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Research Article

PHYSICOCHEMICAL PROPERTIEES OF URBAN SOILS AND MICROBIAL INDICES IN RELATION TO SELECTED HEAVY METALS IN NIGER-DELTA ENVIRONMENT, NIGERIA

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ABSTRACT

Understanding the physicochemical properties of soils with microbial activities, there sensitivity in nature and their changes in the urban environment together with their response to heavy metal stress are very important. However, this study investigated the physicochemical properties of urban soils, microbial indices in relation to heavy metals in the Niger-Delta environment in Nigeria. A free survey technique was used in the study. The sampling sites were divided into 5 land use types namely, commercial, recreational, Agricultural, Residential and Industrial areas. Five (5) profile pits were dug with one pit each on the selected land units. The profile pits were geo-referenced using a hand-held Global positioning system (GPS) receiver. Profile digging, description and sampling were done according to FAO (2006). The result indicated that sand content was highest compared to clay and silt irrespective of the land use. Bulk density varied highly in Agricultural soils (40.65 %) and moderately in soils of residential (19.24 %) and recreational area (CV=11.63 %). Saturated hydraulic conductivity (Ksat) varied highly in soils of commercial area (CV=91.07 %) and lowest in Agricultural soils (CV=11.24 %). Moisture content (Mc) was highest in agricultural soils. Organic C had the highest variation in commercial soils (CV=62.22 %) and lowest in soils of Industrial area (CV=1.92 %). Total N was highest in soils of Industrial area (CV=0.18 %) and lowest in Soils of commercial area (CV=0.14%). Soils were generally acidic. The C/N ratio was below 10 and was highest in soils of commercial area (C/N =3.66) and lowest in soils of industrial area (C/N=2.31). Available P was highest in Agricultural soils (Avail.P= 27.82 mg kg^{-1}) and lowest in soils of commercial area. Effective cation exchange capacity (ECEC) was highest in soils of Industrial area (ECEC =5.82 cmolkg-1) and lowest in agricultural soils (ECEC=4.09 cmolkg-1). However, both Arsenic (As) and Chromium (Cr) concentrations were below the permissible limits of 20 mgkg-1(As) and 100 mgkg-1 (Cr) according to WHO/FAO, 2004 respectively. The concentration of as was highest in soils of residential area (As= 0.67 mgkg-1) and lowest in soils of Industrial area (As=0.27 mgkg-1). Chromium concentration was in this format commercial>recreational>residential>Agricultural>Industrial soils. The microbial population and Microbial Biomass were influenced by heavy metal sources and soil properties. The microbial bacteria were highest in Agricultural and residential soils and lowest in commercial soils. Microbial fungi were highest in soils of commercial area and lowest in soils of Industrial area. MBC and MBN were highest in Industrial soils and lowest in soils of recreational area. Microbial biomass P was highest inAgricultural soils and lowest in soils of commercial area.

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MBC was significantly correlated with OC. MBP correlated positively with Available P. Arsenic (As) correlated positively with ECEC (r=0.05, p<0.05). Therefore, proper use of good soil management practices, remediation, pollution prevention measures such as controlling the release of harmful compounds in human activities from urban environment should be recommended.

Keywords: Physicochemical properties, Microbial indices, Heavy metals, Urban soils, Environment.

INTRODUCTION

Urban Soil Research has over the years increasingly become a global phenomenon (Yuangen *et al*., 2006). Its research work has equally increased due to human population which have greatly affected the world's ecosystem (Ellis *et al*.,2021) Gomez-Brandon *et al*., 2022). According to the United Nation (2018), the world's population is estimated to increase up to 70% by 2050 as against 56% in 2014 (United Nation 2014). Liu *et al*. (2014) explained urban areas to include city centers, roadways, commercial, industrial, residential, vegetated or landscape, undeveloped lands such as managed, urban agriculture, forested areas, reclaimed and wetlands. Urban soils are defined according to Levin *et al*. (2017) as highly disturbed soils and manipulated materials which have been altered through mixing, filling, transportation and other perturbation that are caused by construction related activities. Evans *et al*. (2000) also defined it as anthropogenic soils that are characterized by the presence of artefacts and coarse fractions with high levels of compaction and sealing, poor physical condition, low organic matter and low fertility.

Urban soils play significant role in soils ecosystem which include carbon(C) and nitrogen (N) sequestration (Liu *et al*., 2020) that supports nutrient cycling processes. However, urban soils are used for different purposes which include urban and industrial activities, forestry and agriculture (Hillel, 2005). Urban ecosystem provides clean water and recreational area for inhabitants of the area (Diaz *et al*., 2018) and urban heat mitigation (Christel *et al*., 2023). In urban ecosystem, soil fertility plays a significant role by supporting plant community, providing adequate porosity and nutrients to plants andsustains microbes through soil organic matter (Renella, 2020). Urban land uses host greater bacterial and fungal community (Delgada-Baquerizo *et al*., 2021). Liu *et al*. (2021) reported increased heterogeneity of microbial community composition with urbanization. Also, Ramrez *et al*. (2014) reported higher pathogenic populations in central parks due to increased number of visitors in the area. Microbial Biomas Carbon (MBC), Microbial Biomas Nitrogen (MBN) and Microbial Biomas Phosphorus (MBP) as soil microbial biomas components play significant role in Organic matter mineralization, humus formation, nutrient transformation and cycling (Piotrowska-Dlugosz and Charznski, 2015). Singh and Gupta (2018) also reported that increased microbial biomas and activity in urban soils is dependent on the age, climate, variability and complicity of plant community, SOM, soil properties. Therefore, reduction of SOM causes reduction of soil respiration, soil microbial biomas and soil enzymatic activity (Saikia *et al*., 2019). Therefore, the knowledge of physiochemical properties, soil microbial indices, in urban soils is very important for climate change and nutrient regulations (Lepcha and Devi, 2020). However, despite the human benefits there are environmental challenges by which urban soils are affected. These environmental challenges are as a result of continuous human and anthropogenic activities in the urban areas.In soils under different land uses such as residential, commercial, recreational, industrial areas are characterized by sealing with low infiltration rate due to excessive trampling (Prokofera *et al*., 2020), surface ponding, decreased in porosity and aeration (Zhang *et al*.,2019), decrease in organic matter and decrease in fertility (Martinian *et al*.,2020). In the process, land cover and lands are degenerated, bacterial function and diversity undergo significant differences across the land use (Wu *et al*., 2022) especially during intense repaid urbanization. By so doing, soils are contaminated because they serve as a site for waste disposal (Schmidt *et al*., 2017).

Urban soils serve as a Point Source and Sink for soil pollution. Heavy metals (Arsenic and Chromium) in urban soils are caused by both natural (rock weathering, forest, volcanic eruption) and anthropogenic sources (run off, gasoline, petrochemical, sewage sludge, solid wastes, traffic emission, agricultural wastes, pesticide, parks, factories and industries). There metals are carried out through, run off, via food Chain posing serious threat to human life (Musilora *et al*., 2016). The level of toxicity these heavy metals have especially As and Cr is dependent on several factors which include the level of its exposure, biological role, time and type of exposure of organisms to the metal and level of interaction between these organism (Prokovera *et al*., 2020). Furthermore, heavy metals lower the activity of soil enzymes, microorganism biodiversity and biomass and at same time disrupt the transformation of C, N (Piotrowska -Seget, 2022). Therefore, the effect of heavy metals, microbial activities, visa-vis physicochemical properties in unban soils is very important in other to develop a strategy for bioremediation (Jin *et al*., 2018; Zeng *et al*., 2020).

