RESEARCH

Soil Quality Variations Across Different Land Use Patterns in Central Doon Valley of Dehradun, India: A Comparative Study

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ARTICLE HISTORY
Received: 04 August 2024
Revised: 10 November 2024
Accepted: 17 November 2024
Published: 17 December 2024

KEYWORDS
barren land
Doon valley
forest area
soil quality

EDITOR
Sami Abou Fayssal

eISSN 2583-942X

Abstract

Soil is the most basic and yet most complex component of terrestrial ecosystems. It regulates most of the ecosystem processes and provides a large part of the earth's biodiversity for the physical basis for many human activities. The major objectives of this study are to examine the physio-chemical characteristics of soil in both disturbed and undisturbed areas of Dehradun and to analyze soil pollution indices related to heavy metals in these areas. The study was conducted in the Suddhowala and Selaqui areas of Jhajra Forest Range, Dehradun, India. The soil samples were collected from six different land use patterns of SS1-SS6 from March to May (2024). The Physical parameters such as Moisture Content, Water Holding Capacity, and Electrical Conductivity, and the chemical parameters such as pH, Total Nitrogen, Organic Carbon, Organic Matter, Phosphorus, Potassium, and Sulphur were analyzed and the heavy metals such as Zinc, Boron, Copper, Manganese and Iron were measured. The geo-accumulation index (Igeo), enrichment factor (EF), degree of contamination (CD), and pollution load index (PLI) were studied. The study finds gaps in how micronutrient status is evaluated to meet the soil needs.

Citation: Kamboj, V., Katoch, K., Singh, R. B. P., & Bisht, A. (2024). Soil Quality Variations Across Different Land Use Patterns in Central Doon Valley of Dehradun, India: A Comparative Study. *AgroEnvironmental Sustainability*, 2(4), 159-172. https://doi.org/10.59983/s2024020402

Statement of Sustainability: The present is aimed at the assessment of soil quality across diverse land use in the Central Doon Valley Uttarakhand. By studying physiochemical features and heavy metal contamination in disturbed and undisturbed sites, the study identifies major gaps in the management of soil and nutrient availability. The results highlight the necessity of sustainable land use methods that promote soil health, increase agricultural productivity, and reduce environmental degradation. This study supports the Sustainable Development Goals (SDGs), namely Zero Hunger (SDG 2) and Life on Land (SDG 15), by encouraging soil conservation measures that promote biodiversity and sustainable agricultural systems. It promotes the implementation of environmentally friendly soil management practices, which contribute to long-term ecosystem stability and resilience.

1. Introduction

Sustainable Environment necessitates knowledge of the impact of different land use patterns on the health of soil systems. Soil the uppermost layer of the earth, is a vital source that is generally used by the human being for the development of regional and socio-economic activities (Srinivasan and Poongothai, 2013). Soil is the most basic and yet most complex component of terrestrial ecosystems. It regulates most of the ecosystem processes and provides a large part of the earth's biodiversity for the physical basis for many human activities. Soil is the component of various nutrients, organic matter, water, air, and living organisms determined by various environmental factors, and topography (Bisht et al., 2024). Physio-chemical characteristics of soils vary in space and time because of variations in topography, climate, weathering processes, vegetation cover, microbial activities, and other biotic and abiotic factors (Reddy et al., 2012, Bisht et al., 2020).

Soil quality is defined as the capacity of soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Bunemann et al., 2018). Soil can sustain the productivity, diversity, and environmental services of terrestrial ecosystems and can be determined through physical, chemical, and biological properties which can vary through different soil nutrients, which are modulated by land use or several other management factors. Soil quality can be assessed both for agroecosystems and for natural ecosystems where major aims are maintenance of environmental quality and biodiversity conservation (Bunemann et al., 2018).

The degradation of soil quality in developing countries represents a significant challenge that has the potential to impact agricultural productivity, economic growth, and the health of the global environment. This issue is largely attributed to a combination of factors, including improper land use and soil management practices, erratic and erosive rainfall patterns, and topographical challenges such as steep terrain, deforestation, and overgrazing. Soil quality differs between forested, agricultural, and industrial areas. Agricultural soil has less soil organic matter and a reduced capacity to retain carbon due to the use of agrochemicals, which results in soil degradation and a reduction in soil quality compared to forest soil (Joimel et al., 2016). Conversely, the increasing demand for food in response to population growth has led to an intensification of agricultural practices, which are known to increase runoff and sediment transport, thereby causing erosion and other forms of soil degradation. It is imperative to maintain soil properties through sustainable agriculture, given the detrimental impact of conventional practices on land degradation and the services provided by agricultural areas. Moreover, this approach should be extended to urban agriculture areas, particularly given that these soils are already subjected to other disturbances (Ferreira et al., 2018).

India is one of the developing countries with an increasing population. To meet the growing demand for food, fibers, and economic development, it is necessary to use land for non-agricultural purposes. However, this intensifies competition for land, which is a significant challenge in India. The primary source of income for rural people in India is agriculture, which has a considerable impact on the land use pattern (Pandey and Ranganasthan, 2018). India has a total geographical area of 328.7 million hectares, of which 42% is currently utilized for the cultivation of various food and non-food crops. However, due to the country's rapidly growing population, this figure has decreased to 21% of the geographical area occupied by forests, 8% for non-agricultural purposes, 5% is barren and unculturable, and 7.5% remains fallow (Pandey and Ranganathan, 2018). Dehradun is the capital of Uttarakhand, which covers an area of 58.46 sq. km. Approximately half of the land is utilized for residential purposes, while the remaining portion is allocated for various other purposes, including commercial areas, educational institutes, research institutes, industrial areas, transport nagar, secret ate, and defense-related areas, as well as recreational and open spaces (Agarwal et al., 2018). As the population has grown, construction and development have resulted in the loss or decline of vegetative land for other uses. This has led to changes in soil quality and fertility.

In light of the growing population and the concomitant increase in demand for land for a variety of purposes, the landscape and soil quality have undergone significant alterations. To gain insight into these changes, this study has been undertaken. The primary objectives of this study are twofold: firstly, to examine the physio-chemical characteristics of soil in both disturbed and undisturbed areas of Dehradun; and secondly, to analyze soil pollution indices related to heavy metals in these areas. This dual focus is intended to provide insights into the impact of human activity on soil quality and contamination levels.

2. Material and Methods

2.1. About Study Area

Doon Valley is situated within the Shivalik foothills basin, which is located in the Garhwal Himalayas (Table 1 and Figure 1-3). The valley is 80 km in length and 20 km in width, situated between the Shiwalik Range to its south and the Mussoorie Range to the north. The Doon Valley is, in fact, composed of two distinct valleys. One slopes down towards the Yamuna to the northwest, while the other slopes down towards the Ganges to the southeast (Bahukhandi et al., 2023). Dehradun encompasses an area of 3,088 square kilometers, with approximately half of this area comprising forest land, agricultural land, industrial zones, and residential areas (Mandal et al., 2013). However, in recent years, there has been a significant increase in construction and the settlement of residential areas, resulting in a notable alteration to the land use pattern. Accordingly, the study was conducted in the Suddhowala and Selaqui areas of the Jhajra Forest

Range. Its geographical coordinates are 30°31'40.18" north latitude and 78°03'05.24" east longitude. The site is situated at an altitude of 640 to 1,000 meters above mean sea level. The mean annual temperature oscillates between 10°C and 21°C, while the annual precipitation reaches 1441 mm (Pal et al., 2020). The objective of this study was to compare the soil quality of different land uses in an undisturbed and a disturbed forest region in Suddhowala and Selaqui. The specifics of the various selected study sites are outlined in the following subsections. The SS1, SS2, and SS3 sites represent the soil quality of different land use patterns in Suddhowala, while the SS4, SS5, and SS6 sites represent the soil quality of different land use patterns in Selaqui.

