International Journal of Environmental and Ecology Research
www.environmentaljournal.in
Online ISSN: 2664-7117
Received: 05-05-2026, Accepted: 05-06-2026, Published: 20-06-2026
Volume 8, Issue 2, 2026, Page No. 53-59

Soil nutrient status of different Sal (*Shorea robusta* Roxb.) forest ecosystem in Thakurgaon District, Bangladesh

Md Asaduzzaman, Gazi Mosharof Hossain, Mohammad Mahfuzur Rahman, Sadia Jannat Mim
Department of Botany, Plant Ecology and Environment Laboratory, Jahangirnagar University, Savar, Dhaka, Bangladesh

Abstract
The present study analyzes the soil macronutrients *viz.*, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), magnesium (Mg), and carbon (OC), and the micronutrient *viz.*, zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn) of the different Sal forest ecosystem in Thakurgaon district of Bangladesh, using standard soil analysis methods during 2024-2025. Beside these nutrients, an important chemical parameter, the pH of soil was also analyzed during this investigation. The average pH values of the study area indicated that the soil of all selected sites was moderately acidic in nature and the average values of soil pH varied from 4.51±0.06 to 4.70±0.10. The average values of macro-nutrients including N, P, K, Ca, Mg, S, C (OC) and OM of the study areas varied from 0.05±0.01% to 0.06±0.004%, 6.39±2.24 µg/g to 51.86±8.96 µg/g, 0.15±0.01 meq/100g to 0.17±0.01 meq/100g, 3.11±1.11 meq/100g to 4.83±0.71 meq/100g, 0.32±0.20 meq/100g to 0.51±0.14 meq/100g, 13.30±6.71 µg/g to 19.44±2.09 µg/g, 0.61±0.1% to 0.67±0.06%, and 1.05±0.14% to 1.15±0.09% respectively. On the other hand, the average values of micro-nutrients like Zn, Cu, Fe and Mn of the study area varied from 0.57±0.15 µg/g to 0.92±0.43 µg/g, 0.82±0.25 µg/g to 1.32±0.50 µg/g, 57.26±11.16 µg/g to 117.70±50.9 µg/g, and 13.85±1.40 µg/g to 23.96±1.40 µg/g, respectively. The nutrient status of soil exhibited significant variation across different soil horizons, specifically in the surface layer (0–18 cm), sub-surface layer (18–36 cm), and substratum layer (36–72) cm. The soil nutritional parameters showed correlation with one another and also with soil pH at different levels of significance. Overall, the findings on soil nutrient status indicate that the studied Sal forests ecosystem of Thakurgaon district, especially, Site B and Site C are highly vulnerable due to multifarious anthropogenic interferences. In spite of some common disturbances, Site A is quite good rather than Site B and Site C. Based on soil nutrient quality, the Sal forest ecosystem of Thakurgaon district is still favorable for the restoration of degraded forest areas through implementing and practicing an appropriate masterplan for its conservation, and sustainable development.

Keywords: Soil nutrient status, macronutrients, micronutrients, Sal Forest Ecosystem, Thakurgaon district

Introduction

Bangladesh, a small South Asian country, lies between 20º34´ and 26º38´north latitude and 88º01´and 92º41´east longitude (Khondker *et al.,*2023) [13]. The public forest land, unclassed state forests and home gardens together make up about 17% (2.46 million ha) of the potential tree-growing area of the country. Most people have a high degree of dependency on the forest for their livelihoods, which results in the degradation of forest ecosystems and the depletion of natural resources (Muhammed *et al*., 2008) [19]. Soil is a fundamental integral part of natural resources that is usually unconsolidated into variable depth, massively differentiated into a few horizons of organic constituents and inorganic minerals, which have differences from parental material in terms of morphology, physical, chemical, and biological characteristics and constitutions (Jenny, 1994) [11]. Forest floor has distinct features, mainly consists of decomposing organic matter and litter, which supports a dynamic phase for the development of characteristics in soil flora and fauna (Prichard and Fisher, 1987) [22]. Soil nutrient availability varies due to both natural and anthropogenic factors. Nutrients are supplied through mineral weathering, organic matter decomposition, nitrogen fixation, and atmospheric deposition, while human activities such as fertilization, harvesting and land-use changes may alter nutrient balances (Cole, 1995) [4]. Soil structure, comprising organic and inorganic matter, moisture, air, microorganisms, and soil solution, is crucial for maintaining fertility, carbon sequestration, and overall ecosystem function (Bronick *et al*., 2005) [3]. Measurement of chemical parameters such as pH, electrical conductivity, moisture, water-holding capacity, organic matter, both macro and micronutrients provide insights into soil fertility and productivity.