Niger Delta is a highly developed area in Nigeria due to increasing human population. The area is characterized by constructed buildings and parking lots, industries, tanning factories commercial areas that have close proximity to the residential area. By so doing, all living things including plants and animal, suffer from environmental pollution (Wong, 2013) and habitat degradation. Heavy metals are carried in run off from industries, municipal regions, other urban areas into the soil, sediments, to water bodies and dust to humans through the food chain (Adewumi *et al*., 2022). However, in the tanning factories, Arsenic compounds were used in various tanning processes and such heavy metals were found in soils and buildings surrounding the area. Also, wastes generated from contaminated solid wastes and pesticides from agricultural areas often contain Arsenic (As) and chromium (Cr) which are detrimental to human health. Gao and Schulze (2010) reported the association of As and Cr with Iron oxides and Iron III oxyhydroxides and Al phases in contaminated Soils. Such level of interaction through food web and food chain causes health risk to inhabitants living in the area. Most of the work carried out by researchers focuses mainly on microbial response to soil (Pan *et al*.,2024); heavy metals on soils (Chegara *et al*.,2020); effects of land use on physicochemical properties of soils (Akintola *et al*., 2022) but none have worked on physicochemical properties, microbial indices in relation to heavy metals in urban soils. Therefore, the objectives of this study include to (i) determine the physicochemical properties of urban soils (ii) determine the microbial indices of urban soils (iii) determine the selected heavy metals (As) and (Cr) in urban soils (iv) correlate the soil properties and microbial indices of urban soils.

MATERIALS AND METHODS

Study Area

The study was conducted in the urban areas of Rumuokwurushi Port Harcourt Rivers State Nigeria namely Commercial area (latitude $4^0$52'31.09" N and Longitude $7^0$4'20.65"E), Recreational area (Latitude $4^0$52'30.01"N and Longitude $7^0$4'15.81"E), Residential area (Latitude $4^0$52'28.97"N and Longitude $7^0$4'15.81"E), Agricultural area (Latitude $4^0$52'35.21"N and Longitude $7^0$4'24.61"E) and Industrial area (Latitude $4^0$52'30.53"N and $7^0$4'31.37"E) (Figure 1). The Soils of the area are derived from Niger-Delta Sand Stone. The area is a tropical rainforest area with mangrove swamps and water bodies surrounding it. However, due to the growing population, the area is characterized by the presence of many industries, industrial quarters, recreational areas, parking lots and commercial areas. Also, there are presences of old large part of pipelines construction which served as water distribution system to the area. Additionally, agricultural activities are also going on in the area and most of the waste water from agricultural and industrial area is discharged into the rivers through the ground water for drinking. However, crude oil deposits and natural gas are the State's major mineral resources. We have different Crops grown in the area which include plantain, banana, cassava, coconut and oranges. The methods of clearing of farmland in the area are by slashing and burning system while the biodiversity of the area has been altered by anthropogenic activities like wastes disposal, agriculture, recreational and industrial activities.

Soil sampling

Prior to the sampling proper, a reconnaissance visit was done where information on the vegetation of the area, general land use, and other information concerning the area were recorded. A free survey technique was used on the study. In other words, to make sure a good representative of the sample was made, the sampling sites were divided into five (5) land use areas namely commercial, Recreational, Agricultural, Residential and industrial. Five (5) profile pits were sited according to selected land units with one pit each on the selected land units. The profile pits were geo-referenced using a hand-held Global positioning system (GPS) receiver. Profile digging, description and sampling were done according to FAO (2006). In addition, undisturbed soil samples were collected using core sampler for bulk density and saturated hydraulic conductivity determination. The collected soils sample were air dried, sieved using 2mm sieve in preparation for laboratory analysis.

Physical properties

Particle size distribution was determined by hydrometer method (Gee and Or, 2002), bulk density was determined using core method (Grossman Reinsch, 2002) and calculated using the following formula

$$Bd = \frac{Ms}{Vs} \ (gcm^{-3})$$

where Ms = mass of oven dry soil(g) and Vs=volume of oven dry soil which is assumed to be the volume of the core. Gravimetric moisture content was determined by oven drying saturated soil samples for 24 hours (Obi, 1990). Mc (%) $=m_1-m_2/m_2 x100$.where m is moisture content, m_1=mass of the wet soil, m_2 mass of the dry soil. Total porosity was calculated from bulk density using the relationship between particle density and bulk density assuming a particle density of 2.65gcm^{-3} TP=(1-Bd/Pd) x100 where Bd=bulk density, Pd=particle density. Soil pH was determined using 1:25 soil-liquid ratio using a pH meter (Thomas, 1996). Organic carbon was determined by wet digestion method (Nelson and Sommers, 1982). Total Nitrogen was determined by Micro-kjeldahl digestion method (Bremner and Mulvaney, 1982). Available phosphorus was determined using Bray 2 method (Olson and Sommer, 1982). Effective Cation Exchange Capacity (ECEC) was determined by summation of exchangeable base plus exchangeable acidity expressed in cmolkg^{-1}.

Soil Microbial Population Determination (Bacteria and Fungi)

Numbers of stable bacteria and Fungi were estimated by the plate count Technique. 1g of the 2 mm sieve soil samples were weighed into a beaker and 9 ml of sterile distilled water was added and stirred for some time. Serial dilutions were prepared up to 10^{-5} M concentrations for bacteria and 10^{-4} M concentrations for fungi. Total viable counts of cultural bacteria were obtained by surface plating 1 ml of the serial dilution on potato dextrose agar (PDA). Culture plates were inoculated at room temperature (28^0C) for 48 hours. Plates yielding counts of 30-300 colonies were selected and the counts obtained were multiplied by the dilution factor and expressed as colony forming units (cfu) per gram of soil.

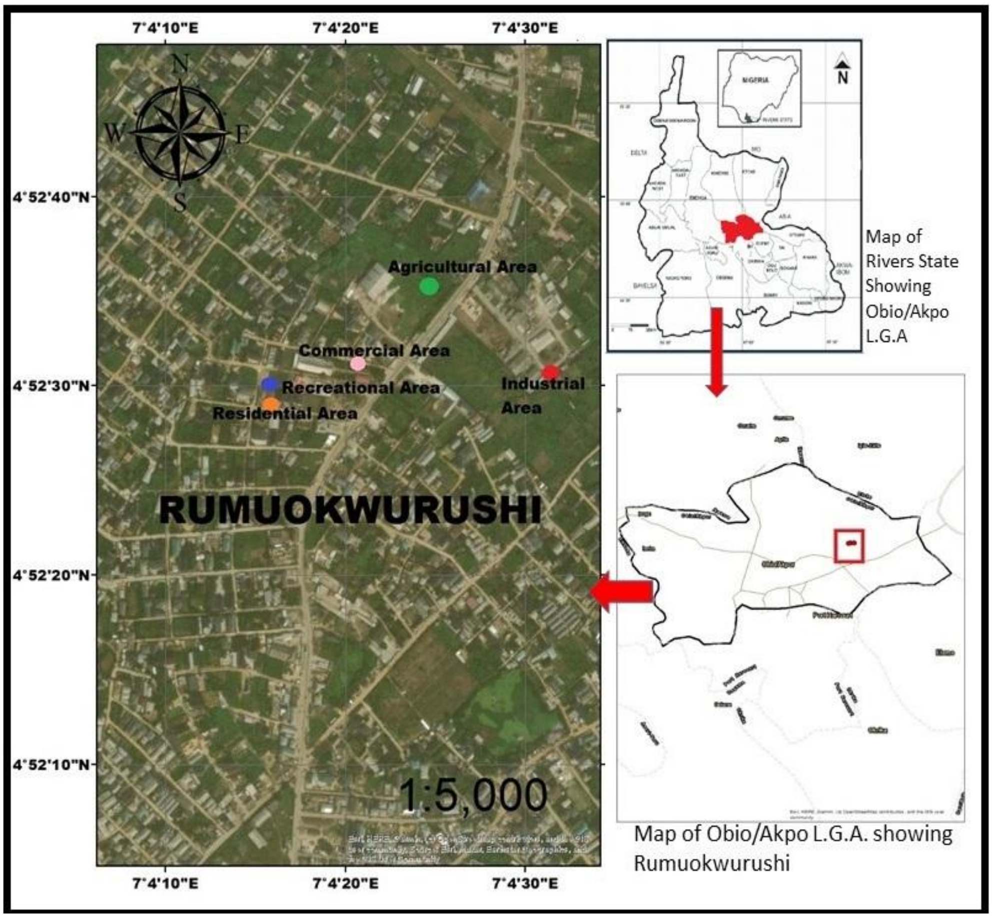

Figure 1. Location Map of the study area.