2.2. Collection of Soil Samples from Selected Sites

The soil samples were collected between March and May of 2024 for the purpose of analyzing the soil characteristics. A composite soil sampling technique was employed, whereby various individual soil cores from the same area were combined into a single, homogeneous sample. This method was utilized to collect samples from six distinct land sites. A minimum of three samples were collected from each site. The soil samples were obtained by excavating a hole 15 cm deep, removing the upper layer of soil, and collecting the soil from the bottom of the hole. Subsequently, the soil samples were air-dried and sieved through a 2 mm sieve, after which they were stored in polyethylene bags and transported to the laboratory for analysis.

Table 1. Geo-Coordinate showing the selected soil sampling location in central Doon Valley.

Location	Sampling Zone	Type of Land Use area	Geo-Coordinates	Elevation
Suddhowala (Undisturbed Area)	SS1	Forest area	Lat- 30°33′12.93″ Long-77°93′85.08″	621 m
	SS2	Agricultural area	Lat- 30°34′78.32″ Long-77°93′48.7″	594 m
	SS3	Barren land	Lat-30°34′84.9″ Long-77°93′75.31″	597 m
Selaqui (Disturbed area)	SS4	Forest area	Lat-30°37′77.51″ Long-77°87′43.62″	598 m
	SS5	Agricultural area	Lat-30°37′09.58″ Long-77°86′31.45″	559 m
	SS6	Barren land	Lat-30°36′52.18″ Long-77°84′61.13″	534 m

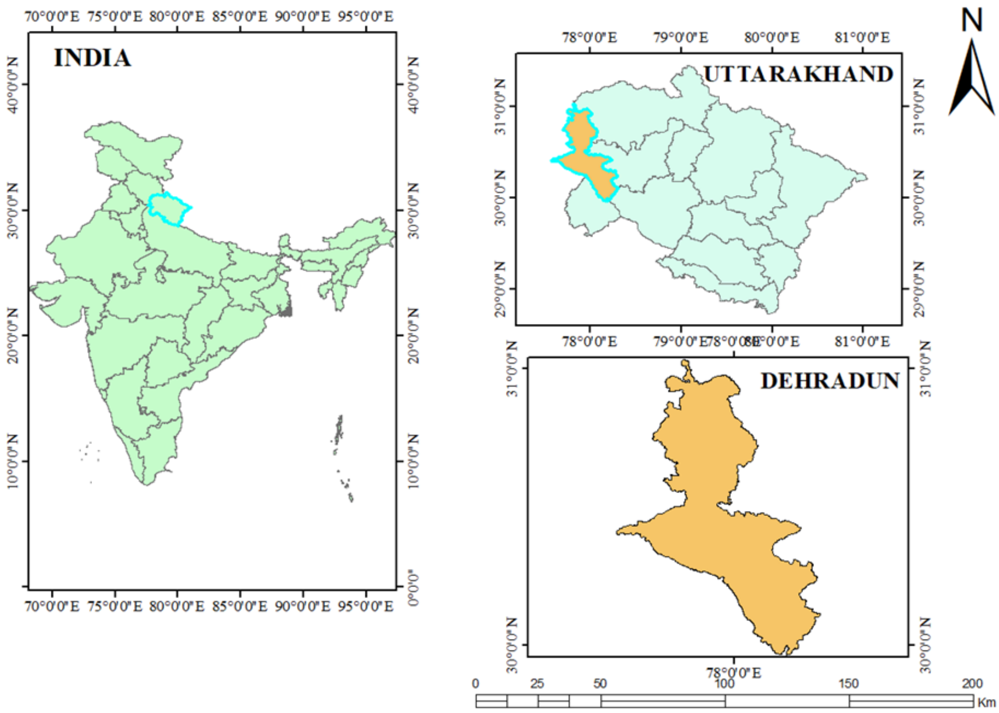

Figure 1. Map of study area of central Doon Valley, Dehradun.

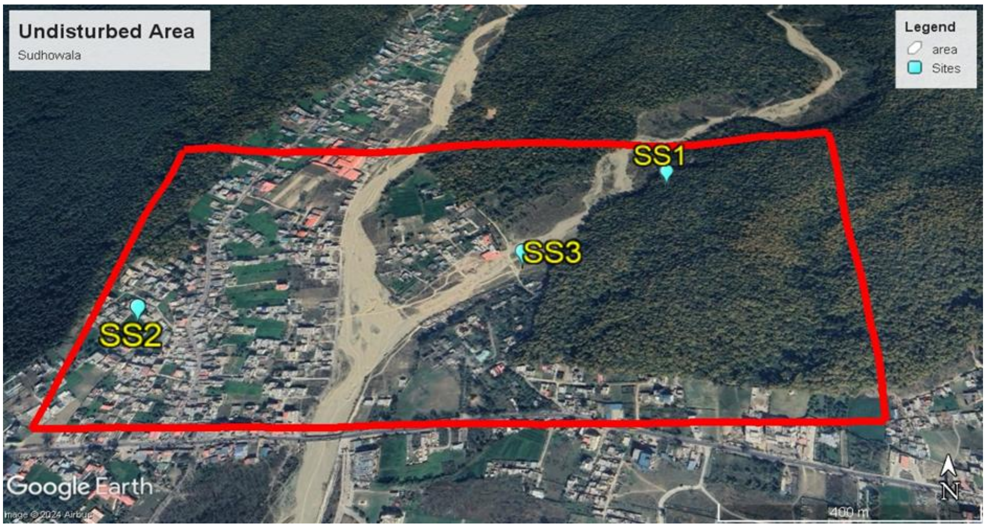

Figure 2. Map of study area showing Undisturbed site in Suddhowala.

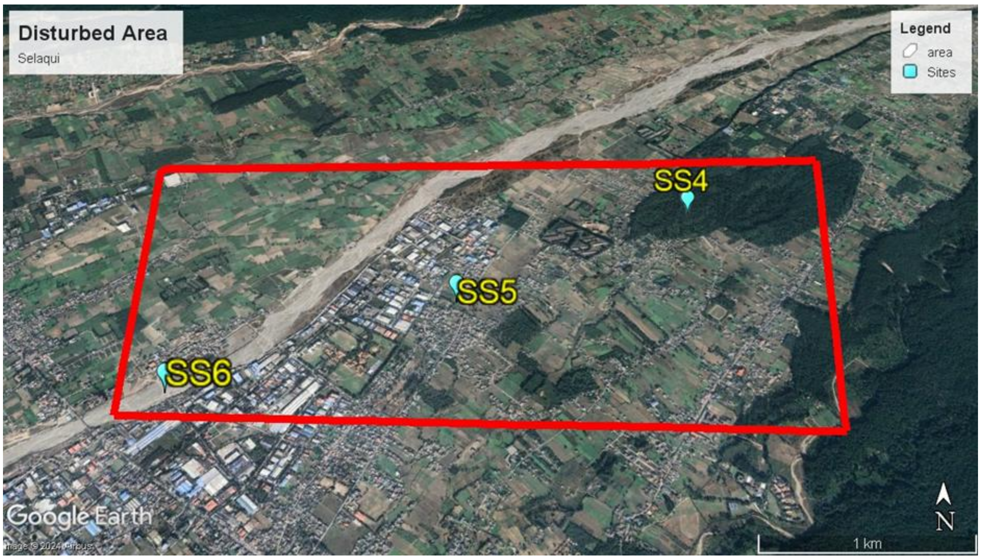

Figure 3. Map of study area showing Disturbed area in Selaqui

2.3. Methodology Adopted for Analysis of Physical and Chemical Parameters

The physico-chemical and heavy metal composition of soil samples was examined across a range of land use patterns (SS1-SS6) between March and May 2024. The physical parameters, including moisture content, water holding capacity, and electrical conductivity, were analyzed, as were the chemical parameters, including pH, total nitrogen, organic carbon, organic matter, phosphorus, potassium, and sulfur. Additionally, the heavy metals zinc, boron, copper, manganese, and iron were measured.