Materials and Methods

Description of the study area

Thakurgaon district is located in the northwestern part of Bangladesh under Rangpur division, which is bordered by an international boundary from India along the north and west. It is also a part of Himalayan plain land. Geographically, it is situated between 25°40' and 26°12' north latitudes and 88°05' and 88°39' east longitudes. Topographically, this district is predominantly flat, fertile alluvial plains, suitable for agriculture, with some low-lying and elevated areas. The forest land of this district is under the surveillance of five forest beats, including Ranisankail, Baliadangi, Horipur, Pirgonj, and Ruhia, which are managed under Thakurgaon Forest range of Dinajpur forest division (Zaman *et al*., 2011) [29]. Three notable Sal Forest areas, namely Thumnia Sal Forest, Shaguni Sal Forest, and Ranisankail Sal Forest are located within the Thakurgaon district, specifically in the Pirganj and Ranisankail beat of the Thakurgaon range. These forests cover an area of 203.81 hectares, 61.64 hectares, and 7.43 hectares, respectively for Thumnia, Shaguni, and Ranisankail Sal Forests (Fig 1).

Sampling design, sample collection and analysis

After an initial reconnaissance survey, the existing three Sal forest sites of Thakurgaon district were selected for this investigation (Fig 1). These three sites were recognized as- Site A (Thumnia Sal forest), Site B (Shaguni Sal Forest), and Site C (Ranisankail Sal forest). Altogether 17 sub-sites were selected from the selected three sites as mentioned in the Fig 1, based on forest administrative units, geo-spatial locations, forest types, forest size or area, micro-habitats, vegetation pattern etc. The sampling was conducted during January 2025 following the standard soil sample collection procedures as outlined in the *soil survey manual* (Anonymous, 1993) [2]. For this study, a total of 51 fresh soil samples were collected from these representative sites across three vertical profiles, *viz.*, surface (S, 0-18 cm), sub-surface (SS, 18-36 cm), and substratum (ST, 36-72 cm) layers, with each layer sampled in triplicate at each site. Soil samples collected from each sub-site were mixed properly to produce composite soil samples (Ahmed *et al*., 2010; Shukla and Chandal, 1994) [1, 24]. For each sample, 500 g of soil was taken in a polybag after the removal of plant material and other debris. The samples were air-dried in the laboratory for further analysis. The dried soils were then gently crushed and passed through a 2 mm sieve to remove all the residual debris prior to analysis.

