

## **Influence of Land-Use Types and Environmental Variables on Soil Properties in Forest Ecosystems of Chittagong, Bangladesh**

Jesmin Akhter<sup>1, \*</sup> and Mohammed Al-Amin<sup>2</sup>

<sup>1</sup>*Institute of Forestry and Environmental Science, University of Chittagong, 4331, Bangladesh;*

<sup>2</sup>*Institute of Forestry and Environmental Science, University of Chittagong, Bangladesh*

*\*Corresponding author: prof.alamin@yahoo.com*

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### **Abstract**

Soil properties play a significant role in ecosystem productivity, especially in forest areas where land-use and environmental variables (such as slope and altitude) strongly influence soil stability and fertility. The objective of this study was to assess the impact of land-use types and environmental variables on soil properties in forest ecosystems in southeast Bangladesh. A total of 81 samples were collected from nine different land-use forest sites, with altitudes ranging from 26.43 m to 106.35 m and slope gradients from 26.07% to 77.30% across the land-use types. About ten soil properties were analyzed using appropriate methods, such as bulk density (BD), soil pH, soil organic carbon (SOC), total nitrogen (TN), carbon to nitrogen ratio (C:N), available phosphorus (AP), available potassium (AK), available sulfur (AS), available zinc (AZn) and available boron (AB). The analysis of variance (ANOVA) results showed significant variations in soil properties among land-use types ( $p < 0.001$ ). Post-hoc analysis was also applied to analyze and compare the mean significant differences between each property under different land-use types. Nutrient Properties such as TN, AP, AK, AS, AZn, and AB, as well as SOC, were higher in natural forests and agroforestry systems than in shifting cultivation and monoculture forests. In contrast, BD and soil pH were highest in the acacia forest compared to the natural forest. Considering environmental variables, correlation analysis revealed a positive relationship with slope, altitude, and BD, but a negative relationship with SOM, TN, AS, and AB. Among the soil properties, BD, pH, and the C:N ratio showed negative correlations, whereas SOC, TN, AP, AK, AS, AZn, and AB exhibited positive correlations. Additionally, regression analyses revealed a significant relationship between BD, SOC, TN, AS, AB, and slope, as well as between SOC and altitude. Land-use and environmental variables strongly affect soil properties and fertility, with steeper slopes and high altitude showing compacted, acidic, low SOC, and low nutrient content in soil. Future research should investigate the combined effects of land-use and seasonal variation, as well as the role of conservation methods in reducing soil degradation in the study area.

**Keywords:** *Land-use type, soil chemical properties, soil nutritional properties, slope gradient, altitude*

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**সারমর্ম:** বাস্তুতন্ত্রের উৎপাদনশীলতায় মাটির বৈশিষ্ট্য গুরুত্বপূর্ণ ভূমিকা পালন করে, বিশেষ করে বন্যপ্রাণী যেকোনো ভূমি-ব্যবহার এবং পরিবেশগত পরিবর্তনশীল (যেমন ঢাল এবং উচ্চতা) মাটির স্থিতিশীলতা এবং উর্বরতাকে দৃঢ়ভাবে প্রভাবিত করে। এই গবেষণার উদ্দেশ্য ছিল দক্ষিণ-পূর্ব বাংলাদেশের বন বাস্তুতন্ত্রের মাটির বৈশিষ্ট্যের উপর ভূমি-ব্যবহারের ধরণ এবং পরিবেশগত পরিবর্তনশীলের প্রভাব মূল্যায়ন করা। নয়টি ভিন্ন ভূমি-ব্যবহারের বনভূমি থেকে মোট ৮১টি নমুনা সংগ্রহ করা হয়েছিল, যার উচ্চতা ২৬.৪৩ মিটার থেকে ১০৬.৩৫ মিটার এবং ঢালের গ্রেডিয়েন্ট ২৬.০৭% থেকে ৭৭.৩০% পর্যন্ত ভূমি-ব্যবহারের ধরণে ছিল। বাক্স ঘনত্ব (BD), মাটির pH, মাটির জৈব কার্বন (SOC), মোট নাইট্রোজেন (TN), কার্বন থেকে নাইট্রোজেন অনুপাত (C:N), উপলব্ধ ফসফরাস (AP), উপলব্ধ পটাসিয়াম (AK), উপলব্ধ সালফার (AS), উপলব্ধ জিঙ্ক (AZn) এবং উপলব্ধ বোরন (AB) এর মতো উপযুক্ত পদ্ধতি ব্যবহার করে প্রায় দশটি মাটির বৈশিষ্ট্য বিশ্লেষণ করা হয়েছিল। ভ্যারিয়েন্স বিশ্লেষণের (ANOVA) ফলাফল ভূমি-ব্যবহারের ধরণগুলির মধ্যে মাটির বৈশিষ্ট্যের উল্লেখযোগ্য তারতম্য দেখিয়েছে ( $p < 0.001$ )। বিভিন্ন ধরণের ভূমি-ব্যবহারের অধীনে প্রতিটি সম্পত্তির মধ্যে গড় উল্লেখযোগ্য পার্থক্য বিশ্লেষণ এবং তুলনা করার জন্য পোস্ট-হক বিশ্লেষণও প্রয়োগ করা হয়েছিল। প্রাকৃতিক বন এবং কৃষি বনায়ন ব্যবস্থায় TN, AP, AK, AS, AZn, এবং AB এর মতো পুষ্টিগুণ, সেইসাথে SOC, স্থানান্তরিত চাষ এবং এক-কালচার বনের তুলনায় বেশি ছিল। বিপরীতে, প্রাকৃতিক বনের তুলনায় বাবলা বনে BD এবং মাটির pH সবচেয়ে বেশি ছিল। পরিবেশগত পরিবর্তনশীল বিবেচনা করে, পারস্পরিক সম্পর্ক বিশ্লেষণে ঢাল, উচ্চতা এবং BD এর সাথে একটি ইতিবাচক সম্পর্ক প্রকাশ পেয়েছে, তবে SOM, TN, AS, এবং AB এর সাথে একটি নেতিবাচক সম্পর্ক প্রকাশ পেয়েছে। মাটির বৈশিষ্ট্যগুলির মধ্যে, BD, pH, এবং C:N অনুপাত নেতিবাচক সম্পর্ক দেখিয়েছে, যেখানে SOC, TN, AP, AK, AS, AZn, এবং AB ইতিবাচক সম্পর্ক প্রদর্শন করেছে। অতিরিক্তভাবে, রিগ্রেশন বিশ্লেষণে BD, SOC, TN, AS, AB এবং ঢালের মধ্যে, সেইসাথে SOC এবং উচ্চতার মধ্যে একটি গুরুত্বপূর্ণ সম্পর্ক প্রকাশ পেয়েছে। ভূমি-ব্যবহার এবং পরিবেশগত পরিবর্তনশীল মাটির বৈশিষ্ট্য এবং উর্বরতাকে দৃঢ়ভাবে প্রভাবিত করে, খাড়া ঢাল এবং উচ্চ উচ্চতা মাটিতে সংকুচিত, অগ্নীয়, কম SOC এবং কম পুষ্টির পরিমাণ দেখায়। ভবিষ্যতের গবেষণায় ভূমি-ব্যবহার এবং ঋতু পরিবর্তনের সম্মিলিত প্রভাব, সেইসাথে অধ্যয়ন এলাকায় মাটির ক্ষয় কমাতে সংরক্ষণ পদ্ধতির ভূমিকা তদন্ত করা উচিত।

## 1. Introduction

Soil is one of the most critical land resources that enables agricultural development and sustains ecological integrity in the context of global climate change. Soil health, such as soil quality, nutrient cycling, and soil fertility, is being affected by climate change, population growth, and unsustainable land-use practices. According to the Food and Agriculture Organization (FAO), soil health has been defined as “the continued capacity of the soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health” [1]. Therefore, healthy soils are essential for maintaining ecosystem functions, supporting soil microorganisms involved in nutrient cycling, preventing erosion, and preserving soil organic matter [2,3]. However, soil properties vary significantly among soil types and across locations, reflecting differences in parent material, climate, and land-use

[4]. Furthermore, soil physical, chemical, and biological characteristics are strongly influenced by land-use type, slope gradient, and land management practices [5]. For example, cleaning the natural forest in most parts of the upper zones for cultivation has contributed significantly to the reduced level of SOC, N, P, and K in the soil [6], and the current study indicates that SOC and TN accumulation in the highland is related to diverse environmental conditions such as altitude, slope, and location [7]. Similarly, environmental variables, particularly the slope gradient, plays a significant role in influencing soil physicochemical properties by controlling runoff, drainage, and soil erosion processes [8]. Previous studies (e.g., Begum 2010) have reported that slope gradient influences soil physicochemical properties through its effects on water flow and material movement [9]. On the other hand, Saha et al. [10] and Malik and Haq [11] assess the chemical characteristics of soil at various altitudes in western Himalayan region and reported that only nitrogen (N) significantly indicated a positive association with altitude whereas all other soil nutrients showed a negative correlation. Consistent with these findings, the present study also observed significant variations in soil properties across different slope gradients and altitudinal zones of Chittagong hilly region. According to Hurni [12], intensive cultivation of farmland has resulted in sediment loss, soil erosion, and increased run-off; moreover, ploughing of rugged topography and steep landscapes is a common practice in the highlands and aggravates soil erosion.

Recently, the demand for agricultural land and food production has led to forced land-use and land-cover changes (LUCC), which have impacted soil properties [13], particularly in areas such as the Chittagong Hills of Bangladesh. The uniqueness of these Hills lies in their varied topographic and ecological features, which support diverse land-use practices crucial to local income, agricultural growth, and ecosystem services. These land-use practices include agroforestry, shifting cultivation (also known as *Jhum*), mixed fruit gardening, timber plantations (such as monocultures like teak, gamar and acacia), and natural forest systems. The region remains vital for agriculture, producing over 35 crop species annually, with fruit plantations covering more than 30% of the land area [14, 15]. At present, agroforestry and other tree-based systems are gradually replacing traditional land-use methods such as *Jhum* cultivation. According to Rahman et al. [16], different crops, fruits, and timber species are grown across various agroforestry systems on the steep slopes of CHT. However, research shows that monoculture plantations, such as those of teak, are associated with severe degradation and increased soil erosion [17]. Deforestation and unsustainable land-use practices have progressively worsened soil conditions, threatening the region's ecological balance [18]. According to Rahman and Bahauddin [19], land-use change and forest management practices directly alter soil biodiversity and soil quality, which in turn affect the functions and productivity of

the forest ecosystem. Therefore, regional differences in soil properties are closely linked to forest management practices. Numerous studies indicate that environmental factors (such as position, elevation, slope, and aspect), organic matter content, climate, and forest cover significantly influence regional variations in soil properties [20- 23]. Along with land-use practices, these factors have accelerated soil erosion and nutrient depletion [24], resulting in the gradual degradation of forest ecosystem.

