

Research Article

Physicochemical and microbial characterization of Silmandi, Ghatail and Sonatala soil series under Old Brahmaputra Floodplains (AEZ 9) in Bangladesh

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ABSTRACT

Understanding the bio-physicochemical characteristics of soil series in the major agroecological zones (AEZs) of Bangladesh is essential for soil health assessment towards supporting sustainable soil management. In this study, the bio-physicochemical characterization of identified genetic horizons from three representative soil series named Silmandi, Ghatail, and Sonatala of AEZ 9 (Old Brahmaputra Floodplain) was performed. Results revealed that irrespective of soil series, the bulk density increased with soil depth ranging from 1.06-1.11 g cm⁻³ in surface Ap1 horizons to 1.48-1.56 g cm⁻³ in C horizons whereas organic matter declined sharply from 1.81-2.38% in Ap1 to 0.109-0.140% in C horizons. Similarly, bacterial populations decreased from 5.6×10⁷-1.6×10⁸ cfu g⁻¹ in Ap1 to 5.1×10⁵- 8.3×10⁵ cfu g⁻¹ in C horizons. Microbial biomass carbon (MBC) declined from 206.83-298.19 mg kg⁻¹ in Ap1 to 0.18-0.24% mg kg⁻¹ in C horizons. These findings provide essential baseline information for future soil management practices and crop production in AEZ 9.

Introduction

Soil is a living, dynamic system with physical, chemical, and biological components that interact to regulate nutrient cycling, turnover of organic matter, and soil fertility. As a critical biological component, the soil microbial community plays a central role in ecosystem functioning by decomposing organic matter, mineralizing essential nutrients, promoting soil aggregation, and suppressing both pathogens and environmental toxicity (Chen et al., 2024; Wang et al., 2024). Microorganisms are responsible for an estimated 80-90% of the biochemical processes in soils (Dubey et al., 2019; Wang et al., 2024). But the distribution of soil microorganisms and their activity is not even in the soil profile and changes at different depths with the variation in environmental conditions and resource availability (Liang et al., 2026; Mdaini et al., 2025).

Soil physicochemical properties (e.g. soil texture, organic matter, pH, and nutrient status) varies considerably with depth, and creating unique microhabitats in each soil horizon (Naylor et al., 2022; Wang et al., 2025). The surface horizons tend to have more organic carbon and nutrients, resulting in a greater number of microbes and their activity, while deeper horizons have less organic matter and oxygen, and hence, less microbial biomass and microbial respiration. It is important to understand the effects of these physicochemical gradients on microbial distribution across soil profiles to evaluate soil fertility, resilience, and long-term sustainability, especially in flood plain soils, which are subject to periodic deposition and erosion.

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The floodplain soils of Bangladesh cover approximately 80% of the land area and contribute most of the agricultural productivity (Faruk and Maharjan, 2023). Of these, the Old Brahmaputra Floodplain (AEZ 9) represents a highly productive zone with silt loam to silty clay loam on the ridges and clay in the basins, moderate drainage, and intensive rice-based cropping system (Ahmmed et al., 2018). Microbial abundance and activity are controlled by the spatial distribution of organic matter and nutrients, which varies with periodic sedimentation and variable hydrological conditions. Even though AEZ 9 is an important agricultural region, limited information is available on the variation in soil microbial properties across soil horizons and their association with soil physicochemical properties.

The previous studies in Bangladesh concentrated primarily on the topsoil properties without paying attention on the vertical distribution of microbial properties and their relationship with soil physicochemical properties. The deep soil horizons are, however, important for sequestering carbon as well as nutrient retention and have a large impact on the fertility and productivity of the floodplain soils in the long term. Microbial parameters like microbial population, microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) when considered with important soil physical and chemical parameters, help assess soil quality and functional capacity at different depths. These horizon-wise evaluations are especially relevant in floodplain soils, where the depositional and hydromorphic nature of these soils known to have a significant effect on the physicochemical gradients as well as the behaviour of the soil microbiota.

Considering the increasing agricultural intensification and land use pressure, the knowledge of subsurface microbial dynamics and their correlations with soil physicochemical properties is essential for sustainable soil management. Therefore, the present study was undertaken to evaluate the depth-wise variation of soil bio-physicochemical properties, and their interrelationships within the soil profiles.

Material and Methods

Study area

The study was conducted in 2023 in the Old Brahmaputra Floodplain (AEZ 9) of Bangladesh. Three representative soil profile sites were selected from the Mymensingh and Netrokona districts (Fig.1). The study sites were distributed across a range of land types varying from highland to medium lowland within this agroecological zone, which occupies a large area of Brahmaputra sediments. The soils of this area are predominantly Dark Grey Floodplain soils, moderately drained, and developed from Brahmaputra alluvial deposits. The climate is subtropical monsoon, with distinct wet and dry seasons.

Three representative soil series Silmandi, Ghatail, and Sonatala were selected to capture the typical soil variability of AEZ 9. The Silmandi and Ghatail soil series were located in Raghurampur village (Char Nilakshmia Union, Mymensingh Sadar Upazila) and Kukail village (Baola Union, Phulpur Upazila), respectively, within Mymensingh District, while the Sonatala soil series was located in Jalshuka village (Gohalakanda Union, Purbadhala Upazila) within Netrokona District of Bangladesh. The geographical locations, land type, and major cropping pattern of the selected profiles are presented in Table 1.

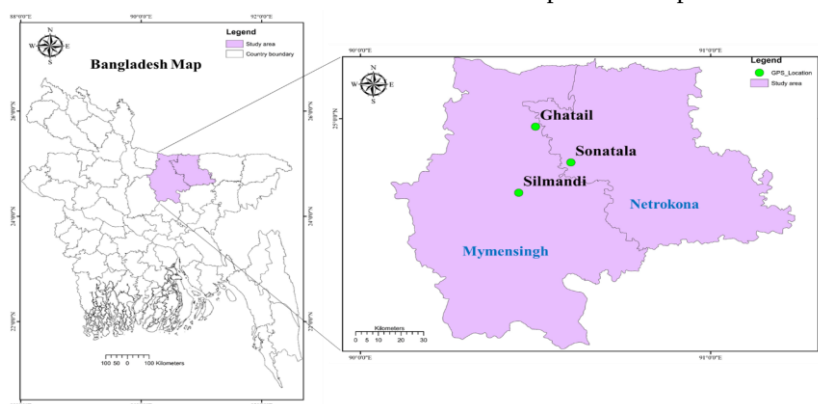


Fig. 1. Map of the study area showing the sampling locations of the Silmandi, Ghatail, and Sonatala soil series in Mymensingh and Netrokona districts of Bangladesh.

Table 1. Geographical location, land type, and major cropping pattern of the studied soil profiles.

