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Distinction between Lithogenic and Anthropogenic Sources of Magnetic Susceptibility Enhancement in Urban Soil Profiles from Jalingo, Taraba State, N-E Nigeria.

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Abstract

Magnetic properties of soils reflect different effects of soil mineralogy. The minerals present in soils due to either natural (lithogenic or pedogenic) or anthropogenic (human activities) origin. The distinction between natural and anthropogenic magnetic signal is crucial for interpretation of the source of magnetic signature. In order to discriminate between both sources, magnetic measurements, basically low field mass specific magnetic susceptibility and its frequency dependence have been performed on samples from seven vertical soil profiles (labeled AWQ1, AWQ2, ABF1, STI, MYG, SGR and MGM) within the same geological setting. Results showed that all the samples in all the profiles had moderate to high magnetic susceptibility values indicating magnetic enhancement in the study area. Varying sources of magnetic enhancement was observed with profiles AWQ2, STI and MGM showing lithogenic magnetic enhancement as the magnetic susceptibility values increased with depth. Profiles ABF1 and SGR showed anthropogenic magnetic enhancement with high magnetic susceptibility values on the surface which decreased with depth, profile AWQ1 displayed varying magnetic susceptibility values with depth while, MYG profile indicated a combination of lithogenic and anthropogenic magnetic enhancement. The results of frequency dependence of susceptibility measurement indicated that most of the samples contained a mixture of ultrafine superparamagnetic grains and coarse multidomain magnetic grains as their values varied between 2 and 10%. Profiles AWQ1, AWQ2 and ABF1 are dominated by the presence of ultrafine superparamagnetic grains while only a few samples had completely multidomain characteristics.

***Keywords*:** Magnetic susceptibility, frequency dependence, anthropogenic, lithogenic, superparamagnetic.

1.0 Introduction

Magnetic properties describe the behaviors of any substance under the influence of magnetic field. The magnetic properties in soils are usually a consequence of the presence of mineral compounds like iron. Iron exists in the form of iron oxides (comprising of iron and titanium oxides and sulfides) phases like magnetite, maghemite, hematite, goethite and limonite in soils depending on the environmental conditions. The concentration of iron oxides in soils is influenced by the parent material (lithogenic), biological activities, age of soil, chemical weathering and pedogenetic processes, soil temperature, physiochemical properties and anthropogenic activities. From the above, magnetic properties present in soils may be inherited from three broad categories: parent rock (lithogenic origin), pedogenesis (that is during soil formation) and anthropogenic activities (effluents from power plants, combustion of fossil fuels, metallurgical industries, road traffic, fertilizers/pesticides/herbicides application etc.).

The concentration of magnetic minerals in soils can be expressed with some simplification by magnetic susceptibility [1]. Magnetic susceptibility is a parameter that is very sensitive to the presence of ferrimagnetic minerals. A soil that has

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elevated values of magnetic susceptibility is said to be magnetically enhanced soil [2]. Measurement of magnetic susceptibility (in conjunction with other magnetic parameters) has found application in the delineation of areas with concentrations of deposited anthropogenic ferrimagnetics significantly above background values, especially around local pollution sources [3- 6]. These studies showed that in polluted areas, the magnetic susceptibility of surface soil layers is considerably higher.

However, magnetic susceptibility enhancement is not a characteristic of polluted soils only but also unpolluted soils and sediments. For better interpretation of magnetic data, criteria for discrimination of the contributions of anthropogenic input and natural background originating from lithogenic sources and/or pedogenic processes are necessary. The vertical distribution of magnetic susceptibility in the upper soil or sediment horizons can speed or assist in such discrimination [7-9]. In natural shallow vertical soil sections, the magnetic signal is controlled by the type of lithogenic/geogenic background constituents and by numerous complex inorganic and organic processes in different soil horizons. Typical magnetic susceptibility signals caused by anthropogenic deposition generally produce pronounced peaks in the upper 10 cm of the soil which generally can be recognized even in the soils with high natural backgrounds [8].

Detailed studies on the vertical distribution of magnetic susceptibility have been found to be in good agreement with heavy metals concentration [10-12]. This shows that magnetic studies can be used as a proxy for pollution studies and therefore can be used to identify the vertical distribution of pollution within soil profiles. Hence magnetic parameters can be used as a method to select sampling points for detailed chemical analyses on surface and vertical soil profiles. Magnetic measurements have several advantages over the traditional geochemical methods as the analysis is (1) non-destructive (2) fast such that a large qualitative and quantitative database can be produce and (3) relatively cheap. It has been used as pollution proxies to detect pollution hotspots [1, 13].

The effect of lithology and soil type on magnetic susceptibility of soils was studied [14]. Seven main classes of profiles, independent of lithology and soil type was distinguished from the analysis of about 600 vertical soil profiles of soil magnetic susceptibility. The applicability of magnetic measurements of soils to discriminate anthropogenic and lithogenic contributions in areas characterized by different environmental and geological settings has been examined [9, 15]. In this study we carry out measurement of soil magnetic susceptibility in urban soil profiles located within the same geological setting with the following objectives: (1) To obtain information on potentially contaminated soil samples within a profile with a view to carrying out geochemical analysis (2) To discriminate between the lithogenic and the anthropogenic contribution to the magnetic enhancement within the soil profiles and (3) To determine the grain sizes of the samples within the profile by measurement of frequency dependence of magnetic susceptibility. The results of this study will also assists in the interpretation of surface magnetic data.

2.0 Materials and Methods

Geographical and Geological setting of the Study Area

Jalingo, the study area is the administrative headquarters of Taraba State which is located between latitude $6^{0}30'$ and $8^{0}30'$ North and between $9^{0}00'$ and $12^{0}00'$ East (see Figure 1). According to the 2006 population figures, it has a total population of 118,000 inhabitants [16].The state has a tropical wet and dry climate, dry season lasts for a minimum of five months (November to March) while the wet season spans from April to October. It has an annual rainfall of about 8000 mm. Jalingo is a city with no major industry. The major pollution source is the emission from traffic and power generating sets and human activities such as indiscriminate dumping of waste.

The study area is underlain by the undifferentiated Basement Complex rocks which consist mainly of the migmatites, gneisses and the Older Granites. Tertiary to Recent basalts also occurs in the area. The undifferentiated Basement Complex particularly the migmatites, generally vary from coarsely mixed gneisses to diffused textured rocks of variable grain size and are frequently porphyroblastic [17]. This rock unit constitutes principally the undifferentiated igneous and metamorphic rocks of Precambrian age [18].