Forest soil is considered the primary source of nutrients for the forest ecosystem, including N, P, K, S, Na, Ca, Mg, and some micro nutrients [25], and assessing its physicochemical characteristics is essential for evaluating soil fertility. In some cases, soil physicochemical properties such as water holding capacity, BD, porosity, soil pH, CEC, SOM, and SOC also affect the forest ecosystem. For example, soil pH is the most important soil property and one of the determining factors in the plant nutrient availability in the soil [26]. The pH range of an ideal soil for plant growth is slightly acidic (pH 6.5) to slightly alkaline (pH 7.5) [27]. Although some research related to land-use and soil properties has already been conducted by [19, 23, 28-39], there is still limited spatially explicit data on the combined effects of land-use and environmental variables on soil properties, especially in the Chittagong and Chittagong Hill Tracts, despite its ecological significance.

Additionally, information is scarce on how forest plantations influence soil pH, SOC, and physical-chemical properties compared to degraded forest soils. Thus, it is important to evaluate the status of soil physicochemical properties across different land-use types and environmental variables for effective land management and sustainable ecosystems in the Chittagong Hills. Given these knowledge gaps, this study aims to evaluate how environmental variables (such as altitude and slope gradient) and land-use types affect soil physicochemical properties. We hypothesize that natural forest soils exhibit higher nutrient stability and lower compaction compared to monoculture forests, shifting cultivation, and degraded agroforest systems, with variability influenced by altitude and slope position. To test this hypothesis and address the research objectives outlined above, the following sections describe the study site, land-use types, experimental design, sampling strategy, and analytical methods used to assess soil physicochemical and nutritional properties, and related environmental variables under nine different forest soil conditions.

## **2. Materials and Methods**

### **2.1. Description of the study area**

The study was carried out in nine hills located at six different union in Chittagong, Bandarban and Rangamati districts of Chittagong division, in the south eastern zone of Bangladesh. There were three sites in Chittagong (agroforest system (AFS), acacia forest (AF) and young teak forest (YTF)), three sites in Bandarban (shifting cultivation (SC), multi-strata agroforest system (MAFS) and mature teak forest (MTF)), and three sites in the Rangamati district (multi-story fruit garden (MSFG), mixed mature timber forest (MMTF) and natural forest (NF)) (**Figure 1**). The latitude varied from 22°15'59.78" N to 22°50'57.84" N and the longitude from 91°77'81.71" E to 92°19'71.56" E. The study area's climate (Köppen-Geiger classification: Am) has a tropical monsoonal climate [28], with an average annual temperature of 25.1 °C and total rainfall of 2,735 mm. Monthly temperature fluctuations average 9 °C, classifying it within the hyperoceanic subtype. The region is part of the tropical moist forest biome, experiencing a brief dry season and intense monsoonal rains for the rest of the year.

### **2.2. Soil and topography**

The soils of the study area are predominantly derived from parent materials of tertiary geological origin, consisting primarily of sandstones and, in some locations, semi-consolidated to consolidated shale or shale fragments [31]. The weathering processes in the region are quite harsh owing to strong oxidation, leaching, and surface runoff. Therefore, soils are generally coarse-textured. The hill soil (dystric cambisols) is mainly yellowish brown to reddish brown loam and naturally moderate to strongly acid in nature [40]. The mean altitude of the study areas varies significantly, ranging from 26.43 to 106.36 meters above sea level (**Table 1**). This geological formation has contributed to the development of steep and variable slopes, with gradients ranging from 26.07% to a maximum of 77.30% in some locations (**Table 3**). These slopes are particularly prone to very severe landslides and soil erosion, especially during the rainy season when most of the yearly rainfall occurs [31]. This continuous loss of soil reduced soil fertility in the forest ecosystem [30].

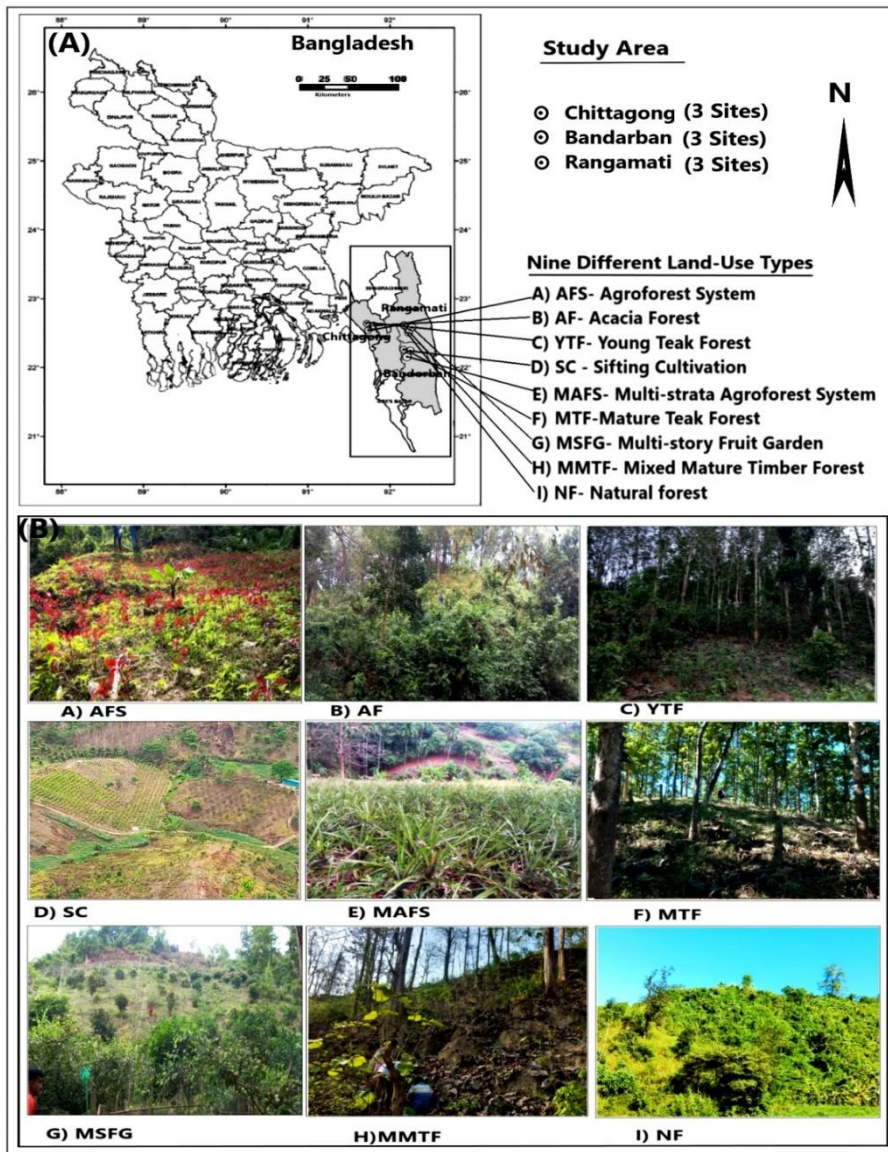


**Figure 1.** Map of the study area; A) Selected nine land-use hills in Chittagong, Bandarban and Rangamati districts; B) AFS- Agroforest system, AF- Acacia forest, YTF- Young teak forest, SC- Shifting cultivation, MAFS- Multi-strata agroforestry system, MTF- Mature teak forest, MSFG- Multi-story fruit garden, MMTF- Mature mixed timber forest, NF- Natural forest

### 2.3. Land-use practices

Research was conducted across nine sites, each representing distinct hills with varying slopes, elevations, land-use and vegetation types. These sites were classified into nine land-use categories: agroforest system (AFs), acacia forest (AF), young teak forest (YTF), shifting cultivation (SC), multi-strata agroforestry system (MAFS), mature teak forest (MTF), multi-story fruit garden (MSFG), mature mixed timber forest (MMTF), and natural forest (NF) (**Figure 1**). At the time of sampling, the agroforestry sites (AFs and MAFS) were under intensive year-round mixed cropping, incorporating fruit and timber production trees such as *Mangifera indica* (mango), *Artocarpus heterophyllus* (jackfruit), *Elaeocarpus serratus* (Jalpai), *Albizia procera* (white Koroï), *Acacia auriculiformis* (acacia), *Tectona grandis* (teak), *Psidium spp.* (guava), *Carica spp.* (papaya), and *Citrus limon* (lemon) etc. The monoculture plantation forests such as acacia and teak forest were predominantly covered by *Acacia auriculiformis* and *Tectona grandis*, both showing minimal ground litter and canopy cover. The shifting cultivation (SC) sites were characterized by diverse seasonal Jhum crops, including *Vigna unguiculata* (long bean), *Abelmoschus esculentus* (okra), *Ananas comosus* (pineapple), *Carica papaya* (papaya), *Musa acuminata* (banana), *Solanum melongena* (brinjal), *Curcuma longa* (turmeric), *Lablab niger* (bean), and *Zea mays* (maize) etc. The multi-story fruit garden sites (MSFG) were dominated by a variety of fruit-bearing trees such as *Punica granatum* (pomegranate), *Litchi chinensis* (lychee), *Mangifera indica* (mango), *Psidium spp.* (guava), *Ziziphusma uritiana* (apple jujube), *Manilkara zapota* (sapodilla), *Citrus maxima* (pomelo), *Citrus sinensis* (sweet orange), and *Citrus reticulata* (mandarin). Mixed mature timber forest (MMTF) featured a diversity of timber species, including *Tectona grandis* (teak), *Swietenia mahagoni* (mahogany), *Acacia auriculiformis* (acacia), *Gmelina arborea* (gamar), along with understory vines and shrubs. Finally, the natural forest (NF) was dominated by native species such as *Swintonia floribunda* (chundul), *Swintonia helferi* (civit or mylum), *Baccaurea ramiflora* (lotkon), *Bombax ceiba* (kapok tree), *Ficus rumphii* (pakur), *Ficus carica* (dumur), *Bambusa spp.* (bamboo), and other indigenous shrubs and climbers.

