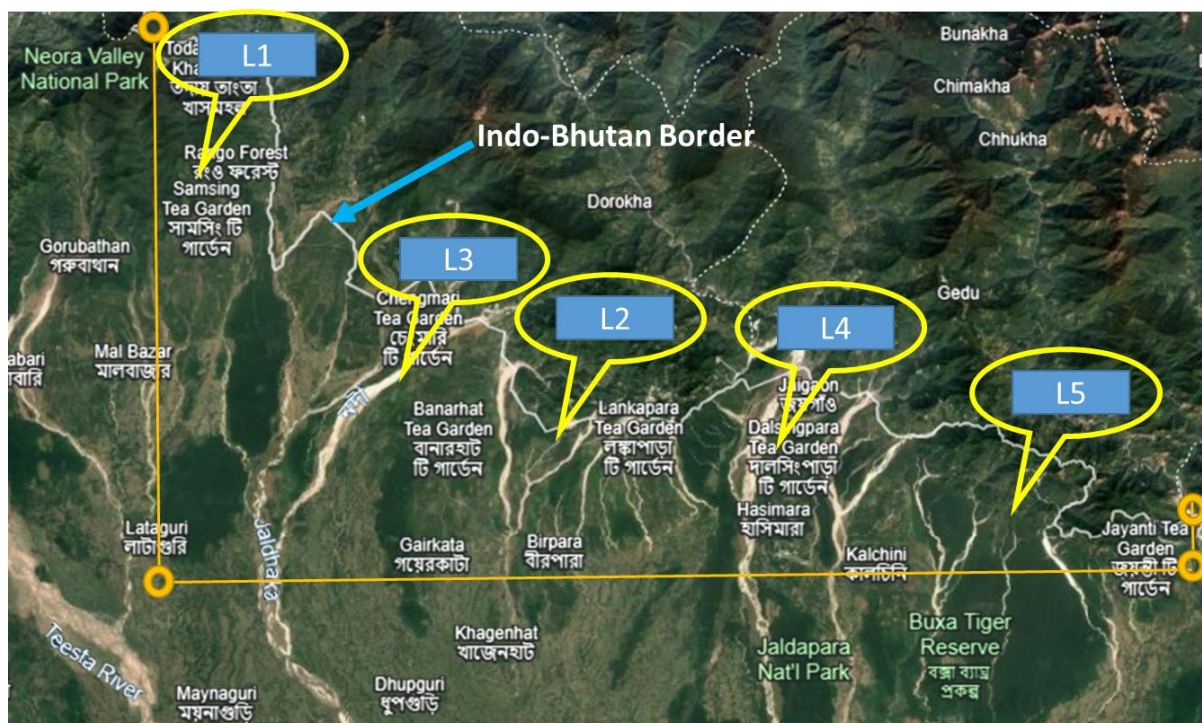


Figure 1. Map showing the overall collection sites. Points on the map represents the clusters selected for the study (L1, L2, L3, L4 and L5), comprised of fourteen tea plantations, fourteen river beds and three natural forests