The Pan African Older Granites are equally widespread in the area. They occur either as basic or intermediate intrusives [19]. Different kinds of textures ranging from fine to medium to coarse grains can be noticed on the Older Granites [20]. Other localized occurrences of minor rock types include some doleritic and pegmatitic rocks mostly occurring as intrusive dykes and vein bodies. These occurrences are common to both the undifferentiated Basement Complex and the Older Granite rocks [21, 20]. The Tertiary basalts on the other hand are found in the Mambila Plateau mostly formed by trachytic lavas and extensive basalts which occur around Nguroje [22].

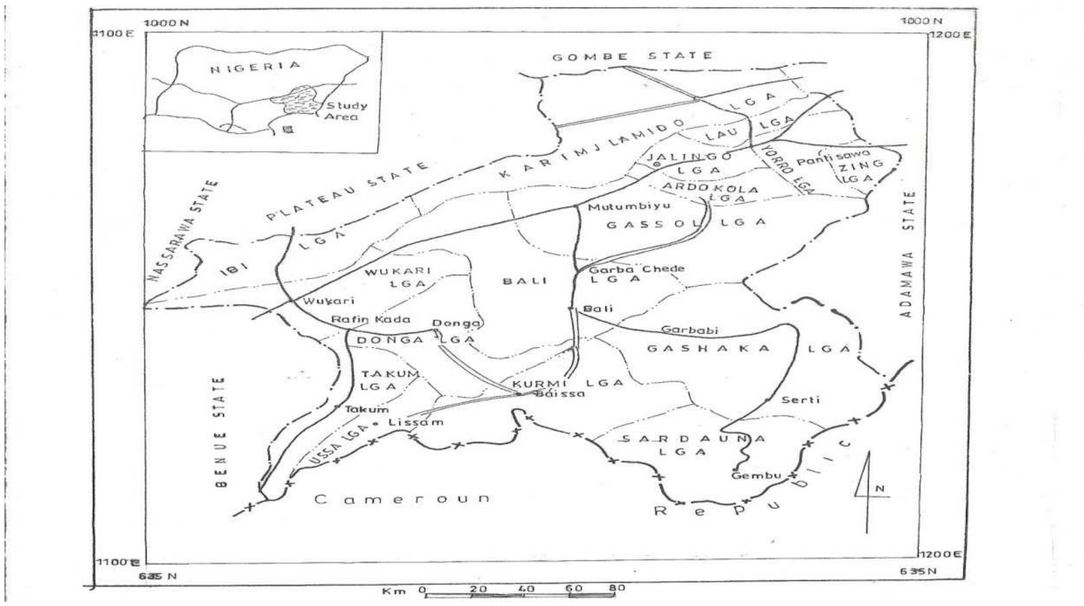

Figure 1: Map of study area (insert: map of Nigeria, showing study area).

Sampling and Analysis

Seven vertical soil profiles were sampled at various locations within the residential areas of the town. The sample points were labeled as follows: AWQ1 (latitude 8°55'374''N, longitude 11° 20'505''E), AWQ2 (latitude 8°55'307''N, longitude 11° 20'402''E), ABF1 (latitude 8°55'357''N, longitude 11° 20'642''E), STI (latitude 8°54'236''N, longitude 11° 21'596''E), MYG (latitude 8°54'729''N, longitude 11° 21'290''E), SGR (latitude 8°52'778''N, longitude 11° 22'244''E), and MGM (latitude 8°54'422''N, longitude 11° 20'927''E). Soil samples were taken from short vertical soil profiles of between 30 and 50 cm depth [7, 8]. The soil profiles samples were collected using a locally sourced plastic rod of 4.5 cm diameter. The rod was inserted to the soil and samples were taken at 5 cm interval after removing the rod from the soil. The samples were enveloped in a labeled plastic bag and transported to the laboratory for further analysis.

In the laboratory the samples were air dried at a temperature of 30^0C for some days to reduce mass contribution of water and to avoid any chemical reactions. They were gently disaggregated using an agate mortar and a pestle and then sieved using a 1 mm mesh [23]. The sieved samples were stored in a plastic container for further laboratory measurements. The mass specific magnetic susceptibility measurement was then carried out on the sieved samples at laboratory temperature. Measurements of magnetic susceptibility were made at both low (0.47 kHz) and high (4.7 kHz) frequencies using Bartington MS2B dual frequency sensor connected to MS2 meter linked to a computer operated using a Multisus2 software. All measurements were conducted at the 1.0 sensitivity setting. Each sample was measured three times with an air reading before and after each series for drift correction. The mass specific frequency dependence susceptibility χ_{fd} was obtained from the relation:

$$\chi fd = \chi lf - \chi hf \qquad (1)$$

Where χlf and χhf are the low frequency and high frequency susceptibilities respectively. This parameter is sensitive only to a very narrow grain size region crossing the superparamagnetic/single domain threshold (~ 20 – 25 nm for maghemite) [24]. For natural samples which generally exhibit a continuous and nearly constant grain size distribution, χ_{fd} can be used as a proxy for relative changes in concentration in pedogenic fined – grained magnetic particles [25]. The relative χ_{fd} also called percentage frequency dependent susceptibility (χ_{fd}%) was then calculated [26] as:

$$\chi fd\ (\%) = \left(\frac{\chi lf - \chi hf}{\chi lf}\right) \times 100 \qquad (2)$$

3.0 Results and Discussion

1. Results of AWQ1 profile

The results of magnetic susceptibility measurements for the AWQ1 are displayed on Table 1. The results showed variable magnetic susceptibility values within the profile. The highest value of 129.4 x 10^{-8} m^3kg^{-1} occurred at a depth of 10 cm, which is part of the organic horizon where susceptibility is expected to be higher due to anthropogenic activities, fire burn and bacteria activity. Soils are classified into three categories based on magnetic susceptibility as follows: normal (χlf < 10 x 10^{-8} m^3kg^{-1}), moderately magnetic (χlf 10 – 100 x 10^{-8} m^3kg^{-1}) and highly magnetic (χlf > 100 x 10^{-8} m^3kg^{-1}) [27]. From this classification, the soil within this profile can be said to be moderately magnetic except at depth of 10 cm.

Table 1: Values of magnetic parameters from the AWQ1 soil profile.