### 2.4. Experimental design, soil sampling and preparation

To gain a comprehensive understanding of soil properties across the hilly regions of Chittagong, a stratified randomized block design was adopted. This method was employed to account for the natural variation in land-use, slope, and vegetation cover across the selected forested areas. Nine land-use sites were selected based on ecological diversity, including an agroforest system, an acacia forest, a young teak forest, a shifting cultivation, a multi-strata agroforest system, a mature teak forest, a mixed mature timber forest, and a natural forest (**Figure 1**). Each site was further divided into three slope positions: top, middle, and bottom to capture micro-

topographic influences on soil properties. Nine soil samples were taken from these three positions along the hill slope, giving a total of 81 soil samples ( $9 \text{ sites} \times 3 \text{ slope positions} \times 3 \text{ points} = 81 \text{ samples}$ ). The surface soil (0–20 cm) was sampled using a soil auger and core because this layer contains most of the nutrients essential for plant growth and is most affected by land-use changes. About 500 g of soil was collected from each sample and stored in labeled zip-lock plastic bags. Sampling locations were geo-referenced with GPS to ensure accuracy and consistency. Soil samples were gathered using standardized procedures to evaluate soil properties. After collection, visible plant residues and debris were removed. All samples were then air-dried at room temperature for seven days. Once dry, the soils were sieved through a 2 mm stainless steel mesh to achieve uniform particle size before laboratory analysis. The sieved samples were then stored in plastic containers at room temperature.

### **2.5. Analysis of soil properties**

Soil bulk density was analyzed using the core method, as described by [41]. Soil pH was measured in a 1:2.5 soil-to-water suspension using an electronic digital pH meter [42]. The rapid titration method was used to determine the concentration of organic carbon (OC) in the soil [43]. Total N was measured using the micro-Kjeldahl digestion and distillation method [42]. Available P was extracted with the Bray and Kurtz No. 2 method and quantified using a spectrophotometer following the  $\text{SnCl}_2$ -reduced molybdophosphoric blue color method [42]. Available S, Zn, B, and K were extracted with a 1N ammonium acetate solution; S, Zn, and B were quantified using atomic absorption spectrophotometry, and K was measured using flame photometry.

### **2.6. Statistical data analysis**

Before conducting a statistical evaluation, the normality of all datasets was tested using the Shapiro–Wilk test. Data normality was considered at a  $p > 0.05$ . A one-way ANOVA was performed to examine differences in the soil chemical and nutritional indicators among the land use types. As a post hoc test to specify differences, we used Duncan's Multiple Range Test (DMRT), with significance indicated by  $p$ -values ( $p < 0.05$ ,  $p < 0.01$ , and  $p < 0.001$ ). Additionally, the Pearson correlation and multiple regression analysis were conducted to explore the relationships between various soil indicators and environmental variables (altitude, slope). All data analysis was performed using Microsoft Excel 2010 and IBM SPSS 27.0.

## **3. Results and Discussion**

### **Soil physicochemical properties along the land-use sites**

The present study revealed statistically significant differences ( $p < 0.05$ ,  $p < 0.01$ , and  $p < 0.001$ ) in the physicochemical properties of the study soils among different land-use types.

**Table 1.** Distribution of mean ( $\pm$  SD) soil physicochemical properties (0-20 cm depth) across different land-use types in Chittagong Hills

| Land-use Types | BD (g/cm <sup>3</sup> ) | Soil pH          | SOC (%)           | C:N              |
|----------------|-------------------------|------------------|-------------------|------------------|
| AFs            | 1.40 $\pm$ 0.02         | 5.12 $\pm$ 0.05  | 2.49 $\pm$ 0.35   | 16.91 $\pm$ 2.34 |
| AF             | 1.48 $\pm$ 0.02*        | 5.94 $\pm$ 0.09* | 1.43 $\pm$ 0.20   | 9.09 $\pm$ 1.08  |
| YTF            | 1.44 $\pm$ 0.01         | 5.21 $\pm$ 0.09  | 1.23 $\pm$ 0.09   | 13.87 $\pm$ 4.72 |
| SC             | 1.42 $\pm$ 0.01         | 5.76 $\pm$ 0.20* | 0.66 $\pm$ 0.17   | 10.50 $\pm$ 4.60 |
| MAFS           | 1.34 $\pm$ 0.02         | 5.50 $\pm$ 0.05  | 2.06 $\pm$ 0.09   | 6.73 $\pm$ 1.81  |
| MTF            | 1.44 $\pm$ 0.04         | 5.21 $\pm$ 0.07  | 0.96 $\pm$ 0.45   | 7.30 $\pm$ 2.04  |
| MSFG           | 1.36 $\pm$ 0.01         | 5.48 $\pm$ 0.05  | 1.74 $\pm$ 0.08   | 8.53 $\pm$ 2.42  |
| MMTF           | 1.33 $\pm$ 0.02         | 4.74 $\pm$ 0.08  | 2.58 $\pm$ 0.14   | 10.87 $\pm$ 4.25 |
| NF             | 1.30 $\pm$ 0.01*        | 4.86 $\pm$ 0.04  | 3.15 $\pm$ 0.23** | 9.74 $\pm$ 2.74  |
| Mean total     | 1.39 $\pm$ 0.06         | 5.31 $\pm$ 0.39  | 1.81 $\pm$ 0.81   | 10.39 $\pm$ 4.06 |
| F - value      | 28.985                  | 57.568           | 37.340            | 3.164            |
| P - value      | 0.000                   | 0.000            | 0.000             | 0.020            |
|                | ***                     | ***              | ***               | *                |

Each value is the mean of three replicated samples. Significance levels are marked as \* $p < 0.05$ , \*\* $p < 0.01$ , and \*\*\* $p < 0.001$ . SD- Standard deviation, AFs- Agroforest system, AF- Acacia forest, YTF- Young teak forest, SC- Shifting cultivation, MAFS- Multi-strata agroforestry system, MTF- Mature teak forest, MSFG- Multi-story fruit garden, MMTF- Mature mixed timber forest, NF- Natural forest; BD-Bulk density, SOC- Soil organic carbon, C:N- Carbon to nitrogen ratio

#### **Soil bulk density (BD)**

The results of the analysis of variance showed that soil bulk density (BD) differed highly significantly among the various land-use types ( $p < 0.001$ ) (**Table 1**). The highest BD was recorded under the acacia forest (1.48g/cm<sup>3</sup>) followed by mature teak forest (1.44g/cm<sup>3</sup>), young teak forest (1.44g/cm<sup>3</sup>), shifting cultivation (1.42g/cm<sup>3</sup>),

agroforest system ( $1.40\text{g/cm}^3$ ), multi-strata fruit garden ( $1.36\text{g/cm}^3$ ), mixed mature timber forest ( $1.33\text{g/cm}^3$ ) and the least was recorded under natural forest ( $1.30\text{g/cm}^3$ ) site (Table 1). The overall mean BD was  $1.39\text{g/cm}^3$  across nine different land-use sites. The post-hoc multiple comparison test of BD among land-use types also confirmed significant differences ( $p < 0.05$ ) in the acacia and natural forests. In contrast, no significant differences were observed in other land-use types ( $p < 0.05$ ).

In the present study, monoculture plantation forests as well as shifting cultivation and agroforestry systems showed higher BD, which may also be attributed to erosion, intensive agricultural activities, and frequent tillage or machinery use [44]. Several other studies have also reported that agricultural lands generally exhibit higher BD compared to natural forest sites [45], likely due to the continuous removal of organic matter and limited replenishment in cultivated areas. On the contrary, natural forest and multi-strata agroforest system exhibited lower BD in the present study, probably due to maintaining higher organic matter content and dense litter [46]. These findings are slightly consistent with previous studies, such as Chowdhury et al. [32], who reported higher dry BD in agroforestry systems, while Mamun et al. [33] observed the highest BD in monoculture plantations and the lowest in natural forests in Chittagong hills. Similarly, Salim et al. [47] reported higher BD in monoculture plantations and lower BD in mixed plantations. This lower BD in natural forest soils contributes to better soil structure and increased water-holding capacity [48]. Furthermore, Amponash and Meyer [17] and Mongya and Bandyopadhyay [49] observed that high-value plantation forests lead to increased soil degradation and surface bulk density compared to virgin forest soils. Bulk density is also closely associated with several key soil properties, such as soil aeration, water dynamics, and mechanical resistance to root growth [50].

### Soil pH

The ANOVA results showed that soil pH was significantly influenced by land-use ( $p < 0.001$ ) (**Table 1**). The post-hoc analysis showed significant ( $p < 0.05$ ) mean differences in acacia forest and shifting cultivation, while no significant ( $p > 0.05$ ) mean differences were observed among agroforestry, young teak forest, multi-strata agroforestry system, mature teak forest, multi-story fruit garden, mature mixed timber forest, and natural forest (**Table 1**). The lowest soil pH was observed (4.74) in mixed mature timber forest, followed by (4.86) in natural forest. On the other side, the highest soil pH was observed (5.94) in the acacia forest, followed by (5.76) in shifting cultivation. The overall mean soil pH was 5.31 across all land-use sites (**Table 1**). The lower pH levels in mixed timber and natural forests are a characteristic of natural forest ecosystems, where the decomposition of organic matter produces organic acids that enhance nutrient solubility and microbial activity [51]. Previous studies have found the lowest pH in natural forest land, which is consistent with this result [38, 52, 53]. The

results of the present study showed that most of the forested area soils are strongly acidic to slightly acidic, as the Brown Hill soils are naturally moderate to strongly acidic due to intense weathering, erosion, and leaching processes [40, 29, 35, 36]. Biswas et al. [31] and Gafur et al. [30] also found higher soil pH in shifting cultivation compared to a natural forest site.

### **Soil organic carbon (SOC)**

Soil organic carbon (SOC) was statistically significantly affected by land-use type ( $p < 0.001$ ). Post-hoc tests also revealed significant differences ( $p < 0.01$ ) in natural forest, while no significant differences ( $p > 0.05$ ) were observed among other land-uses (**Table 1**). The natural forest exhibited the highest SOC, with mean values of 3.15%. The highest SOC is likely attributable to the dense vegetation cover and the continuous input of organic matter from litter fall and plant residues returned to the soil [54]. In contrast, the shifting cultivation site recorded the lowest SOC of 0.66% which could also be due to severe erosion and intensive cultivation. The overall mean SOC was 1.81% across all land-use sites (**Table 1**). The finding was consistent with Biswas et al. [31], Osman et al. [34], and Mamun et al. [33], who observed that soil OC content was found to be higher in forest land compared to the shifting cultivation site in Chittagong Hill Tract. Similar to this study, Achalu et al. [55] reported that compared to forest land, cultivation and grazing land-use types have a lower percentage of OC content in soils. Majule [6] reported that clearing the natural forest in most upper zones for cultivation has contributed significantly to the reduced soil level of SOC. However, variations in SOC among different studies likely reflect differences in land-use type, climate, and altitudinal gradients, as noted by Tashi et al. [56] and Ahirwal [57].