Microbial Biomas Determination

Microbial Biomas C and Microbial Biomas N were determined by the fumigation extraction method (Vance *et al*., 1987; Brookers *et al*.,1985). A 20g subsample of soil (oven-dried basis) was fumigated by exposing the soil to alcohol -free $CHCl_3$ vapour in a sealed vacuum desiccator for 24hr. The fumigated soil was evacuated until the odour of $CHCl_3$ was not detected and then extracted with 80ml 0.5M K_2SO_4(Soil: K_2SO_4=1:4) for 30min. The extraction of non- fumigated soil was the same as that of the fumigated soil. Microbial Biomas C and N were established by the difference between the total Organic C or total N in the fumigated and non-fumigated extracts with a conversion factor (K_{EC}) of 0.38 and (K_{EN}) of 0.45(40-41) respectively. Soil Microbial Biomas Phosphorus (MBP) was fumigated by chloroform and extracted by 0.5 Mol L^{-1} $NaHCO_3$(Soil - water ratio:1:4). P in the extract was determined by the molybdenum -antimony resistance colorimetric method.

Heavy Metals Determination (Arsenic (As) and Chromium (Cr))

Ig of dried samples was digested in standard Erlenmeyer flask using 12ml, aquaregia solution. The solution was prepared at a ratio of 1:3 of HNO_3 to HCL. The beaker was covered and healed using medium hot plate heat for 2hr. The mixture was left to cool down after heating which was later filtered using a whatman No42 fillen paper. The filtrate was de-ionized with distilled water and was diluted to 50 ml. The solutions were further analyzed for As and Cr using absorption Spectrophotometer (Adebayo *et al*., 2017; Dogra *et al*., 2019).

Statistical Analysis

The field and laboratory analytical data generated were subjected to mean, coefficient of variation, and correlation analysis. The coefficient of variation was used to determine the variability of the soil physicochemical properties and was ranked according to Wilding *et al* (1994) where CV< 15% indicated low variation, CV<15<35% = moderate variation and CV> 35% indicated high variation while the linear correlation was used to compare the physicochemical properties with microbial biomas.

RESULTS AND DISCUSSION

The results of the physical properties in Table I indicated that Sand content was higher compared to clay and silt contently irrespective of the land use. The highest mean

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Sand content was recorded on soils of the commercial area (Mean=870.20kg^{-1}) and lowest on soils of the industrial area (Mean=769.20kg). The highest sand content observed on soils of commercial area may be attributed to the parent materials of the study area which is Niger-Delta- Sand Stone. Also, the Sandy anthropogenic soils from urban areas such as gardens, parks, industrial area, and agricultural area may have contributed to the increase in sand content (Halecki and Gasiorek, 2015). However, soils in the industrial area had higher clay content (Mean=159.60 gkg^{-1}) compared to other urban soils. In contrast, silt was highest on soils of recreational area (Mean=183.20 gkg^{-1}) and lowest on soils of commercial area (Mean=29.70 gkg^{-1}). Bulk density (Bd) varied moderately on soils of residential area (CV=19.74%), commercial (CV=18.98%) and industrial area (CV=15.90 %). In agricultural area, Bd varied highly (CV=40.65%) and with the highest mean value of 1.54 g cm^{-3} which could be attributed to the use of heavy machines in the area, under story, root growth soil biota activities (Devigne *et al*; 2016). This value could restrict root development and plant growth (Sunal *et al*., 2017). This result in line with the results of Obidike-Ugwu *et al*; 2023 and Tomasella and Hodnett, 2004) who reported high bulk density in vegetated soils and bare soils. In contrast, soils of recreational area had moderate variation of Bd (CV=11.63%). Saturated Hydraulic conductivity (Ksat) varied highly in soils of commercial area (CV=91.07%) compared to soils of recreational (Ksat=CV=18.49%), Agricultural (CV=11.24 %), Residential (CV=23.37%) and industrial area (CV=27.33%). The highest Ksat observed in soils of commercial area could be attributed to the presence of large pores (Coarse Sand) which signifies high infiltration Prokofeva *et al*., 2020). Generally, moisture (Mc) varied highly in all the urban soils and their variation ranges from CV= 44.69 % - 121.50%. The high variation was more in Agricultural soils (CV=121.50%) compared to commercial, industrial, recreational, residential probably due to under-story vegetation and surface litters which may have increased the moisture content in the study site (Livesley *et al*., 2016).

Table 1. The results of the physical properties.

Depth (cm)	Horizon	Sand g/kg	Clay g/kg	Silt g/kg	MC %	BD g/cm³	TP %	Ksat cms^{-1}
Commercial								
0-13	A	915.20	27.60	57.20	3.33	1.60	39.62	0.208
13-33	EA	855.20	117.60	27.20	12.34	1.20	54.71	0.353
33-52	Bt1	845.20	127.60	27.20	10.50	1.03	61.13	0.032
52-120	Bt2	865.20	127.60	7.20	12.49	1.23	53.58	0.059
Mean		**870.20**	**100.10**	**29.7**	**9.67**	**1.27**	**52.26**	**0.163**
CV		**3.57**	**48.51**	**69.41**	**44.69**	**18.98**	**17.33**	**91.07**
Recreational								
0-25	A	835.20	147.60	17.20	11.00	1.10	58.49	0.136
25-41	BA	815.20	117.60	67.20	8.47	1.70	35.85	0.278
41-64	Bt1	795.20	147.60	57.20	10.85	1.10	58.49	0.225
64-82	Bt2	765.20	137.60	97.20	10.78	1.10	58.49	0.391
82-145	Bt3	755.20	157.60	87.20	11.72	1.20	54.71	0.205
Mean		**793.20**	**141.60**	**65.20**	**10.56**	**1.24**	**53.21**	**0.247**
CV		**4.22**	**10.71**	**47.77**	**48.37**	**11.63**	**21.03**	**18.49**
Agricultural								
0-11	Ap1	863.20	87.60	49.20	3.76	1.69	36.23	0.355
11-29	Ap2	865.20	37.60	97.20	13.20	1.36	48.68	0.306
29-59	BA	775.20	147.60	77.20	15.40	1.52	42.64	0.173
59-92	Bt1	765.20	177.60	57.20	15.47	1.52	42.64	0.314
92-150	Bt2	755.20	217.60	27.20	16.49	1.62	38.87	0.271
Mean		**804.80**	**61.60**	**61.60**	**12.86**	**1.54**	**41.81**	**0.284**
CV		**6.795**	**43.46**	**43.46**	**121.5**	**40.65**	**8.079**	**11.24**
Residential								
0-25	A	905.20	27.60	67.20	13.68	1.26	52.45	0.191
25-39	AB	755.20	117.60	127.20	15.75	1.54	41.89	0.101
39-69	B	775.20	157.60	67.20	17.49	1.78	32.83	0.148
69-92	Bw1	755.20	157.60	87.20	9.95	1.00	62.26	0.160
92-145	Bw2	735.20	197.60	67.20	14.30	1.40	47.17	0.162
Mean		**785.2**	**131.60**	**83.20**	**14.23**	**1.40**	**47.32**	**0.15**
CV		**8.731**	**49.13**	**31.34**	**89.92**	**19.74**	**20.99**	**23.37**

Industrial									
0-11	AB	875.20	37.60	87.20		19.19	1.89	28.68	0.412
11-29	BA	725.20	217.60	57.20		10.15	1.00	62.26	0.435
29-59	Bt1	775.20	147.60	77.20		10.45	1.03	61.13	0.241
59-92	Bt2	745.20	177.60	77.20		14.32	1.40	47.17	0.284
92-150	Bt3	725.20	217.60	57.20		11.32	1.11	58.11	0.200
Mean		**769.20**	**159.60**	**71.20**		**13.82**	**1.29**	**51.47**	**0.31**
CV		**8.15**	**46.55**	**18.84**		**115.5**	**15.9**	**28.99**	**27.33**

Mc=Moisture content, Bd=Bulk density, TP= Total porosity, Ksat= Saturated hydraulic conductivity, CV= Coefficient of variation.