Sample	**Depth (cm)**	**Mass (g)**	**χ_{lf} x10^{-8} m^{3}kg^{-1}**	**X_{hf} x 10^{-8} m^{3}kg^{-1}**	**χ_{fd} x 10^{-8} m^{3}kg^{-1}**	**χ_{fd} (%)**
AWQ1 1	0.0	11.97	98.7	91.6	7.10	7.19
AWQ1 2	5.0	13.15	101.8	99.2	2.60	2.55
AWQ1 3	10.0	12.92	129.4	118.3	11.10	8.58
AWQ1 4	15.0	14.86	92.9	81.2	11.70	12.59
AWQ1 5	20.0	14.14	102.7	89.1	13.60	13.24
AWQ1 6	25.0	17.92	60.9	53.2	7.70	12.64
AWQ1 7	30.0	14.92	90.1	80.2	9.90	10.99
AWQ1 8	35.0	15.06	104.9	92.4	12.50	11.92

The source of the moderate magnetic enhancement can be attributed to high geogenic background. In soils with higher geogenic background, the vertical distribution of the magnetic susceptibility signals is similar in the top soil and organic soil horizons, but with depth it is increasingly dominated by higher and often fluctuating magnetic susceptibility values [8]. This observation can be seen clearly in Figure 2. χlf , χhf, χfd and χfd% showed similar trend. The lowest value of χlf was found at a depth of 25 cm. The reason for this anomaly is not very clear, further investigations need to be carried out on this sample. Measurement of frequency dependence of susceptibility is used to detect the presence of ultrafine ferrimagnetic [also called super paramagnetic (SP) fraction of < 0.005µm] by using two or more frequencies at the constant low applied field [1, 28]. Higher frequency measurements do not allow SP grains to react with the applied field, as it changes more quickly than the relaxation time for SP grains. As a result, in the higher frequency, lower values of susceptibility are encountered and the difference is used to estimate the SP ferrimagnetic particles. The values of χfd % ranged from 2.55 to 13.24% with an average value of 10.35%. About 60% of the samples had values greater than 10%. This implied that the samples contained superparamagnetic (SP) ferrimagnetic grain sizes, an indication that pedogenesis/lithogenesis caused the magnetic enhancement within the profile. This observation agreed with our earlier conclusion. Samples with SP characteristics occurred between 15 and 35 cm in this profile. Other samples with χfd% values between 2 and 10% are said to possess a mixture of multidomain (MD) and SP grains. Within the profile χfd% values fluctuates with depth but generally showed increased values with depth (Figure 2).

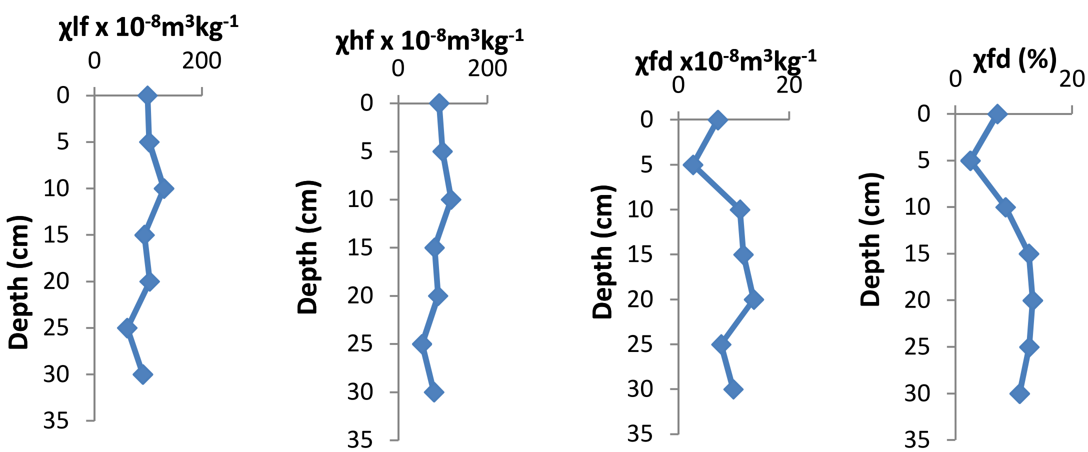

Figure 2: Variation of magnetic parameters with depth for AWQ1 Soil Profile

The model for the interpretation of χfd% was given by [26] and it is shown in Table 2.

Table 2: Model for the interpretation of χfd%

Low χfd%: < 2%	Virtually no (<10%) SP grains
Medium χfd%: 2.0 – 10.0%	Admixture of SP and coarser non SP grains or grains < 0.005µm
High χfd%: 10.0- 14.0%	Virtually all (> 75%) SP grains
Very high χfd%: > 14%	Rare values, erroneous measurement, anisotropy, weak samples or contamination

According to [29], samples with χfd% values greater than 10%, SP grains dominate the assemblage and χfd can be used to quantitatively estimate their total concentration. Hence, in the AWQ1 profile, the average concentration of SP grains was 11.08 x 10^{-8} m^{3}kg^{-1}.

2. Results of AWQ2 Profile

The AWQ2 soil profile exhibit moderate mass specific low frequency magnetic susceptibility χlf values ranging from 51.3 to 66.8 x 10^{-8} m^3kg^{-1}, with the highest value occurring at the 25 cm depth (Table 3). The high value at the depth of 25 cm contrasts the earlier observation in AWQ1 where the lowest value of χlf occurred at the depth of 25cm. again the samples at this depth need to be investigated further. The profile generally showed gradual increasing χlf values with depth as shown in Figure 3. This trend indicated that the moderate magnetic enhancement is due to lithogenesis or pedogenesis. A similar result was obtained [30] from lake sediment from Ayyanakere catchment area, India. Another reason for increased susceptibility at the bottom of the profile could be attributed to leaching of magnetic minerals during rainy season. AWQ profiles are located in a residential area occupied by top government functionaries, and so, anthropogenic sources of magnetic enhancement is expected to be minimal, hence the attribution of the magnetic enhancement to lithogenesis is expected.

Table 3: Values of magnetic parameters from AWQ2 soil profile.