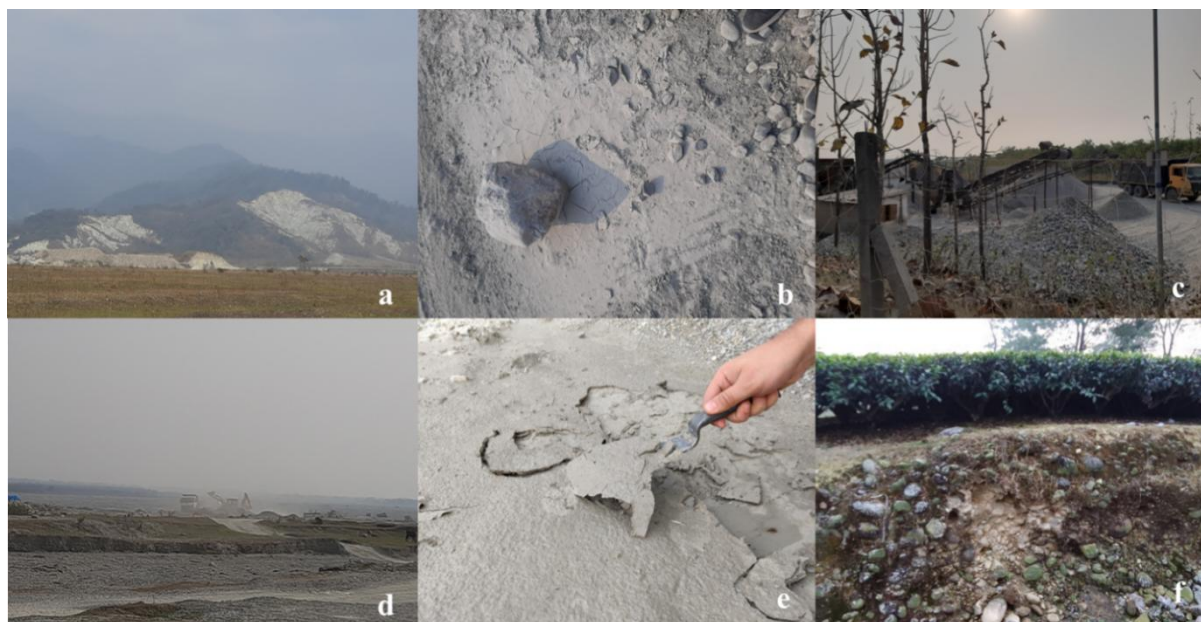


Figure 2. **a** - Lesser Himalayas, **b** - top soil of affected area, **c** - dolomite crushing unit, **d** - neighbouring area of Lesser Himalayas, **e** - dolomite sediment crust, **f** - soil profile of tea plantation

Soil moisture content

The overall mean soil moisture content was 17.90%, indicating relatively low moisture availability across the study area. The lowest mean moisture content was recorded in the riverbed soils ($11.75 \pm 8.47\%$), followed by the tea plantation soils ($13.21 \pm 7.88\%$), whereas the forest soils exhibited substantially higher moisture content ($68.54 \pm 9.37\%$), [Figure 3](#). The low moisture content in the riverbeds is quite unusual. The rivers of this region are seasonal, with occasional flooding during the monsoon period. The presence of abundant pebbles and sand in the riverbeds

may increase porosity and drainage while reducing water-holding capacity. The low moisture in riverbeds may be attributed to frequent water drainage, deposition of sediments and the prevalence of coarse soil textures with low retention capacity ([Ferro, 2017](#)). Similarly, the relatively low moisture content of tea plantation soils, particularly those located near riverbanks, may be related to the coarse sediments and high drainage capacity of the affected soils. Consequently, supplemental irrigation may be required during the dry season to maintain adequate soil moisture for tea cultivation.