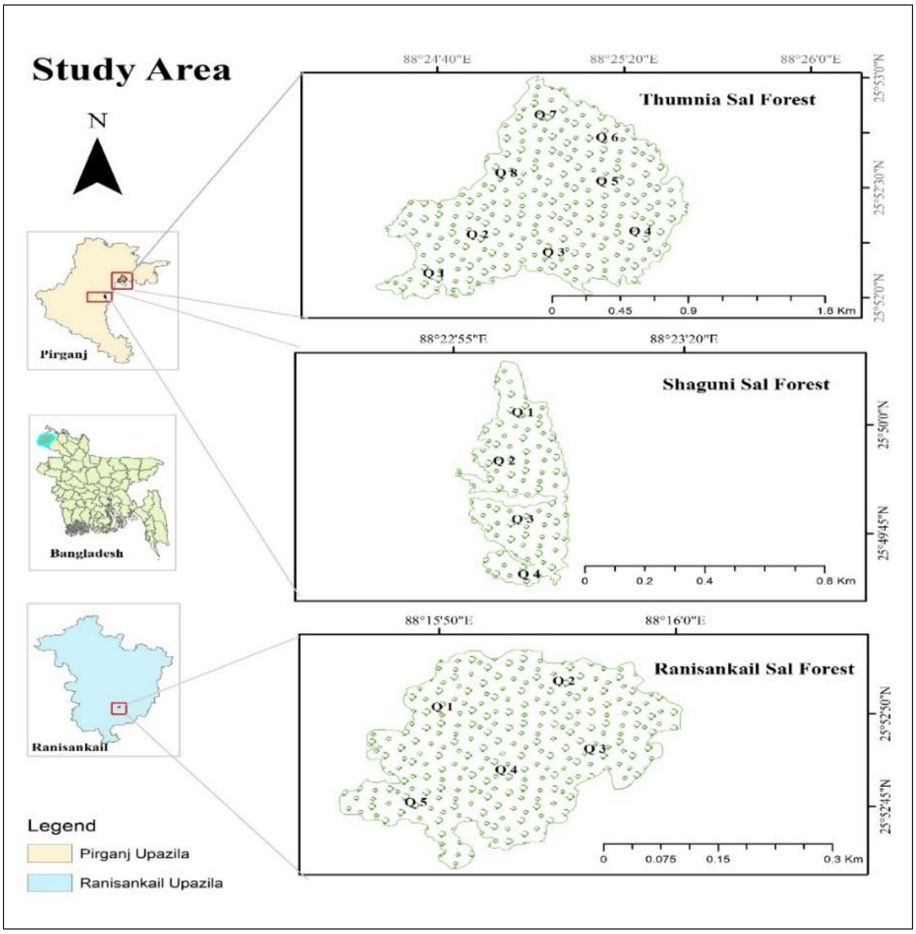

Fig 1: Map of the study area with representative sites and quadrats

Soil pH was determined through preparing a soil-water (1:2.5 ratio) suspension and measuring the pH with a calibrated pH meter (Jackson, 1962) [10]. Soil macronutrients such as the total nitrogen (TN) was determined by alkaline permanganate method which described by Sparks *et al.* (2020); [26]; phosphorus (P) using Olsen's method (Olsen and Sommers, 1982) [20]; potassium (K) using flame photometer (Ghosh *et al.*, 1983) [6]; organic carbon (OC) was measured by using wet oxidation method (Walkley and Black, 1934) [28] and organic matter (OM) was calculated by multiplying with a conversion factor of 1.724; available sulfur (S) content using the turbidimetric method as described by Fox *et al.*, (1964)[5]; available calcium (Ca) was determined by the titrimetric method (Lanyon and Heald, 1982) [15]. On the other hand, soil micronutrients such as iron (Fe) determined using atomic absorption spectroscopy (Loeppert *et al.*, 1996) [16]; copper (Cu), manganese (Mn) and zinc (Zn) were analyzed by the DTPA extraction method using a NOV AA-300 atomic absorption spectrophotometer (SRDI, 2012) [27]. Statistical analyses, including mean values and standard deviations were calculated by using MS Excel to compare the different parameters. The correlation matrix was determined by using the standard Pearson correlation method using SPSS (ver. 16.0) software.

Results and Discussion

The nutrient status of the soil recorded from Thakurgaon Sal forests ecosystem were presented in Fig 2, Table 1 and Table 2. The average values of soil pH across the study sites indicate acidic nature and it values ranged from 4.51±0.06 to 4.70±0.10. The highest pH value of 4.70±0.10 was recorded in the soil samples collected from Site A, followed by 4.64±0.05 from Site B, whereas the lowest value of 4.51±0.06 was recorded from soil samples of Site C (Fig 2). The average pH value across different horizons, exhibited a range from 4.55±0.09 to 4.69±0.12. The maximum value of 4.69±0.12 was recorded in the soil samples of substratum (ST) layer, followed by 4.62±0.09 and 4.55±0.09 from subsurface (SS) and surface (S) layers, respectively (Fig 2). The present records on soil pH indicate acidic reaction, and invariably found a vertical increasing trends with soil depth, where the lower values are always in surface layer, and gradually higher in subsurface and substratum layers, which is fully corroborated with earlier studies conducted on similar Sal (*Shorea robusta*) forests ecosystem by Paudel and Sah (2003) [21], Hoque *et al*. (2008) [8], Hossain *et al.* (2010) [9], Kashem *et al*. (2016) [12], Rahman *et al*. (2022) [23], etc. However, Hasan and Mamun (2015) [7], reported higher pH values of 6.38–6.62 in the pure and mixed Sal forests in Bangladesh, indicating regional variability influenced by site-specific edaphic and ecological factors.