### **Carbon to nitrogen ratio (C:N ratio)**

Carbon-to-Nitrogen (C:N) ratio is important because it directly impacts residue decomposition and nitrogen cycling in our soils. **Table 1** showed that the C:N ratio was significantly different ( $p < 0.05$ ) among different land-use types. The highest C:N ratio was recorded (16.91) in the agroforest system, and the lowest C:N ratio was recorded (6.73) in the multi-strata agroforest system. Among the remaining land-use types, the C:N ratio was recorded as 13.87 in the young teak forest, followed by 10.87 in the mature mixed timber forest, 10.50 in the shifting cultivation, 9.74 in the natural forest, 9.09 in the acacia forest, 8.53 in the multi-story fruit garden, and 7.30 in the mature teak forest, respectively. In addition, the overall C:N ratio was 10.39 (**Table 1**). The high C:N ratios of the agroforest system and young teak forest represent slower nitrogen cycling and more organic-bound nitrogen, and the low C:N ratios of the multi-strata agroforest system, mature teak forest, and multi-story fruit garden suggest an accelerated nitrogen cycling. When the C:N ratio is greater

than 30:1, nitrogen is fixed by soil microorganisms, whereas when the C:N ratio is less than 20:1, mineral nitrogen is released into the soil environment. In the present study, the C:N ratio was lower than 20:1, indicating that mineral nutrients are released into the plant and soil environment [54]. Other researchers have reported that the C:N ratio is affected by land-use due to competing interests for space, such as crop production, livestock, and settlement [58, 59].

### Soil nutritional properties along the land-use sites

#### Total Nitrogen (TN)

**Table 2.** Distribution of mean ( $\pm$  SD) soil nutritional properties (0-20 cm depth) across different land-use types in the Chittagong Hills

| Land-use Types | TN (%)           | AP (ppm)          | AK (meq/100g soil) | AS (ppm)          | Azn (ppm)          | AB (ppm)         |
|----------------|------------------|-------------------|--------------------|-------------------|--------------------|------------------|
| AFs            | 0.16 $\pm$ 0.06  | 12.28 $\pm$ 1.25  | 0.17 $\pm$ 0.03    | 11.81 $\pm$ 1.51  | 0.97 $\pm$ 0.07**  | 0.23 $\pm$ 0.03  |
| AF             | 0.16 $\pm$ 0.04  | 6.30 $\pm$ 2.92   | 0.14 $\pm$ 0.02    | 4.43 $\pm$ 2.45*  | 1.59 $\pm$ 0.05*   | 0.14 $\pm$ 0.01* |
| YTF            | 0.10 $\pm$ 0.05  | 5.05 $\pm$ 2.32   | 0.25 $\pm$ 0.02    | 9.63 $\pm$ 1.55   | 1.17 $\pm$ 0.07    | 0.32 $\pm$ 0.05  |
| SC             | 0.08 $\pm$ 0.03  | 3.07 $\pm$ 2.99   | 0.11 $\pm$ 0.01*   | 13.86 $\pm$ 1.37  | 0.75 $\pm$ 0.04    | 0.25 $\pm$ 0.04  |
| MAFS           | 0.25 $\pm$ 0.03  | 18.48 $\pm$ 2.42* | 0.31 $\pm$ 0.01*   | 14.91 $\pm$ 1.50  | 1.80 $\pm$ 0.10*** | 0.33 $\pm$ 0.03  |
| MTF            | 0.13 $\pm$ 0.06  | 8.50 $\pm$ 1.23   | 0.16 $\pm$ 0.01    | 7.53 $\pm$ 1.42   | 0.83 $\pm$ 0.04    | 0.39 $\pm$ 0.03* |
| MSFG           | 0.22 $\pm$ 0.07  | 14.79 $\pm$ 1.00  | 0.27 $\pm$ 0.03    | 15.22 $\pm$ 2.28  | 1.47 $\pm$ 0.04    | 0.20 $\pm$ 0.05  |
| MMTF           | 0.24 $\pm$ 0.04  | 10.19 $\pm$ 1.22  | 0.21 $\pm$ 0.01*   | 11.94 $\pm$ 2.14  | 1.36 $\pm$ 0.04*   | 0.45 $\pm$ 0.02* |
| NF             | 0.32 $\pm$ 0.02* | 12.45 $\pm$ 2.13  | 0.26 $\pm$ 0.03    | 19.07 $\pm$ 1.55* | 1.15 $\pm$ 0.02*   | 0.26 $\pm$ 0.03  |
| Mean total     | 0.18 $\pm$ 0.08  | 10.12 $\pm$ 5.04  | 0.21 $\pm$ 0.07    | 12.04 $\pm$ 4.49  | 1.23 $\pm$ 0.34    | 0.29 $\pm$ 0.10  |
| F- value       | 9.128            | 16.922            | 44.567             | 18.092            | 120.809            | 25.310           |
| P- value       | 0.000            | 0.000             | 0.000              | 0.000             | 0.000              | 0.000            |

Each value is the mean of three replicated samples. Significance levels are marked as \* $p < 0.05$ , \*\* $p < 0.01$ , and \*\*\* $p < 0.001$ . SD- Standard deviation, AFs- Agroforest system, AF- Acacia forest, YTF- Young teak forest, SC- Shifting cultivation, MAFS-

Multi-strata agroforestry system, MTF- Mature teak forest, MSFG- Multi-story fruit garden, MMTF- Mature mixed timber forest, NF- Natural forest; TN-Total Nitrogen, AP-Available Phosphorus, AK-Available Potassium, AS-Available Sulfur, AZn-Available Zinc, AB-Available Boron

**Table 2** shows that the total nitrogen (TN) concentration was significantly affected by land use types ( $p < 0.001$ ). Among the nine land-use type, the highest mean TN content was recorded under the natural forest (0.32%) followed by multi-strata agroforest system (0.25%), mixed mature timber forest (0.24%), multi-strata fruit garden (0.22%), acacia forest (0.16%), agroforest system (0.16%), mature teak forest (0.13%), young teak forest (0.10%) and the least was recorded under shifting cultivation (0.08%). Besides, the overall mean TN content was (0.18%) across different land-use types. Post-hoc multiple comparison test of TN among land-use types revealed significant differences ( $p < 0.05$ ) in the natural forest, whereas no significant differences ( $p > 0.05$ ) were observed among the multi-strata agroforestry system, acacia forest, agroforest system, mature teak forest, young teak forest, shifting cultivation, mixed mature timber forest, and multi-strata fruit garden (**Table 2**). This nitrogen enrichment in natural forest may be due to the high OM content, which is the main source of soil TN due to the release of nitrogen during mineralization, and ideal forest microclimate conditions, which tempered soil temperature and therefore reduced TN loss through volatilization [60, 54]. Additional studies by Chowdhury et al. [32], Biswas et al. [31], Zaman et al. [61], and Chen et al. [62], consistently report higher nitrogen in forest soils compared to other land-uses. Conversely, shifting cultivation presents the lowest TN concentration, which might be due to continuous cultivation that leads to the depletion of organic matter residue [63,64], surface runoff [33,65], and downward leaching of negatively charged nitrates [65]. Erosion on steep slopes can strip away nitrogen-rich soil, thereby reducing nitrogen availability in these hilly areas. Findings by Osman et al. [34] highlight nitrogen differences between shifting cultivation and the forested areas, showing higher levels in multi-year cultivated soils and lower levels in 2-year cultivated areas compared to natural forests. Besides, Berger et al. [66] emphasized the link between soil nitrogen and organic matter, which may explain the elevated nitrogen in undisturbed forests. The TN levels observed in this study are generally on the lower side, consistent with trends reported by the Soil Resource Development Institute (SRDI) [67], which found that soils in Bangladesh typically exhibit low nitrogen content. Demelash and Stahr [68], Yonas et al. [69] found that higher total nitrogen content was registered in conserved farmland compared with unconserved fields. According to the rating scale suggested by Hasan et al. [70], the TN content in the study soils ranged from very low (0.32% in shifting cultivation) to medium (0.08% in multi-strata agroforest system).

#### **Available Phosphorus (AP)**

The ANOVA results indicated that available phosphorus (AP) concentration in the soils of the study area was significantly affected by land-use type ( $p < 0.001$ ) (**Table**

2). Besides, among the nine land-use types, the highest mean AP concentration was observed in multi-strata agroforest system (18.48ppm) followed by multi-story fruit garden (14.79ppm), natural forest (12.45ppm), agroforest system (12.28ppm), mixed mature timber forest (10.19ppm), mature teak forest (8.50ppm), acacia forest (6.30ppm), young teak forest (5.05ppm) and the least was observed in the shifting cultivation (3.07ppm) (**Table 2**). The post-hoc multiple comparison test of AP among land-use types revealed significant differences ( $p < 0.05$ ) in the multi-strata agroforestry system. But no significant differences ( $p > 0.05$ ) were observed in the other land-use types. The overall mean AP across land-use types was 10.12 ppm (**Table 2**). Higher AP in multi-strata agroforest system, multi-story fruit garden, and agroforest systems may be due to the application of phosphorus-rich fertilizers, namely diammonium phosphate ( $(\text{NH}_4)_2\text{HPO}_4$ ), and the addition of manure on cultivated land [71, 72]. Similarly, Sharpley et al. [73] and Annabi et al. [74] also found that tillage and phosphorus fertilization increase P availability. In contrast, lower P levels in shifting cultivation and young teak forest may result from reduced organic inputs and erosion, as reported by Mamun et al. [33]. Phosphorus cycling in soil involves processes such as plant uptake, adsorption-desorption, mineralization, and microbial immobilization [75], with factors like pH and soil type also affecting phosphorus fixation [76]. Previous studies [77, 71] indicated that acid hill soils are rich in Fe/Al oxides and hydroxides, and the fixation of P by these compounds may be a possible reason for low P in soil. According to the rating scale suggested by Hasan et al. [70] and SRDI [67], the AP content in the study soils ranged from very low (3.07 ppm in shifting cultivation) to medium (18.48 ppm in the multi-strata agroforest system).

### Available Potassium (AK)

The results presented in **Table 2** indicate that the available potassium (AK) content was significantly influenced by land-use type ( $p < 0.001$ ). Available potassium (AK) levels exhibited considerable variation; the highest mean AK was recorded in the multi-strata agroforestry system (0.31meq/100g) followed by the multi-story fruit garden (0.27meq/100g), natural forest (0.26meq/100g), young teak forest (0.25meq/100g), mixed mature timber forest (0.21meq/100g), agroforest system (0.17meq/100g), mature teak forest (0.16meq/100g), acacia forest (0.14meq/100g) and the least was recorded in the shifting cultivation(0.11meq/100g) (**Table 2**).