The results of the chemical properties indicated in Table 2 showed that organic C(OC) was moderately low according to the rating of FPDD, 1990(<2.0%). The concentration of OC varied highly in soils of commercial area (CV=62.22%) compared to other urban soils (recreational CV=4.18 %, Agricultural soils CV=9.25 %, Residential soils CV=8.40 % industrial soils CV=1.92%). However, the mean concentration of organic C showed OC was higher in soils of commercial area (OC=0.56%), industrial area (OC=0.45%) and residential area (OC=0.43%) respectively. Similarly, the mean Total N(TN) was moderately low in all the land use types according to the rating of FDALR, 1985(0.101-0.150%). However, TN was high in soils of three urban areas industrial, residential and commercial area with the highest concentration of TN in soils of industrial area (TN=0.18%) residential (TN=0.15%) and commercial (TN=0.14%). The higher concentration of OC and TN in these urban soils may be attributed to high organic matter, high root biomass, little content, increase in rainfall, temperature which may have improved the growth and reproduction of microorganisms, rapid turnover of abundant biomass and litter increasing carbon and nitrogen to the soil (Lu *et al*., 2023). The low mean concentrations of OC and TN in soils of recreational area were due to management practices. The pH (H_2O) values of the urban soils varied from 4.82-6.06. High acidity was observed on soils of the residential area (pH (H_2O), 4.82) compared to other urban soils (commercial pH =5.72), recreational (5.42), agricultural soils (pH=5.14) and industrial soils (pH =6.06) probably due to solid wastes, pesticides (Schroth *et al*., 2007). The maximum pH value closer to a neutral reaction was recorded in soils of industrial area (pH=6.06) due to anthropogenic influence (Enescu *et al*., 2022), leaching that is caused byacid deposition (Schroth *et al*. 2007). Shen *et al*. (2022) observed a decrease value of pH (4.88 and 4.50) in the suburban and rural areas.

Table 2. Chemical Properties of the Studied Area.

Depth (cm)	Horizon	pH (H20)	O.C (%)	TN (%)	AP (mg/kg)	C/N	ECEC (cmo/kg-1	% BS
Commercial								
0-13	A	5.55	1.06	0.194	13.12	5.45	5.17	95.36
13-33	EA	5.91	0.50	0.132	16.79	3.77	3.92	95.92
33-52	Bt1	5.96	0.42	0.129	8.19	3.24	5.30	94.71
52-120	Bt2	5.45	0.26	0.118	1.96	2.20	4.97	91.95
Mean		5.72	0.56	0.140	10.02	3.66	4.84	94.49
CV		4.465	62.22	23.99	64.13	37.06	12.94	1.864
Recreational								
0-25	A	5.75	0.56	0.159	39.23	3.51	5.60	97.86
25-41	BA	5.51	0.38	0.133	39.24	2.85	2.96	81.09
41-64	Bt1	5.15	0.26	0.124	14.00	2.09	4.63	69.75
64-82	Bt2	5.30	0.16	0.119	15.19	1.34	5.18	50.59
82-145	Bt3	5.39	0.20	0.103	2.450	1.93	2.86	72.23
Mean		5.42	0.31	0.128	22.02	2.34	4.25	74.30
CV		38.55	4.18	51.87	16.19	23.20	43.14	29.81
Agricultural								
0-11	Ap1	5.58	0.80	0.149	34.60	5.36	5.93	93.93
11-29	Ap2	5.47	0.64	0.144	24.64	4.43	4.00	64.01
29-59	BA	5.35	0.26	0.14	39.17	1.85	3.59	65.41
59-92	Bt1	5.37	0.22	0.127	27.02	1.72	3.52	80.64

92-150	Bt2	4.38	0.18	0.114	20.43	1.57	5.27	76.48
Mean		5.14	0.32	0.13	27.82	2.39	4.09	71.64
CV		24.23	0.25	66.97	10.54	16.08	38.76	24.3
Residential								
0-25	A	5.54	0.84	0.159	19.98	5.26	5.01	96.81
25-39	AB	4.70	0.50	0.127	11.27	3.92	6.84	67.84
39-69	B	4.64	0.38	0.163	10.15	2.33	5.03	60.25
69-92	Bw1	4.58	0.30	0.144	15.19	2.08	4.35	52.17
92-145	Bw2	4.64	0.14	0.132	19.32	1.05	3.69	55.51
Mean		4.82	0.43	0.15	15.18	2.93	4.98	66.52
CV		21.52	8.40		10.98	26.95	38.95	23.62
Industrial								
0-11	AB	6.09	1.32	0.224	14.84	5.88	3.43	98.83
11-29	BA	6.09	0.22	0.188	12.03	1.17	6.11	98.04
29-59	Bt1	6.20	0.26	0.16	13.3	1.62	6.74	95.85
59-92	Bt2	5.88	0.34	0.171	8.84	1.98	6.26	97.44
92-150	Bt3	6.05	0.12	0.133	7.98	0.90	6.57	95.74
Mean		0.06	0.45	0.18	11.40	2.31	5.82	97.18
CV		33.16	1.92	31.2	19.3	1.40	22.57	23.37

Oc=organic carbon, TN=Total N, Avail. P=Available.P, ECEC=Effective cation exchange capacity, BS= Base saturation, C/N= Carbon/Nitrogen ratio, CV= Coefficient of Variation.

The C/N ratio explains the degradation level of organic matter (OM). Assandri *et al*. (2020) reported that C/N ratio>12 in urban soils indicated slow decomposition of organic matter (OM) and stable humus. However, from our study, we observed C/N ratio <10 in all the urban soils possibly due to changes in land use such as conversion of forest lands to residential area, industrial, commercial, recreational and agricultural area and other anthropogenic activities which may have caused a shift in SOC, TN and available P. The highest mean C/N ratio observed on soils of commercial area(C/N=3.66) may be attributed to higher soil C content (Pan *et al*., 2024). The low C/N ratio in soils of industrial area may be due to high TN, changes in Temperature and precipitation and higher decomposition and mineralization of organic matter resulting to loss of carbon and Nitrogen due to disturbance in the soils of the area (Pan *et al*., 2004). Additionally, increased N accumulation due to N deposition lowers the C/N ratio (Vanguelova *et al*; 2024). In contrast, agricultural soils had the highest available P (Avail P=27.82 $mgkg^{-1}$) compared to other urban soils probably due to increased phosphate fertilizers and presence of organic materials. Effective cation exchange capacity (ECEC) was generally low in all the urban soils. Buol *et al*. (1980) reported ECEC of <10$cmolkg^{-1}$ in soils as strongly weathered. From our result, the ECEC of all the urban soils was lower than 10$cmolkg^{-1}$indicating that the soils are strongly weathered. However, the soils of industrial area were highest in ECEC (Mean=5.82 $cmolkg^{-1}$) compared to other land uses indicated lower infiltration rate, increase in flooding experienced in the urban areas and unsuitability of this soil for waste disposal (Bonarius, 1975). Agricultural soils exhibited low ECEC (Mean=4.09 $cmolkg^{-1}$) due to litter reduction, leading to decreased Om, low pH, N, K (Mashagiro *et al*., 2024). The mean concentration of Arsenic (As) and Chromium (Cr) in the urban soils as shown in Table 3 ranges from 0.27 $mgkg^{-1}$ - 0.67 $mgkg^{-1}$ for As and 0.12 $mgkg^{-1}$ - 0.82 $mgkg^{-1}$ for Cr respectively. Arsenic concentration (As) was highest in soils of residential area.