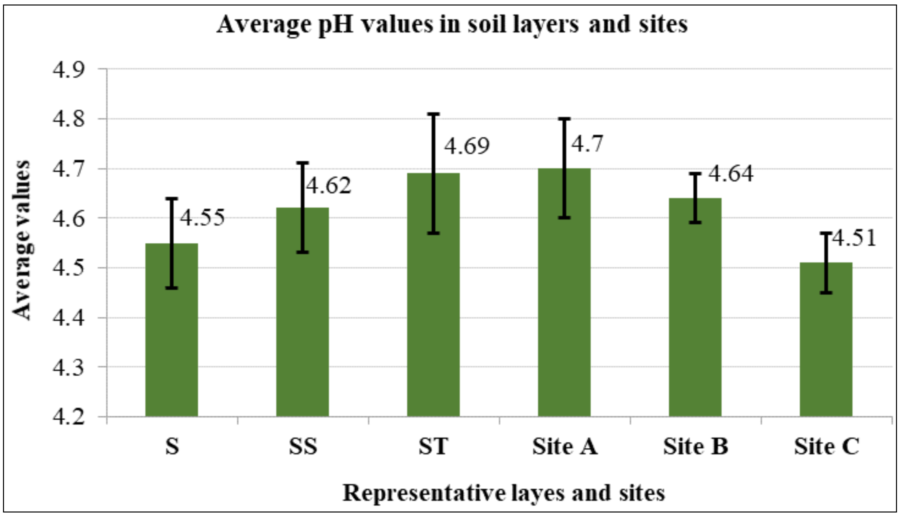

Fig 2: Mean values of pH in the soils of three sites and layers

Soil macronutrients

The average value of total nitrogen (TN) in the soil samples of the studied sites ranged from 0.05±0.003% to 0.06±0.004%. The highest TN value of 0.06±0.004% was recorded in the soil samples collected from Site B, followed by 0.05±0.01% from Site A, while the lowest value of 0.05±0.003% was recorded from Site C (Table 1). The average TN values among the soil profiles varied from 0.05±0.00% to 0.06±0.00%. The maximum TN value of 0.06±0.00% was recorded in the soil samples collected from surface (S) layer, followed by
0.05±0.01% in the subsurface (SS) layer, while the lowest value of 0.05±0.00% was recorded in the soil samples of substratum (ST) layer (Table 1). The present findings corroborated with the findings of Paudel and Sah (2003) [21], Hossain *et al.* (2010) [9], and Kashem *et al.,* (2016) [12], who reported the higher TN value in top soils and decreasing with increasing soil depth. In contrast, few studies including Hasan and Mamun (2015) [7], Mia *et al*. (2016) [17], Kumar and Saikia (2021) [14] reported reverse pattern in vertical distribution of TN concentration, which may be due to variations in local ecological conditions, vegetation composition, soil-forming processes, or environmental stresses.

The average values of soil phosphorus (P) in the soil samples of the studied sites were found to range from 6.39±2.24 µg/g to 51.86±8.96 µg/g. The maximum P value of 51.86±8.96 µg/g was recorded in the soil samples of Site B, followed by 20.30±8.60 µg/g in Site A, while the minimum value of 6.39±2.24 µg/g was observed in the soil samples of Site C (Table 1). The average P value across three different soil layers exhibited a range from 20.89±20.27 µg/g to 33.50±26.39 µg/g. The highest P value of 33.50±26.39 µg/g was found in the surface (S) layer, followed by 24.17±23.49 µg/g in the subsurface (SS) layer, while the lowest value of 20.89±20.27 µg/g was observed in the soil samples of the substratum (ST) layer. The present findings supported by the previous studies conducted in different Sal (*Shorea robusta*) forest ecosystems across Nepal, India, and Bangladesh (*viz.*, Hasan and Mamun, 2015; Hossain *et al*., 2010; Kashem *et al*., 2016; Kumar and Saikia, 2021; Mia *et al*., 2016; Paudel and Sah, 2003; Rawat *et al*., 2021) [7, 9,12, 14, 17, 21, 24], which reported spatial variability in soil P influenced by forest composition and soil depth. Additionally, Kashem *et al*., (2016) [12] observed a minor variation of P across soil depths in Sal forests of Bangladesh, which supported the general patterns observed in the present study.

The average value of soil potassium (K) content across the studied sites ranged from 0.15±0.01 to 0.17±0.01 meq/100 g. The highest K value of 0.17±0.01 meq/100 g) was observed in the soil sample of Site A, followed by 0.17±0.01 meq/100g in Site B, while the lowest value of 0.15±0.01 meq/100g was occurred in the soil samples of Site C (Table 1). The mean values of K across soil layers ranged from 0.16±0.02 to 0.17±0.01 meq/100g. The highest K value of 0.17±0.01 meq/100g was recorded in the soil samples of surface (S) layer, followed by 0.16±0.02 meq/100g in the substratum (ST) layer, while the lowest value of 0.16±0.01 meq/100g was recorded in the soil samples in the subsurface (SS) layer (Table 1). The present records corroborated with the findings of Paudel and Sah (2003) [21], Hoque *et al*. (2008) [8]; Hossain *et al*. (2010) [9], Hasan and Mamun (2015) [7], Mia *et al*. (2016) [17], Kumar and Saikia (2021) [14].

The average value of soil calcium (Ca) across the studied sites exhibited a range from 3.11±1.11 to 4.83±0.71 meq/100g. The maximum Ca value of 4.83±0.71 meq/100g was recorded in the soil samples of Site A, followed by 4.53±1.21 meq/100g in Site B, while the minimum value of 3.11±1.11 meq/100g) was observed in the soil samples of Site C (Table 1). The average value of Ca across soil layers expressed a range from 3.23±0.86 to 4.87±0.51 meq/100g. The highest Ca value of 4.87±0.51 meq/100g was observed in the soils of subsurface (SS) layer, followed by 4.37±1.62 meq/100g in the soils of surface (S) layer, while the lowest value of 3.23±0.86 meq/100g was found in the soils of substratum (ST) layer. These findings are consistent with previous studies in Sal (*Shorea robusta*) forests in Bangladesh conducted by Hoque *et al*. (2008) [8] and Mia *et al*. (2016) [17].