2.4. Statistical Analysis of Data

The data were validated using Microsoft Excel 2021. The tables and graphs were prepared following an analysis of the data with the statistical tool MS Excel version 2013. In the present study, a variety of fundamental statistical techniques were employed, including mean, standard deviation, Pearson correlation, geo-accumulation index, pollution load index, and enrichment index. These were utilized with the assistance of Microsoft Excel version 2021.

2.5. Soil Pollution Indices

In order to assess the levels of heavy metal contamination in the study areas, a series of pollution indices were employed, including the geo-accumulation index (Igeo), enrichment factor (EF), degree of contamination (CD), and pollution load index (PLI). The geo-accumulation index was employed to assess the degree of heavy metal contamination in relation to the background or reference value. In the present study, the background/reference value of heavy metals, namely zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and boron (B), is 0.75, 1.51, 1.65, 0.51, and 0.42, respectively. The background values of Zn, B, and Mn were obtained from the Vikas Nagar area (Amritanshu et al., 2023), while the values of Fe and Cu were derived from the Dehradun forest region (Kumar et al., 2021; Bisht et al., 2024).

- **Geo Accumulation Index (Igeo):** It is defined as a measure of the contamination level in samples compared to a reference environment. It compares the measured concentration of the element in the fine-grain sludge fraction Cn (observed value) with the Bn (geochemical background value). The formula for calculating the Igeo is given below (Table 2). Here, Cn= concentration of heavy metals; Bn= background/reference value of heavy metals

$$\mathrm{Igeo} = \log2\,(\mathrm{Cn}/1.5 \times \mathrm{Bn})$$

Table 2. Classification of contamination levels based on the Geo-Accumulation Index (Igeo).

Indices Name	Value	Status
Geo Accumulation Index	Igeo<0	Uncontaminated
	0<Igeo<1	Uncontaminated to moderately contaminated
	1<Igeo<2	Moderately contaminated
	2<Igeo<3	Moderately to heavily contaminated
	3<Igeo<4	Heavily contaminated
	4<Igeo<5	Heavily to extremely contaminated
	Igeo>5	Extremely contaminated

- **Pollution load index (PLI):** It is defined as the measurement of the level of heavy metal contaminants present in a sample compared to the baseline sample. It evaluates the degree to which the soil sediment is associated with heavy metals (Bisht et al., 2024). The formula for calculating the PLI is given below (Table 3). Here, Cf=contamination factor.

$$\mathrm{PLI} = (\mathrm{Cf1} * \mathrm{Cf2} * \mathrm{Cf3} * \ldots\ldots..\mathrm{Cfn})\ 1/n$$

Table 3. Classification of pollution levels based on the Pollution Load Index (PLI).

Indices Name	Value	Status
Pollution Load Index	PLI<1	No pollution
	1<PLI<2	Moderate pollution
	2<PLI<3	Heavy pollution
	PLI>3	Extremely heavy pollution

- **Enrichment factor (EF):** It is an indicator used to assess the presence and intensity of anthropogenic contamination deposition on surface soil (Bisht et al., 2024). The formula for calculating the enrichment factor is given below (Table 4):

$$\mathrm{EF} = (\mathrm{Cnx}/\mathrm{CFex})/\,(\mathrm{Cnb}/\mathrm{CFeb})$$

Where: Cnx= concentration of heavy metal in a soil sample, Cnb= concentration of heavy metals in background/reference value, CFex= concentration of Iron in the soil sample, CFeb= concentration of Iron in background/reference value.

Table 4. Classification of metal contamination levels based on the Enrichment Factor (EF).

Indices name	Value	Status
Enrichment Factor	EF<2	Deficiency to minimal enrichment
	2<EF<5	Moderate enrichment
	5<EF<20	Significant enrichment
	20<EF<40	Very high enrichment
	EF>40	Extremely high enrichment

3. Result And Discussion

3.1. Results of Physico-chemical and Heavy Metals

The Physico-chemical and heavy metals of soil samples were analyzed in different land use patterns of SS1-SS6 in the months of March to May (2024). Physical parameters such as MC, WHC, and EC, and chemical parameters such as pH, TN, OC, OM, P, K, and S were analyzed, and the heavy metals such as Zn, B, Cu, Mn, Fe. The result of the study can be seen in Table 5 and Figure 4 and correlation between the selected parameters is shown in Table 6, respectively.

3.1.1. Moisture Content (%)

The moisture content demonstrates the greatest mean value of 21.24 ± 1.07% in SS1 and the lowest mean value of 10.37 ± 0.18% in SS6. Therefore, it can be concluded that the moisture content in forest soil is higher than in other land use patterns. In the present study, forest soil exhibited a higher moisture content than agricultural and barren land. It has been documented that forest soil exhibits a higher moisture content than agricultural and barren land (Pandey et al., 2019). The moisture content demonstrated a statistically significant and positive correlation with water holding capacity (0.97), organic carbon (0.27), and nitrogen and phosphorus. However, it exhibited a negative and non-significant correlation with potassium (r = -0.15) and sodium (r = -0.38).

3.1.2. Water Holding Capacity (WHC)

The water-holding capacity is enhanced by an increase in the level of organic carbon and the percentage of silt and clay particles in the soil. This is due to the fact that clay and silt particles possess a significantly higher surface area. The WHC exhibits the greatest mean value of 51.22 ± 0.35 in SS1, while SS6 displays the lowest mean value of 40.16 ± 0.09. As organic matter content increases, the water-holding capacity of the soil also rises (Meng et al., 2013). The water-holding capacity demonstrated a highly significant and positive correlation with P (r = 0.527) and a negative correlation with K (r = -0.07) and S (r = -0.34).

3.1.3. pH

It is a quantitative measure of the level of acidity in a substance. The term is employed extensively in the fields of chemistry and biology, wherein it is utilized to translate the values of hydrogen ion concentration. In the present study, the pH values ranged from a minimum of 4.16 ± 0.05 in SS6 to a maximum of 6.67 ± 0.16 in SS5. The soil sample taken from SS6 is more acidic in comparison to the other sites, due to the disturbance caused by industrialization and urbanization. Additionally, the slightly acidic soil in the agricultural land is a result of agricultural practices and the chemical fertilizers used in the field. Previous research has indicated that soil in industrial areas tends to be more acidic (Joimel et al., 2016).

Table 5. The result of soil quality parameters measured across six sampling sites (SS1 to SS6).