Table 3. Heavy metal contents in the Studied Area.

Location	Depth (cm)	Horizon	Arsenic (As) $mgkg^{-1}$	Chromium (Cr) $mgkg^{-1}$
Commercial	0-13	A	0.07	1.49
	13-33	EA	2.11	1.44
	33-52	Bt1	0.08	0.23
	52-120	Bt2	0.05	0.11
	Mean		**0.58**	**0.82**
	CV		**176.9**	**91.7**
Recreational	0-25	A	1.12	3.00
	25-41	BA	0.08	0.09

	41-64	Bt1	0.10	0.11
	64-82	Bt2	0.10	0.02
	82-145	Bt3	0.07	0.31
	Mean		**0.29**	**0.71**
	CV		**157.1**	**182.3**
Agricultural	0-11	Ap1	0.10	0.10
	11 – 29	Ap2	0.28	0.22
	29-59	BA	0.12	0.09
	59-92	Bt1	1.01	1.13
	92-150	Bt2	0.26	0.12
	Mean		**0.35**	**0.33**
	CV		**106.10**	**135.30**
Residential	0-25	A	0.06	0.07
	25-39	AB	3.10	2.06
	39-69	B	0.08	0.06
	69-92	Bw1	0.07	0.08
	92-145	Bw2	0.04	0.09
	Mean		**0.67**	**0.47**
	CV		**202.80**	**188.10**
Industrial	0-11	AB	0.11	0.11
	11-29	BA	0.13	0.3
	29-59	Bt1	0.07	0.07
	59-92	Bt2	1.00	0.08
	92-150	Bt3	0.05	0.04
	Mean		**0.27**	**0.12**
	CV		**150.10**	**86.10**

Mean=0.67mgkg^{-1}) compared to soils of other urban area (Commercial =As=0.58mgkg^{-1}, Agricultural= mean 0.35mgkg^{-1}, recreational=0.29 mgkg^{-1}, industrial=mean=0.27mgkg^{-1}). This increase may be due to increased population leading to throwing of solid wastes, garbage waste, (Weolu, 2024), house hold dust, waste water from leacking pipes situated in the area, coal burning, Fossil fuel combustion (Chen *et al*., 2021; Zhao *et al*., 2022). However, the concentration of As was below the permissible limit of 20mgkg^{-1} established by WHO/FAO (2004). On the other hand, soils of Commercial area had the highest concentration of Cr(Mean=0.82 mgkg^{-1}) compared to other urban soils which could be from traffic emission, tanning dyes, burning of heavy-duty oils, fuel stations which are released on the surface of the soil (Alloway, 1995; Hassan and AL-Jumaily, 2016). However, the distribution of Cr is in this format: commercial area> recreational>residential>agricultural soils>industrial soils respectively. Also, the concentration of Cr was below the permissible limit of 100mgkg^{-1} established by WHO/FAO (2004). The relationship between As and Cr with some soil properties in Fig.5 showed that As had positive relation with ECEC(r=0.05, P<0.05). Bacteria and Fungi plays significant role in organic matter and nutrient availability and are the major population in microbial biomass (Hu *et al*., 2021). However, the microbial population results analysed for both bacteria and fungi were indicated in figure 2 and 3. The result indicated that the mean number of microbial bacteria (Figure 2) was similar in both.

Agricultural soil and soils of the residential area followed by soils of industrial area, recreational and lowest in commercial area. The highest microbial bacterial population in agricultural and soils of residential area may be due to lower pH, lower Clay, Organic matter, (Xie *et al*., 2017; Wang *et al*., 2018). Hu *et al*. (2021) reported that lower pH promotes some microbial function especially acid bacterial and can adapt in slightly acid soil pH. The lowest bacteria observed in soils of commercial area (Figure 2.) maybe due to heavy metal stress (Fernandez-Calvino and Baath, 2016). Desou *et al*. (2000) reported a reduction in microbial abundance and activity due to Cr contamination especially the sensitive ones (Ma *et al*., 2021). Additionally, increased clay content decreases soil microbial bacteria (Chau *et al*., 2011). The increase in human activities intensity such as land use, impervious surface coverage in the area lead to microbial taxa loss, changes in nitrogen cycling process, microbial nitrification and de -nitrification, (Zhang *et al*.,2020). However, microbial fungi was highest in soils of the commercial area 4.3x10^{4} (Figure 3) compared to soils in recreational area (3.9x10^{4}) probably due to the resistance of fungal species to heavy metal pollution (Chenjara *et al*.,2021). The lowest microbial fungi in soils of industrial area may be due to heavy metal stress (Pan and Yu, 2011), changes in soil properties, reduction in plant species richness due to urbanization pressure where some plant species are selected (Norton *et al*., 2016; Chen *et al*., 2021).

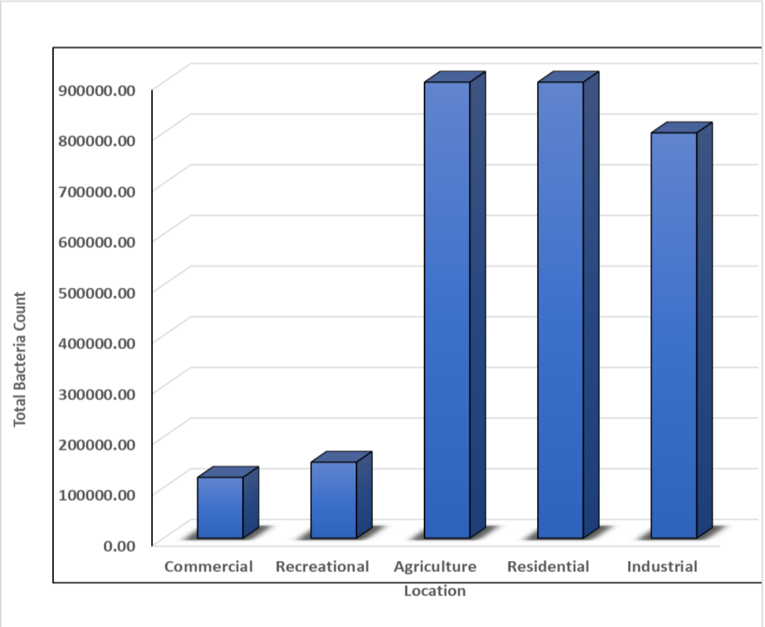

Figure 2. Distribution of total bacteria count in the studied locations**.**

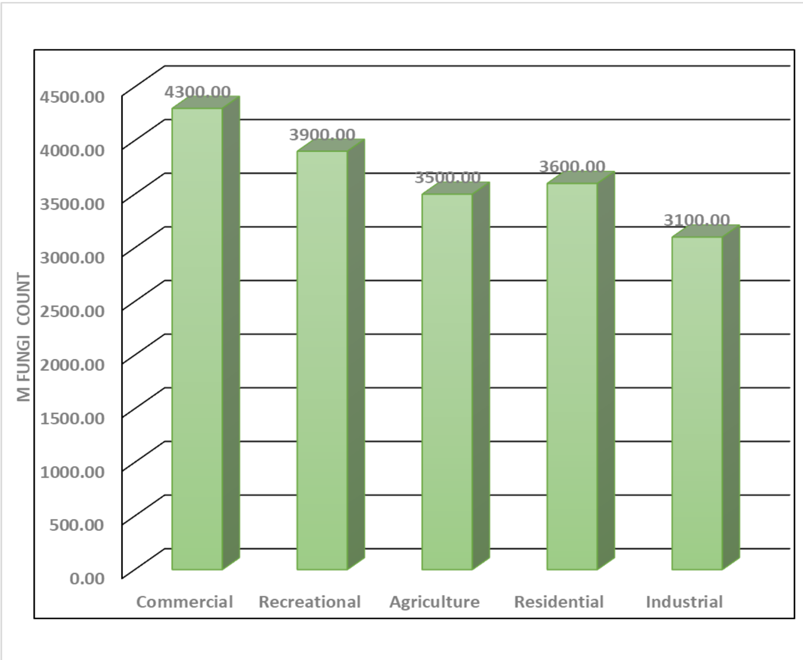

Figure 3. Distribution of Microbial fungi population in the studied locations.