The average value of soil magnesium (Mg) across the studied sites found to show a range from 0.32±0.20 to 0.51±0.14 meq/100g. The highest Mg value of 0.51±0.14 meq/100g) was recorded in the soils of Site A, followed by 0.41±0.28 meq/100g in the soils of Site B, while the lowest value of 0.32±0.20 meq/100g was recorded in the soils of Site C (Table 1). The mean value of Mg across different soil layers showed a range from 0.24±0.19 to 0.59±0.07 meq/100g. The highest Mg value of 0.59±0.07 meq/100g was observed in the soils of subsurface (SS) layer, followed by 0.42±0.18 meq/100g in the soils of surface (S) layer, while the lowest value of 0.24±0.19 meq/100g was observed in the soils of substratum (ST) layer, (Table 1). The present findings fully agreed with the findings of Hoque *et al*. (2008) [8] and Mia *et al*. (2016) [17], where Hoque *et al*., (2008) [8] reported a decline pattern in Mg with increasing soil depth in the Madhupur Sal forest of Bangladesh. Similarly, Mia *et al*., (2016) [17] documented Mg concentration in mixed Sal forests, and in *Acacia*-associated stands, indicating that vegetation composition and site-specific conditions influence soil magnesium availability.

Table 1: Mean values of some common macronutrients in the soils of Thakurgaon Sal Forest

Soil parameters	Soil layers	Values in different sites			Average value ± SD
		Site A (Thumnia)	Site B (Shaguni)	Site C (Ranisankail)	
TN (%)	S	0.06	0.06	0.06	0.06±0.00
	SS	0.05	0.06	0.05	0.05±0.01
	ST	0.05	0.05	0.05	0.05±0.00
	Average ± SD	0.05±0.01	0.06±0.004	0.05±0.003	0.05±0.01
P (µg/g)	S	30.16	61.4	8.94	33.50±26.39
	SS	16.44	50.55	5.51	24.17±23.49
	ST	14.31	43.63	4.73	20.89±20.27
	Average ± SD	20.30±8.60	51.86±8.96	6.39±2.24	26.18±23.30
K (meq/100g)	S	0.18	0.18	0.16	0.17±0.01
	SS	0.17	0.17	0.15	0.16±0.01
	ST	0.17	0.16	0.14	0.16±0.02
	Average ± SD	0.17±0.01	0.17±0.01	0.15±0.01	0.16±0.01
Ca (meq/100g)	S	5.55	5.04	2.53	4.37±1.62
	SS	4.81	5.41	4.39	4.87±0.51
	ST	4.13	3.15	2.41	3.23±0.86
	Average ± SD	4.83±0.71	4.53±1.21	3.11±1.11	4.16±0.92
Mg (meq/100g)	S	0.42	0.6	0.24	0.42±0.18
	SS	0.67	0.54	0.55	0.59±0.07
	ST	0.45	0.09	0.17	0.24±0.19
	Average ± SD	0.51±0.14	0.41±0.28	0.32±0.20	0.41±0.10
S (µg/g)	S	5.55	17.64	17.33	13.51±6.89
	SS	17.02	18.95	17.8	17.92±0.97
	ST	17.33	21.74	20.45	19.84±2.27
	Average ± SD	13.30±6.71	19.44±2.09	18.53±1.68	17.09±3.31
OC (%)	S	0.72	0.72	0.68	0.71±0.02
	SS	0.60	0.68	0.60	0.63±0.05
	ST	0.52	0.60	0.60	0.57±0.05
	Average ± SD	0.61±0.10	0.67±0.06	0.63±0.05	0.64±0.03
OM (%)	S	1.24	1.24	1.17	1.22±0.04
	SS	1.03	1.17	1.03	1.08±0.08
	ST	0.89	1.03	1.03	0.98±0.08
	Average ± SD	1.05±0.14	1.15±0.09	1.08±0.07	1.09±0.05

Notes: S= Surface, SS= Sub-surface, ST= Substratum, SD= Standard deviation

The average values of soil sulphur (S) at three studied sites were found a range from 13.30±6.71 to 19.44±2.09 µg/g. The maximum S value of 19.44±2.09 µg/g was recorded in the soils of Site B, followed by 18.53 ± 1.68 µg/g in the soils of Site C, while the minimum value of 13.30±6.71 µg/g was recorded in the soils of Site A (Table 1). The average values of S across different soil layers exhibited a range from 13.51±6.89 to 19.84±2.27 µg/g. The highest S value of 19.84±2.27 µg/g was observed in the soils of substratum (ST) layer, followed by 17.92±0.97 µg/g in the soils of subsurface (SS) layer, while the the lowest value of 13.51±6.89 µg/g was observed in the soils of surface (S) layer (Table 1). These findings corroborated with previous studies in Sal (*Shorea robusta*) forests in Bangladesh conducted by Hasan and Mamun (2015) [7], and Mia *et al*., (2016) [17].

The average soil organic carbon (OC) content across the selected sites ranged from 0.61±0.10% to 0.67±0.06%. The highest OC value of 0.67±0.06% was recorded in the soil samples of Site B, followed by 0.63±0.05% in Site C, while the lowest value of 0.61±0.10% was observed in the soil samples of Site A (Table 1). The average OC value across different soil layers showed a range from 0.57±0.05% to 0.71±0.02%. The highest OC value of 0.71 ± 0.02% was recorded in the soil sample of surface (S) layer, followed by 0.63 ± 0.05% in the subsurface (SS) layer, while the lowest value of 0.57±0.05% was recorded in the soil sample of substratum (ST) layer The present records agreed with the findings of Kumar and Saikia (2021) [14], and Rawat *et al.* (2021) [24], Kashem *et al.* (2016) [12], who reported higher OC in surface soils and a decreasing trend with depth. However, Mia *et al.,* (2016) [17] reported a contrasting pattern with the highest OC in the substratum layer in the Madhupur Sal forest of Bangladesh, which may be due to variation in spatial and temporal conditions as well as edaphic factors.