Parameter	SS1	SS2	SS3	SS4	SS5	SS6
Moisture content	21.24±1.07	16.27±0.22	11.21±0.47	21.33±0.77	16.86±0.27	10.37±0.18
Water holding capacity	51.22±0.35	45.59±1.67	40.47±1.67	49.97±0.54	43.69±0.95	40.16±0.09
pH	6.22±0.04	6.10±0.06	6.37±0.06	5.23±0.15	6.67±0.16	4.16±0.05
EC (dS/m)	0.06±0.02	0.06±0.02	0.12±0.01	0.22±0.06	0.13±0.03	0.18±0.03
OC (%)	0.87±0.06	0.65±0.07	1.23±0.07	1.89±0.09	0.13±0.03	0.76±0.10
OM (%)	1.19±0.44	1.11±0.12	2.12±0.13	3.24±0.16	0.44±0.11	1.29±0.17
P (mg/Kg)	45.82±3.27	24.02±4.62	36.53±6.86	41.22±5.58	16.96±3.84	30.38±3.96
K (mg/Kg)	110.56±6.09	218.69±59.11	136.8±3.8	295.6±24.88	82.1±7.21	114.79±4.37
S (mg/Kg)	15.78±4.56	7.46±2.03	2.84±0.61	5.02±0.16	16.67±4.32	36.68±7.38
Zn (mg/Kg)	2.25±0.09	1.81±0.22	0.79±0.06	0.49±0.05	0.79±0.05	0.20±0.05
B (mg/Kg)	0.59±0.05	0.44±0.03	0.87±0.05	0.61±0.03	0.34±0.04	0.24±0.01
Fe (mg/Kg)	24.42±1.76	21.1±0.78	22.13±0.78	14.53±0.53	18.10±0.44	15.72±0.94
Mn (mg/Kg)	15.83±0.43	25.43±1.47	31.04±1.08	6.90±0.92	10.93±0.65	5.51±0.61
Cu (mg/Kg)	0.005±0.007	0.04±0.05	0.07±0.09	0.013±0.01	0.07±0.09	0.08±0.10
TN (Kg/hac)	321.31±0.69	363.51±5.69	221.16±0.64	265.23±5.88	289.09±3.68	188.95±9.63

3.1.4. Electrical Conductivity (EC; dS/m)

The measurement indicates the quantity of salts present in the soil. However, the presence of excess salt will impede growth by affecting the soil-water balance. The electrical conductivity (EC) values ranged from a minimum of 0.06 ± 0.02 dS/m in SS1 and SS2 to a maximum of 0.22 ± 0.06 dS/m in SS4. Consequently, the elevated EC value indicates that SS4 has a more saline soil than SS1, SS2, SS3, SS5, and SS6, due to the presence of clay-textured soil with a high water holding capacity, which increases the soil's ability to conduct electrical charges. The EC value is higher in forest soil than in other areas (Ahirwal and Maiti, 2016). There is a positive correlation between EC and organic matter (r = 0.57), as well as between EC and water holding capacity. Conversely, there is a negative correlation between EC and Zn (r = -0.45) and Mn (r = -0.73).

3.1.5. Organic Carbon (OC) and Organic Matter (OM; %)

The quantity of organic carbon present in the soil is a quantifiable component of the total organic matter content of the soil. The organic carbon content ranges from a maximum of 1.88 ± 0.09% in SS4 to a minimum of 0.13 ± 0.03% in SS5. The elevated organic carbon levels observed in the disturbed zone can be attributed primarily to the impact of forest fires and the deposition of greater quantities of carbon components relative to other zones. It has been reported that the oxidizable carbon fraction is present in greater quantities in forest soil (Maini et al., 2020). Organic matter demonstrated a highly significant and positive correlation with organic carbon, moisture content, and water-holding capacity. However, it showed no significant correlation with potassium content and a negative correlation with Fe (r = -0.53) and Mn (r = -0.74).

3.1.6. Available Phosphorus (AP; mg/Kg)

Phosphorus is of particular benefit in the production of legumes, as it increases the activity of nodular bacteria, which are responsible for fixing nitrogen in the soil. It facilitates the formation of seeds and fruits, particularly in legumes. It has been demonstrated to stimulate early root growth and development. The availability of phosphorus is reduced in soils with high moisture content and low temperatures. The available phosphorus in soil exhibits a range of values, from a minimum average of 16.96 ± 3.84 mg/kg at SS5 to a maximum value of 45.82 ± 3.27 mg/kg at SS1. The present study revealed that forest soil exhibited a higher phosphorus level in comparison to other zones, which can be attributed to the decomposition of organic matter (fallen leaves, branches, and dead organisms) that releases phosphorus into the soil. A negative correlation was observed between pH and phosphorus content (Armenise et al., 2013). Additionally, a positive correlation was noted between phosphorus and manganese (r = 0.32) and copper (r = 0.15), while a negative correlation was observed between phosphorus and potassium (r = -0.15).

3.1.7. Sulphur (S; mg/Kg)

Sulphur is a constituent of numerous proteins and plays a role in the formation of chlorophyll and root growth. The presence of an abundant supply of sulfur in plants is associated with the development of dark green leaves and an extensive root system. In the present study, the sulfur content in the soil ranged from a minimum of 2.84 ± 0.61 mg/kg at SS3 to a maximum of 36.68 ± 7.38 mg/kg at SS6. The results demonstrate that the barren land of the undisturbed zone exhibits a lower sulfur content in comparison to the barren land of the disturbed zone. The results indicate that the lack of vegetation and reduced atmospheric deposition from industrial activities result in a lower contribution of sulfur to the soil. However, the increased use of sulfur-based construction materials, industrial activities, and agricultural practices, including the application of fertilizers and pesticides, has led to an overall increase in sulfur content in the soil. The data demonstrate a negative correlation between sulfur and soil moisture content (r = -0.38), water holding capacity (r = -0.34), and pH (r = -0.64), while showing a positive correlation with electrical conductivity.

3.1.8. Zinc (Zn; mg/Kg)

Zinc is a micronutrient that is essential for plant growth and development. The availability of zinc is reduced in alkaline soil (high pH) and increased in acidic soil (low pH). The results of the study indicate that the minimum zinc level is 0.20±0.05 mg/kg in SS6, while the maximum is 2.25±0.09 mg/kg in SS1. The results demonstrate that the forest zone exhibits a significantly higher zinc content in comparison to the agricultural and barren zones. This is attributed to the elevated decomposition of leaf litter and organic matter, the acidic nature of the soil, and the low zinc content observed in the agricultural zone, which results in an alkaline soil condition and extensive agricultural practices. The extensive utilization of phosphorus or inorganic fertilizers has been shown to reduce the availability of zinc (Kaur et al., 2021).

3.1.9. Boron (B; mg/Kg)

Boron is crucial for synthesis and plant growth, even though plants require it in smaller amounts compared to macronutrients. Boron plays a critical role in various physiological processes in plants. It is crucial for the synthesis and stability of cell walls. Boron availability decreases in alkaline soils (high pH) and also in highly acidic soils. It is low in sandy soils which have low organic matter content. In the present study, the minimum average value ranges from 0.24±0.01 mg/Kg in SS6 to the maximum value of 0.87±0.05 mg/Kg in SS3. The alkaline nature of soil and disturbance can accelerate the decomposition of existing organic matter which reduces the soil's capacity to hold boron (Armenise et al., 2013).

3.1.10. Iron (Fe; mg/Kg)

It is an essential nutrient for plant growth and soil health. It exists in two forms in soil: ferrous (Fe^{2+}) and ferric (Fe^{3+}). Plants primarily take up iron in the ferrous form. The iron content in soil is affected by soil pH, soil aeration, and organic matter. Iron in soil ranges from average value ranges from a minimum of 14.53±0.53 mg/Kg in SS4 to 24.42±1.76 mg/Kg in SS1. The low content of Iron in agricultural soil is due to plant uptake for their growth, alkaline soil, and less organic matter in April (Marzaioli et al., 2013).