Soil Series	Location (District)	Geographical Coordinates	Land Type	Major Cropping Pattern
Silmandi	Mymensingh	24°45'30" North latitude & 90°27'7" East longitude	Medium Highland	Boro-Fallow-T. Aman
Ghatail	Mymensingh	24°58'29" North latitude & 90°30'0" East longitude	Medium Lowland	Boro-Fallow-T. Aman
Sonatala	Netrokona	24°50'36" North latitude & 90°34'3" East longitude	Highland	Boro-Fallow-T. Aman

Soil profile identification and sample collection

For each soil series, a representative soil profile (three profiles in total) was excavated in December 2023 to a depth of 100 cm at the same spot previously evaluated by the Soil Resource Development Institute (SRDI) using GPS coordinates. Sampling was done during the fallow period between the harvest of Transplanted Aman rice and the planting of Boro rice. Identification of soil profiles was carried out according to the USDA Soil Survey Manual (USDA Soil Survey Staff, 1951) and the FAO Guidelines for soil description (FAO, 2006). The soil samples were taken from each identified horizons of the soil profiles. Three replicated composite samples were collected from each identified horizons, yielding a total of 18, 21, and 18 samples for the Silmandi, Ghatail, and Sonatala profiles respectively. Samples for physicochemical and microbial analyses were collected from each identified horizon using a clean stainless steel trowel; however, where the C horizon extended below 100 cm, a hand auger was used. For microbial analysis, soil samples were collected and transported in an ice-box (Daiwa SNOWLINE S-20D). Undisturbed soil samples were collected separately using a core sampler for bulk density determination. Samples were air-dried, ground, and passed through a 2-mm sieve for physicochemical analyses, while fresh, field-moist samples were preserved at 4°C for microbial analyses. All the laboratory processing, physicochemical and microbial analyses were carried out at the Department of Soil Science Laboratory, Gazipur Agricultural University, Bangladesh.

Soil physical properties analysis

Soil texture was assessed by the hydrometer method (Bouyoucos, 1962), following the removal of organic matter and carbonates to ensure accurate particle size distribution. Bulk density was measured using core technique (Blake and Hartge, 1986) with three replicates per horizon. Soil moisture content was measured gravimetrically by oven-drying moist soil samples at 105°C for 24 hours.

Soil chemical properties analysis

Soil pH was determined using a glass electrode pH meter after preparing a 1:2.5 soil-water suspension (Jackson, 1958). Organic carbon was determined by wet oxidation method (Walkley and Black, 1934). Total nitrogen (N) was determined by the Kjeldahl digestion and distillation method (Bremner and Mulvaney, 1982). Available phosphorus (P) was determined by Bray and Kurtz method (Acid soils) (Bray and Kurtz, 1945), and Modified Olsen method (Neutral + Calcareous soils) (Olsen et al., 1954). Available sulphur (S) was determined by $\text{CaH}_4(\text{PO}_4)_2$. H_2O extraction followed by turbidimetric method with BaCl_2 (Fox et al., 1964). Exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were determined by NH_4OAc extraction method (Schollenberger and Simon, 1945). Available copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) were determined by DTPA extraction method (Lindsay and Norvell, 1978) and available boron (B) was determined by CaCl_2 extraction method (Jeffery and McCallum, 1988).

Soil microbial analysis

To assess the population of bacteria, fungi, and actinomycetes in soil, a serial dilution and plate count method was employed using selective media for each microbial group. For bacterial enumeration, nutrient agar (NA) was used. Plates were incubated at 28–30°C for 24–48 hours, and colonies were counted. Fungal populations were assessed using Potato Dextrose Agar (PDA) and plates were incubated at 25–28°C for 3–5 days, and visible fungal colonies were counted. Actinomycetes were isolated using Actinomycetes Isolation Agar (AIA) and plates were incubated at 28–30°C for 5–7 days, and visible actinomycetes colonies were enumerated.

The chloroform fumigation-extraction method was used to determine microbial biomass carbon (MBC) (Vance et al., 1987). Soil samples were fumigated using alcohol-free chloroform (CHCl₃). After washing the desiccators with boiled water, about 200 mL of boiled water was added inside the chamber. A 100 mL beaker containing alcohol-free chloroform was then placed at the bottom of the desiccator, and the conical flasks containing the soil samples were carefully arranged inside it. After sealing the desiccators tightly, the air inside was removed using a mini vacuum pump (Yamato, Hitachi, Model Minivoc PD-52) for approximately ten minutes. The desiccators were subsequently kept in the dark for 24 hours. Fumigated and non-fumigated soils were extracted with 0.5 M K₂SO₄ (soil: K₂SO₄ solution = 1:4) for 30 min and filtrated. From the extracts the amount of biomass C was measured according to the method described by Vance et al. 1987 where 10 mL extract in 100 mL conical flask and 2 mL 0.4 N K₂Cr₂O₇, 10 mL concentrated H₂SO₄ were added to it. After heating (200°C for 30 min) in a hot plate, it was titrated with Mohr's salt. The biomass carbon (B_c) was estimated using the equation:

$$\text{Biomass carbon} = E_c \times 2.64$$

Where, E_c is the difference between the amount of C extracted from the fumigated and non-fumigated samples.

Biomass N was measured following the methodology provided by Brookes et al., 1988 and 1985. Biomass C and N were determined from the identical extract. Ten mL extract was taken in a 100 mL Kjeldahl flask, to which 5 mL of concentrated H₂SO₄, 0.5 mL of CuSO₄ (0.2 N) and 2–3 stones were added. After heating in a digestion chamber for 4 h, it was distilled

with 10 N NaOH. The 50 mL distillate was collected in 5 mL of 2% boric acid and titrated with 0.005 N H₂SO₄. The Biomass nitrogen (B_n) was determined from the equation:

$$\text{Biomass nitrogen} = E_n \times 1.85$$

Where, E_n is the difference between the amount of N extracted from the fumigated and non-fumigated samples.

Statistical Analysis

The statistical package Statistix 10 (Analytical Software, 2013) was used to analyze the data and Duncan's Multiple Range Test (DMRT) was used for mean separation (Steel and Torrie, 1960). Pearson's correlation analysis was performed in R statistical environment to examine relationship between microbial characteristics and soil physicochemical properties. The study area map was prepared using ArcGIS Pro 3.4 (Esri, 2024).

Results and Discussion

Soil profile description and horizon identification

The morphological features of the three representative soil profiles were examined in the field to support their horizon differentiation and to establish the basis for subsequent physicochemical and microbial analyses. The identified horizons and their key morphological characteristics are presented in Table 2.

Silmandi soil profile

In the Silmandi soil profile, six horizons were identified at different depths, namely Ap1 (0–8 cm), Ap2 (8–13 cm), B1 (13–30 cm), B21 (30–55 cm), B22 (55–104 cm), and C (>104 cm). The surface horizon was divided into Ap1 and Ap2 based on distinct vertical variations in soil colour and soil consistence. The surface horizons exhibited olive grey to grey colour, massive structure and abrupt wavy boundaries, indicating repeated cultivation and limited structural development. The B horizon was divided into B1, B21, and B22 based on clear vertical changes in boundary features, soil colour, consistence, and mottling frequency. The B horizons had a prismatic structure with firm to friable consistency and showed increasing mottling, suggesting moderate pedogenic development under seasonal wetness conditions. The C horizon was massive, grey in colour, and weakly structured, which indicates that it remains close to the original Old Brahmaputra Alluvium parent material.

Table 2. Identified horizons and key morphological features of the studied soil profiles in the Old Brahmaputra Floodplain (AEZ 9), Bangladesh.