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} m^3kg^{-1}	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
AWQ2 1	0.0	15.55	51.3	46.4	3.90	0.69
AWQ2 2	5.0	13.18	58.9	54.0	4.90	8.32
AWQ2 3	10.0	13.88	58.0	51.2	6.80	11.72
AWQ2 4	15.0	14.72	56.7	51.5	5.20	9.17
AWQ2 5	20.0	14.21	58.2	54.1	4.10	7.04
AWQ2 6	25.0	12.98	66.8	60.9	5.90	8.83
AWQ2 7	30.0	13.36	63.9	55.7	8.20	12.83
AWQ2 8	35.0	14.08	63.1	54.8	8.30	13.15
AWQ2 9	40.0	12.76	66.0	57.8	8.20	12.42
AWQ2 10	45.0	13.12	65.2	56.8	8.40	12.88
AWQ2 11	50.0	13.73	60.9	53.5	7.40	12.15

χhf, χfd and $\chi fd\%$ showed similar trend as χlf (Figure 2). $\chi fd\%$ values ranged from 0.69 to 13.15% with about 60% of the samples having values greater than 10%, indicating that SP grains dominate the samples within the profile. This further confirmed the presence of lithogenic or pedogenic contribution to the observed magnetic enhancement. Soils dominated by MD grains usually have $\chi fd\% < 2\%$ and is a characteristics of soils dominated by anthropogenic activities [29, 30]. The lowest value of $\chi fd\%$ was obtained from the topsoil of the profile and is an evidence of the presence of coarse MD grains in the sample. The presence of MD grains in the litter horizon of the profile is expected as a lot of human activities take place on the soil surface. The increase of $\chi fd\%$ with depth is an indication of the gradual shift from MD grain state to SP grain state. The average concentration of SP grains measured by χfd in the AWQ2 is 7.88 x 10^{-8} m^3kg^{-1}.

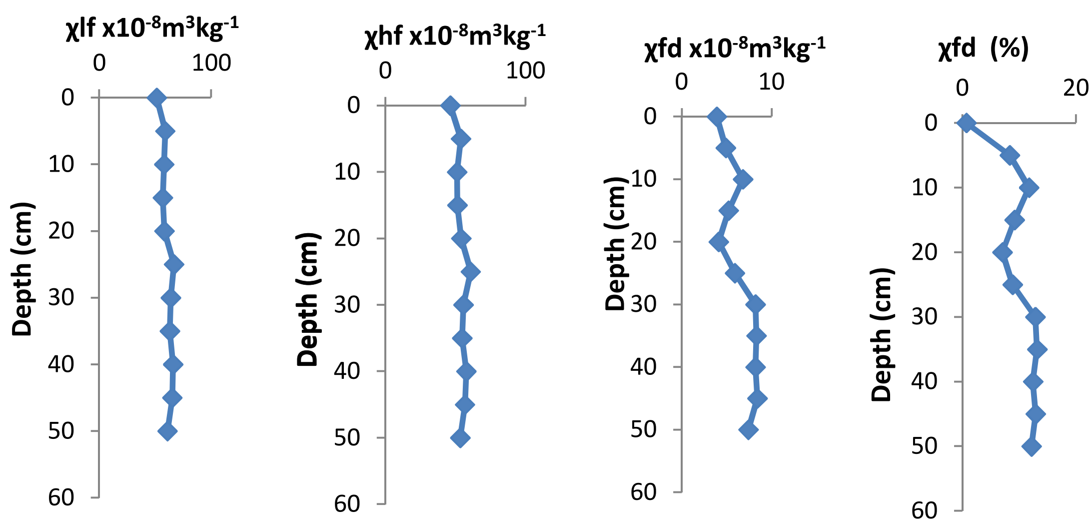

Figure 3: Variation of magnetic parameters with depth for AWQ2 Soil Profile.

3. Results of ABF1 Profile

In ABF1 profile, the highest χlf values was obtained on the topsoil and reached its maximum at 5 cm depth, thereafter it fluctuates down the column (Table 4). Generally, the χlf value showed a decrease with increase in depth with deviations at the 35 cm and 40 cm depth (Figure 4). This trend indicated that the magnetic enhancement is due to anthropogenic sources from local brewing activities that takes place around this area and the long distance transport from remote sources of emissions or the presence of bacterial magnetite. The soil profile displayed moderate to highly magnetic values ranging from 85.1 to 148.9 x $10^{-8}m^3kg^{-1}$. The high magnetic susceptibility obtained at the topsoil is a characteristic of the 'O or A' horizon that is rich in organic matter [31]. Similar result was obtained for soil profiles from Shanghai [11].

Table 4: Values of magnetic parameters from ABF1 soil profile

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} $m^3kg^{-13.0}$	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
ABF1 1	0.0	15.55	141.0	137.2	3.80	2.70
ABF1 2	5.0	16.42	148.9	145.2	3.70	2.48
ABF1 3	10.0	15.85	105.4	102.8	2.60	2.47
ABF1 4	15.0	14.97	85.7	78.4	7.30	8.52
ABF1 5	20.0	14.95	92.6	83.1	9.50	10.26
ABF1 6	25.0	15.23	95.7	85.4	10.30	10.76
ABF1 7	30.0	14.39	87.8	76.6	11.20	12.76
ABF1 8	35.0	13.00	110.0	97.8	12.20	11.09
ABF1 9	40.0	14.38	100.4	87.4	13.0	12.95
ABF1 10	45.0	15.46	85.1	73.7	11.40	13.40
ABF1 11	50.0	14.58	94.3	82.0	12.3	13.04

While χlf and χhf followed the same trend down hole, χfd and χfd% showed an opposite trend. Their values ranged from 2.60 – 13.0 x$10^{-8}m^3kg^{-1}$ and 2.47 – 13.40% respectively (Table 3), with values increasing with increase in depth (Figure 4). Within this profile, about 70% of the samples are composed of ultrafine SP grain sizes while the remaining are composed of a mixture of MD and SP particles. At the top 10 cm, samples are dominated by coarse MD ferrimagnetic grains confirming the presence of anthropogenic magnetic signals at the topsoil samples.