The average soil organic matter (OM) content across the selected sites ranged from 1.05±0.14% to 1.15±0.09%. The highest OM value of 1.15±0.09% was recorded in the collected soil samples of Site B, followed by 1.08±0.07% in Site C, while the lowest value of 1.05±0.14% was observed in the soil samples of Site A (Table 1). The average OM value across soil layers exhibited a range from 0.98±0.08% to 1.22±0.04%. The highest OM value of 1.22±0.04% was found in the surface (S) layer, followed by 1.08±0.08% in the subsurface (SS) layer, while the lowest value of 0.98±0.08% was recorded in the substratum (ST) layer. The present findings are consistent with Hoque *et al*., (2008) [8], who reported the higher OM value in surface soils and exhibited a decreasing trend in deeper layers in the Madhupur Sal forest.

Soil micronutrients

The average values of zinc (Zn) in the soils of the studied sites were found to range from 0.57±0.15 to 0.92±0.43 µg/g. The highest Zn value of 0.92±0.43 µg/g was recorded in the soil samples collected from Site C, followed by 0.86±0.36 µg/g from Site A, while the lowest value of 0.57±0.15 µg/g was recorded from Site B (Table 2). The average values of Zn across different soil layers found to show a range from 0.46±0.06 to 1.04±0.29 µg/g. The highest value of 1.04±0.29 µg/g was found in the soil samples of surface (S) layer, followed by 0.85±0.29 µg/g in the soils of subsurface (SS) layer, while the lowest value of 0.46±0.06 µg/g was recorded in the soil samples of substratum (ST) layer (Table 2). The current results contradict to those of Hasan and Mamun (2015) [7], who reported a higher value of Zn in soils of pure Sal Forest, and mixed Sal Forest areas in the Madhupur forest range of Bangladesh, which are far greater than those of the current investigation.

The average values copper (Cu) in the soil samples of the studied sites exhibited a range from 0.82±0.25 to 1.32±0.50 µg/g. The highest Cu value of 1.32±0.50 µg/g was recorded in the soils of Site B, followed by 0.89±0.06 µg/g in Site A, while the lowest value of 0.82±0.25 µg/g was recorded in the soil smple of Site C (Table 2). The average values of Cu across different soil layers found to range from 0.74±0.11 to 1.26±0.41 µg/g, with the highest value of 1.26±0.41 µg/g was found in the soil samples of surface (S) layer, followed by 1.03±0.39 µg/g in the soils of subsurface (SS) layer, while the lowest value of 0.74±0.11 µg/g was observed in the soil samples of substratum (ST) layer (Table 2). The present findings are consistent with Mim *et al.* (2026) [18], who reported higher Cu concentrations in surface soils that decreased in deeper layers within the Chandra Sal forest ecosystem of the Gazipur District, Bangladesh.

Table 2: Mean values of some micronutrients in the soils of the Thakurgaon Sal Forest

Soil parameters	Soil layers	Values in different sites			Average Value ± SD
		Site A (Thumnia)	Site B (Shaguni)	Site C (Ranisankail)	
Zn (µg/g)	S	1.24	0.71	1.18	1.04±0.29
	SS	0.81	0.58	1.15	0.85±0.29
	ST	0.53	0.42	0.42	0.46±0.06
	Average ± SD	0.86±0.36	0.57±0.15	0.92±0.43	0.78±0.19
Cu (µg/g)	S	0.95	1.72	1.11	1.26±0.41
	SS	0.89	1.47	0.73	1.03±0.39
	ST	0.84	0.76	0.63	0.74±0.11
	Average ± SD	0.89±0.06	1.32±0.50	0.82±0.25	1.01±0.27
Fe (µg/g)	S	59.06	159.37	70.12	96.18±55.00
	SS	57.84	132.75	51.49	80.69±45.19
	ST	57.23	60.97	50.16	56.12±5.49
	Average ± SD	58.04±0.93	117.70±50.9	57.26±11.16	77.67±34.67
Mn (µg/g)	S	13.00	18.70	25.57	19.09±6.29
	SS	13.09	17.12	23.09	17.77±5.03
	ST	15.46	15.59	23.21	18.09±4.44
	Average ± SD	13.85±1.40	17.14±1.56	23.96±1.40	18.32±5.16