Horizon	Soil depth (cm)	Boundary	Color matrix (moist)	Mottles	Structure	Consistence
Profile 1: Silmandi series						
Ap1	0-8	Abrupt wavy	Olive grey (5Y 5/2)	Yellowish brown	Massive	Friable moist
Ap2	8-13	Abrupt wavy	Grey (5Y 5/1)	Yellowish brown	Massive	Firm moist
B1	13-30	Abrupt wavy	Dark greyish brown (10YR 4/2)	Many fine distinct dark yellowish	Prismatic	Firm moist
B21	30-55	Abrupt wavy	Greyish brown (10YR 5/2)	Many fine distinct dark yellowish	Prismatic	Friable moist
B22	55-104	Clear smooth	Greyish brown (10YR 5/2)	Many fine distinct dark yellowish brown and few dark brown	Prismatic	Friable moist
C	>104	-	Grey (5Y6/1)	Many fine distinct reddish brown	Massive	Non sticky and tightly plastic wet
Profile 2: Ghatail series						
Ap1	0-10	Abrupt wavy	Dark grey (5Y 4/1)	Yellowish brown	Massive	Extremely hard dry
Ap2	10-17	Abrupt wavy	Very dark grey (5Y 3/1)	Yellowish brown	Massive	Extremely hard dry
B21	17-33	Clear smooth	Dark grey (5Y 4/1) and yellowish brown (10YR 5/4)	-	Prismatic	Very firm moist
B22	33-57	Abrupt wavy	Dark grey (5Y 4/1) and yellowish brown (10YR 4/4)	-	Prismatic	Very firm moist
B23	57-89	Abrupt wavy	Yellowish brown (10YR 5/8)	Many fine and medium distinct grey	Prismatic	Firm moist
B3	89-140	Abrupt wavy	Yellowish brown (10YR 5/8) and dark yellowish brown (10YR 4/4)	-	Prismatic	Slightly firm moist
C	>140	-	Dark yellowish brown (10YR 4/6)	Strong brown	-	Slightly firm moist
Profile 3: Sonatala series						
Ap1	0-10	Abrupt smooth	Grey (5Y 5/1)	Common fine distinct dark yellowish brown	Massive	Slightly firm moist
Ap2	10-18	Abrupt wavy	Grey (5Y 5/1)	Many fine and medium faint yellowish brown	Massive	Slightly sticky, slightly plastic, friable moist
B21	18-69	Clear smooth	Grey (5Y 5/1)	Common fine distinct yellowish brown	Coarse prismatic	Slightly sticky, slightly plastic, friable moist
B22	69-91	Clear smooth	Grey (5Y 5/1)	Common fine and medium faint yellowish brown	Coarse prismatic	Slightly sticky, slightly plastic, friable moist
C1	91-112	-	Grey (5Y 5/1)	Common fine faint yellowish brown	Massive	Nonsticky, nonplastic, very friable moist
C2	>112	-	Grey (5Y 5/1)	Common fine medium distinct yellowish brown	Massive and dark	Nonsticky, nonplastic, very friable moist

Ghatail soil profile

In the Ghatail soil profile, seven horizons were identified at different depths, namely Ap1 (0-10 cm), Ap2 (10-17 cm), B21 (17-33 cm), B22 (33-57 cm), B23 (57-89 cm), B3 (89-140 cm), and C (>140 cm). The surface horizon was divided into Ap1 and Ap2 based on differences in soil colour. The surface horizons showed dark grey to very dark grey colour, massive structure, and extremely hard consistency when dry, indicating the effects of prolonged cultivation and surface compaction. The B horizon was divided into B21, B22, B23, and B3 based on vertical changes in boundary characteristics, soil colour, mottling frequency, and consistence within the profile. The B21 to B3 horizons, developed from Old Brahmaputra Alluvium parent material had prismatic structure with very firm to slightly firm consistence and mixed grey and yellowish-brown colour, which indicate redoximorphic changes under fluctuating water table conditions. The C horizon extended beyond 140 cm and showed dark yellowish-brown colour with strong brown mottles.

Sonatala soil profile

In the Sonatala soil profile, six horizons were identified at varying depths, namely Ap1 (0-10 cm), Ap2 (10-18 cm), B21 (18-69 cm), B22 (69-91 cm), C1 (91-112 cm), and C2 (>112cm). The surface horizon was divided into Ap1 and Ap2 based on differences in boundary characteristics, mottling patterns, and soil consistence. These horizons were grey, massive and showed common fine distinct dark yellowish brown to many fine and medium faint yellowish-brown mottles, indicating seasonal saturation in the surface horizon. The subsurface B horizon was divided into B21 and B22 because of clear differences in mottling characteristics. Both B21 and B22 horizons showed coarse prismatic structure with slightly sticky and slightly plastic consistence, indicating strong redoximorphic processes associated with prolonged waterlogging conditions. These horizons (B21 and B22) showed common fine to medium yellowish-brown mottles, indicating development of reduction-oxidation cycles under seasonally saturated conditions. The C horizon was further differentiated into C1 and C2 based on differences in mottle colour and frequency.

These horizons were grey in colour and massive structured, which indicates that the parent material, Old Brahmaputra Alluvium, was gleyed under persistent wet conditions.

Soil physical properties

The physical properties of the three soil series are presented in Table 3, showing significant variations among the horizons in terms of soil texture, bulk density, and moisture content.

In the Silmandi profile, loam was prominent in the surface horizons while silt loam was more prominent in the subsurface. Bulk density increased with depth from 1.11 g cm⁻³ in Ap1 to 1.56 g cm⁻³ in C horizon, due to compaction and decreasing organic matter inputs. Similar results were found by Keshavarzi et al. (2018) and Lepcha et al. (2020), who noted that bulk density increases with soil depth. The soil moisture content was found to be steadily increasing in depth with the highest moisture level in C horizon (36.52%). This pattern suggested that relatively porous surface horizons favoured root growth, whereas the subsurface horizons had higher water holding capacity, finer texture, and less aeration.

The Ghatail profile showed silty clay loam texture at the surface horizon, while the underlying horizons were predominantly clay. The soil bulk density increased from 1.09g cm⁻³ in Ap1 to 1.48g cm⁻³ in the B3 horizon. The moisture content increased from 27.20% to 34.90% that was consistent with the dominance of clay minerals which improved the water holding capacity.

The Sonatala profile was mostly silt loam in texture with bulk density of 1.06 g cm⁻³ in Ap1 horizon to 1.50 g cm⁻³ in C2 horizon. The moisture content increased from 26.57% in Ap1 to 32.23% in C2 horizon. The low bulk density of the surface horizons suggests good tilth and rooting conditions, while the moderate bulk density at depth represents natural soil consolidation.