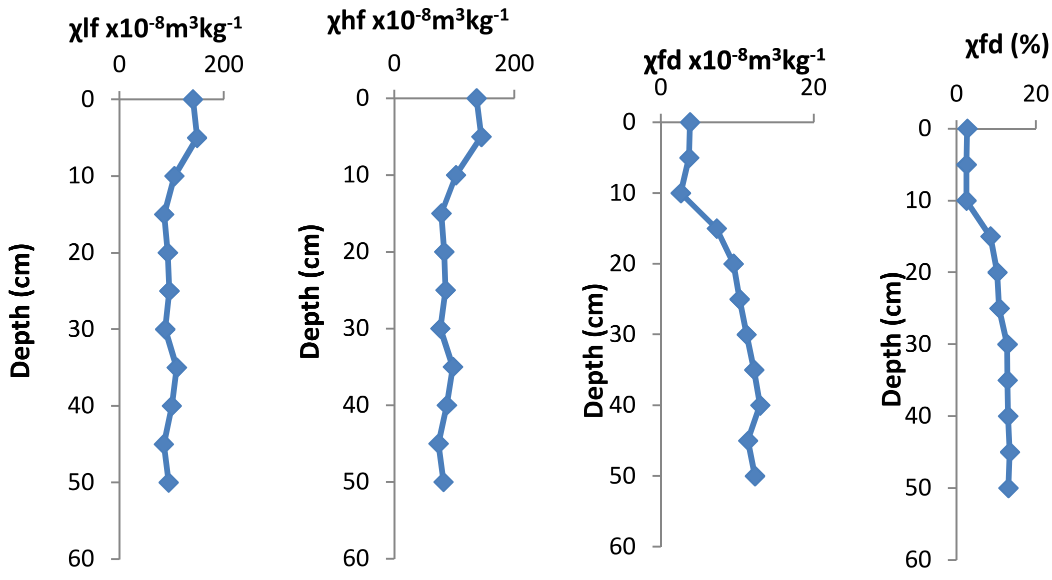

Figure 4: Variation of magnetic parameters with depth for ABF1 soil Profile

A plot of χfd% against χlf or χfd may help to discriminate between grain size and domain state and may give a first order classification of magnetic properties or even sources [26]. A plot of χfd% against χlf (not shown here) displayed an inverse relationship with a good correlation coefficient (R^2 = 0.76). Many authors [e.g 32, 33] reported a similar negative correlation for polluted urban topsoils, which indicated that the magnetic enhancements in urban soils are contributed by coarse MD magnetic grains from industrial and anthropogenic sources.

4. Results of STI Profile

The magnetic data for STI profile are presented in Table 5 and Figure 5. The results of χlf values showed that the soils within this profile are highly magnetic with an exception at the 5 cm depth which showed moderate magnetic enhancement. The values ranged from 88.4 – 220.8 x $10^{-8}m^3kg^{-1}$(average 157.53 x 10^{-8} m^3kg^{-1}), with values increasing with depth (Figure 5). χhf showed similar trend with values ranging from 85.1 – 208.2 x $10^{-8}m^3kg^{-1}$. The increase in susceptibility with depth may be attributed to either the presence of magnetite/maghemite which might have been inherited from the weathered parent rock [34] or lessivage of fine-grained magnetic minerals formed during pedogenesis.

Table 5: Values of magnetic parameters from STI soil profile.

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} m^3kg^{-1}	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
STI 1	0.0	15.29	121.4	119.8	1.60	1.32
STI 2	5.0	14.05	88.4	85.1	3.30	3.73
STI 3	10.0	16.05	114.7	110.0	4.70	4.10
STI 4	15.0	16.75	101.6	96.9	4.70	4.63
STI 5	20.0	15.44	138.8	135.0	3.80	2.74
STI 6	25.0	15.98	181.0	171.2	9.80	5.41
STI 7	30.0	15.91	179.8	170.2	9.60	5.34
STI 8	35.0	16.16	178.4	172.2	6.20	3.42
STI 9	40.0	16.18	199.3	186.3	13.00	6.52
STI 10	45.0	14.62	220.8	208.2	12.60	5.71
STI 11	50.0	15.20	208.6	196.9	11.70	5.61

The χfd and χfd% showed similar trend but fluctuating down the profile. For natural samples which generally exhibit a continuous and nearly constant grain size distribution; χfd can be used as a proxy for relative changes in concentration of pedogenic fine-grained magnetic particles [25], while χfd% is used to approximate the total concentration of SP grains in a sample [26]. χfd% showed MD grain character on the soil surface (χfd% = 1.32%) indicative of anthropogenic sources of enhancement. The values of χfd% fluctuate down the profile with values ranging from 2.74 – 6.52% from 5 cm to 50 cm depth. This implied that within the profile, samples had a mixture of MD and SP ferrimagnetic grains.

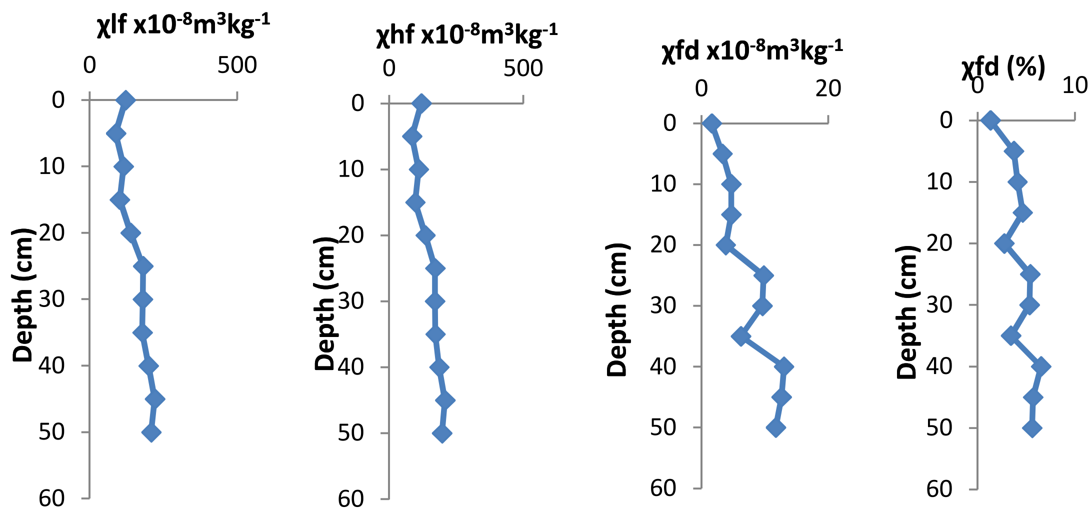

Figure 5: Variation of magnetic parameters with depth for STI Soil Profile

Table 6: Values of magnetic parameters from MYG soil profile

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} m^3kg^{-1}	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
MYG 1	0.0	14.94	114.4	106.7	7.70	6.73
MYG 2	5.0	15.27	62.4	58.2	4.20	6.73
MYG 3	10.0	15.37	90.1	82.1	8.00	8.88
MYG 4	15.0	15.59	82.9	75.3	7.60	9.17
MYG 5	20.0	16.40	73.8	66.9	6.90	9.35
MYG 6	25.0	15.70	86.2	77.8	8.40	9.74
MYG 7	30.0	15.11	98.5	86.7	11.80	11.98
MYG 8	35.0	14.76	101.1	89.4	11.70	11.57
MYG 9	40.0	14.54	96.4	84.9	11.50	11.93
MYG 10	45.0	13.73	99.6	87.2	12.40	12.45
MYG 11	50.0	14.37	90.3	80.4	9.90	10.96