Notes: S= Surface, SS= Sub-surface, ST= Substratum, SD= Standard deviation

The average values of iron (Fe) in the soil samples of the studied sites were showed a range from 57.26±11.16 to 117.70±50.9 µg/g. The highest Fe value of 117.70±50.9 µg/g was documented from the soil samples at Site B, followed by 58.04±0.93 µg/g at Site A, while the lowest value of 57.26±11.16 µg/g was documented from the collected soil samples at Site C (Table 2). The mean Fe values across the soil layers were found a range from 56.12±5.49 to 96.18±55.00 µg/g. The highest value of 96.18±55.00 µg/g was

found in the soil samples of surface (S) layer, followed by 80.69±45.19 µg/g in the soils of subsurface (SS) layer, while the lowest value of 56.12±5.49 µg/g was observed in the soil samples of substratum (ST) layer (Table 2). The current records by the findings Hoque *et al*. (2008) [8], who reported that the Fe concentrations are higher in the surface soils and gradually decreasing with increasing depth.

The average values of manganese (Mn) across the studied sites were observed a range from 13.85±1.40 to 23.96±1.40 µg/g. The highest value of 23.96±1.40 µg/g was recorded in the soil samples at Site C, followed by 17.14±1.56 µg/g at Site B, while the lowest value of 13.85±1.40 µg/g was recorded in the soil samples at Site A (Table 2). The average value of Mn across the soil layers exhibited a range from 17.77±5.03 to 19.09±6.29 µg/g. The highest Mn value of 19.09±6.29 µg/g was observed in the soil samples of surface

(S) layer, followed by 18.09±4.44 µg/g in the substratum (ST) layer, while the lowest value of 17.77±5.03 µg/g was observed in the soil samples of subsurface (SS) layer (Table 2).

The present results aligned with the findings of Hoque *et al*., (2008) [8], who reported that the Mn values are higher in the surface soils and showed a decreasing trend in the deeper layers of the Madhupur Sal forest of Bangladesh.

Table 3: The 2-tailed Pearson correlation among different chemical parameters in the soils of Thakurgaon Sal Forest

Para-meter	pH	OC	OM	TN	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn
pH	1	-0.124	-0.087	0.208	0.491	0.951	0.989	0.971	-0.644	-0.362	0.333	0.219	-1.000**
OC		1	.999*	0.945	0.804	0.189	0.026	-0.356	0.839	-0.88	0.895	0.941	0.134
OM			1	0.956	0.825	0.225	0.063	-0.321	0.818	-0.897	0.911	0.953	0.098
TN				1	0.954	0.5	0.352	-0.03	0.614	-0.987	0.992	1.000**	-0.198
P					1	0.736	0.615	0.269	0.351	-0.99	0.985	0.958	-0.481
K						1	0.987	0.85	-0.376	-0.632	0.608	0.51	-0.948
Ca							1	0.925	-0.523	-0.497	0.47	0.362	-0.987
Mg								1	-0.807	-0.13	0.099	-0.019	-0.974
S									1	-0.48	0.507	0.605	0.652
Zn										1	-1.000*	-0.989	0.352
Cu											1	0.993	-0.323
Fe												1	-0.209
Mn													1

Notes: **. Correlation is significant at the 0.01 level; *. Correlation is significant at the 0.05 level

The two-tailed Pearson correlation analysis of soil parameters revealed a highly significant positive correlation between total nitrogen (TN) and iron (Fe) at the 1% ($\alpha = 0.01$) level of significance, but organic carbon (OC) and organic matter (OM) at the 5% ($\alpha = 0.05$) level of significance. Furthermore, a strong negative significant correlation was observed between soil pH and manganese (Mn) at the 1% ($\alpha = 0.01$) level, as well as between zinc (Zn) and copper (Cu) at the 5% ($\alpha = 0.05$) level of significance (Table 3).

Limitation

The study was conducted during the winter season, which may not capture seasonal variability in soil properties, and the sample size may not fully represent the spatial heterogeneity of the study area.

Conclusion

The soils of the Thakurgaon Sal Forest exhibit a favorable nutrient status that support quite healthy growth and restoration potentiality for Sal Forest. Spatial variations in soil macro and micro nutrients availability reflect differences in vegetation cover and forest quality. Despite notable regenerative capacity, ongoing anthropogenic threats such as deforestation, unsustainable resource use, and agricultural encroachment threaten soil fertility, biodiversity, and ecosystem stability. The present findings underscore the need for timely, science-based management to enhance ecological sustainability, promote biodiversity, and support local livelihoods.

Acknowledgements

The first author acknowledges the Ministry of Science and Technology, Government of the People's Republic of Bangladesh for awarding the National Science and Technology (NST) Fellowship to complete this research. The author expresses his sincere thanks to the Chief Conservator of Forests, Conservator of Forests, and field staffs of the study areas for their cordial assistance during fieldwork. The authors extend their gratitude to the Chief Editor and Reviewers for their valuable comments and suggestions that improved the quality of this manuscript.