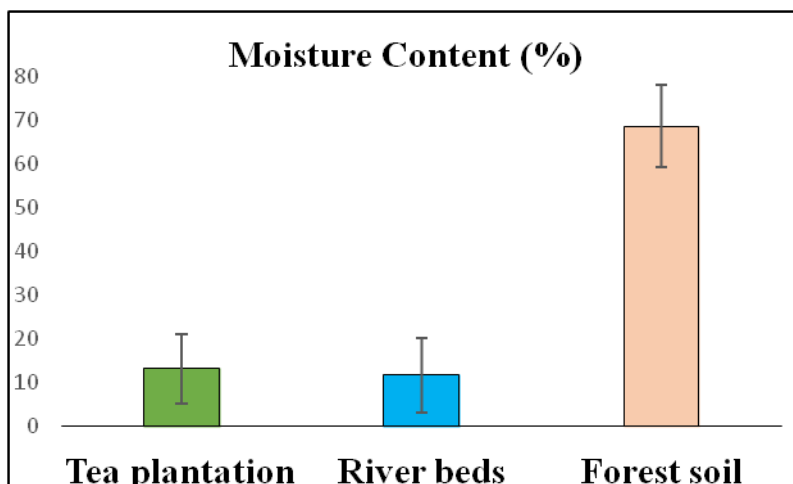


Figure 3. Biotope-wise moisture content percentage in the study area

Soil nutritional status

The overall representation of nutritional status is illustrated in [Figure 4](#). Organic carbon (OC), total nitrogen (N), available phosphate (P) and available potash (K) were quantified to determine the quality of soil or the nutritional status of soil. The average values of organic carbon, total nitrogen, available phosphate and potash of the overall samples were $1.34 \pm 0.98\%$ (3.18–0%), $0.10 \pm 0.08\%$ (0.27%–0%), $20.27 \pm 38.58\text{ppm}$ (168.5–0 ppm) and $199.18 \pm 270.37\text{ppm}$ (1075–20ppm), respectively. The tea garden samples had an average of $1.91 \pm 0.002\%$ (3.18%–0.41%) total organic carbon, $0.15 \pm 0.05\%$ (0.27%–0.03%) of total nitrogen, $38.9 \pm 0.57\text{ppm}$ (168.5–0 ppm) of available phosphate, and $321.41 \pm 0.40\text{ppm}$ (1075–20 ppm) of available potash. The riverbed soil samples showed $0.51 \pm 0.007\%$ (1.89%–0) of total organic carbon, $0.03 \pm 0.04\%$ (0.16%–0) of nitrogen, $1.1 \pm 0.06\text{ppm}$ (5.7–0) of available phosphate and $51.42 \pm 0.12\text{ppm}$ (115–25) of available potash. The natural forest samples exhibited $2.61 \pm 0.08\%$ (3.15%–1.80%) of total organic carbon, $0.22 \pm 0.06\%$ (0.27%–0.15%) of nitrogen, $30.34 \pm 0.009\text{ppm}$ (33.7–26.2) of available phosphate and $318.33 \pm 10\text{ppm}$ (565–140) of available potash. Moreover, the Kruskal Wallis test followed by the Dunn's post hoc multiple comparison test was performed and significant differences were observed among all the biotopes for parameters such as organic carbon (OC) and nitrogen (N) percentage ($p < 0.001$). In the case of available phosphate, significant differences were observed between the riverbeds and tea gardens ($p < 0.001$), as well as between the riverbeds and natural forests ($p < 0.001$), whereas the difference between the tea gardens and natural forests was significant at $p < 0.01$. In contrast, no significant difference in available potash was observed between the tea gardens and natural forests; however, significant differences were recorded between the tea gardens and riverbeds, and between the riverbeds and natural forests. Comparable differences in nutrient status have also been reported between the Pranmati Basin, which is prone to flooding, and the surrounding natural forests ([Sharma et al., 2026](#)).

The quantitative pattern of organic carbon (natural forest > tea plantation > river bed), total nitrogen (natural forest > tea plantation > river bed), phosphate (natural forest > tea plantation > river bed) and potash (tea plantation > natural forest > river bed) in the biotopes shows a regular pattern of natural forest > tea plantation > river bed except in case of potash; where the quantity is marginally larger in the tea plantation soil than the natural forest. Considering the recommended level of organic carbon, total nitrogen, phosphorus as phosphate, potassium as potash is 1–2%, 0.1–0.2%, 20–40 ppm and 60–80 ppm, respectively ([Mukherjee et al. 2020](#)), the tea plantations have exhibited the normal quantity of organic carbon, total nitrogen but high quantities of phosphate and potash. Similar results were also observed in the tea plantation soil on the banks of the Kaljani River with potash below the range ([Nandi et al. 2024](#)). The quantity of high nutrients in the natural forest and tea plantation soil over the river bed soil is certainly due to natural process of nutrient addition by the decomposition of organic matter and their slow release.

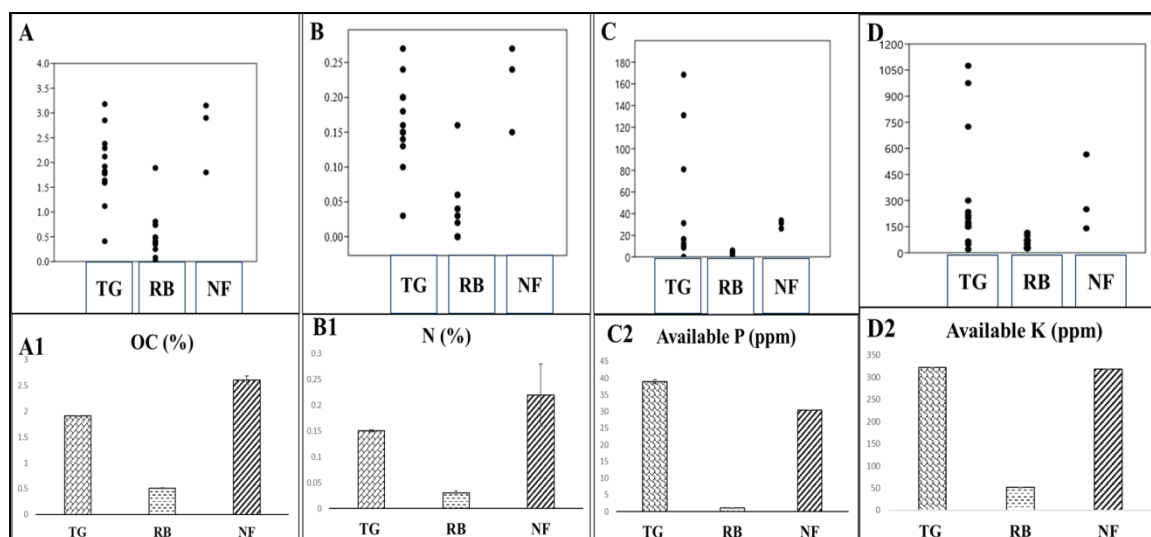


Figure 4. Representation of soil organic carbon (A): jitter plot of the sample value; (A1): biotope-wise average; B: jitter plot of total nitrogen content; B1: average of biotopes; C: jitter plot of available phosphate; C1: biotope-wise average; D: jitter plot of available potash in soil; D1: biotope-wise average value