Soil Chemical properties

Silmandi soil profile

The Silmandi soil profile showed significant variations in macronutrient and micronutrient contents, as well as organic matter dynamics, among

the different horizons (Tables 4 and 5). From the table, it was observed that soil pH increased from strongly acidic in Ap1 (5.3) to slightly alkaline in B22 (7.7) horizons, reflecting the accumulation of basic cations in the subsurface layer. Organic matter was highest in the surface Ap1 horizon (2.31%) and decreased steadily with depth, reaching 0.23% in the C horizon. The total N content followed a similar trend to organic matter, starting at 0.134% in the Ap1 horizon and reducing to 0.015% in C horizon. This result was similar to the findings of Chen et al. (2021) who observed that soil organic matter and total N declined with increasing soil depth. Available P and S were highest in the Ap1 horizon ($5.06 \mu\text{g g}^{-1}$ P; $17.52 \mu\text{g g}^{-1}$ S), whereas exchangeable Ca and Mg were relatively higher in subsurface layers, reaching maximum in the B horizons ($7.76\text{--}7.97 \text{ cmol kg}^{-1}$ Ca; $3.97\text{--}4.07 \text{ cmol kg}^{-1}$ Mg), indicating leaching of bases, higher clay content and their subsequent accumulation in subsoil layers. Exchangeable K showed relatively low variability, with the highest in the Ap1 horizon, and remained slightly higher in the deeper horizons. Micronutrient availability also declined sharply with depth. The available B, Zn, Fe, Mn, and Cu were highest in Ap1 horizon but decreased markedly in the B and C horizons due to reduced organic matter content with increasing soil depth. Overall, the nutrient richness in the surface horizons was strongly controlled by organic matter inputs, while deeper horizons were dominated by exchangeable bases but depleted in available micronutrients.

Ghatail soil profile

The chemical properties of the Ghatail soil profile showed a pronounced vertical stratification of both macro and micronutrients, strongly influenced by organic matter dynamics and pedogenic processes (Tables 6 and 7). Soil pH increased from strongly acidic in Ap1 (5.1) to slightly alkaline in the B horizon (>7.3), due to leaching of acidic constituents and accumulation of basic cations at depth. The Ap1 horizon showed the highest organic matter (2.38%) and total nitrogen (0.140%), whereas the C horizon exhibited the lowest values (0.24% OM; 0.015% total N). Available P, S and exchangeable K were highest in Ap1 and decreased in subsurface horizons, suggesting strong

dependence on biological cycling and fertilizer or manure additions at the surface. The exchangeable Ca and Mg were relatively higher in the subsoil, possibly because of bases have been leached from the surface and accumulated in the clay-rich layers. The outcomes were comparable to those of Mao et al. (2022) who reported the reduction of organic matter, total N and available nutrients with the increase of soil depth, while exchangeable Ca and Mg were

Table 3. Physical properties of soil profiles of the Silmandi, Ghatail and Sonatala series under AEZ 9.

Horizon	Soil depth (cm)	Soil Texture	Soil moisture content (%)	Bulk density (g cm^{-3})
Profile 1: Silmandi series				
Ap1	0-8	Loam	27.24 ^d	1.11 ^e
Ap2	8-13	Loam	26.92 ^d	1.36 ^d
B1	13-30	Silt loam	28.95 ^c	1.48 ^c
B21	30-55	Silt loam	33.96 ^b	1.54 ^{ab}
B22	55-104	Silt loam	35.99 ^a	1.52 ^b
C	>104	Silt loam	36.52 ^a	1.56 ^a
SE ($\pm$)			0.58	0.01
CV (%)			2.25	1.16
Profile 2: Ghatail series				
Ap1	0-10	Silty Clay loam	27.20 ^c	1.09 ^e
Ap2	10-17	Clay	28.53 ^c	1.22 ^d
B21	17-33	Clay	28.96 ^c	1.42 ^c
B22	33-57	Clay	31.38 ^b	1.45 ^b
B23	57-89	Clay	32.06 ^b	1.47 ^a
B3	89-140	Clay	34.90 ^a	1.48 ^a
C	>140	Silt loam	-	-
SE ($\pm$)			0.87	0.02
CV (%)			3.42	1.54
Profile 3: Sonatala series				
Ap1	0-10	Silt loam	26.57 ^c	1.06 ^e
Ap2	10-18	Silt loam	28.54 ^b	1.28 ^d
B21	18-69	Silt loam	28.87 ^b	1.37 ^c
B22	69-91	Silt loam	30.07 ^b	1.46 ^b
C1	91-112	Silt loam	31.73 ^a	1.47 ^{ab}
C2	>112	Silt loam	32.23 ^a	1.50 ^a
SE ($\pm$)			0.71	0.02
CV (%)			2.95	1.47

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 4. Soil pH, OM, total N, available and exchangeable macronutrient status of soil profile of the Silmandi series under AEZ 9.

Horizon	Soil depth (cm)	pH	OM (%)	Total N (%)	Available		Exchangeable		
					P	S	K	Ca	Mg
					(µg g ⁻¹)		(cmol kg ⁻¹)		
Ap1	0-8	5.3 ^d	2.31 ^a	0.134 ^a	5.06 ^a	17.52 ^a	0.16 ^a	5.25 ^d	3.10 ^c
Ap2	8-13	5.8 ^c	1.71 ^b	0.092 ^b	3.39 ^b	7.56 ^b	0.12 ^b	5.85 ^c	3.53 ^b
B1	13-30	7.0 ^b	0.37 ^c	0.024 ^c	1.04 ^d	1.32 ^d	0.08 ^c	7.76 ^a	3.97 ^a
B21	30-55	7.2 ^b	0.3 ^{cd}	0.017 ^d	1.67 ^c	2.25 ^{cd}	0.11 ^b	7.01 ^b	3.65 ^b
B22	55-104	7.7 ^a	0.26 ^{cd}	0.015 ^d	1.46 ^c	1.56 ^{cd}	0.12 ^b	7.97 ^a	4.07 ^a
C	>104	7.6 ^a	0.23 ^d	0.015 ^d	1.04 ^d	2.85 ^c	0.10 ^{bc}	7.08 ^b	3.66 ^b
SE (±)		0.1	0.05	0.003	0.11	0.62	0.01	0.13	0.11
CV (%)		2.0	6.37	6.82	5.74	6.80	7.79	2.26	3.53

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 5. Available micronutrient status of soil profile of the Silmandi series under AEZ 9.

Horizon	Soil depth (cm)	Available				
		B (µg g ⁻¹)	Zn (µg g ⁻¹)	Fe (µg g ⁻¹)	Mn (µg g ⁻¹)	Cu (µg g ⁻¹)
Ap1	0-8	0.91 ^a	1.73 ^a	193.84 ^a	16.96 ^a	6.50 ^a
Ap2	8-13	0.89 ^a	0.54 ^b	105.63 ^b	15.47 ^b	5.19 ^b
B1	13-30	0.73 ^b	0.10 ^c	6.80 ^c	9.36 ^c	0.87 ^c
B21	30-55	0.66 ^c	0.09 ^c	4.53 ^c	2.83 ^d	0.45 ^e
B22	55-104	0.62 ^c	0.09 ^c	3.16 ^c	2.39 ^d	0.43 ^e
C	>104	0.61 ^c	0.03 ^c	7.60 ^c	1.23 ^e	0.63 ^d
SE (±)		0.03	0.05	3.10	0.37	0.08
CV (%)		5.26	6.81	5.78	5.57	4.31

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 6. Soil pH, OM, total N, available and exchangeable macronutrient status of soil profile of the Ghatail series under AEZ 9.