3.1.11. Manganese (Mn; mg/Kg)

Manganese is an essential element and appears to have a role in the formation of synthesis of chlorophyll. Manganese availability decreases as soil pH increases. In the present study, the maximum average value ranges from 31.04±1.08 mg/Kg in SS3 to the minimum value of 5.51±0.61 mg/Kg in SS6, which is due to the high soil pH, sandy texture, low organic matter, construction, deforestation, and land clearing. The soil with less organic matter and water-holding capacity has a high level of Mn (Allen et al., 2016). Manganese shows a negative relation with MC (r = -0.26) and WHC (r = -0.21) and a positive relation with pH (r = 0.60).

3.1.12. Copper (Cu; mg/Kg)

It is an essential micronutrient for the health of plants and soil, playing a vital role in various physiological and biochemical processes. The present study demonstrates a minimum value of 0.005 ± 0.007 mg/kg in SS1 and a maximum value of 0.013 ± 0.01 mg/kg in SS4. These findings are attributed to industrial factors, high soil pH, and sandy soil. The elevated copper levels observed in undisturbed, barren land are predominantly the result of natural geological and environmental processes over time (Leul et al., 2023). Copper demonstrates a negative correlation with electrical conductivity (EC) and a positive correlation with moisture content (MC), water holding capacity (WHC), and pH.

3.1.14. Total Nitrogen (TN; mg/Kg)

Nitrogen is an essential nutrient for the production of amino acids, proteins, nucleic acids, and other biological compounds. Stone fruit trees require an adequate annual supply of nitrogen for optimal growth and productivity. The TN content in the soil samples ranged from the minimum average value of 188.95 ± 9.63 mg/kg in SS6 to the maximum value of 363.51 ± 5.69 mg/kg in SS2. The study indicates a low nitrogen content in SS6, which can be attributed to several factors, including a reduced organic matter content, a high pH, soil erosion, limited biological activity, and the absence of nitrogen-fixing plants. It has been documented that soil with elevated electrical conductivity (EC) exhibits diminished nitrogen content (Ahirwal and Maiti, 2016).

3.1.15. Potassium (K; mg/Kg)

Potassium plays a crucial role in the synthesis of amino acids and proteins from ammonium ions, which are absorbed from the soil. The potassium content in the soil exhibits a range from the minimum average value of 16.96 ± 3.84 mg/kg in SS5 to the maximum value of 45.82 ± 3.27 mg/kg in SS1. The results demonstrate that SS5 exhibits a comparatively low potassium content in comparison to SS1, SS2, SS3, SS4, and SS6. This is attributed to the high intake of potassium by plants for their growth, as well as the pre-planning soil preparation, which reduces the availability of potassium as it becomes mixed into deeper soil layers. Conversely, SS4 displays a high potassium content, which can be attributed to anthropogenic activity, specifically the occurrence of a forest fire, which has the effect of increasing the potassium content in the soil.

The soil exhibits elevated macro- and micro-nutrient content when compared to other soil types (Kaur et al., 2021). It demonstrates a positive correlation with Mn and Cu while exhibiting a negative correlation with MC (r = -0.15) and WHC (r = -0.07).

3.2. Soil Pollution Indices

3.2.1. Geo-accumulation Index (Igeo)

In the study, the following elements were utilized for the purpose of determining the geo-accumulation index: zinc, boron, iron, manganese, and copper.

Table 6. Correlation between Average value of selected soil samples of disturbed and undisturbed area.

→	MC	WHC	pH	EC	OC	OM	P	K	S	Zn	B	Fe	Mn	Cu	TN
MC	1														
WHC	0.97	1													
pH	0.299	0.195	1												
EC	0.308	0.327	-0.554	1											
OC	0.277	0.349	-0.296	0.608	1										
OM	0.206	0.262	-0.32	0.576	0.992	1									
P	0.098	0.224	-0.394	0.612	0.948	0.925	1								
K	-0.15	-0.07	-0.393	-0.392	-0.087	-0.04	-0.125	1							
S	-0.384	-0.346	-0.643	0.252	-0.46	-0.462	-0.296	0.109	1						
Zn	0.492	0.575	0.554	-0.456	-0.256	-0.346	-0.231	0.1	-0.298	1					
B	0.11	0.161	0.438	0.009	0.602	0.571	0.622	-0.424	-0.779	0.186	1				
Fe	0.082	0.169	0.657	-0.545	-0.282	-0.361	-0.152	-0.19	-0.316	0.832	0.463	1			
Mn	-0.263	-0.212	0.606	-0.739	-0.052	-0.05	0.004	0.061	-0.622	0.446	0.647	0.731	1		
Cu	0.178	0.237	0.58	-0.186	0.452	0.409	0.468	-0.331	-0.821	0.415	0.966	0.642	0.764	1	
TN	0.491	0.287	0.553	-0.189	-0.083	-0.039	-0.385	-0.056	-0.516	0.018	-0.044	-0.21	-0.04	0.002	1