The average organic carbon (OC), organic matter (OM), total nitrogen (N), available phosphate (P) and potash (K) in each grid and cluster are depicted in [Table 1](#). Two grids (Grid 2 and Grid 4) also have low to very low organic matter, organic carbon, total nitrogen and available phosphate. Grid 2 contains tea plantations such as MPTG and riverbeds such as MBR, TR1, PT1 and DR1, whereas Grid 4 contains tea plantations such as JB1 and riverbeds such as BK1 and BR1. The potash content was found to be low in Grid 4. Cluster 5 containing tea plantations such as JB1 and riverbeds such as BK1 and BR1 showed very low organic matter, organic carbon, total nitrogen and available potash. Cluster 2, 3 and 5 showed low available phosphate content.

Quantification of pH and CaCO_3

The overall soil pH of the study area varied between 7.85 and 3.91 with an average of 6.16 ± 1.02 ([Figure 5](#)). The riverbeds showed highest average pH 6.94 ± 0.46 (8.10 to 6.01), followed by the tea plantations with an average of 5.61 ± 0.91 (7.01 and 3.7) and the forest area with an average pH of 5.03 ± 0.53 (5.9 to 4.3).

The quantity of soil calcium carbonate of the study area varied between 10% to 16% with an average value of 7.09% ([Table 2](#)). The level of calcium carbonate in dolomite unaffected soil was found to be less than $0.4 \pm 0.2\%$. The riverbeds showed the highest average calcium carbonate content of $9.92 \pm 1.9\%$ (16% to 7.7%), followed by the tea plantations with an average of $5.41 \pm 3.87\%$ (15% and 0.8%). The forest area showed the least average calcium carbonate content amounting to $1.33 \pm 0.49\%$ (2.3% and 0.97%). Significant differences were observed for the obtained data of pH and CaCO_3 between all the tested biotopes ($p < 0.001$).

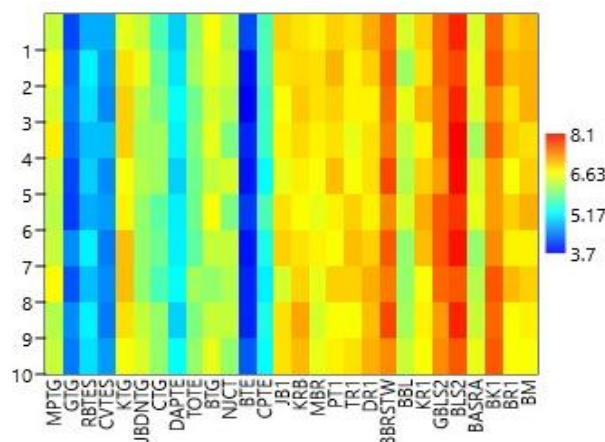


Figure 5. pH of the soil samples of the study area

1

Table 1. The quantity of OC, OM, N, P and K of the studied grids and locations

Soil parameters across grids and locations		G1 (n=40)	G2 (n=50)	G3 (n=170)	G4 (n=30)	G5 (n=20)	L1 (n=60)	L2 (n=50)	L3 (n=70)	L4 (n=100)	L5 (n=30)
OC	Mean	1.77±0.88	0.60±0.69	1.59±0.89	0.29±0.36	1.7±1.56	1.74±1.14	1.06±0.61	1.89±1.89	1.16±1.16	0.29±0.29
	Minimum	0.74	0.08	0	0	0.25	0.25	0.37	0	0.08	0
	Maximum	2.9	1.82	5.46	0.48	3.15	3.15	1.82	3.18	2.85	0.48
OM	Mean	3.02±1.48	1.03±1.19	2.73±1.53	0.50±0.44	2.91±3.51	2.98±1.94	1.83±1.05	3.26±1.6	2±1.64	0.50±0.44
	Minimum	1.27	0.13	0	0	0.43	0.43	0.63	0	0.13	0
	Maximum	4.9	3.13	5.46	0.82	5.4	5.4	3.13	5.46	4.90	0.82
N	Mean	0.14±0.086	0.04±0.06	0.13±0.07	0.02±0.02	0.14±0.17	0.14±0.10	0.08±0.06	0.16±0.08	0.10±0.1	0.02±0.02
	Minimum	0.03	0	0	0	0.02	0.02	0	0	0	0
	Maximum	0.24	0.15	0.27	0.04	0.27	0.27	0.15	0.27	0.24	0.04
P	Mean	18.32±13.98	3.24±7.24	30.07±49.31	0	15.6±22.06	17.41±14.71	5.56±7.78	8.71±7	43.52±61.78	0
	Minimum	3.7	0	0	0	0	0	0	0	0	0
	Maximum	33.7	16.2	168.5	0	31.2	33.7	16.2	16.2	168.5	0
K	Mean	160±86.02	74±90.51	260.57±331.02	26.66±5.77	332.5±328.80	217.5±184.38	124±82.64	146.42±87.45	314.48±431.77	26.6±5.77
	Minimum	50	25	25	20	100	50	30	65	25	20
	Maximum	250	235	1075	30	565	565	235	300	1075	30