The results obtained from Microbial Biomas C (MBC), Microbial BiomasNitrogen (MBN) and Microbial Biomas Phosphorus (MBP) (Figur 4) indicated that there were differences in the soil microbial biomas among the urban soils. The difference may be due to the different composition of soil microbial community as a result of changes in soil physicochemical properties, (Yuan *et al*., 2020), precipitation (rainfall) (Yang *et al*; 2021), soil moisture (Muhammed and Buba 2020). However, the MBC and MBN were relatively highest in soils of industrial area MBC=0.20979, MBN=0.07906% compared to MBC and MBN in soils of recreational, commercial, agriculture and residential areas respectively possibly due to low C/N ratio, high Total N and organic matter (organic

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C) in the studied site Heijboer *et al.*,2016). Also, the C/N ratio is said to be a good predictor of decomposition of organic materials (Benbi and Khosa., 2014; Sauvad *et al.*,2017). Therefore, organic materials that has low C/N ratio supplied enough nutrients to soil microbes (Hussain *et al.*, 2023) which probably increased MBC and MBN. Furthermore, availability of C, the C/N ratio, N, and P content determines the size of microbial biomas (Chen *et al.*, 2015) which at the same time provides energy source for microorganism growth. Additionally, increase in rainfall in the study area increases the decomposition of litter which in turn increases immobilization of soil carbon (Devi and Yadava, 2010) and increase in soil microbial biomas (Yang *et al.*, 2010). However, the low MBC and MBN observed in recreational soils may be due to urban activities (recreational activities) going on in the area, high pollution (Schmidt *et al.*,2017) and contaminated soil wastes (Cances *et al.*,2008). Zhang *et al.* (2010) reported decrease in MBN with increased heavy metals.

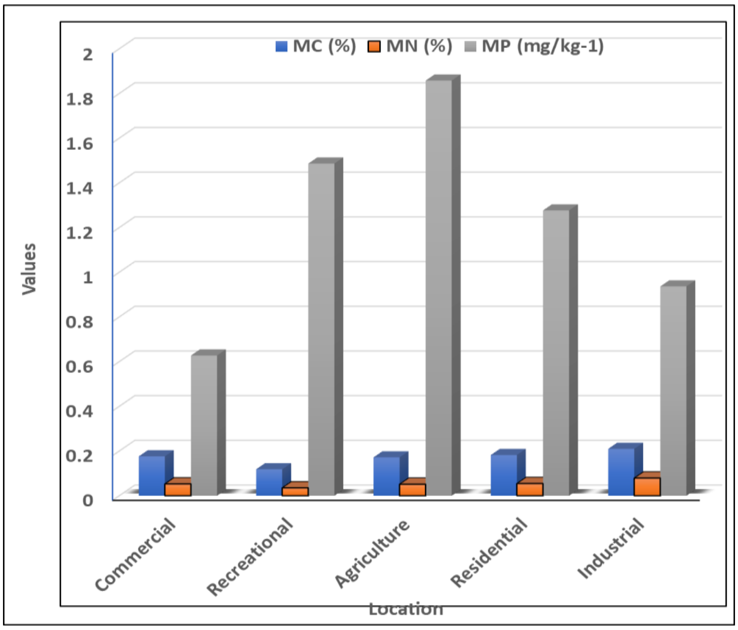

Figure 4. Distribution of MC, MN and MP in the studied locations.

On the other hand, Microbial Biomas Phosphorus(MBP) ranges from 0.63 mgkg^{-1} to 1.86mgkg^{-1} (Fig.4). Microbial Biomas P(MBP) was highest in agricultural soil (1.86 mgkg^{-1}) compared to soils in recreational (1.49 mgkg^{-1}), residential (1.28mgkg^{-1}), industrial (0.94mgkg^{-1}), commercial (0.63mgkg^{-1}). The highest MBP observed in agricultural soils may be attributed to vegetation, variability of plant species, phosphate fertilizers and increase in amount of biomass carbon (khan and Jorge Sen, 2012). Also, plant root increases hydrogen ions, bicarbonate and extracellular phosphate by producing organic acid in the rhizosphere which releases phosphate from organic matter (Take 1985., Halecki and Gasiorek., 2015). The lowest microbial phosphorus (MBP) observed in soils of commercial area was attributed to lower pH(5.72), Sandy anthropogenic soils from the commercial area and leaching and migration of phosphorus from soil to surface water (Potarzycki, 2000., Halecki and Gasiorek., 2015).

The correlation between soil MBC, MBN, MBP and physicochemical properties as shown in Table 4 indicated that MBC was significantly positively correlated with organic matter (OM)=r=0.94), Total nitrogen (TN=r=0.71) P<0.01) respectively). These correlations explain the fact that organic matter (OM) is the main source of C and N and a good relationship between organic matter and microbial biomass (Xie *et al.*, 2017). On the other hand, MBC and MBP correlated negatively with clay (MBC=r=-0.79; MBN=r=-0.55,p<0.05; 0.01) implying that the decrease in clay content increases MBC(Chau *et al.*,2011). Also, microbial biomass phosphorus (MBP) correlated positively with available P (r=0.73; P<0.01) indicating that increased in available P increased microbial biomas phosphorus.

Table 4. Relationship between Biological Properties with soil Physiochemical properties.

Soil property	MBP	Total Fungi Count	Total Bacteria Count	MBN	MBC
BS	0.12	0.12	0.12	0.47	0.42
AP	0.73**	-0.13	-0.24	0.09	0.15

BD	0.46	-0.12	-0.06	0.30	0.48
CLAY	-0.37	-0.18	-0.14	-0.55*	-0.77*
ECEC	-0.12	-0.03	-0.40	0.03	-0.06
KSAT	0.18	0.26	0.00	0.44	0.27
MC	0.04	-0.01	-0.16	-0.01	0.06
OM	0.49	0.09	0.13	0.79**	0.94**
SAND	0.32	0.19	0.19	0.49	0.68*
SILT	0.09	-0.04	-0.11	0.09*	0.14
TN	0.26	-0.10	-0.19	0.79**	0.71**
pH	-0.04	0.31	0.08	0.39	0.31
SILT	0.09	-0.04	-0.11	0.09	0.14

MBC= Microbial biomass carbon, MBN= Microbial biomass Nitrogen, MBP= Microbial biomass phosphorus,Mc=Moisture content, ECEC= Effective cation exchange capacity, TN= Total Nitrogen,* and ** = Sig at 0.05 and 0.01 probability levels respectively.