The post-hoc multiple comparison test of AK among land-use types also confirmed significant differences ( $p < 0.05$ ) in shifting cultivation, multi-strata agroforest system, and the multi-story fruit garden, whereas no significant differences ( $p > 0.05$ ) were observed in other land-use types. The overall mean AK across all land-use types was (0.21meq/100g) (**Table 2**). High potassium levels in multi-strata agroforest system and multi-story fruit garden may result from nutrient recycling and fertilizer

applications. Biswas et al. [31] found more potassium in bushy lands and forest sites than in shifting cultivation sites in the Chittagong Hills. In contrast, Mamun et al. [33] also reported lower potassium in *Tectona grandis* plantations and higher potassium in cultivated areas, which partially aligns with the present study. Again, Brand and Pfund [78] observed about 20 kg ha<sup>-1</sup> increases in K after burning. Overall, potassium levels across the land-use ranged from low (0.11meq/100g in shifting cultivation) to optimum (0.31meq/100g in a multi-strata agroforestry system), aligning with the classification reported in the 'Soil Fertility Trends in Bangladesh 2010 to 2020' by Hasan et al. [70] and SRDI [67]. That is, the content of the available potassium is also dependent on the specific factors such as climate, topography, altitude, and land-use.

### **Available Sulfur (AS)**

According to the ANOVA results, the amount of available sulfur (AS) was significantly affected ( $p < 0.001$ ) by land-use types (**Table 2**). The post-hoc multiple comparison test of AS among land-use types revealed significant differences ( $p < 0.05$ ) in the acacia forest and natural forest. No significant differences ( $p > 0.05$ ) were observed in the other land-use types (**Table 2**). The highest mean AS content was observed in the natural forest (19.07ppm) followed by multi-story fruit garden (15.22ppm), multi-strata agroforestry system (14.91ppm), shifting cultivation (13.86ppm), mixed mature timber forest (11.94ppm), agroforest system (11.81ppm), young teak forest (9.63ppm), mature teak forest (7.53ppm) and the least was recorded in the acacia forest (4.43ppm) (**Table 2**). And the overall mean AS content was (12.04ppm) across the nine land-use types. These findings partially align with Mamun et al. [33]. The possible reason could be the high OM content, which is the main source of soil AS. On the other hand, the higher AS levels in multi-story fruit gardens and multi-strata agroforestry systems were probably due to the application of commercial fertilizers. Hassan et al. [39] found AS levels between 1.00 and 20.36 mg/kg in the Chittagong Hill Tracts, which partially supports these findings. Besides, according to the rating scale suggested by Hasan et al. [70] and SRDI [67], the AS content in the study soils ranged from very low (4.43 ppm in acacia forest) to medium (19.07 ppm in natural forest).

### **Available Zinc (AZn)**

The ANOVA results also showed that available zinc (AZn) content varied significantly ( $p < 0.001$ ) among land-use types (**Table 2**). The highest mean AZn content was observed in the multi-strata agroforest system (1.80ppm) followed by acacia forest (1.59ppm), multi-story fruit garden (1.47ppm), mixed mature timber forest (1.36ppm), young teak forest (1.17ppm), natural forest (1.15ppm), agroforest system (0.97ppm), mature teak forest (0.83ppm), and the least was recorded in the shifting cultivation

(0.75ppm) (Table 2). Additionally, the post-hoc multiple comparison tests of AZn among land-use types confirmed significant differences in the multi-strata agroforest system at  $p < 0.001$ , agroforestry system at  $p < 0.01$ , and acacia forest, mixed timber forest, and natural forest at  $p < 0.05$  level. No significant differences ( $p > 0.05$ ) were observed in other land-use types (Table 2). These findings align with Hassan et al. [39], who reported zinc levels ranging from 0.44 to 0.71 mg/kg in the Chittagong Hill Tracts. Overall, AZn levels across land-use types ranged from low (0.75ppm in shifting cultivation) to optimum (1.80ppm in the multi-strata agroforestry system), consistent with the classification reported in 'Soil Fertility Trends in Bangladesh 2010 to 2020' by Hasan et al. [70] and SRDI [67].

### Available Boron (AB)

The results of ANOVA showed that the amount of available boron (AB) was significantly affected by land-use type ( $p < 0.001$ ) (Table 2). The highest AB content was recorded in the mixed mature timber forest (0.45ppm), indicating boron sufficiency in plantation forested areas. The lowest AB content was recorded in the acacia forest (0.14ppm), which could restrict plant growth, particularly in acacia-dominated areas. Among the remaining land-use types, the AB content was recorded as 0.39ppm in the mature teak forest, followed by 0.33ppm in the multi-strata agroforest system, 0.32ppm in the young teak forest, 0.26ppm in the natural forest, 0.25ppm in the shifting cultivation, and 0.23ppm in the agroforest system, respectively (Table 2). The average AB concentration across all sites was 0.29ppm. The post-hoc multiple comparison tests of AB among land-use types confirmed significant differences ( $p < 0.05$ ) in mature mixed timber forest, mature teak forest, and acacia forest, while no significant differences were shown in other land-uses (Table 2). Hassan et al. [39] found boron levels between 0.23 and 0.25 mg/kg in hill soils of the Chittagong Hill Tracts. Boron availability is influenced by soil parent material, texture, and climatic conditions, as described by Shorrocks [79]. According to the rating scale suggested by Hasan et al. [70] and SRDI [67], the AB content in the study soils ranged from low (0.14 ppm in an acacia forest) to medium (0.45 ppm in a mixed mature timber forest).

**Environmental variables (altitude and slope) along land use sites**

**Table 3.** Environmental Variables (altitude and slope) across different land-use types in the Chittagong Hills

| Land-use Types | Altitude (m) |             |             |                    | Slope (%) |             |             |                   |
|----------------|--------------|-------------|-------------|--------------------|-----------|-------------|-------------|-------------------|
|                | Hill top     | Hill middle | Hill bottom | Mean $\pm$ SD      | Hill top  | Hill middle | Hill bottom | mean $\pm$ SD     |
| AFs            | 53.05        | 41.23       | 28.02       | 40.77 $\pm$ 12.52  | 95.04     | 68.55       | 9.68        | 57.76 $\pm$ 43.69 |
| AF             | 54.23        | 40.67       | 22.09       | 39.00 $\pm$ 16.14  | 107.54    | 72.05       | 28.47       | 69.35 $\pm$ 39.60 |
| YTF            | 52.43        | 34.17       | 19.33       | 35.31 $\pm$ 16.58  | 65.67     | 49.43       | 19.07       | 44.72 $\pm$ 23.65 |
| SC             | 81.76        | 65.96       | 37.26       | 61.66 $\pm$ 22.56  | 84.15     | 75.76       | 30.17       | 63.36 $\pm$ 29.05 |
| MAFS           | 130.01       | 110         | 79.04       | 106.35 $\pm$ 25.68 | 100.54    | 90          | 41.36       | 77.30 $\pm$ 31.57 |
| MTF            | 119.6        | 99.13       | 78.15       | 98.96 $\pm$ 20.73  | 84.15     | 61.96       | 25.36       | 57.16 $\pm$ 29.67 |
| MSFG           | 98.56        | 78.55       | 50.21       | 75.77 $\pm$ 24.29  | 84.15     | 58.8        | 29.43       | 57.46 $\pm$ 27.38 |
| MMTF           | 40.33        | 28.18       | 10.78       | 26.43 $\pm$ 14.85  | 49.43     | 19.09       | 9.68        | 26.07 $\pm$ 20.77 |
| NF             | 44.55        | 30.46       | 18.62       | 31.21 $\pm$ 12.98  | 65.21     | 32.46       | 5.78        | 34.48 $\pm$ 29.77 |
| F- value       |              |             |             | 7.461              | F-value   |             |             | 0.822             |
| P- value       |              |             |             | 0.000              | P-value   |             |             | 0.594             |

SD- Standard deviation, AFs- Agroforest system, AF- Acacia forest, YTF- Young teak forest, SC- Shifting cultivation, MAFS- Multi-strata agroforestry system, MTF- Mature teak forest, MSFG- Multi-story fruit garden, MMTF- Mature mixed timber forest, NF- Natural forest

**Table 3** results showed that significant environmental variables (altitude and slope) were observed across different land-use types in the study area. Specifically, altitude ranged from 10.78 meters in mature mixed timber forest to a maximum of 130.01 meters in multi-strata agroforestry systems. Similarly, slope gradients varied considerably, from a gentle incline of 5.78% in natural forests to a steep slope of 107.54% in an acacia forest. Multi-strata agroforestry systems situated at Talukdar Para, Bandarban, take the lead with the highest mean elevation (106.35m) and slope (77.30%), indicative of typical upland cultivation practices in Bangladesh. On the contrary, the mean altitude (26.43m) and slope (26.07%) of the mature mixed timber forest in Kaptai, Rangamati, indicate much less steep terrain. Mean altitudes were observed across the sites, 26.43 to 106.35 m, and the gentlest to

steepest slopes were 26.07 to 77.30% **Table 3**. The study indicates that variations in altitude and slope across different land-use types are affecting soil drainage, erosion, and fertility, which corroborates previous studies in hilly terrains of Bangladesh. According to Biswas et al. [31], the increase in altitude along with slope steepness will lead to better-drained soil, making it prone to erosion. On the other hand, steep slopes (e.g., MAFS at 77.30%) are problematic for soil retention. Shoaib et al. [37] reported that soil erosion was higher in areas of shifting cultivation (40-45 t ha<sup>-1</sup> yr<sup>-1</sup>) and on slopes (33-42%) than on gentle slopes (15%), highlighting the necessity for sustainable land use planning.