Horizon	Soil depth (cm)	pH	OM (%)	Total N (%)	Available		Exchangeable		
					P	S	K	Ca	Mg
					(µg g ⁻¹)		(cmol kg ⁻¹)		
Ap1	0-10	5.1 ^d	2.38 ^a	0.140 ^a	5.71 ^a	23.33 ^a	0.11 ^a	6.51 ^e	2.64 ^b
Ap2	10-17	6.9 ^c	1.01 ^b	0.060 ^b	4.24 ^b	9.12 ^b	0.07 ^b	9.11 ^d	3.67 ^a
B21	17-33	7.5 ^{ab}	0.37 ^c	0.024 ^c	3.33 ^c	2.15 ^c	0.06 ^{bc}	10.4 ^c	3.71 ^a
B22	33-57	7.6 ^a	0.37 ^c	0.023 ^{cd}	3.15 ^d	2.03 ^c	0.05 ^c	10.68 ^{bc}	3.70 ^a
B23	57-89	7.4 ^{ab}	0.33 ^{cd}	0.019 ^{de}	2.70 ^e	1.32 ^c	0.06 ^{bc}	11.48 ^a	3.78 ^a
B3	89-140	7.3 ^b	0.30 ^{cd}	0.017 ^e	1.24 ^f	1.12 ^c	0.07 ^b	9.17 ^d	3.72 ^a
C	>140	7.3 ^b	0.24 ^d	0.015 ^e	1.03 ^g	1.10 ^c	0.07 ^b	9.12 ^d	3.71 ^a
SE (±)		0.1	0.05	0.002	0.08	0.88	0.01	0.28	0.12
CV (%)		1.8	7.37	5.98	3.13	8.78	6.07	3.52	4.14

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 7. Available micronutrient status of soil profile of the Ghatail series under AEZ 9.

Horizon	Soil depth (cm)	Available				
		B ($\mu\text{g g}^{-1}$)	Zn ($\mu\text{g g}^{-1}$)	Fe ($\mu\text{g g}^{-1}$)	Mn ($\mu\text{g g}^{-1}$)	Cu ($\mu\text{g g}^{-1}$)
Ap1	0-10	0.58 ^a	1.42 ^a	267.73 ^a	28.72 ^a	5.91 ^a
Ap2	10-17	0.39 ^b	0.19 ^b	121.29 ^b	9.21 ^b	1.54 ^b
B21	17-33	0.36 ^{bc}	0.12 ^{bc}	3.16 ^c	2.35 ^e	0.53 ^e
B22	33-57	0.31 ^{cd}	0.08 ^c	7.28 ^c	2.97 ^d	0.44 ^e
B23	57-89	0.28 ^d	0.07 ^c	7.91 ^c	4.24 ^c	0.55 ^e
B3	89-140	0.27 ^d	0.05 ^c	3.48 ^c	1.74 ^f	1.05 ^d
C	>140	0.24 ^d	0.07 ^c	8.39 ^c	1.52 ^f	1.33 ^c
SE ($\pm$)		0.04	0.04	4.37	0.26	0.06
CV (%)		6.79	6.76	5.96	4.41	4.37

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 8. Soil pH, OM, total N, available and exchangeable macronutrient status of soil profile of the Sonatala series under AEZ 9.

Horizon	Soil depth (cm)	pH	OM (%)	Total N (%)	Available		Exchangeable		
					P ($\mu\text{g g}^{-1}$)	S ($\mu\text{g g}^{-1}$)	K ($\mu\text{g g}^{-1}$)	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})
Ap1	0-10	5.3 ^c	1.81 ^a	0.109 ^a	7.08 ^a	9.43 ^a	0.13 ^a	4.20 ^c	1.45 ^d
Ap2	10-18	7.1 ^{ab}	0.84 ^b	0.049 ^b	6.93 ^a	3.22 ^b	0.09 ^b	7.02 ^b	3.01 ^{bc}
B21	18-69	7.2 ^a	0.50 ^c	0.036 ^c	6.10 ^b	2.15 ^c	0.07 ^b	7.92 ^a	3.22 ^{ab}
B22	69-91	7.2 ^a	0.43 ^c	0.025 ^d	5.80 ^c	2.13 ^c	0.08 ^b	7.73 ^a	3.27 ^a
C1	91-112	7.0 ^b	0.27 ^d	0.021 ^d	3.30 ^d	1.15 ^d	0.07 ^b	7.03 ^b	2.95 ^c
C2	>112	7.0 ^b	0.18 ^e	0.014 ^e	2.95 ^e	1.10 ^d	0.07 ^b	7.00 ^b	3.04 ^{bc}
SE ($\pm$)		0.1	0.04	0.003	0.07	0.17	0.01	0.12	0.10
CV (%)		1.3	7.27	7.77	1.70	6.70	6.58	2.40	4.40

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

Table 9. Available micronutrient status of soil profile of the Sonatala series under AEZ 9.

Horizon	Soil depth (cm)	Available				
		B ($\mu\text{g g}^{-1}$)	Zn ($\mu\text{g g}^{-1}$)	Fe ($\mu\text{g g}^{-1}$)	Mn ($\mu\text{g g}^{-1}$)	Cu ($\mu\text{g g}^{-1}$)
Ap1	0-10	0.32 ^a	1.06 ^a	370.77 ^a	32.61 ^a	4.13 ^a
Ap2	10-18	0.24 ^b	0.16 ^{bc}	25.58 ^{bc}	14.51 ^b	1.95 ^b
B21	18-69	0.2 ^{bc}	0.12 ^{cd}	14.88 ^c	3.12 ^c	1.62 ^c
B22	69-91	0.18 ^c	0.10 ^d	28.18 ^b	1.74 ^c	1.23 ^d
C1	91-112	0.12 ^d	0.17 ^b	15.20 ^c	2.54 ^c	0.45 ^e
C2	>112	0.10 ^d	0.15 ^{bc}	16.47 ^c	2.32 ^c	0.41 ^e
SE ($\pm$)		0.03	0.02	5.18	0.85	0.07
CV (%)		5.22	5.02	6.08	5.97	5.08

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

comparatively lower in the topsoil than in the subsoil. Micronutrient concentrations were clearly surface-enriched, with Fe, Mn, Zn, Cu and B having maximum concentrations in the Ap1 horizon and declining significantly below Ap2, which is indicative of less organic complexation and their inherent low availability in the deeper soil horizons. The overall results showed that the nutrient availability was largely in the surface horizons, while the subsoil horizons were highly depleted, due to leaching loss, poor organic matter addition, and lower biological activity.

Sonatala soil profile

The Sonatala soil profile showed significant variations in macro and micronutrient contents, as well as organic matter dynamics, among the different horizons (Tables 8 and 9). Soil pH increased from moderately acidic in Ap1 (5.3) to neutral in deeper horizons (7.0–7.2). Organic matter and total N decreased significantly with depth from 1.81% and 0.109% in Ap1 to 0.18% and 0.014% in C2, respectively. Available P and S were highest in the Ap1 horizon (7.08 $\mu\text{g g}^{-1}$ and 9.43 $\mu\text{g g}^{-1}$, respectively) and decreased gradually to the lowest concentrations in the C2 horizon. Exchangeable K (0.13 cmol kg^{-1}) was highest in the Ap1 horizon and lowest in the B21, C1 and C2 horizons. Accumulation of higher Ca and Mg occurred in subsoil layers indicating leaching of bases downwards and increasing clay content. In the case of micronutrients, strong surface enrichment was observed with Fe (370.77 $\mu\text{g g}^{-1}$), Mn (32.61 $\mu\text{g g}^{-1}$), Zn (1.06 $\mu\text{g g}^{-1}$), Cu (4.13 $\mu\text{g g}^{-1}$), and B (0.32 $\mu\text{g g}^{-1}$) and declining significantly in the sub surface horizons due to decreasing organic matter content and reduced organic complexation with depth. The overall results showed that nutrient availability in the Sonatala series was mainly restricted to the surface horizons while deeper horizons were generally nutrient depleted due to leaching and reduction of biological inputs.