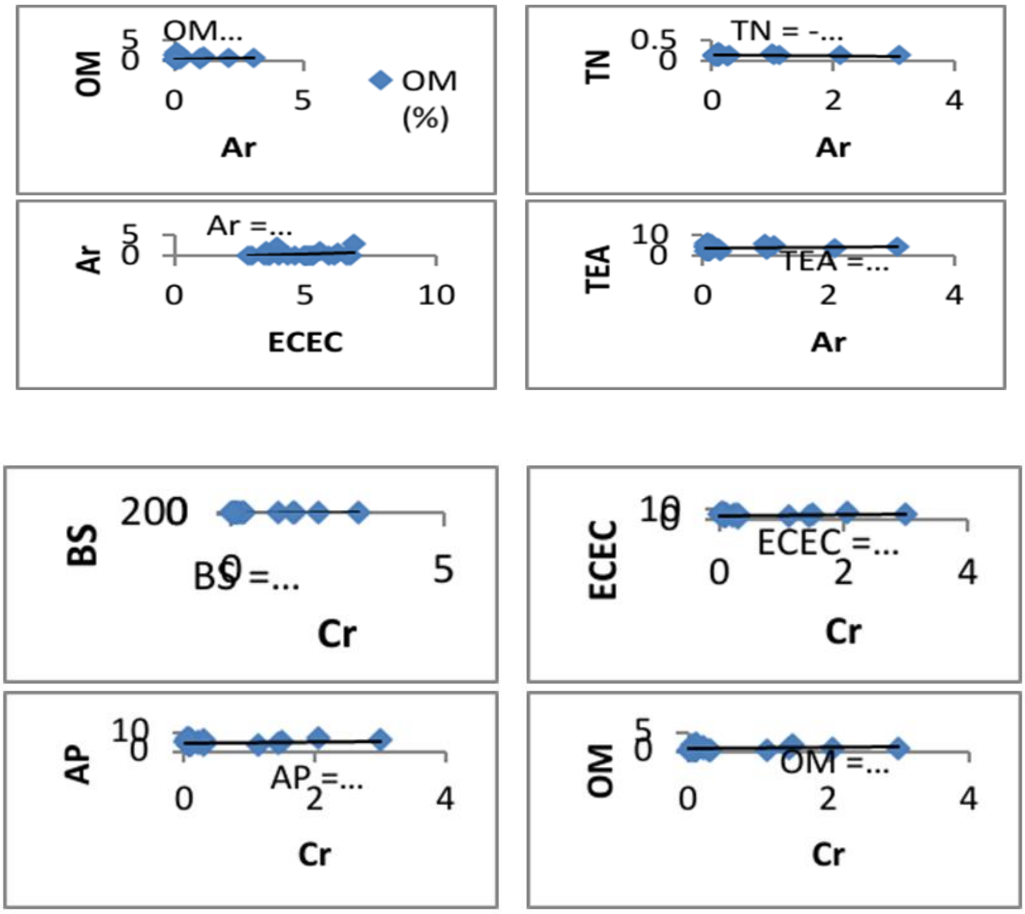

Figure 5. Relationship between As with some soil properties.

CONCLUSION

The soils of the urban areas varied differently based on the differences in physical and chemical properties. The soils of the urban area were sandy irrespective of the landuses. Agricultural soils had high compaction compared to other urban soils. The soils of the commercial area had higher infiltration rate (Ksat) compared to other urban soils. Agricultural soils had higher variation of moisture content more than other urban soils. The soils of residential area were more acidic while the soils of industrial area were closer to a neutral reaction. However, there were significant changes in soil C, N and P in all the urban soils. The soils of commercial, industrial and residential area had the highest concentration of SOC, and N while soils of the residential area indicated that anthropogenic activities influenced the SOC and N processes. In contrast, agricultural soils exhibited greater effect of management practices by the highest availability of phosphorus. All the urban soils had C/N ratio below 25 suggesting the potentiality of these soils for nitrate leaching. Generally, the urban soils were low in ECEC below $10cmokg^{-1}$ indicating low adsorption of nutrient cations such as exchangeable bases and N. Based on the metal concentration, both Arsenic (AS) and Chromium (Cr) were below the permissible limit of WHO/FAO (2004) in all the urban soils studied and indicated less impact to the environment. However, soils of the residential and commercial area were influenced by high concentration of these heavy metals (As and Cr) implying that it was strongly disturbed by anthropogenic and human activities more than other urban areas. Moreover, in their distribution, the heavy metals (As and Cr) followed this order: As: Residential > commercial > agricultural soils > recreational > industrial while Cr: commercial > recreational >residential >agricultural > industrial. Also, agricultural soils and soils of the residential area gave the highest microbial bacterial population while soils of commercial area exhibited inadequate nitrogen and limited microbial growth due to high C/N ratio. High organic C and Total N determined the highest MBC and MBN in soils of industrial area while low SOC, high pollution from heavy metals in soils of the recreational area decreased MBC and MBN. However, vegetation, variability of plant species and increased phosphate fertilizer increased MBP in agricultural soils. The sandy anthropogenic soils in commercial area, leaching and migration of phosphorus to surface water, confirmed low MBP in soils of commercial area. This study therefore showed that urbanization and conversion of land to other landuses has affected the soils structure, fertility and productivity of soils and the environment. Therefore, proper use of good soil management practices, remediation, pollution prevention measures such as reducing wastes generation and raising up awareness of heavy metal risk should be adopted for sustainability and ecosystem management.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

REFRENCES

Adebayo, A. A., Tayoye, J. T., Adejoro, F., Ilemobayo, I. O., & Labunmi, L. (2017). Heavy metals pollution of auto mechanic workshop soils within Okitipupa, Ondo State, Nigeria. *Academic Journal of Environmental Science, 5*, 215. https://dx.doi.org/10.15413/ajes.2017.0131

Akintola, O. O., Abodunrin, E. K., Odeyale, O. C., Falana, A. R., Ogunbanjo, A. R., & Ademiran, T. (2022). Influence of land use types on physical and chemical properties in Oba Hill Forest Reserve, Iwo, South-Western Nigeria. *Journal of Applied Science and Environmental Management, 26*(7), 1307–1311. https://dx.doi.org/10.4314/jasem.v26i7.18

Alloway, B. J. (1995). *Heavy metals in soils*. London: Blackie Academic & Professional.

Assandri, D., Pampuro, N., Zara, G., Cavallo, E., & Budroni, M. (2020). Suitability of composting process for the disposal and valorization of brewer's spent grain. *Agriculture, 11*(1). https://doi.org/10.3390/agriculture11010002

Benbi, D. K., & Khosa, M. K. (2014). Effects of temperature, moisture and chemical composition of organic substrates on C mineralization in soils. *Communications in Soil Science and Plant Analysis, 45*, 2734–2753.

Bonarius, H. M. (1975). *Suitability guide for rating soils for waste disposal*. West Germany: German Agency for Technical Cooperation.

Bremner, T. M., & Mulvaney, G. S. (1982). Total nitrogen. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis* (pp. 595–624). Madison, WI: American Society of Agronomy.

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Brookes, P. C., Landman, A., Pruden, G., & Jenkinson, D. S. (1985). Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method for measuring microbial biomass nitrogen in soil. *Soil Biology and Biochemistry, 17*, 837–842.

Buol, S. W., Hole, F. D., & McCracken, R. J. (1980). *Soil genesis and classification*. Ames, IA: Iowa State University Press.

Cances, B., Juillot, F., Morin, G., Laperche, V., Polya, D., Vaughan, D. J., Hazemann, J. L., Proux, O., Brown, G. E., & Calas, G. (2008). Changes in arsenic speciation through a contaminated soil profile: A XAS-based study.

Chau, J. F., Bagtzoglou, A. C., & Willig, M. R. (2011). The effect of soil texture on richness and diversity of bacterial communities. *Environmental Forensics, 12*, 333–341.

Chen, W., Zhu, K., Cai, Y., Wang, Y., & Liu, Y. (2021). Distribution and ecological risk assessment of arsenic and trace elements in soils of different land-use types in Tianba Town, China. *Environmental Technology & Innovation, 24*, 102041. https://doi.org/10.1016/j.eti.2021.102041

Chen, Y., Martinez, A., Cleavenger, S., Rudolph, J., & Barberán, A. (2021). Changes in soil microbial communities across an urbanization gradient: A local-scale temporal study in the arid southwestern USA. *Microorganisms, 9*(7), 1470. https://doi.org/10.3390/microorganisms9071470

Chen, X., Wang, D., Chen, X., Wang, J., Diao, J., & Zhang, J. (2015). Soil microbial functional diversity and biomass as affected by different thinning intensity in a Chinese forest plantation. *Applied Soil Ecology, 92*, 35–44.

Christel, A., Dequiedt, S., Chemidlin-Prévost-Bouré, N., Mercier, F., Triplet, J., Commeaux, G., Djemiel, C., Bargeot, L., Matagne, E., Fougeron, A., Passi, J. B. M., Ranjard, L., & Maron, P. A. (2023). Urban land uses shape soil microbial abundance and diversity. *Science of the Total Environment, 883*, 163455. https://doi.org/10.1016/j.scitotenv.2023.163455

Devi, N. B., & Yadava, P. S. (2010). Influence of climate and litter quality on litter decomposition and nutrient release in subtropical forests of Northeast India. *Journal of Forestry Research, 21*(2), 143–150.