### Pearson correlation coefficient analysis between the soil properties and environmental variables

**Table 4.** Pearson correlation coefficient between the soil physical indication and environmental variables of soil in the Chittagong hills

|                           | Altitude<br>(m) | Slope<br>(%) | BD<br>(g/cm <sup>3</sup> ) | pH          | SOC<br>(%) | C:N        | TN<br>(%)  | AP<br>(ppm) | AK<br>(meq/100g<br>soil) | AS<br>(ppm) | A Zn<br>(ppm) | AB<br>(ppm) |
|---------------------------|-----------------|--------------|----------------------------|-------------|------------|------------|------------|-------------|--------------------------|-------------|---------------|-------------|
| Altitude<br>(m)           | 1               |              |                            |             |            |            |            |             |                          |             |               |             |
| Slope (%)                 | .679**          | 1            |                            |             |            |            |            |             |                          |             |               |             |
| BD (g/cm <sup>3</sup> )   | 0.142           | .407*        | 1                          |             |            |            |            |             |                          |             |               |             |
| pH                        | 0.229           | 0.301        | .537**                     | 1           |            |            |            |             |                          |             |               |             |
| SOC (%)                   | -.430*          | -.424*       | -<br>.784**                | -<br>.607** | 1          |            |            |             |                          |             |               |             |
| C:N                       | -<br>0.168      | 0.332        | 0.225                      | -<br>0.319  | 0.043      | 1          |            |             |                          |             |               |             |
| TN (%)                    | -<br>0.262      | -<br>.499**  | -<br>.829**                | -<br>0.362  | .836*<br>* | -.440*     | 1          |             |                          |             |               |             |
| AP (ppm)                  | 0.185           | -<br>0.199   | -<br>.681**                | -<br>0.179  | .625*<br>* | -.385*     | .737*<br>* | 1           |                          |             |               |             |
| AK<br>(meq/100<br>g soil) | 0.085           | -<br>0.225   | -<br>.661**                | -<br>0.283  | .513*<br>* | -<br>0.278 | .657*<br>* | .760*<br>*  | 1                        |             |               |             |
| AS (ppm)                  | -<br>0.120      | -.385*<br>*  | -<br>.867**                | -<br>0.294  | .555*<br>* | -<br>0.221 | .649*<br>* | .561*<br>*  | .568*<br>*               | 1           |               |             |
| A Zn<br>(ppm)             | 0.057           | 0.026        | -<br>0.280                 | 0.208       | 0.323      | -<br>0.367 | .512*<br>* | .586*<br>*  | .643*<br>*               | 0.05<br>7   | 1             |             |
| AB (ppm)                  | -<br>0.011      | -.454*<br>*  | -<br>0.316                 | -<br>.560** | 0.115      | -<br>0.249 | 0.182      | 0.127       | 0.213                    | 0.11<br>9   | -<br>0.095    | 1           |

\*. Correlation is significant at the 0.05 level (2-tailed). \*\*. Correlation is significant at the 0.01 level (2-tailed).

The correlation matrix between soil physicochemical properties and environmental variables of different land-use types showed strong and statistically significant relationships at the 95% and 99% confidence levels ( $p < 0.05$  and  $p < 0.01$ ,

respectively) (**Table 4**). The Pearson correlation analysis revealed a significant positive relationship between altitude and slope ( $r = 0.679, p < 0.01$ ), indicating that higher elevation areas in the study region are generally associated with steeper slopes. Both altitude and slope also showed a significant negative correlation with SOC ( $r = -0.430, p < 0.05$ , and  $r = -0.424, p < 0.05$ , respectively), suggesting that SOC content decreases significantly as altitude and slope gradient increase [80, 60, 81]. The slope gradient showed a negative correlation with TN ( $r = -0.499, p < 0.01$ ), indicating that the TN content was higher in the lower slope than in the higher slope gradients [82, 83, 60]. But, TN has a non-significant negative correlation with altitude ( $r = -0.262$ ). Moreover, the slope gradient showed a negative correlation with AS ( $r = -0.385, p < 0.05$ ) and AB ( $r = -0.454, p < 0.05$ ), suggesting that less nutrient availability is associated with higher slope gradients. On the other hand, slope gradient showed a positive correlation with BD ( $r = 0.407, p < 0.05$ ), indicating that BD at the upper slope was significantly higher than at lower positions, suggesting that soils are more compacted at the upper slope [60]. Besides, **Table 4** shows that BD has a negative correlation with SOC ( $r = -0.784, p < 0.01$ ), TN ( $r = -0.829, p < 0.01$ ), AP ( $r = -0.681, p < 0.01$ ), AK ( $r = -0.661, p < 0.01$ ) and AS ( $r = -0.867, p < 0.01$ ) suggesting that soil becomes more compacted and less nutrient availability [84]. The number of pore spaces and SOM is inversely related to BD [85]. On the contrary, the positive correlation of BD with pH ( $r = 0.537, p < 0.01$ ), indicates that compact soil's low acidity is due to low OM content. Besides, soil pH negatively correlates with SOC ( $r = -0.607, p < 0.01$ ) and AB ( $r = -0.560, p < 0.01$ ) as acidic conditions enhance nutrient solubility [86]. Soil OC strongly positively correlates with TN ( $r = 0.836, p < 0.01$ ), AP ( $r = 0.625, p < 0.01$ ), AK ( $r = 0.513, p < 0.01$ ), and AS ( $r = 0.555, p < 0.01$ ), suggesting its role in nutrient availability [87]. On the contrary, the C:N ratio is negatively correlated with TN ( $r = -0.440, p < 0.01$ ) and AP ( $r = -0.385, p < 0.01$ ) (Table 4). Additionally, TN positively correlated with AP ( $r = 0.737, p < 0.01$ ), AK ( $r = 0.657, p < 0.01$ ), AS ( $r = 0.649, p < 0.01$ ), and AZn ( $r = 0.512, p < 0.01$ ), indicating the role of nitrogen, which increases the soil nutrient availability. Similarly, AP showed a positive correlation with AK ( $r = 0.760, p < 0.01$ ), AS ( $r = 0.561, p < 0.01$ ), and AZn ( $r = 0.586, p < 0.01$ ), indicating that AP enhances nutrient availability. AK also showed a positive correlation with AS ( $r = 0.568, p < 0.01$ ) and AZn ( $r = 0.643, p < 0.01$ ), which indicated that AK increases AS and AZn availability. This correlation analysis provided valuable insights into the complex interactions between soil properties and environmental variables.

### Linear regression analysis between slope, altitude and soil physicochemical properties

**Table 5** Linear regression analysis between soil physicochemical properties and environmental variables (altitude and slope) in the Chittagong Hills

| Independent variables | Dependent variables     | Multiple <i>R</i> | <i>R</i> <sup>2</sup> | Adjusted <i>R</i> <sup>2</sup> | <i>F</i> | Sig   |
|-----------------------|-------------------------|-------------------|-----------------------|--------------------------------|----------|-------|
| Altitude (m)          | BD (g/cm <sup>3</sup> ) | 0.142             | 0.020                 | -0.019                         | 0.514    | 0.480 |
| Altitude (m)          | pH                      | 0.229             | 0.052                 | 0.014                          | 1.379    | 0.251 |
| Altitude (m)          | SOC (%)                 | 0.430             | 0.185                 | 0.152                          | 5.676    | 0.025 |
| Altitude (m)          | C:N                     | 0.168             | 0.028                 | -0.011                         | 0.724    | 0.403 |
| Altitude (m)          | TN (%)                  | 0.272             | 0.074                 | 0.037                          | 2.004    | 0.169 |
| Altitude (m)          | AP (ppm)                | 0.185             | 0.034                 | -0.005                         | 0.882    | 0.357 |
| Altitude (m)          | AK (meq/100g soil)      | 0.085             | 0.007                 | -0.032                         | 0.182    | 0.673 |
| Altitude (m)          | AS (ppm)                | 0.120             | 0.014                 | -0.025                         | 0.368    | 0.550 |
| Altitude (m)          | AZn (ppm)               | 0.057             | 0.003                 | -0.037                         | 0.083    | 0.776 |
| Altitude (m)          | AB (ppm)                | 0.011             | 0.000                 | -0.040                         | 0.003    | 0.956 |
| Slope (%)             | BD (g/cm <sup>3</sup> ) | 0.407             | 0.166                 | 0.132                          | 4.969    | 0.035 |
| Slope (%)             | pH                      | 0.301             | 0.091                 | 0.054                          | 2.493    | 0.127 |
| Slope (%)             | SOC (%)                 | 0.424             | 0.180                 | 0.147                          | 5.484    | 0.027 |
| Slope (%)             | C:N                     | 0.332             | 0.110                 | 0.075                          | 3.099    | 0.091 |
| Slope (%)             | TN (%)                  | 0.506             | 0.256                 | 0.227                          | 8.622    | 0.007 |
| Slope (%)             | AP (ppm)                | 0.199             | 0.040                 | 0.001                          | 1.036    | 0.319 |
| Slope (%)             | AP (meq/100g soil)      | 0.225             | 0.051                 | 0.013                          | 1.336    | 0.259 |
| Slope (%)             | AS (ppm)                | 0.385             | 0.149                 | 0.114                          | 4.360    | 0.047 |
| Slope (%)             | A Zn (ppm)              | 0.026             | 0.001                 | -0.039                         | 0.017    | 0.897 |
| Slope (%)             | AB (ppm)                | 0.454             | 0.206                 | 0.174                          | 6.486    | 0.017 |

BD-Bulk density, SOC- Soil organic carbon, C:N- Carbon to nitrogen ratio, TN-Total Nitrogen, AP-Available Phosphorus, AK-Available Potassium, AS-Available Sulfur, AZn-Available Zinc, AB-Available Boron