Legend: Grids are denoted as “G” and clusters are denoted as “L”

2

3

4

Table 2. Value of pH and calcium carbonate of the studied grids and clusters

Parameters		G1 (n=40)	G2 (n=50)	G3 (n=170)	G4 (n=30)	G5 (n=20)	L1 (n=60)	L2 (n=50)	L3 (n=70)	L4 (n=100)	L5 (n=30)
pH	Mean	5.44±1.12	6.68±0.19	6.07±1.05	6.98±0.36	5.69±1.56	5.52 ±1.12	6.92±0.64	6.01±1.02	6.04±1.0	6.98±0.36
	Minimum	4.28	6.4	3.91	6.7	4.58	4.28	6.4	4.56	3.91	6.7
	Maximum	6.86	6.9	7.8	7.4	6.8	6.86	7.4	7.5	6.90	7.4
CaCO ₃ (ppm)	Mean	3.25%	9.8%	6.88%	9.6%	5.50%	4.0%	9.40%	6.85%	7.20%	9.60%
	Minimum	10%	8%	10%	8%	10%	10%	7%	2%0000	10%	8%
	Maximum	9%	12%	14%	11%	10%	10%	12%	14%	13%	11%

Dolomite has already been proven to increase the pH of the soil and hence is extensively used as a liming material because its dissolution can ameliorate excessive soil acidity. In tea cultivation, maintaining an acidic soil reaction within the recommended pH range of 4.5–5.5 is generally considered desirable. In the present study, the average pH of the study area (6.16), river bed samples (6.94), tea plantations (5.61) and natural forests (5.03) were higher than the previous reports. The average pH of converted lands from forests to crop lands or tea gardens was found to be 5.38 (De et al., 2022), 4.67 for Dooars tea plantations (Malakar et al., 2022), pH above the recommended level in the tea plantations was found on the banks of the Kaljani river (Nandi et al., 2024) and on the banks of rivers and streams flowing from the neighbouring hills in the Dooars region (Mukherjee et al., 2020).

The influence of dolomite in increasing soil pH was logically justified by high level of positive correlation ($r = 0.81$) between calcium carbonate and pH (Figure 6). Fourteen riverbed sites (BBRSTW, GBLS2, BLS2, BK1, BBL, DR1, PT1, KR1, KRB, BM, TR1, BRI, MBR, and BASRA) and seven tea plantation sites (NJCT, CTG, TOTE, BTG, MPTG, KTG, and JB1) exhibited CaCO_3 contents above the threshold used in this study and soil pH values above the recommended range of 4.5–5.5 for tea cultivation. Like other parameters, there is no required value or critical range for calcium carbonate in soil. However, according to Singare et al. (2022), calcareous soil can contain from 3% to more than 25% of calcium carbonate. According to this data, the study area is highly influxed with dolomite. Two soil collection sites (one tea plantation (JBDNTG) and 1 natural forest (TRP)) showed high pH but calcium carbonate within threshold level, whereas 6 tea plantations (CVTES, DAPTE, CPTE, RBRES, GTG and BTE) and 2 natural forests (SP and KF) showed moderate pH with calcium carbonate level within the threshold level.