Soil microbial properties

Microbial population

The microbial populations of the Silmandi, Ghatail, and Sonatala soil profiles are presented in Table 10, showing a sharp decrease with increasing soil depth. In the Silmandi soil profile, the Ap1 horizon showed the highest microbial abundance, where the bacteria, fungi and actinomycetes population were 1.4×10^8 cfu g^{-1} soil, 3.7×10^5 cfu g^{-1} soil, and 3.3×10^6 cfu g^{-1} soil, respectively.

Microbial populations declined significantly in subsurface horizons, indicating reduced organic substrate and poorer aeration at depth. Similar studies by Bhattarai et al. (2015) reported a decreasing trend in microbial population with increasing soil depth.

In the Ghatail soil profile, microbial populations were highest in Ap1, where bacteria, fungi and actinomycetes were 1.6×10^8 cfu g^{-1} soil, 2.5×10^6 cfu g^{-1} soil, and 4.2×10^6 cfu g^{-1} soil, respectively. Microbial populations declined progressively in deeper horizons, and in the C horizon bacteria, fungi and actinomycetes were 8.3×10^5 cfu g^{-1} soil, 9.2×10^3 cfu g^{-1} soil, and 6.9×10^4 cfu g^{-1} soil, respectively.

In the Sonatala soil profile, the Ap1 horizon showed the highest microbial populations, where bacteria, fungi and actinomycetes were 5.6×10^7 cfu g^{-1} soil, 2.8×10^5 cfu g^{-1} soil, and 1.2×10^6 cfu g^{-1} soil, respectively.

Microbial populations declined progressively with depth, reaching their lowest values in the C2 horizon. The uniform silt loam texture provided moderate aeration, but limited organic matter inputs constrained microbial growth in deeper layers.

Microbial Biomass C and N

In the Silmandi soil profile, the highest MBC (285.40 mg kg^{-1}) and MBN (31.62 mg kg^{-1}) content were recorded in the surface horizon (Ap1 horizon), whereas the lowest MBC (22.55 mg kg^{-1}) and MBN (4.18 mg kg^{-1}) content were observed in the C1 horizon (Fig. 2), reflecting reduced organic matter and aeration in subsurface layers. This result was similar to the findings of Lepcha and Devi (2020) who observed that both MBC and MBN decreased significantly with soil depth and had the maximum values in surface soil.

In the Ghatail soil profile, the surface horizon (Ap1) showed the highest MBC (298.19 mg kg^{-1}) and MBN (34.30 mg kg^{-1}), while the lowest values of MBC (24.22 mg kg^{-1}) and MBN (4.02 mg kg^{-1}) were found in the C horizon (Fig. 3).

In the Sonatala soil profile, the highest MBC (206.83 mg kg^{-1}) and MBN (24.85 mg kg^{-1}) were found in the Ap1 horizon, whereas the C2 horizon showed the lowest MBC (16.50 mg kg^{-1}) and MBN (4.03 mg kg^{-1}) (Fig. 4). Although the uniform silt loam texture provided moderate aeration, the gradual decline in organic matter with depth restricted microbial growth.

Table 10. Microbial population of soil profiles of the Silmandi, Ghatail and Sonatala series under AEZ 9.

Horizon	Soil depth (cm)	Bacterial population (cfu g ⁻¹ soil)	Fungal population (cfu g ⁻¹ soil)	Actinomycetes population (cfu g ⁻¹ soil)
Profile 1: Silmandi series				
Ap1	0-8	1.4×10 ^{8a}	3.7×10 ^{5a}	3.3×10 ^{6a}
Ap2	8-13	9.3×10 ^{7b}	2.4×10 ^{5b}	1.8×10 ^{6b}
B1	13-30	6.8×10 ^{6c}	5.2×10 ^{4c}	6.7×10 ^{5c}
B21	30-55	5.4×10 ^{6c}	2.8×10 ^{4cd}	5.2×10 ^{5c}
B22	55-104	3.1×10 ^{6c}	3.1×10 ^{4cd}	2.7×10 ^{5d}
C	>104	7.8×10 ^{5c}	7.5×10 ^{3d}	8.2×10 ^{4d}
SE (±)		4.4 ×10 ⁶	1.1×10 ⁴	9.5×10 ⁴
CV (%)		9.1	8.2	7.5
Profile 2: Ghatail series				
Ap1	0-10	1.6×10 ^{8a}	2.5×10 ^{6a}	4.2×10 ^{6a}
Ap2	10-17	5.7×10 ^{7b}	8.2×10 ^{5b}	1.4×10 ^{6b}
B21	17-33	7.2×10 ^{6c}	4.7×10 ^{5c}	5.4×10 ^{5c}
B22	33-57	3.9×10 ^{6c}	7.3×10 ^{4d}	3.6×10 ^{5cd}
B23	57-89	2.7×10 ^{6c}	4.1×10 ^{4de}	3.8×10 ^{5cd}
B3	89-140	1.1×10 ^{6c}	3.5×10 ^{4de}	1.7×10 ^{5de}
C	>140	8.3×10 ^{5c}	9.2×10 ^{3e}	6.9×10 ^{4e}
SE (±)		3.2 ×10 ⁶	2.8×10 ⁴	9.9×10 ⁴
CV (%)		8.1	6.3	7.9
Profile 3: Sonatala series				
Ap1	0-10	5.6×10 ^{7a}	2.8×10 ^{5a}	1.2×10 ^{6a}
Ap2	10-18	2.6×10 ^{7b}	7.9×10 ^{4b}	4.8×10 ^{5b}
B21	18-69	7.2×10 ^{6c}	4.7×10 ^{4c}	2.3×10 ^{5c}
B22	69-91	5.8×10 ^{6c}	3.4×10 ^{4d}	9.7×10 ^{4d}
C1	91-112	1.3×10 ^{6d}	6.2×10 ^{3e}	6.3×10 ^{4e}
C2	>112	5.1×10 ^{5d}	5.9×10 ^{3e}	2.7×10 ^{4f}
SE (±)		9.0 ×10 ⁵	1.9×10 ³	8.4×10 ³
CV (%)		8.9	7.2	5.9

Means assigned the same letter(s) do not differ significantly at the 5% significance level.