Devigne, C., Mouchon, P., & Vanhee, B. (2016). Impact of soil compaction on soil biodiversity: Does it matter in urban context? *Urban Ecosystems, 19*, 1163–1178.

Delgado-Baquerizo, M., Eldridge, D. J., Liu, Y. R., Sokoya, B., Wang, J. T., Hu, H. W., He, J. Z., Bastida, F., Blanco-Pastor, J. L., & Fierer, N. (2021). Global homogenization of the structure and function in the soil microbiome of urban greenspaces. *Science Advances, 7*(28), eabg5809.

Diaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., & others. (2018). Assessing nature's contributions to people. *Science, 359*(6373).

Dorgra, M., Sharma, M., Sharma, A., Keshavarzi, A., Bhardwaj, A., Thukral, K., & Kumar, V. (2019). Pollution assessment and spatial distribution of roadside agricultural soils: A case study from India. *International Journal of Environmental Health Research*. https://doi.org/10.1080/09603123.2019.1578865

Ellis, E. C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Diaz, S., Fuller, D., Gill, J., Kaplan, J. O., & Kingston, N. (2021). People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences, 118*. https://doi.org/10.1073/pnas.2023483118

Enescu, R. E., Dinca, L., Zup, M., Davidescu, S., & Vasile, D. (2022). Assessment of soil physical and chemical properties among urban and peri-urban forests: A case study from the metropolitan area of Brasov. *Forests, 13*(7), 1070. https://doi.org/10.3390/f13071070

Evans, C. V., Fanning, D. S., & Short, J. R. (2000). Human-influenced soils. In R. J. Brown *et al*. (Eds.), *Managing soils in an urban environment* (pp. 33–67). Agronomy Monograph 39.

FAO. (2006). *World reference base for soil resources 2006*. Rome: Food and Agriculture Organization of the United Nations.

Fernandez-Calino, D., & Baath, E. (2016). Interaction between pH and Cu toxicity on fungal and bacterial performance in soil. *Soil Biology and Biochemistry, 96*, 20–29.

Gee, G. W., & Or, D. (2002). Particle-size analysis. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis: Physical methods* (pp. 255–295). Madison, WI: Soil Science Society of America.

Grossman, R. B., & Reinsch, T. G. (2002). Bulk density and linear extensibility. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis* (pp. 201–228). Madison, WI: Soil Science Society of America.

Gomez-Brandon, M., Herbon, C., Probst, M., Fornasier, F., Barral, M. T., & Paradelo, R. (2022). Influence of land use on microbiological properties of urban soils. *Applied Soil Ecology, 175*, 104452. https://doi.org/10.1016/j.apsoil.2022.104452

Halecki, W., & Gasiorek, M. (2015). Seasonal variability of microbial biomass phosphorus in urban soils. *Science of the Total Environment, 502*, 42–47.

Hillel, D. (2005). *Encyclopedia of soils in the environment*. Oxford: Elsevier.

Hu, X., Wang, J., Lv, Y., Liu, X., Zhong, J., Cui, X., Zhang, M., Ma, D., Yan, X., & Zhu, X. (2021). Effects of heavy metals and soil properties on microbial communities in farmland near a metal smelter. *Frontiers in Microbiology, 12*. https://doi.org/10.3389/fmicb.2021.707786

Khan, S. K., & Joergensen, R. G. (2012). Relationships between phosphorus fractions and microbial biomass in soils under different land-use management. *Geoderma, 173–174*, 274–281.

Levin, M. J., Kim, K. H., Morel, J. L., Burghardt, W., Charzynski, P., & Shaw, R. K. (2017). *Soils within cities*. Stuttgart: Schweizerbart Science Publishers.

Liu, C., Lu, M., Cui, J., Li, B., & Fang, C. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology, 20*, 1366–1381.

Liu, H., Wang, C., Xie, Y., Luo, Y., Sheng, M., & Xu, F. (2020). Ecological response of soil microbial abundance and diversity to cadmium in farmland soils. *Journal of Hazardous Materials, 392*, 122478. https://doi.org/10.1016/j.jhazmat.2020.122478

Liu, L., Barberán, A., Gao, C., Zhao, C., Zhang, M., Wurzburger, N., Wang, X., Zhang, R., Li, J., & Zhang, J. (2021). Impact of urbanization on soil microbial diversity in Shanghai. *Land Degradation & Development, 33*. https://doi.org/10.1002/ldr.4145

Livesley, S. J., Ossola, A., Threlfall, C. G., Hahs, A. K., & Williams, N. S. G. (2016). Soil carbon and carbon/nitrogen ratio change under tree canopy and grass areas in urban green spaces. *Journal of Environmental Quality, 45*(1), 215–223.

Ma, J., Ullah, S., Niu, A., Liao, Z., Qin, Q., Xu, S., & Lin, C. (2021). Heavy metal pollution increases CH4 and decreases CO2 emissions due to soil microbial changes in mangrove wetlands. *Chemosphere, 269*, 128735.

Musilova, J., Arvay, J., Vollmannova, A., Toth, T., & Tomas, J. (2016). Environmental contamination by heavy metals in a region with previous mining activity. *Bulletin of Environmental Contamination and Toxicology, 97*(4), 569–575.

Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis* (pp. 539–579). Madison, WI: American Society of Agronomy.

Norton, B. A., Evans, K. L., & Warren, P. H. (2016). Urban biodiversity and landscape ecology. *Current Landscape Ecology Reports, 1*, 178–192.

Olson, S. R., & Sommers, L. E. (1982). Phosphorus. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis* (pp. 15–72). Madison, WI: American Society of Agronomy.

Pan, J., & Yu, L. (2011). Effects of Cd and Pb on soil enzyme activities and microbial community structure. *Ecological Engineering, 37*, 1889–1894.

Ramirez, K. S., Leff, J. W., Barberán, A., Bates, S. T., Betley, J., Crowther, T. W., Kelly, E. F., Oldfield, E. E., Shaw, E. A., Steenbock, C., Bradford, M. A., Wall, D. H., & Fierer, N. (2014). Biogeographic patterns in belowground diversity in Central Park, New York. *Proceedings of the Royal Society B*.

Schmidt, D. J. E., Pouyat, R., Szlavecz, K., Setälä, H., & Kotze, D. J. (2017). Urbanization erodes ectomycorrhizal fungal diversity. *Nature Ecology & Evolution, 1*, 0123.

Singh, J. S., & Gupta, V. K. (2018). Soil microbial biomass: A key soil driver in ecosystem functioning. *Science of the Total Environment, 634*, 497–500.

Thomas, G. W. (1996). Soil pH and soil acidity. In D. L. Sparks (Ed.), *Methods of soil analysis* (pp. 159–165). Madison, WI: Soil Science Society of America.

Vance, E. D., Brookes, P. C., & Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry, 19*, 703–707.

Wong, M. H. (2013). *Environmental contamination: Health risks and ecological restoration*. Boca Raton, FL: CRC Press.

Zhang, F. P., Li, C. F., Tong, L. G., Yue, L. X., Li, P., & Ciren, Y. (2010). Response of microbial characteristics to heavy metal pollution of mining soils in central Tibet. *Applied Soil Ecology, 45*, 144–151.

Zhang, J., Li, S., Sun, X., Tong, J., Fu, Z., & Li, J. (2019). Sustainability of urban soil management: Soil physicochemical properties and bacterial communities under different green spaces. *Sustainability, 11*(5), 1395. https://doi.org/10.3390/su11051395

Zhao, H., Wu, Y., Lan, X., Yang, Y., Wu, X., & Du, L. (2022). Comprehensive assessment of harmful heavy metals in contaminated soils. *Scientific Reports, 12*, 3552.