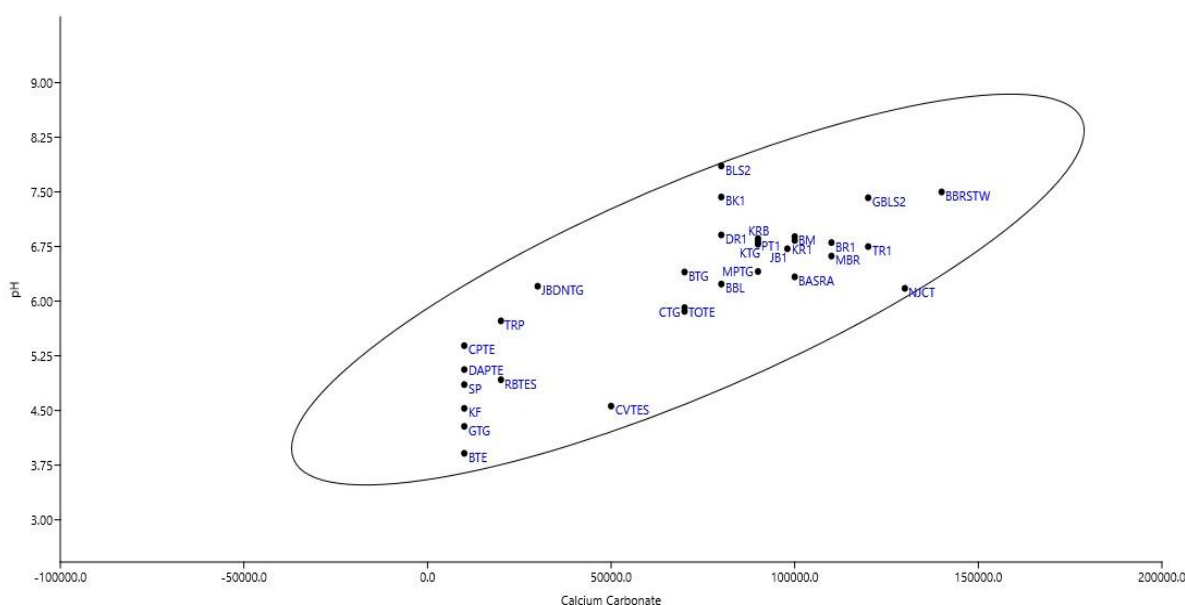


Figure 6. A XY graph of calcium carbonate (x axis) and pH (y axis)

The principal component analysis (PCA) plot of calcium carbonate and pH value of the soil in the study areas (Figure 7) shows clustering of sites with similar values: tea plantations (KTG and JB1) clustered with riverbeds (BLS2, BK1, DR1, KRB, PT1, KR1, BM and GBLS2), tea plantations (MPTG and NJCT) clustered with riverbeds (BBL, BASRA, BR1, MBR, TR1 and BBRSTW), tea plantations (JBDNTG, CPTE and DAPTE) clustered with natural forests (TRP), and tea plantations (TOTE, RBRES, CTG, GTG, BTE and CVTES) clustered with natural forests (SP and KF). KTG and JB1 have poor condition of soil nutrients with high pH and calcium carbonate content due to their proximity to dolomite deposited riverbeds. Similar results were obtained for MPTG and NJCT. The tea plantations such as JBDNTG, CPTE and DAPTE clustered with natural forests (TRP) and the tea plantations such as TOTE, RBRES, CTG, GTG, BTE and CVTES clustered with natural forests (SP and KF) due to their almost similar distance from the river beds.