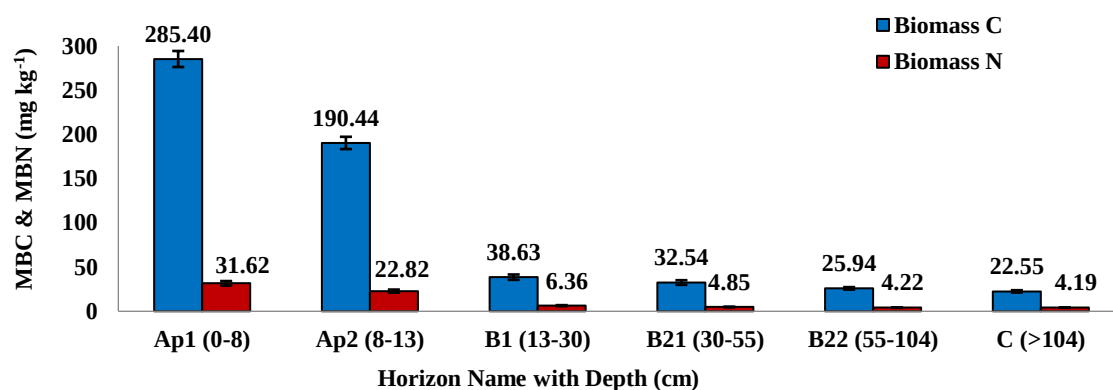


Fig. 2. Status of microbial biomass C and N in different horizons of Silmandi soil profile under AEZ 9. [The bar on the column indicates standard error]

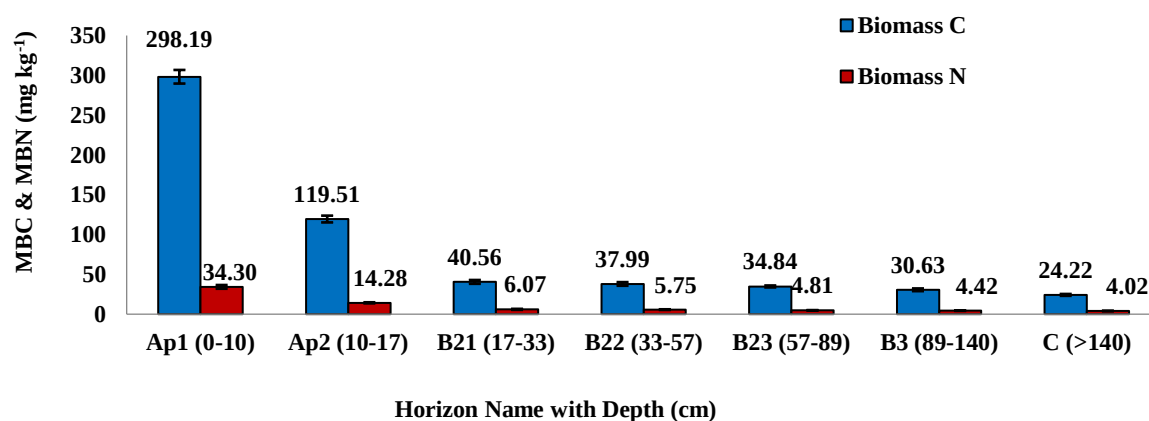


Fig. 3. Status of microbial biomass C and N in different horizons of Ghatail soil profile under AEZ 9. [The bar on the column indicates standard error].

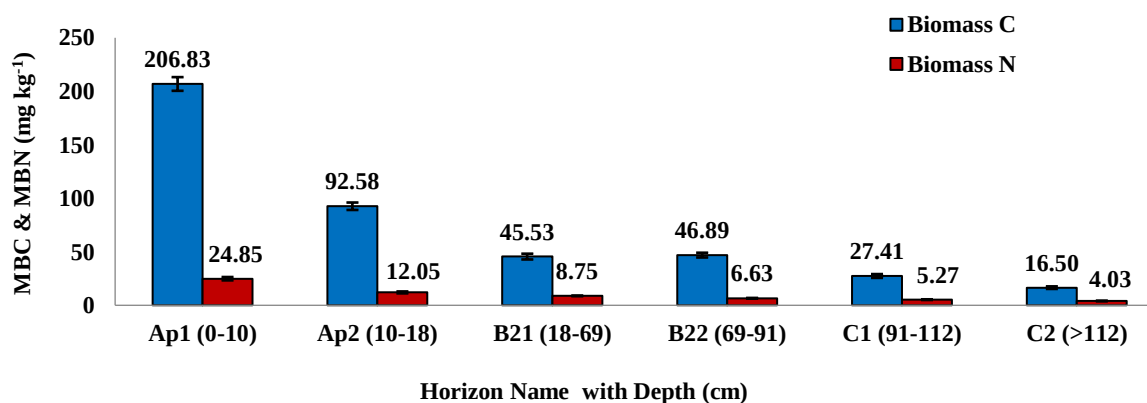


Fig. 4. Status of microbial biomass C and N in different horizons of Sonatala soil profile under AEZ 9. [The bar on the column indicates standard error].

Relationship of soil physicochemical and microbial properties

Silmandi soil profile

In the Silmandi soil profile, organic matter (OM) showed strong positive correlations with microbial characteristics, including MBC ($r = 0.99^{***}$), MBN ($r = 0.99^{***}$), BP ($r = 0.99^{***}$) and FP ($r = 0.99^{***}$), demonstrating that microbial biomass and microbial populations were highest in organic matter enriched horizons (Fig. 5). This result was similar to the findings of Bhattarai et al. (2015) who observed that organic matter has positive correlation with microbial population where depth has the negative correlation. OM was also strongly negatively correlated with bulk density ($r = -0.95^{**}$) and soil depth ($r = -0.73$). Bulk density showed strong negative correlations with MBC ($r = -0.97^{**}$) and MBN ($r = -0.96^{**}$), indicating that compact horizons with low porosity supported less microbial activity. Soil pH exhibited strong negative correlations with microbial indices ($r = -0.96$ to -0.97^{**}), likely reflecting a co-correlation with soil depth rather than a direct effect of pH on microbial activity. Total N, available P and S similarly exhibited strong positive correlations with MBC, MBN, BP, and FP (all $r > 0.94^{**}$), reflecting the strong dependency of microbial processes on nutrient availability along the profile. The study results are consistent with the findings of Lepcha and Devi (2020) who observed that soil organic carbon had significant positive correlation with total N, available P and microbial biomass C but showed negative correlation with soil pH and bulk density.

Ghatail soil profile

In the Ghatail soil profile, OM showed very strong correlations with MBC ($r = 0.99^{***}$) and MBN ($r = 0.99^{***}$), and similarly strong associations with BP ($r = 0.99^{***}$) and FP ($r = 0.98^{***}$), confirming that microbial abundance was strongly correlated with organic matter across horizons (Fig. 6). OM was negatively correlated with BD ($r = -0.95^{**}$) and soil depth ($r = -0.63$), while BD had strong negative relationships with MBC ($r = -0.94^{**}$) and MBN ($r = -0.94^{**}$), indicating reduced microbes due to soil compaction. Nutrients such as total N ($r = 0.99^{***}$ with MBC; $r = 0.99^{***}$ with MBN) and available S ($r =$

0.99^{***} with MBC; $r = 0.99^{***}$ with MBN) also showed consistently high positive correlations with microbial properties, reflecting nutrient-driven vertical variation of microbial activity within the profile.