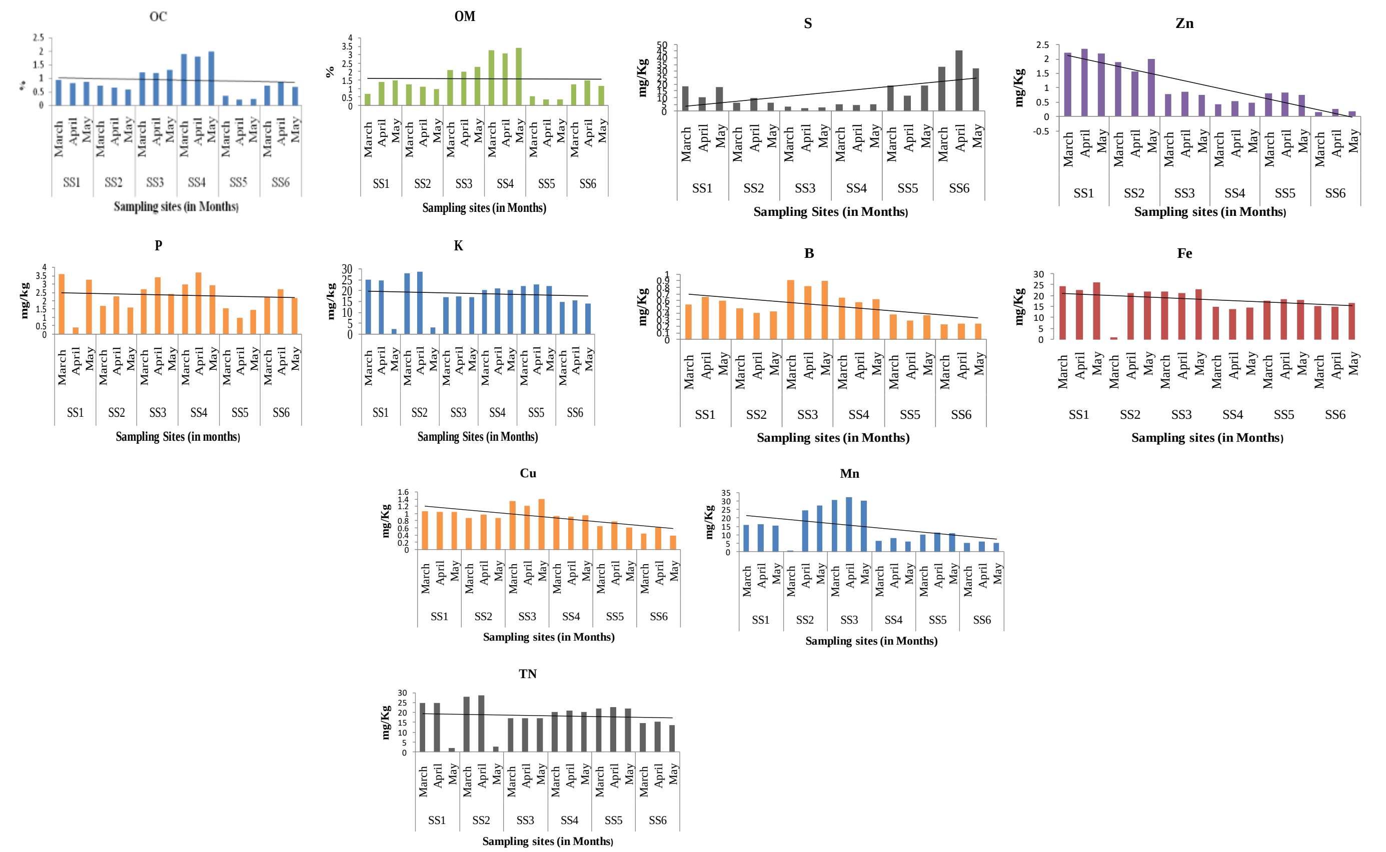

Figure 4. Variation in Physico-chemical and heavy metal parameters of soil in selected sampling locations.

The zinc content was found to be in an uncertain to medium amount, with a minimum value of -0.99 ±0.24 in SS3 and a maximum value of 1.03 ±0.05 in SS1. The boron demonstrated a minimum value of -1.63 ±2.69 in SS2 and a maximum value of 0.96 ±0.03 in SS3, indicating an uncertain to medium status. The iron was found to be present in concentrations ranging from uncertain to high. The lowest concentration was observed in sample SS2, with a value of -1.63 ±2.69, while the highest concentration was observed in sample SS3, with a value of 1.53 ±2.64. The concentration in sample SS1 was intermediate, with a value of 3.22 ±0.05. With regard to manganese, the maximum concentration was observed in SS1, with a value of 4.40. This was followed by SS3, with a value of 2.13 ±2.98, which exhibited elevated concentration, and SS2, with a minimum value of -1.16 ±3.01, which demonstrated uncertain concentration. The highest concentration of copper was observed in SS3, with a value of 0.41 ± 0.17, indicating a medium status. In contrast, SS1 exhibited the lowest concentration, with a value of -0.16 ± 0.09, suggesting an uncertain status. As illustrated in Table 7, there are notable fluctuations in the concentration of elements per sample, with the majority exhibiting either negative or low values, particularly for zinc, boron, and copper. The levels of iron and manganese are slightly elevated in some samples. In SS1, iron is present at a medium level, while in SS3, it is present at a high concentration. Similarly, manganese is present at a high concentration in SS1. Indeed, a considerable number of the samples exhibit an "uncertain" status, indicating a lack of certainty in the associated measurements, particularly with regard to boron and copper. Figure 5 illustrates the variation of the geo-accumulation index. In a study conducted in the United States, regional characteristics were identified. For instance, certain elements were found to be more prevalent in the eastern region, while the western region exhibited a higher concentration of heavy metals (Najwah and Philip, 2020). Accordingly, the micronutrient content, agricultural practices, and geographical characteristics of the studies in question have been shown to exert a significant influence on their respective results. The study identifies deficiencies in the evaluation of micronutrient status to meet soil requirements.

3.2.2. Pollution Load Index (PLI) and Degree of Contamination (CD)

The PLI and CD demonstrate the collective metal contamination level in the soil. The result of PLI and CD is illustarted in Table 8 and Figure 6. The PLI in SS1, SS3, SS4, and SS5 has consistently demonstrated the presence of extremely heavy pollution (EHP) throughout the course of the study, with SS3 exhibiting the highest average PLI of 7.87 ± 0.10. The pollution rating for SS2 is moderate to extreme, while SS6 indicates moderate pollution with the lowest mean PLI (1.87 ± 0.27). In contrast, the highest degree of contamination (HDC) is observed in SS1, SS2, SS4, and SS5, while SS3 exhibits the highest CD average of 134.39 ± 3.71. SS2 exhibits the highest degree of contamination, while SS6 displays a considerable concentration with the lowest average CD (28.91 ± 2.32). The data obtained indicates that the pollution issues are significant and require attention. In particular, localized cleaning procedures should be employed at SS1, SS3, and SS5 to address these concerns.

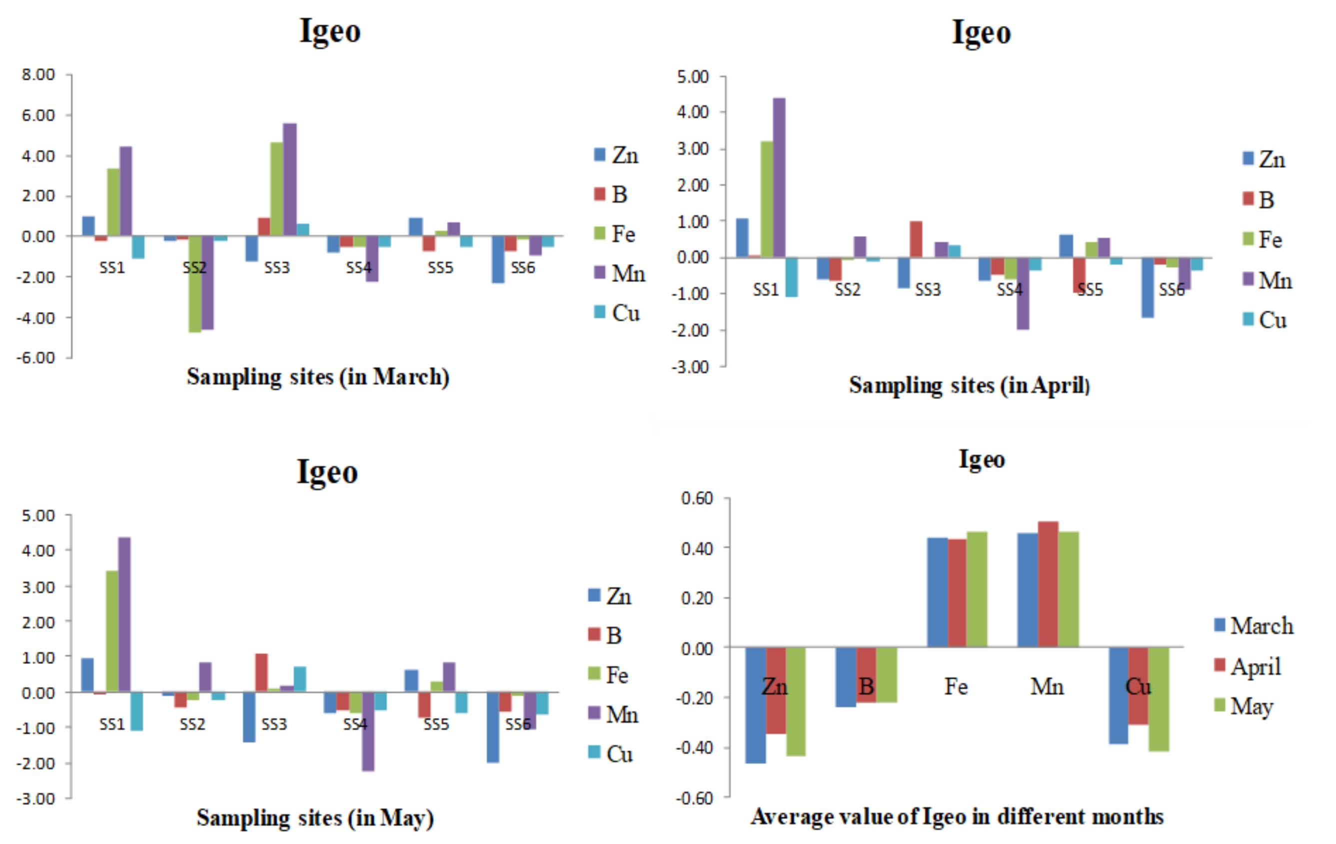

Figure 5. Variation in the Geo-accumulation index.