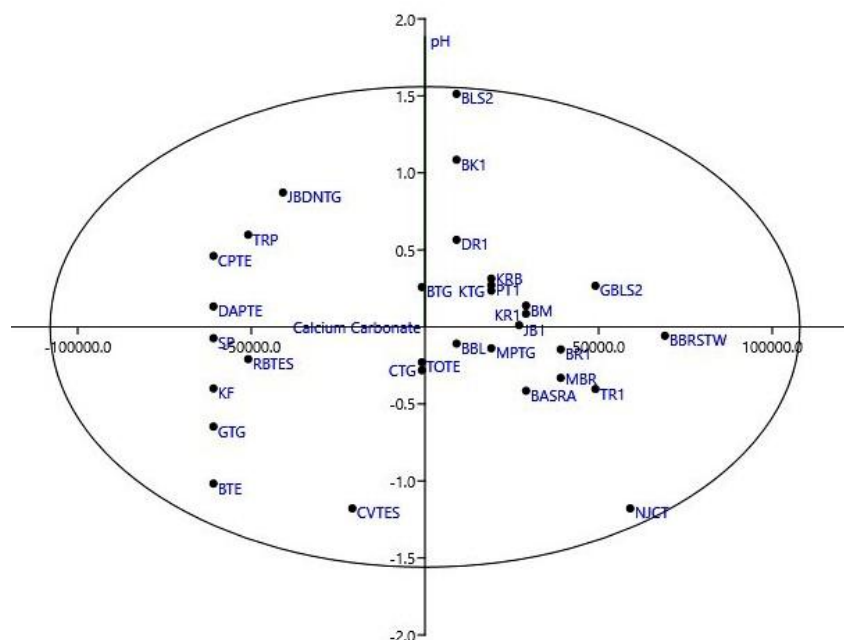


Figure 7. PCA plot of calcium carbonate and pH value of soil in the study area

In the study area, the influx of dolomite takes place from the streams and rivers that flow down from the dolomite mining areas of the Lesser Himalayas, besides aerial transport as dust. The influx of dolomite by flood during the rainy season takes place in the area, that depositing dolomite as sediment in tea gardens and natural forests. However, the pH of natural forests is less than that of tea plantations. This may be due to the accumulation of more organic matter in natural forests, producing humic and fulvic acids that lowers the pH. Moreover, dolomite carried on with irrigation water may be a cause for increase in the pH of tea plantations. Bhutan, a part of the Himalayan mountain chain is a fold and thrust belt that is usually divided into four zones bounded by thrusts from south to north viz. Sub-Himalaya, Lesser Himalaya, Greater Himalaya and Tethyan Himalaya. Our study area, mostly the Sub-Himalaya is composed of Miocene to Pleistocene molassic sediments derived from the erosion of the Himalaya. The rivers of the study area originate or flow through the Lesser Himalayas that developed during the Cambrian to Permian age and consist of sedimentary rocks dominated with dolomite, sandstone, shale, graywacke, quartzite, phyllite, coal beds etc. The limestone content of the Lesser Himalayan region neighbouring the study area is high as it contains more than 76% CaCO_3 (more than 43% CaO) on average (JICA, 2021). The study area of Grid 2 (MBR, TR1, DR1 river), 3 (CTG, KR1, BASRA river basin) and 4 (Jayanti, JB1, BK1, BR1 river basin) are the closest point to the neighbouring hills and are the most dolomite affected area. Cluster 2 (Makrapara border region), 3 (Chamurchi border region), 4 (Torsa, Dima, Kaljani Basin) and 5 (Jayanti river basin) are the most dolomite affected area.

The River Kaljani emerges from Chukha District in Bhutan ($26^\circ 52' \text{ N}$, $89^\circ 51' \text{ E}$) and is fed by the Basra and Alaikuri rivers that also originate in the Bhutan Himalayas and eventually meet at the foothills located in West Bengal State (India) to form the main course of the Kaljani. The other important tributaries in the basin are the Raimatang, Dima and Bala, all of which drain through the mountain frontal zone of Bhutan hills (Roy and Das, 2021). The high average pH (6.94 ± 0.45) and calcium carbonate (9.92%) of the fourteen rivers is mainly contributed by rivers such as the Kaljani (KR1), the Dima (DR1), the Torsa (TR1), the Bajekhola (BK1), the Bala (BR1), and their tributaries.

The flow of these rivers depends on monsoon precipitation that occurs between June and October (about 75–80% of the annual rainfall) with some occasional downpour during the winter (Roy and Das, 2021). During the dry months, sections of the streams and river channels in the foothill region become exposed, revealing previously deposited sediments that form alluvial fans. Bhutan hosts deposits of several minerals, including copper, dolomite, quartzite, limestone, marble, slate, gypsum, coal, and graphite, and mining activities may contribute to the downstream transport of mineral-rich sediments through the river systems, potentially affecting the receiving river basins (Bhattacharya et al., 2024).

Multivariate analysis

The multivariate cluster analysis of the sites based on pH and calcium carbonate content exhibited two distinct groups (A and B), [Figure 8](#). Cluster A had a comparatively low pH and calcium carbonate content in soil than group B. Cluster A consisted 7 tea plantations (DAPTE, BTE, CPTE, GTG, RBTES, JBDNTG, and CVTES) and 3 natural forests (SP, KF and TRP), whereas Cluster B consisted 7 tea plantations (KTG, MPTG, JB1, CTG, TOTE, BTG and NJCT) and 14 riverbeds (KRB, PT1, KR1, BASRA, BM, DR1, BK1, BBL, BLS2, TR1, GBLS2, MBR, BR1 and BBRSTW). In Cluster A, the tea plantation CVTES with comparatively low pH but high calcium carbonate content than the other sites of the group got separated as a discrete out-group. Cluster B segregated into two Cluster B1 and B2. B1 consisted 6 tea plantations (KTG, MPTG, JB1, CTG, TOTE and BTG) and 9 riverbeds (KRB, PT1, KR1, BASRA, BM, DR1, BK1, BBL and BLS2), whereas B2 consisted 1 tea plantation (NJCT) and 5 riverbeds (TR1, GBLS2, MBR, BR1 and BBRSTW).