A plot of χfd% against χlf assists in the interpretation of the source of magnetic enhancement in the soil. In this profile, a plot of χfd% against χlf (not shown here) showed a positive correlation (but with a poor correlation coefficient R^2 of 0.40) between the two parameters. The positive correlation is an indication that the magnetic enhancement in this profile is contributed by pedogenic SP grains.

5. Results of MYG Profile.

In the MYG profile, the situation is not too different from the STI profile. Here the χlf values varied between 62.4 and 114.4 x 10^{-8} m^3kg^{-1} (average, 90.45 x 10^{-8} m^3kg^{-1}). High frequency susceptibility χhf varied between 62.4 and 106.7 x 10^{-8} m^3kg^{-1} (average, 81.42 x 10^{-8} m^3kg^{-1}); χfd varied between 4.2 and 12.40 x $10^{-8}m^3kg^{-1}$ (average, 9.10 x 10^{-8} m^3kg^{-1}) while χfd% varied between 6.73 and 12.45% (average, 9.95%) (Table 6).

The highest value of the concentrated dependent parameter, χlf occurred at the soil surface with a value of 114.4 x 10^{-8} m^3kg^{-1}, showing that the soil surface might be contaminated by organic matter, bacterial magnetite or anthropogenic sources. Apart from the topmost sample, other samples within the profile showed moderate magnetic enhancement with fluctuating values down the profile. The trend as shown in Figure 6 seems to be that of increasing χlf with increase in depth (though not pronounced). This trend is typical of soil with lithogenic/pedogenic Magnetic enhancement. With the behavior of the samples in this profile with respect to the χlf values, it can be said that both anthropogenesis and lithogenesis contribute to the magnetic signatures observed in the profile.

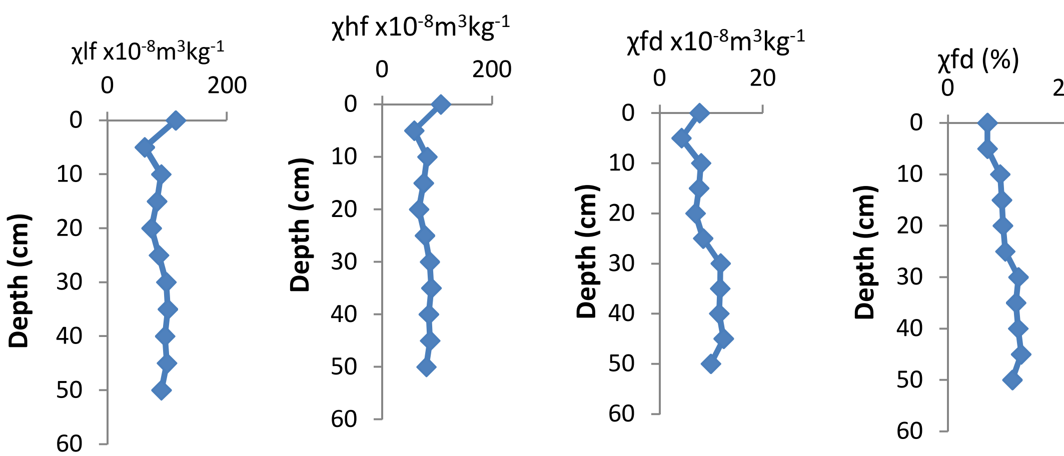

Figure 6: Variation of magnetic parameters with depth for MYG Soil Profile

Table 7: Values of magnetic parameters from SGR soil profile

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} m^3kg^{-1}	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
SGR 1	0.0	14.44	46.5	43.9	2.60	5.59
SGR 2	5.0	14.15	62.0	60.5	1.50	2.42
SGR 3	10.0	15.36	44.9	42.5	2.40	5.35
SGR 4	15.0	14.72	40.7	36.5	4.20	10.32
SGR 5	20.0	14.14	34.2	32.9	1.30	3.80
SGR 6	25.0	14.71	25.9	25.5	0.40	1.54
SGR 7	30.0	14.08	20.5	18.7	1.80	8.78
SGR 8	35.0	13.49	15.6	13.9	1.70	10.90
SGR 9	40.0	11.57	14.3	13.5	0.80	5.59
SGR 10	45.0	13.52	12.9	11.9	1.00	7.75
SGR 11	50.0	13.04	14.8	14.4	0.40	2.70

The χfd and χfd% showed similar but more pronounced trend than χlf and χhf. From values of χfd%, about 45% of the samples had SP magnetic grains while 55% of the samples contained a mixture of MD and SP magnetic grain size. This confirmed that the moderate magnetic enhancement cannot be completely attributed to lithogenesis/pedogenesis but also anthropogenic activity played a role. To further confirmed the source of the magnetic enhancement in this profile, the graph of χfd% against χlf was plotted (not shown here). The graph showed a strong positive correlation with correlation coefficient R^2 of 0.83, implying that increase in magnetic susceptibility led to increase in χfd%. This strong positive correlation indicates that magnetic susceptibility is enhanced mainly by the ultrafine pedogenic component of the samples. The average concentration of SP grains given by the χfd is 11.46 x 10^{-8} m^3kg^{-1}.

6. Results of SGR Profile.

The SGR profile had the lowest values of magnetic susceptibility compared to other profiles. The samples in the profile were moderately enhanced with values of χlf ranging from 12.9 to 62.0 x 10^{-8} m^3kg^{-1} (average, 30.21 x 10^{-8} m^3kg^{-1}) (Table 7). The highest values were obtained within the top 15 cm while the least values were found at depth of 40 – 50 cm.