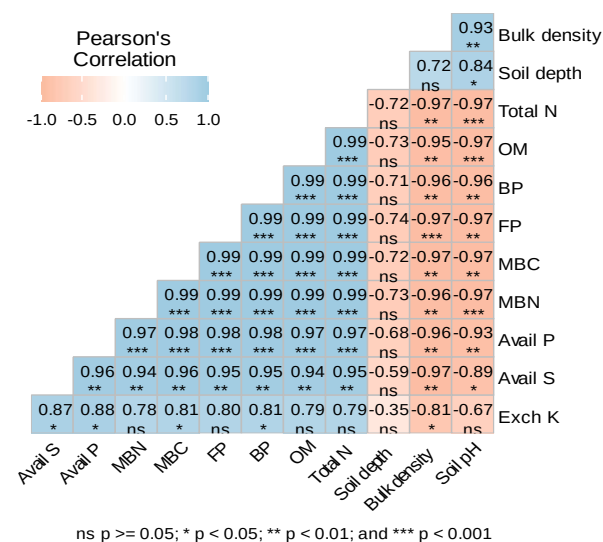


Fig. 5. Pearson Correlation matrix of soil physicochemical and microbial properties across profile horizons of the Silmandi series under AEZ 9 (n = 6). [OM = organic matter; BP = bacterial population; FP = fungal population; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen].

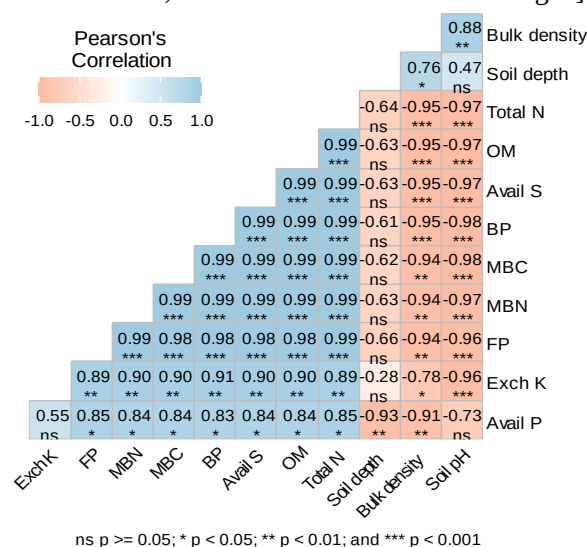


Fig. 6. Pearson Correlation matrix of soil physicochemical and microbial properties across profile horizons of the Ghatail series under AEZ 9 (n = 7). [OM = organic matter; BP = bacterial population; FP = fungal population; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen].

Sonatala soil profile

In the Sonatala soil profile, organic matter (OM) showed very strong positive correlations with MBC ($r = 0.99^{***}$) and MBN ($r = 0.99$), BP ($r = 0.99^{***}$) and FP ($r = 0.99^{***}$), highlighting the key role of OM in regulating microbial biomass and microbial populations (Fig. 7).

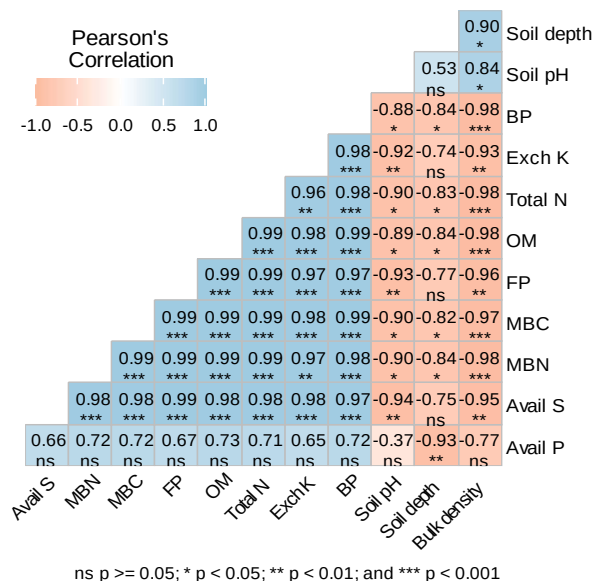


Fig. 7. Pearson Correlation matrix of soil physicochemical and microbial properties across profile horizons of the Sonatala series under AEZ 9 (n = 6). [OM = organic matter; BP = bacterial population; FP = fungal population; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen].

OM was strongly negatively correlated with bulk density (BD) ($r = -0.98^{***}$) and soil depth ($r = -0.84^*$), while BD showed strong negative correlations with MBC ($r = -0.97^{**}$) and MBN ($r = -0.98^{***}$), indicating that soil compaction reduced microbial abundance across horizons. Total N, available S and exchangeable K showed strong positive correlations with microbial characteristics demonstrating that organic matter and nutrient rich horizons supported enhanced microbial activity within the profile.

Cross-series comparison and synthesis

The Ghatail soil series consistently exhibited higher organic matter, total nitrogen, microbial population, and microbial biomass across most horizons,

indicating comparatively better soil biological health. The Ghatail series was characterized by clay-dominated subsoil, exhibited relatively higher exchangeable base accumulation. In contrast, the Sonatala series was characterized by lower organic matter and microbial biomass but comparatively higher Fe and Mn concentrations in the surface horizons, reflecting distinct geochemical conditions and pedogenic development. The extremely high Fe concentrations in surface of Sonatala may reflect periodic reduction-oxidation cycles and upward movement of soluble Fe during flooding events. Meanwhile, the Silmandi series generally showed intermediate values for most physicochemical and microbial properties, falling between Ghatail and Sonatala series.

Across all three soil series, microbial populations and biomass declined sharply with increasing depth, corresponding closely with reductions in organic matter, nutrient availability, and increasing bulk density. The reduction in microbial levels differed among the profiles, with Ghatail showing comparatively higher levels even in the subsurface horizons. These indicate that changes in organic matter and related soil properties collectively influence microbial distribution among the three soil series in AEZ 9.

Conclusion

The soil profiles of Old Brahmaputra Floodplain (AEZ 9) showed well-developed horizonation and significant depth-wise variability in bio-physicochemical properties. The surface horizons were the most biologically active, had highest organic matter, available nutrients, and microbial biomass. In contrast, the subsurface horizons showed gradual decreases in these attributes, and increases in bulk density and base accumulation. The strong positive correlation between organic matter and microbial indices across all profiles reflects the importance of organic matter in regulating microbial activity and nutrient cycling in floodplain soils. Overall, these findings provide useful information into the interrelated bio-physicochemical processes of

floodplain soil profiles and serve as an important baseline for assessment of soil quality in AEZ 9. Regular monitoring of soil properties across different AEZs of Bangladesh are recommended for proper soil management towards sustainable crop productivity.

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Authors contribution

Ibne Saleh Md. Farhad: Conceptualization, data curation, formal analysis, methodology, software, visualization, writing-original draft preparation, Md Humayun Kabir: Conceptualization, methodology, software, supervision, visualization, writing-reviewing and editing, Mohammad Saiful Alam: Conceptualization, supervision, investigation, writing-reviewing and editing, Md Tofazzal Islam: Conceptualization, supervision, investigation, writing-reviewing and editing, GKM Mustafizur Rahman: Conceptualization, methodology supervision, investigation, writing -reviewing and editing.

Conflict of interest

The authors declare that no conflict of interest regarding the publication of this paper.

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