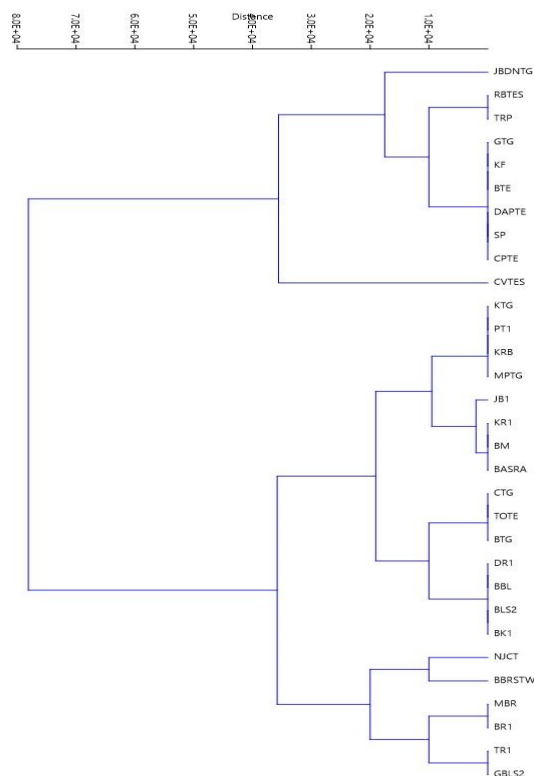


Figure 8. UPGMA generated dendrogram representation of the study area relative to the quantity of pH and calcium carbonate

Nutrient index (NI)

The calculated NI of the study area is depicted in [Table 3](#). The overall study area and the tea plantations contain high pH, which is a matter of great concern. It is a well-established fact that tea plants are most productive and produce best quality leaves when they are planted in soil with a pH ranging between 4.5 and 5.5. The levels of OC and N were within the normal range. The phosphate level of the overall study area was found to be low while in the tea plantations it was within the normal range. Potash was found to be high in tea plantations but its overall status was within the range. The medium range of nutritional index was reported for organic carbon and available phosphate in sub-Himalayan region ([Mukherjee et al., 2020](#)). The obtained results also corroborated with the result reported by [Malakar et al. \(2022\)](#), where the medium range was found in most of the tea gardens in the Dooars region.

Excessive deposition of dolomite increases the soil pH, forming a crust that compacts the soil to prevent water infiltration, while increasing subsurface compaction that minimizes root penetration. High pH also causes ammonia volatilization resulting in low nitrogen ([Bolan et al., 2023](#)). High soil pH can reduce the plant availability of several micronutrients, including Fe, Mn, Zn, and Cu, due to precipitation and adsorption reactions that decrease their soluble forms. Phosphorus availability may also decline in calcareous soils through the formation of poorly soluble calcium phosphates. In contrast, Ca and Mg are generally more available under neutral to alkaline conditions. Dolomite increases osmotic stress and ion toxicity. All these activity lowers soil microbial activity that in turn

reduces soil fertility by prohibiting normal nutrient cycling. The low phosphate can be due to excessive amount of dolomite in soil as the phosphorus bind to calcium and magnesium present in dolomite reducing the solubility (Wahba et al., 2019). The overall data of phosphate level was much influenced by the very low amount of phosphate in the riverbed soil. Organic carbon is amended in tea plantations by addition of organic inputs and by natural decomposition of weeds, tea bush and shade tree litters while, phosphate and potassium level are managed in tea plantation soil by providing inorganic inputs.

Table 3. Nutritional index of the study area

Parameters	Overall study area	Tea plantations
pH	High (2.67)	High (2.42)
Organic carbon	Medium (1.77)	Medium (2.28)
Nitrogen	Medium (1.70)	Medium (2.14)
Phosphorus as phosphate	Low (1.64)	Medium (2.00)
Potassium as potash	Medium (2.16)	High (2.64)
High > 2.33, 2.33 < Medium > 1.67 and Low < 1.67		

Recommendations

Over the past three decades, there have been several floods and flash floods in the region that have brought huge amount of dolomite from the neighbouring hills. In addition, open-pit mining and surface mining have deteriorated the problem of dolomite influx in the region. Necessary steps are required from governmental agencies to reduce mining. Dredging of heavily sedimented stream and river sections, together with appropriately designed check dams or other sediment-control structures, may help reduce the downstream transport and deposition of carbonate-rich sediments. In tea plantations affected by elevated soil pH, the use of river water for irrigation should be evaluated carefully because irrigation water containing suspended or dissolved carbonate material may contribute to further carbonate accumulation. Mulching and the incorporation of suitable organic amendments may also help improve soil structure, increase organic-matter inputs, and mitigate some of the effects associated with surface crust formation. Site-specific soil testing should guide nutrient and soil-management practices.

CONCLUSION

Low moisture content of soil, high pH and high calcium carbonate are the major soil related constraints in the tea plantations of the region; which mostly happened due to the influx of dolomite from the neighbouring hills. This has certainly affected the soil microflora. Among the surviving ones, calcite solubilizing microbes may play a crucial role in soil reclamation. Proper integrated nutrient management can reduce future debacle in the tea plantation of the area, which is facing tremendous production loss.

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