The decreasing values of χlf with depth (Figure 7) are a clear indication that the profile is enhanced mainly by anthropogenic pollution [35]. The SGR profile is located in an area were a lot of commercial and local brewing activities etc. takes place. There is also high population density which gives rise to high vehicular traffic. Hence the topsoil magnetic enhancement in this profile is expected.

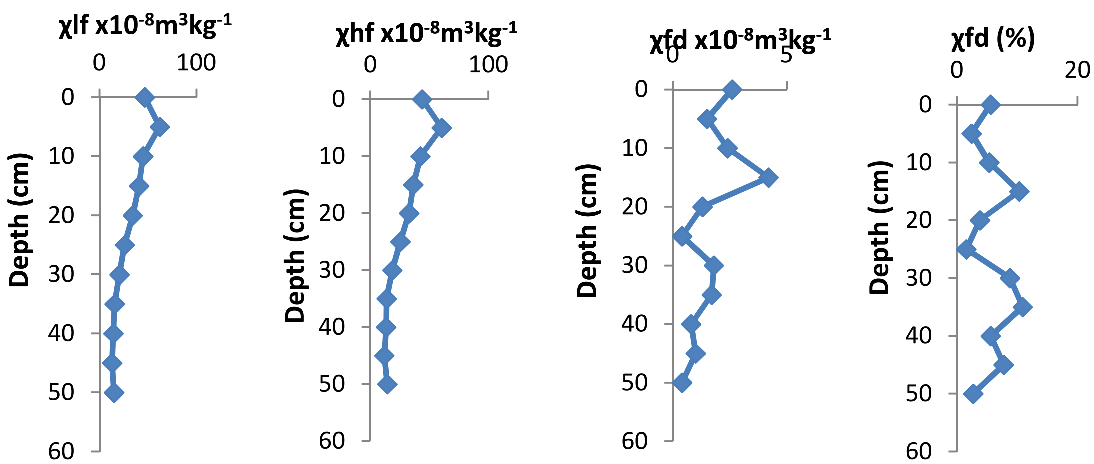

Figure 7: Variation of magnetic parameters with depth for SGR Soil Profile

Table 8: Values of Magnetic parameters from MGM soil profile

Sample	Depth (cm)	Mass (g)	χ_{lf} x10^{-8} m^3kg^{-1}	X_{hf} x 10^{-8} m^3kg^{-1}	χ_{fd} x 10^{-8} m^3kg^{-1}	χ_{fd} (%)
MGM 1	0.0	15.75	60.3	54.6	5.70	9.45
MGM 2	5.0	13.86	68.8	61.3	7.50	10.90
MGM 3	10.0	13.39	69.0	62.1	6.90	10.00
MGM 4	15.0	15.37	73.6	69.6	4.00	5.43
MGM 5	20.0	14.97	73.7	67.8	5.90	8.01
MGM 6	25.0	13.34	82.5	75.9	6.60	8.00
MGM 7	30.0	15.34	83.7	74.1	9.60	11.47

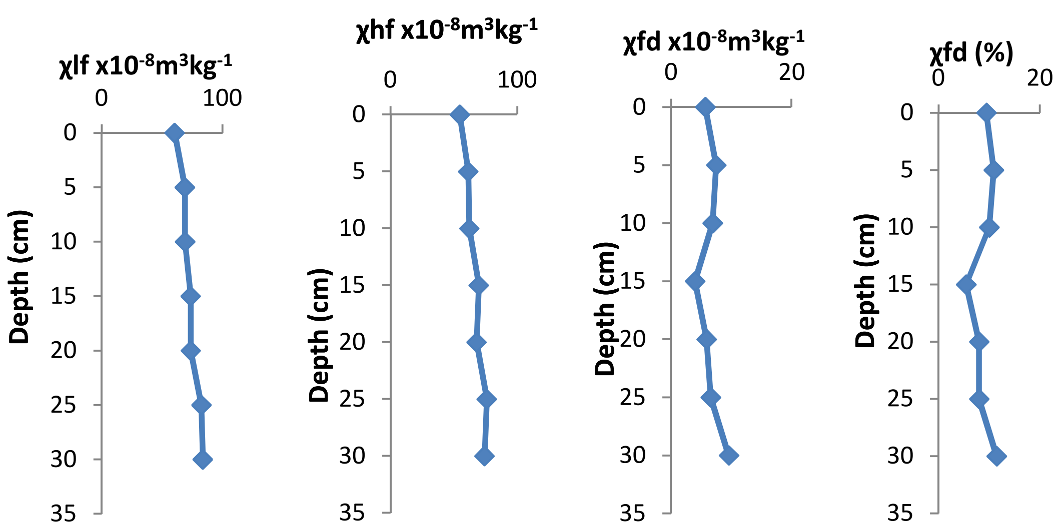

Figure 8: Variation of magnetic parameters with depth for MGM Soil Profile

The frequency dependent susceptibility χfd% was observed to be fluctuating with depth (Figure 7). It values varied from 1.54 to 10.90%. Only two samples (SGR 3 and SGR 7) showed the presence of SP grains; others had a mixture of MD and SP grain sizes, with one sample (SGR 5) displaying completely MD characteristics. The average concentration of SP grains in the profile SGR was 2.95 x 10^{-8} m^3kg^{-1}.

7. Results of MGM Profile

The results of the magnetic measurements of MGM profile are displayed on Table 8. Results showed that χlf values increased with depth. The values ranged from 60.3 to 83.7 x 10^{-8} m^3kg^{-1} with a mean value of 73.6 x 10^{-8} m^3kg^{-1}, showing moderate magnetic susceptibility enhancement in the profile. The moderate magnetic enhancement is attributed to lithogenesis and or pedogenesis resulting from weathering of the parent rock units, as evidenced in the χlf versus depth plot (Figure 8).

In Figure 8, χlf and χhf, followed the same trend but χfd and χfd% had a constriction at the 15 cm mark and increased afterwards with depth.