References

1. Ahmed A, Ohlson M, Hoque S, Moula MG. Edaphic conditions of different islands under different hydrological regimes in the coastal zone of Bangladesh. Dhaka University Journal of Biological Sciences,2010:19(1):27–40.
2. Anonymous. Soil survey manual, Soil Survey Staff. Open Journal of Geology,1993:5(1):10.
3. Bronick CJ, Lal R. Soil structure and management, a review. Geoderma,2005:124(1–2):3–22.
4. Cole DW. Soil nutrient supply in natural and managed forests. Plant and Soil,1995:168(1):43–53.
5. Fox RL, Olson RA, Rhoades HF. Evaluating the sulfur status of soils by plant and soil tests. Soil Science Society of America Journal,1964:28(2):243–246.
6. Ghosh AB, Bajaj JC, Hasan F, Singh D. Soil and water testing methods, a laboratory manual. ICAR, 1983.
7. Hasan MK, Mamun MB. Influence of different stands of sal (*Shorea robusta* C.F. Gaertn.) forest of Bangladesh on soil health. Research in Agriculture, Livestock and Fisheries,2015:2(1):17–25.
8. Hoque AE, Nazrul-Islam AK, Huq SI. Seasonal variation of edaphic features of Madhupur Sal forest, Bangladesh. Ecoprint: An International Journal of Ecology,2008:15:7–14.
9. Hossain MZ, Saha ML, Aziz CB, Hoque S. Effects of deforestation on the properties of soil of Sal forests in Bangladesh. Dhaka University Journal of Biological Sciences,2010:19(1):63–72.
10. Jackson ML. Soil Chemical Analysis. Prentice Hall, Inc., 1962.
11. Jenny H. Factors of soil formation, a system of quantitative pedology. Courier Corporation, 1994.
12. Kashem MA, Ahmed A, Hoque S, Hossain MZ. Effects of land-use change on the properties of top soil of deciduous Sal Forest in Bangladesh. Journal of Mountain Area Research,2016:1:5–12.
13. Khondker M, Bhuiyan MAH, Bashar MA. Towards an appraisal of biodiversity in Bangladesh. Journal of Biodiversity Conservation and Bioresource Management,2023:9(1):79–100.

14. Kumar R, Saikia P. Spatio-temporal soil nutrient dynamics and plant species diversity in selected Sal forests of Ranchi, Eastern India. Vegetos,2021:34(1):235–248.
15. Lanyon LE, Heald WR. Magnesium, calcium, strontium, and barium. Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties,1982:9:247–262.
16. Loeppert RH, Suarez DL. Carbonate and gypsum. Methods of Soil Analysis, Part 3, Chemical Methods,1996:5:437–474.
17. Mia MN, Hasan MK, Islam KK. Geochemical analysis of forest floor leaf litters of Madhupur Sal forest of Bangladesh. Fundamental and Applied Agriculture,2016:1(1):23–27.
18. Mim SJ, Rahman MM, Hossain GM. Soil physico-chemical properties of the Chandra Sal forest ecosystem in Gazipur District, Bangladesh. International Journal of Forestry, Ecology and Environment,2026:8(1):283–296.
19. Muhammed N, Koike M, Haque F, Miah MD. Quantitative assessment of people-oriented forestry in Bangladesh, a case study in the Tangail forest division. Journal of Environmental Management,2008:88(1):83–92.
20. Olsen SR, Sommers LE. Phosphorus. In Page AL, ed. Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties. American Society of Agronomy, Soil Science Society of America,1982:8:403–430.
21. Paudel S, Sah JP. Physiochemical characteristics of soil in tropical sal (*Shorea robusta* Gaertn.) forests in eastern Nepal. Himalayan Journal of Sciences,2003:1(2):107–110.
22. Prichard WL, Fisher RF. Properties and management of forest soil. John Wiley & Sons Inc.,1987:397–418.
23. Rahman M, Hossain ME, Hoque S, Islam S. Variation in soil organic carbon stock and forest biomass carbon density at different locations of sal forest in Bangladesh. Journal of Tropical Forestry,2022:38:1–22.
24. Rawat V, Bagri AS, Singh H, Tiwari P, Tiwari JK. Altitudinal variation in soil physico-chemical properties of a Western Himalayan Forest, Uttarakhand, India. Journal of Mountain Research,2021:16(3):111–119.
25. Shukla RS, Chandel PS. Plant ecology and soil science. S. Chand, 1994.
26. Sparks DL, Page AL, Helmke PA, Loeppert RH, eds. Methods of Soil Analysis, Part 3, Chemical Methods. John Wiley & Sons,2020.
27. SRDI. Soil analysis manual. Soil Resource and Development Institute, 2012, 8–20.
28. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter. Soil Science,1934:37(1):29–38.
29. Zaman S, Siddiquee SU, Katoh M. Species composition and forest structure in tropical moist deciduous forest of Bangladesh, a case study in Thakurgaon. Arabian Journal of Geosciences,2011:4(7):1315–1321.