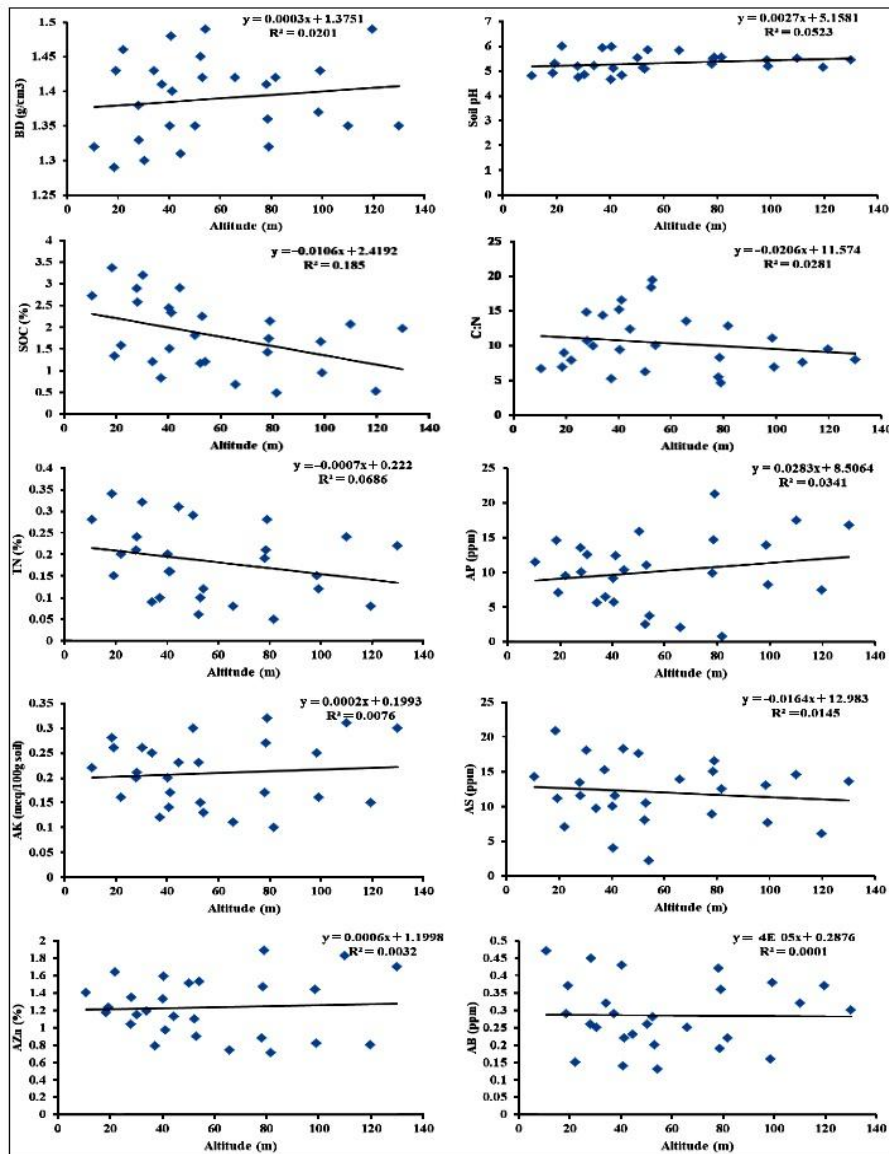


**Figure 2.** Linear regressions showing the effect of altitude on soil properties in the Chittagong Hills

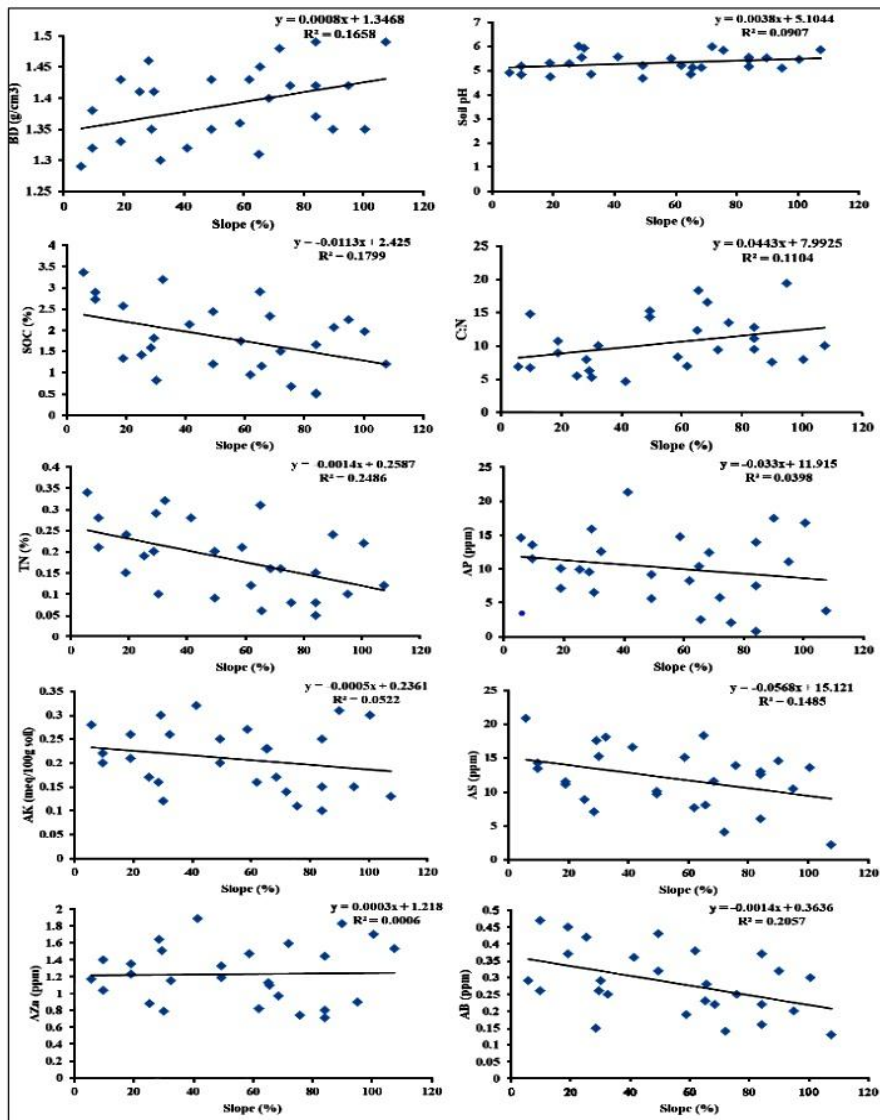


**Figure 3.** Linear regressions showing the effect of slope on soil properties in the Chittagong Hills

The linear regression analysis revealed that soil properties were significantly related to both slope and altitude (**Figures 2 and 3**). Regarding altitude, only SOC explained 18.9% of the variance ( $R^2 = 0.185$ ,  $p < 0.05$ ), indicating a moderate yet significant

effect. Other properties, such as BD, soil pH, C:N ratio, TN, AP, AK, AS, AZn, and AB, displayed weak, statistically non-significant relationships with altitude, accounting for between 0% and 10% of the variance ( $p > 0.05$ ) (**Table 5**). Similarly, considering the slope gradient, TN accounted for 25.6% of the variance ( $R^2 = 0.256$ ,  $p < 0.01$ ), while AB and SOC explained 20.6% ( $R^2 = 0.206$ ,  $p < 0.05$ ) and 18.0% ( $R^2 = 0.180$ ,  $p < 0.05$ ) of the variance, respectively. Moreover, BD and AS accounted for 16.6% ( $R^2 = 0.166$ ,  $p < 0.05$ ) and 14.9% ( $R^2 = 0.149$ ,  $p < 0.05$ ) of the variance, indicating moderate but significant effects associated with slope gradient (**Table 5**). Other properties, such as soil pH, C:N ratio, AP, AK, and AZn, exhibited weak, statistically non-significant relationships with slope gradient, explaining between 0.01% and 12% of the variance ( $p > 0.05$ ) (**Table 5**). Overall, these findings suggest that soil properties are moderately to weakly influence by both slope and altitude; the best relations were observed with slope, which had a slightly stronger influence than altitude.

#### **4. Conclusion**

The analysis of soil physicochemical properties revealed that both land-use types and environmental variables significantly influence soil quality and fertility in the south-eastern hilly regions of Bangladesh. Compared to natural forest soils, other land uses generally showed distinct variations in soil properties. Forest soils exhibited higher organic carbon content, lower bulk density, and lower pH, reflecting healthier nutrient cycling and minimal anthropogenic disturbance. But shifting cultivation, monoculture plantations (e.g., teak and acacia), and degraded agroforestry systems exhibited reduced soil organic carbon, higher bulk density, and lower nutrient availability due to continuous tillage, erosion, and insufficient organic matter inputs.

Considering the environmental variables, Pearson correlation analysis revealed a positive correlation between altitude and slope, whereas it was negatively correlated with soil organic carbon. On the other hand, slope gradient was positively correlated with bulk density (BD) but negatively correlated with soil organic carbon (SOC), total nitrogen (TN), available sulfur (AS), and available boron (AB). Among soil properties, positive correlations were observed between BD, pH, SOC, TN, AP, AK, and AS. In contrast, negative correlations were observed between BD, soil pH, SOC, C: N ratio, TN, AP, AK, and AS. Regression analysis showed that soil properties are moderately to weakly influence by both slope and altitude, but the best relations were seen with slope.

Overall, the study findings suggest that maintaining vegetation cover, adopting conservation-oriented farming practices, and enhancing organic matter inputs are important for improving soil physicochemical properties in hilly ecosystems. Implementing sustainable land management strategies that integrate both land-use planning and environmental variability (especially high altitude and slope of forest)

will help prevent further degradation and promote long-term soil productivity in this region. Additionally, site-specific adaptive land management practices are required to maintain soil productivity and ecosystem resilience in the Chittagong Hills for generations to come. Further studies should investigate the combined effects of and seasonal variation and land-use types on soil quality and health among various land-use systems that contribute to soil degradation.

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### Author Contributions

The first author performed all the research with the supervision of the second author. The first author wrote the research concept and experimental design; carried out the experiments; collected data; and performed data analysis, with continuous input from the second author. First author drafted the manuscript and it was revised with input and guidance from the second author.

### References

- [1] [FAO] Food and Agriculture Organization of the United Nations. 2015. *Soil is a non-renewable resource*. Rome: FAO
- [2] H. C. J. Godfray, J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, , J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas and C. Toulmin: *Science*, 2010, **327**(5967), 812-818.
- [3] R. Lal: *Land Degradation and Development*, 2001, **12**(6), 519–539.
- [4] E. Elias: *South African Journal of Plant and Soil*, 2019, **36**(2) 153-156.
- [5] Y. G. Selassie, F. Anemut and S. Addisu: *Environ. Syst. Res.* 2015, **4**, 3–7.
- [6] A. E. Majule: LUCID Working Paper, no. **26**. 2003, Nairobi (Kenya): ILRI
- [7] N. Arunrat, N. Pumijumnong, S. Sereenonchai, U. Chareonwong: *Agronomy*, 2020, **10**, 305.
- [8] N. Pitta-Osses, C. Centeri, Á. Fehér and K. Katona: *Forests*, 2022, **13**, 1234.
- [9] F. Begum, R. M. Bajracharya, S. Sharma and B. K. Sitaula: *International Journal of Sustainable Development & World Ecology*, 2010, **17**(5), 438–443.
- [10] S. Saha, G. S. Rajwar and M. Kumar: *Acta Ecologica Sinica*, 2018, **38**(1), 1-8.
- [11] Z. A. Malik and S. M. Haq: *Journal of Forest and Environmental Science*, 2022, **38**(1), 21-37.