The results of the χfd% measurement showed values varying from 5.43% to 11.47% (Table 8). Three samples (about 42%) contain ultrafine superparamagnetic grain size, while the remaining consists of a mixture of MD and SP grains. The χfd% results does not agree totally with our earlier conclusion based on χlf values that lithogenesis or pedogenesis is the major cause of magnetic enhancement in the profile. Soils where magnetic enhancement are attributed to pedogenesis or lithogenesis usually show the presence of ultrafine SP between properties with χfd% values between 10 -14%, while anthropogenic influenced soils show large grains MD properties [9, 26]. In view of this, the magnetic enhancement might be attributed to both anthropogenic activities to a lesser extent and lithogenic parent rock to a greater degree. To further identify the cause of magnetic enhancement in the profile, determination of other concentration and grain size parameter such as Anhysteric magnetization (ARM), Saturation Isothermal Remanent Magnetization (SIRM), ARM/χlf and SIRM/ARM is required. This will be carried out in our subsequent studies.

Comparison of the Magnetic Properties of the Different Vertical Soil Profiles.

The descriptive statistics of the χlf values of the various soil profiles are displayed on Table 9.

Table 9: Descriptive statistics of χlf values for the 7 profiles

Xlf x $10^{-8}m^3kg^{-1}$	**AWQ1 n = 8**	**AWQ2 n = 11**	**ABF1 n = 11**	**STI n = 11**	**MYG n =11**	**SGR n =11**	**MGM n =7**
Mean	97.68	60.82	104.26	157.53	90.52	30.21	73.09
Standard error	6.72	1.42	6.52	13.89	4.28	4.99	3.09
Median	100.25	60.9	95.7	178.4	90.3	25.9	73.6
Standard Deviation	19.03	4.72	21.64	46.08	14.18	16.54	8.17
Kurtosis	2.55	-0.06	0.98	-1.55	0.63	-0.69	-0.38
Skewness	-0.49	-0.58	1.42	-0.18	-0.48	0.65	-0.09
Range	68.5	15.5	63.8	132.4	52.0	49.1	23.4
Minimum	60.9	51.3	85.1	88.4	62.4	12.9	60.3
Maximum	129.4	66.8	148.9	220.8	114.4	62.0	83.7

Table 10: Descriptive statistics of χfd% for the different profiles

χfd%	**AWQ1 n = 8**	**AWQ2 n = 11**	**ABF1 n = 11**	**STI n = 11**	**MYG n =11**	**SGR n =11**	**MGM n =7**
Mean	9.96	9.93	9.29	4.41	9.95	5.89	9.04
Standard error	1.30	1.13	1.38	0.46	0.61	0.97	0.78
Median	11.45	11.72	10.76	4.63	9.74	5.59	9.45
Standard Deviation	3.67	3.74	4.57	1.53	2.02	3.20	2.07
Kurtosis	1.36	3.03	-1.16	0.09	-0.90	-1.16	0.22
Skewness	-1.35	-1.64	-0.84	-0.70	-0.46	0.29	-0.72
Range	10.69	12.46	10.93	5.2	5.72	9.36	6.04
Minimum	2.55	0.69	2.47	1.32	6.73	1.54	5.43
Maximum	13.24	13.15	13.4	6.52	12.45	10.9	11.47

From Table 9, the STI profile is the most magnetically enhanced soil as it showed the highest mean value when compared with other profiles, while SGR and AWQ2 showed the least concentration of magnetic susceptibility. The highest values of χlf correspond to highly contaminated samples [9]. Within a profile, the STI profile showed the most variability between the samples as they showed the highest standard deviation of 46, while AWQ2 had standard deviation of 4.6, indicating that the samples do not exhibit wide variation of magnetic susceptibility between samples in the profile a characteristic of lithogenic enhanced soils. AWQ1 showed the most fluctuating χlf and χhf values down the profile. STI, MYG and MGM profiles showed increasing χlf and χhf values with depth suggesting lithogenesis and pedogenesis as the source of magnetic enhancement while ABF1 and SGR soil profiles displayed magnetic enhancement in the topsoil which decreased down the profile, indicating anthropogenic magnetic enhancement within the soil column.

The frequency dependent magnetic susceptibility is supposed to reflect the significance of ultrafine SP particles. Large grains of magnetite (e.g. from combustion processes or traffic emissions) are insensitive to change in frequency of the applied magnetic field. Therefore such samples usually exhibit less than 2% frequency dependence of susceptibility. Our data showed that most of the samples displayed a mixture of MD magnetite and ultrafine SP ferrimagnetic particles. The descriptive statistics of χfd% is shown in Table 10.

Profiles AWQ1, AWQ2 and ABF1 are dominated by the presence of ultrafine SP ferrimagnetic grains, as about 62.5%, 54.6% and 70.0% respectively of the samples had χfd% values between 10 and 14%. Only about 3 samples, one each from AWQ2, STI and SGR showed completely multidomain grain size characteristics with χfd% values less than 2 %. Other samples showed a mixture of MD and SP magnetic grains. Profiles STI had the least χfd% values.

4.0 Conclusion

Vertical soil profiles from residential areas within the same geological settings were studied to characterize the significance of anthropogenic and lithogenic contributions to mineral magnetic properties in the soil. Ordinarily, one would have expected that all the soil profiles will show the same or similar characteristics, since they all have the same geology but differences in the magnetic properties exist within profiles and between profiles. This indicates that magnetic properties of a soil samples does not depend on parent rock only; other factors also contributes to the magnetic enhancement in soils. In this study, the major conclusions reached are as follows:

1. The results of low field mass specific magnetic susceptibility measurement showed moderate to highly magnetic values indicating magnetic enhancement in the soil samples.
2. Anthropogenic effects were observed in some soil profiles where magnetic susceptibility values are higher at the surface and decreased steadily with depth.
3. Lithogenic effects were observed in soil profiles where magnetic susceptibility values were lower at the topsoil and increased with depth.
4. A mixture of anthropogenic and lithogenic effects was observed in profile where the magnetic susceptibility increased at the surface, decreased and later increased with depth.
5. Frequency dependence of susceptibility measurement showed that most samples contained a mixture of ultrafine SP and coarse non-SP grains. The presence of SP grains in a sample indicated lithogenic contribution to the magnetic susceptibility; if MD grains is present, anthropogenic effect caused the magnetic susceptibility enhancement while a mixture of SP and MD grains indicated a combination of anthropogenic and lithogenic effects.
6. A plot of χfd% against χlf could assist in determining the source of magnetic enhancement. A positive correlation reflects the contribution of pedogenic SP grains to the magnetic susceptibility enhancement while a negative correlation indicated coarse MD magnetic grains as the source of magnetic enhancement.
7. Other studies such as heavy metal contents should be carried out to determine concentration of the metals responsible for the moderate to high magnetic enhancement obtained in the profiles.

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