Table 7. the Average value of Geo accumulation index of selected site.

Parameter	SS1		SS2		SS3		SS4		SS5		SS6	
	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status
Zinc	1.03±0.05	UC to M	-0.47±0.21	UC	-0.99±0.24	UC	-0.73±0.10	UC	0.70±0.14	UC to M	-1.88±0.36	UC
Boron	-0.04±0.15	UC	-1.63±2.69	UC	0.96±0.03	UC to M	-0.50±0.05	UC	-0.89±0.12	UC	-0.38±0.29	UC
Iron	3.22±0.05	M	-1.63±2.69	UC	1.53±2.64	HC	-0.6±0.03	UC	0.35±0.09	UC	-0.27±0.06	UC
Manganese	4.4	HC	-1.16±3.01	UC	2.13±2.98	EC	-2.09±0.12	UC	0.57±0.06	UC	-0.92±0.05	UC
Copper	-1.11	UC	-0.16±009	UC	0.41±0.17	M	-0.42±0.08	UC	-0.31±0.16	UC	-0.42±0.09	UC

Note: UC: Uncontaminated, M: Moderate, HC: Heavy contaminated, EC: Extreme contamination.

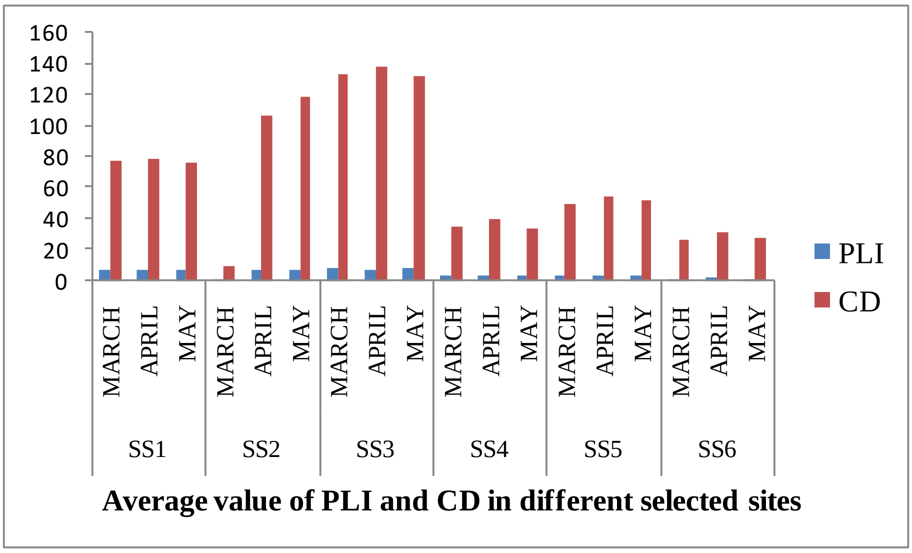

Figure 6. The average values of PLI and CD in the study area.

Table 8. PLI and CD value and status of different sites in different months.

Parameter	Months	SS1	Status	SS2	Status	SS3	Status	SS4	Status	SS5	Status	SS6	Status
PLI	March	7.45	EHP	1.30	MP	7.95	EHP	3.53	EHP	3.85	EHP	1.69	MP
	April	7.78	EHP	6.68	EHP	7.75	EHP	3.74	EHP	3.99	EHP	2.19	MP
	May	7.62	EHP	7.23	EHP	7.91	EHP	3.57	EHP	3.80	EHP	1.75	MP
	Average	7.61 ±0.61	EHP	5.07 ±3.27	EHP	7.87 ±0.10	EHP	3.61 ±0.11	MP	3.88 ±0.09	MP	1.87 ±0.27	MP
CD	March	77.85	HDC	9.25	MP	132.96	HDC	35.29	HDC	49.74	HDC	27.17	CC
	April	78.82	HDC	106.49	HDC	138.62	HDC	40.31	HDC	54.64	HDC	31.55	CC
	May	76.28	HDC	118.46	HDC	131.61	HDC	34.24	HDC	52.64	HDC	28.02	CC
	Average	77.65 ±1.28	HDC	78.06 ±59.89	HDC	134.39 ±3.71	HDC	36.61 ±3.24	HDC	52.34 ±2.46	HDC	28.91 ±2.32	CC

Note: EHP (extremely heavy pollution), HDC (High degree of contamination), MP (Moderate Pollution), CC (Considerable Contamination).

3.2.3. Enrichment Factor (EF)

Table 9 and Figure 7 illustrate the mean enrichment factor (EF) values for five metals (zinc, boron, iron, manganese, and copper) across six sampling sites (SS1 to SS6). The enrichment factor is employed to evaluate the extent of contamination, with distinct statuses denoting the degree of enrichment. The zinc levels in SS1 and SS2 indicate moderate enrichment, with values of 2.99 ± 0.11 and 2.41 ± 0.30, respectively. The remaining sites (SS3 to SS6) indicate a deficiency, with SS6 exhibiting the lowest EF (0.266 ± 0.07). With regard to boron, the majority of sites exhibit deficiency, with the exception of SS3, which displays moderate enrichment with an EF of 2.07 ± 0.12. Furthermore, SS5 and SS6 even exhibit negative values, indicative of deficiency. The iron content of all sites exhibits significant enrichment, with SS1 displaying a value of 14.80 ± 1.06 and SS3 exhibiting a value of 13.41 ± 0.47, representing the highest observed values. In contrast, SS6 exhibits the lowest iron content, with a value of 9.53 ± 0.57. The manganese in SS1, SS2, SS3, and SS5 exhibits high enrichment (HE), with SS3 displaying the highest EF value of 60.87 ± 2.13. Significant enrichment is observed in SS4 and SS6. The copper values across all sites indicate a deficiency, with values ranging from -0.45 ± 0.05 at SS5 to 0.86 ± 0.06 at SS3. This study reveals varying levels of metal enrichment across the sites, with manganese showing particularly high contamination at some locations.