- [12] H. Hurni: *Mountain Research and Development*, 1983, **3**(2), 14–19.
- [13] J. A. Foley: *Scientific American*, 2011, **305**, 60–65.
- [14] R. Ahammad and N. Stacey: “*Agrarian Change in Tropical Landscapes*”, 2016, 190–233.
- [15] B. K. Bala, S. Majumder, S. A. Hossain, M. A. Haque and M. A. Hossain: *Environment, Development and Sustainability*, 2013, **15**(4), 949–966.
- [16] S. A. Rahman, M. F. Rahman and T. Sunderland: *Agroforestry Systems*, 2012, **84**(2), 141–155.
- [17] I. Amponsah and W. Meyer: *Communications in Soil Science and Plant Analysis*, 2000, **31**(3-4), 355–373.
- [18] A. Rahman, K. J. Mustanoja: *Bano Biggyan Patrika*, 1978, **7**(1-2), 48–59.
- [19] M. H. Rahman and M. Bahauddin: *Proceedings of Pakistan Academy of Sciences: B. Life and Environmental Sciences* 2018, **55**(4), 71–84.
- [20] L. Jiang, Z. He, J. Liu, C. Xing, X. Gu, C. Wei, J. Zhu and X. Wang: *Forests*, 2019, **10**(12), 1089.
- [21] Y. Zhang, J. Ai, Q. Sun, Z. Li, L. Hou, L. Song, G. Tang, L. Li and G. Shao: *Catena*, 2021, **196**, 104872.
- [22] B. P. Umali, D. P. Oliver, S. Forrester, D. J. Chittleborough, J. L. Hutson, R. S. Kookana and B. Ostendorf: *Catena*, 2012, **93**, 38–48.
- [23] S. M. I. Huq and J. U. M. Shoaib: “*The Soils of Bangladesh*”. World Soils Book Series, 2013, **1**, Springer Science & Business Media, Dordrecht, 178.
- [24] F. Assefa, E. Elias, T. Soromessa and G. T. Ayele: *Air, Soil Water Res.* 2020, **13**.
- [25] C.-C. Tsui, Z. -S. Chen and C. -F. Hsieh: *Geoderma*, 2004, **123**, 131–142.
- [26] M. A. Hajabbasi, A. Jalalinat and H. R. Karizdadeh: *Plant and Soil*, 1997, **190**, 301–307.
- [27] T. L. Jensen: “*Soil pH and the Availability of Plant Nutrients. International Plant Nutrition Institute (IPNI)*”, Fall 2010, No. 2. Georgia, USA (2010).
- [28] S. M. Feroz, M. R. Alam, P. Das and A. Al-Mamun: *Journal of Forestry Research*, 2014, **25**(2), 311–318.
- [29] S. Biswas, M. E. Swanson, J. U. M. Shoaib and S. M. S. Haque: *Journal of Forestry Research*, 2010, **21**(4), 451–456.
- [30] A. Gafur, O. K. Borggaard, J. R. Jensen, L. Petersen: *Danish Journal of Geography*, 2000, **100**, 37–46.
- [31] A. Biswas, M. Alamgir, S. M. S. Haque and K. T. Osman: *Journal of Forestry Research*, 2012, **23**(2), 261–265.
- [32] F. I. Chowdhury, I. Barua, A. I. Chowdhury, V. Resco de Dios and M. S. Alam: *Geology, Ecology, and Landscapes*, 2022, **6**(1), 48–54.
- [33] M. M. A. A. Mamun, S. B. T. A. Emon and M. S. Alam: *International Journal of Forestry, Ecology, and Environment*, 2021, **5**(1), 202–214.

- [34] K. S. Osman, M. Jashimuddin, S. M. S. Haque and S. Miah: *Journal of Forestry Research*, 2013, **24**(4), 791–795.
- [35] M. Akhtaruzzaman, M. E. Haque and K. T. Osman: *Open Journal of Soil Science*, 2014, **4**(1), 26–35.
- [36] M. Akhtaruzzaman, S. Roy, M. S. Mahmud and T. Shormin: *Journal of Forest and Environmental Science*, 2020, **36**(2), 133–142.
- [37] J. U. Shoaib, G. Mostafa and M. Rahman: A Case Study on Soil Erosion Hazard in Hilly Regions of Bangladesh, *Annual Report*, Soil Resource Development Institute, Dhaka, 1998.
- [38] K.R. Islam and R. R. Weil: *Agric. Ecosyst. Environ.* 2000, **79**(1), 9–16.
- [39] M. Hassan, S. Ratna and M. Aktar: *Inter J. of Plant Soil Science*, 2017, **18**(1), 1-9.
- [40] [SRDI] Soil Resource Development Institute, Dhaka, Bangladesh, 1976. *Reconnaissance soil survey reports of Chittagong North and Sadar Subdivision (1971-1973)*.
- [41] G. R. Blake, and K. H. Hartge: “Bulk density. In A. Klute (Ed.)”, *Methods of soil analysis: Part 1 physical and mineralogical method*, 1986, 363-375. American Society of Agronomy.
- [42] M. L. Jackson: “*Soil chemical analysis*”, 1973, Prentice-Hall.
- [43] A. Walkley and I. A. Black: *Soil Science* 1934, **37**(1), 29-38.
- [44] T. Ewunetu, Y.G. Selassie, E. Molla, H. Admase and Gezahegn: *Front. Environ. Sci.* 2025, **13**, 1518068.
- [45] A. R. Vaezi, M. Ahmadi and A. Cerdà: *Sci. Total Environ.* 2017, **583**, 382–392.
- [46] D. V. Guimarães, M. I. S. Gonzaga, T. O. Da Silva, T. L. Da Silva, N. Da Silva Dias and M. I. S. Matias: *Soil Tillage Res*, 2013, **126**, 177-182.
- [47] M. Salim, S., Kumar, P. Kumar and M. K. Gupta: *International Journal of Scientific and Research Publications*, 2018, **8**(1), ISSN 2250-3153
- [48] M. Acín-Carrera, M. José Marques, P. Carral, A. Álvarez, C. López, B. Martín-López: *Soil Use Manag.*, 2013, **29**, 547–556.
- [49] R. P. C. Mongya and A. K. Bandyopadhyay: “*Soils of the Tropics*”, Jangpura, New Delhi: Vikas Publishing House Pvt. Ltd. 1994.
- [50] M. R. Cherubin, C. A. Tormena, D. L. Karlen: *Revista Brasileira de Ciencia do Solo* 2017, **41**.
- [51] K. Fujii: *Ecol Res.* 2014, **29**, 371-381.
- [52] N. Abate and K. Kibret: *Environ. Pollut.* 2016, **5** (2), 57–71.
- [53] M. K. Abbasi, M. Zafar, S. R. Khan: *Nutrient Cycl. Agroecosyst*, 2007, **78** (1), 97–110.
- [54] M. Tumayro and D. Tesgaye: *J. Soil Sci. Environ. Manag*, 2021, **12** (1), 10–16.
- [55] C. Achalu, G. Heluf, K. Kibebew and T. Abi: *Journal of Biodiversity and Environmental Sciences*, 2012, **2**(3), 57-71.
- [56] S. Tashi, B. Singh, C. Keitel and M. Adams: *Global Change Biology*, 2016, **22**(6), 2255–2268.

- [57] J. Ahirwal, A. Nath, B. Brahma, S. Deb, U. K. Sahoo and A. J. Nath: *Science of the Total Environment*, 2021, **770**, 145292.
- [58] T. Tolessa and F. Senbeta: *Journal of Ecology and Environment*, 2018, **42**, 20.
- [59] M. Liu, D. A. N. Ussiri and R. Lal: *Communications in Soil Science and Plant Analysis*, 2016, **47**(12), 1528–1541.
- [60] W. Seifu, E. Elias, G. Gebresamuel: *Appl. Environ. Soil Sci.*, 2020. Article ID: 8816248.
- [61] M. A. Zaman, K. T. Osman, S. S. Haque: *J. For. Res.* 2010, **21**(3), 319–322.
- [62] X. Chen and B. L. Li: *Forest Ecology and Management*, 2003, **186**, 197–206.
- [63] T. Bizuhoraho, A. Kayiranga, N. Manirakiza: *Sustainable Agriculture Research*, 2018, **7**(2), 30–30.
- [64] K. Jemal, H. Tesfaye: *Mod. Chem.* 2020, **8** (3), 40.
- [65] N. Emiru and H. Gebrekidan: *ARPJ J. Agric. Biol. Sci.*, 2013, **8** (3), 206–2012.
- [66] T. W. Berger, C. Neubauer and G. Glatzel: *Forest Ecology and Management*, 2002, **159**, 3–14.
- [67] [SRDI] Soil Resource Development Institute (SRDI), Ministry of Agriculture, Bangladesh. 2020. *Soil Fertility Atlas Bangladesh 2020*, 36.
- [68] M. Demelash and K. Stahr: *Journal of Soil Science and Environmental Management*, 2010, **1**(7), 164–176.
- [69] A. Yonas, K. Temesgen, M. Alemayehu and S. Toyiba: *Journal of Soil Science and Environmental Management*, 2017, **8**(3), 70–79.
- [70] M. N. Hasan, M. A. Bari and M. R. Lutfar: Soil Resource Development Institute. *Soil Fertility Trends in Bangladesh 2010 to 2020*. SRSRF project. Ministry of Agriculture, Dhaka, Bangladesh, 2020, 84.
- [71] [SRDI] Soil Resource Development Institute, Dhaka, Bangladesh, 2002. *Land and soil resource use directory: Thanchi Upazilla, Bandarban Hill District*.150.
- [72] M. Chemed, K. Kibret, T. Fite: *Int. J. Environ. Sci. Nat. Resour.* 2017, **4** (2), 555634.
- [73] A. Sharpley, B. Foy and P. Withers: *Journal of Environmental Quality*, 2000, **29**, 1–9.
- [74] M. Annabi, Y. Le Bissonnais, M. Le Villio-Poitrenaud and S. Houot: *Agriculture, Ecosystems & Environment*, 2011, **144**: 382–389.
- [75] E. Frossard, L. M. Condron, A. Oberson, S. Sinaj and J. C. Fardeau: *Journal of Environmental Quality*, 2000, **29**:15–23.
- [76] D. Jones, B. F. L. Smith, M. J. Wilson and B. A. Goodman: *Mycological Research*, 1991, **95**,1090–1093.
- [77] M. S. Hussain: “Soil classification: with special reference to the soils of Bangladesh”. University of Dhaka, Dhaka, 1992, 105–109.
- [78] J. Brand, J. L. Pfund: *Agriculture, Ecosystems & Environment*, 1998, **71**(1-3), 169–183.
- [79] V. Shorrocks: *Plant Soil*, 1997, **121**, 75–148.
- [80] E. Elias: *Environmental Systems Research*, 2017, **6** (20).

- [81] D. Jendoubi, H. Liniger, and C. Ifejika Speranza: *Soil*, 2019, **5** (2), 239–251.
- [82] A. Challa, A. Abdelkadir and T. Mengistu: *International Journal of Natural Resource Ecology and Management*, 2016, **1**(2),42–50.
- [83] W. Hailu, A. Moges and F. Yimer: *Resource Environmental*, 2012, **2** (4), 132–140.
- [84] W. Seifu, E. Elias, G. Gebresamuel, S. Khanal: *Heliyon*, 2021, **7** (2021), e06770.
- [85] N. C. Brady and R. R. Weil: *The Nature and Properties of Soils*, Pearson, Jodhpur, India, 2016.
- [86] E. Babur and T. Dindaroglu: *Environ Factors Affecting Hum Health*, 2020, **1**, 1-21.
- [87] D. Powlson, Cai Zu, C. Z. Cong and P. Lemanceau: “Soil carbon dynamics and nutrient cycling”. In: *Soil carbon: science, management and policy for multiple benefits*. Wallingford, UK: CABI; 2015, 98-107.