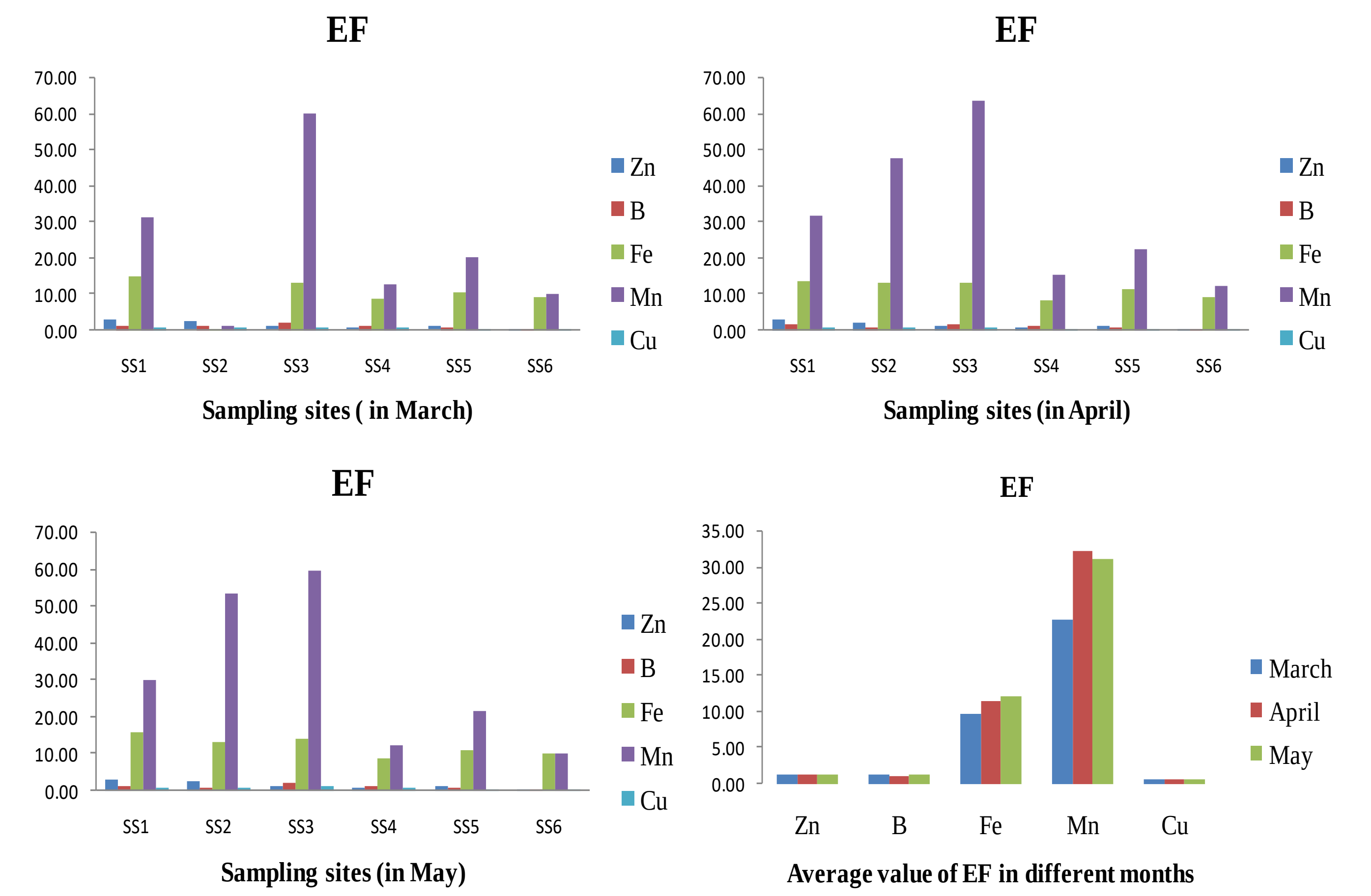

Figure 7. Variation of Enrichment factor in the study area.

Table 9. The average value of the enrichment factor of selected sites.

Parameter	SS1		SS2		SS3		SS4		SS5		SS6	
	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status
Zinc	2.99±0.11	ME	2.41±0.30	ME	1.05±0.09	D	0.64±0.07	D	1.04±0.07	D	0.266±0.07	D
Boron	1.41±0.13	D	1.04±0.08	D	2.07±0.12	ME	1.45±0.08	D	-0.82±0.11	D	-0.58±0.03	D
Iron	14.80±1.06	SE	8.94±7.26	SE	13.41±0.47	SE	8.80±0.31	SE	10.96±0.27	SE	9.53±0.57	SE
Manganese	31.04±0.85	HE	33.94±28.44	HE	60.87±2.13	HE	13.54±1.81	SE	21.43±1.27	HE	10.81±1.20	SE
Copper	0.7±1.35	D	0.59±0.03	D	0.86±0.06	D	0.61±0.01	D	-0.45±0.05	D	0.31±0.07	D

Note: ME (moderate enrichment), D (deficiency), SE (significant enrichment), HE (high enrichment), EHE (extreme high enrichment).

4. Conclusion and Recommendations

The observations made during the study across the six sampling sites (SS 1 to SS 6) indicated that the extent of soil physical, chemical properties, nutrient availability, and heavy metal contents differed under varying degrees of land-use management. The soil moisture, moisture holding capacity, and organic carbon content in the forest land were found to be significantly higher than those observed in the agricultural and barren land samples. It can be observed that samples SS3 and SS1 exhibit markedly elevated concentrations of phosphorus and potassium in comparison to other sites. However, SS6 indicates comparatively diminished nutrient values. The soil pH level exhibited significant variation between the sampling sites, with the lowest value observed at SS6, which was attributed to the presence of industrial and urban hazards. The analysis of heavy metals revealed that forest zones exhibited elevated concentrations of iron and manganese. The sample sites SS1 and SS3 exhibited elevated concentrations of heavy metals that are significant for the ecosystems. In particular, the Pollution Load Index (PLI) indicated that SS1, SS3, SS4, and SS5 are subject to extreme pollution, while the Contamination Degree (CD) demonstrated that these stations are significantly contaminated. The study recommends that the pollution issues at SS1, SS3, and at least SS5 require urgent attention due to their high-intensity levels.

- The sites SS 1, SS3, and SS5 must undergo immediate remediation through the implementation of phytoremediation or bioremediation techniques. This is a crucial step in the process of removing the majority of contaminants, particularly manganese and iron, from the environment.
- In light of the elevated levels of contamination, waste management protocols must be strictly adhered to in order to curtail the further dissemination of pollutants originating from industrial activities and the inadequate disposal of harmful waste products.
- It is recommended that the government implement policies to encourage the utilization of organic land management practices, particularly in regions where agriculture is prevalent, to combat soil acidification and enhance nutrient accessibility. The elimination of chemical fertilizers will result in an enhancement of soil quality.
- It is imperative to implement a program of routine data collection on soil pH, heavy metal concentration, and nutrient availability, particularly in the identified sensitive areas. This will enable the early detection of contamination and the implementation of appropriate remediation measures.
- Compositing practices, such as afforestation and conservation, must be employed, particularly in the following areas, in order to enhance water holding capacity, and soil organic matter, and to check soil erosion. Such measures will also contribute to the overall health of the soil, thereby reducing the likelihood of soil contamination.
- The continuation of awareness programs for farmers and industries regarding soil health, land usage, and pollution control can also facilitate the implementation of optimal practices that support the maintenance of ecosystem health and enhance long-term sustainability.

Author Contributions: Conceptualization: Vishal Kamboj, Aditi Bisht; Data curation: Vishal Kamboj, Kajal Katoch, Ram Bhushan Prasad Singh; Funding acquisition: Vishal Kamboj, Kajal Katoch; Investigation: Vishal Kamboj, Kajal Katoch; Methodology: Vishal Kamboj, Aditi Bisht, Kajal Katoch; Resources: Vishal Kamboj, Kajal Katoch; Software: Vishal Kamboj, Kajal Katoch; Supervision: Vishal Kamboj, Ram Bhushan Prasad Singh; Validation: Vishal Kamboj, Ram Bhushan Prasad Singh; Visualization: Vishal Kamboj, Aditi Bisht; Writing-original draft: Vishal Kamboj, Kajal Katoch; Writing-review and editing: Vishal Kamboj, Aditi Bisht. All authors have read and agreed to the published version of the manuscript.

Funding: This study did not receive project funding or external financial support.

Acknowledgment: The authors highly thank to BFIT Group of Institutions and Guru Nanak College Dehradun to provide the Laboratory facility.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: The authors confirm that the data supporting the findings of this study are available within the article (and/or) its supplementary materials.

Supplementary Information Availability: Not applicable.

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