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Identification of Anthropogenic Materials in Topsoil from the Urban Area of Banjarmasin, Indonesia Using Geochemical and Rock Magnetic Properties

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Abstract

The city of Banjarmasin is located in a peatland and has a tropical climate. Peat areas have their own uniqueness, plus this city is traversed by many tributaries and is very rarely researched, especially in relation to the use of rock magnetism. This research is important because it investigates the feasibility of using magnetic techniques to identify anthropogenic materials produced by human activities, using rock magnetism, geochemical analysis, and pollution index calculations. When compared with the background, the magnetic signal of the urban topsoil is greatly enhanced with a magnetic susceptibility (χ_{LF}) of (0.22–13.60) × 10^{-6} m^3/kg. However, the urban topsoil contains only a small number of pedogenic superparamagnetic (SP) grains, as indicated by the low average value of χ_{FD}% (< 2%). The geochemical properties of the magnetic fraction in urban topsoil differ significantly from those of topsoil found in peatland generally. This further demonstrates that the magnetic minerals accumulating in the urban topsoil not only originate from pedogenic processes but also from parent soil materials from the surrounding area of the research. In this instance, the research area's surface soil serves as embankment land for the construction of settlements, roads, and other infrastructures. Significant correlational magnetic techniques can screen topsoil pollution in this area, as evidenced by the significant correlation between χ_{LF} with V, Mn, Fe, and Ni, as well as χ_{HF} with Fe. The Igeo pollution index indicates a slight-to-high level of pollution in Cr, Ni, Cu, and Zn.

Keywords:
peatland, pedogenic, magnetic susceptibility, pollution index, rock magnetism, correlation

1. Introduction

Banjarmasin is the largest city in South Kalimantan. Prior to its replacement with the city of Banjarbaru as a capital city in 2022, the city of Banjarmasin served as the hub for economic and government activities. This role positions the city of Banjarmasin as the most densely populated and most active city in this region. As time goes by, the population of Banjarmasin city continues to increase, causing an increase in the number of settlements, infrastructure, and activity. Human activities, which can lead to the accumulation of anthropogenic materials, contribute to the decline in the physical, chemical, and biological functions of soil, rivers, and air (**Li et al., 2012**).

Anthropogenic materials are accumulations of heavy metals and toxic metalloids resulting from human activity processes. Urban topsoil contains this anthropogenic material, which has garnered significant attention and research. Geochemical analysis can identify the presence of anthropogenic material in topsoil. Geochemical analysis to determine the presence of anthropogenic materials in urban areas has been widely used, such as **Tarvainen et al. (2018); Plak et al. (2024); Xia et al. (2011); Wang et al. (2018)**.

Urban areas have widely used the rock magnetism method to identify the presence of metalloids and heavy metals in topsoil samples by correlating magnetic parameters with their presence. Researchers widely use these environmentally friendly, non-damaging, and fast methods to investigate pollution from anthropogenic materials in soil (**Evans and Heller, 2003**). **Dearing (1999)** bases the principle of this method on the magnetic properties of the sample, which stem from the characteristics of the mineral grains that comprise it, including their abundance, shape, and size. The abundance of magnetic minerals in the soil can used as a proxy indicator for the presence of anthropogenic material. Nu-

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merous studies on soil from urban areas in the Urals, Russia (**Vasiliev et al., 2020**), in Zagreb city of the Republic of Croatia (**Frančišković-Bilinski et al., 2023**), and in Shanghai, China (**Wang et al., 2022**) have employed this approach. Some studies also utilize X-ray diffractometry (XRD) to identify magnetic mineral domains in soil samples (**Kierlik et al., 2019; Kirana et al., 2021; Lu et al., 2007**). Magnetic mineral morphology is frequently identified by energy-dispersive X-ray (EDS) studies and scanning electron microscopy (SEM). A distinctive characteristic of SEM pictures of samples affected by anthropogenic contaminants is typically a spherical form. Similar imagery has also been observed by researchers in urban soil (**Ali et al., 2023; Sharma et al., 2016**).

The relationship between rock magnetism and the presence of anthropogenic materials in urban topsoil has been the subject of several studies. Various samples, including urban areas in Manchester, England, have also demonstrated this correlation (**Robertson et al., 2003**), as have other locations such as Shanghai, China (**Hu et al., 2007**), and Hangzhou city, China (**Lu and Bai, 2006**). A correlation between rock magnetic parameters and anthropogenic material in soil samples can indicate that the soil sample has experienced pollution. Pollution indicators such as the geoaccumulation index (Igeo), the enrichment factor (EF), the contamination factor (CF), and the load index of pollution (PLI) can determine the level of pollution in soil samples. Researchers in Ufa city, Russia (**Goncharov et al., 2024**) have used these indices to identify Cr and Ni as anthropogenic pollution elements in urban areas. In most of Ufa, Russia, the level of soil enrichment and pollution is in the medium class, but there are some areas with critical threshold values. In Lianyungang, China, the elements Cd > Zn > Pb > Cu > As > Cr are found as materials that are man-made, and Cd posed the greatest ecological risk (**Li et al., 2017**). Researchers conducted research on pollution levels using pollution indices on other urban soils (**Sezgin et al., 2024; Polyakov et al., 2021; Zhang et al., 2022**).

In recent decades, extensive research has frequently focused on environmental evaluation using rock magnetism and chemical properties, particularly by examining the abundance of magnetic minerals and their relationship to chemical characteristics. However, studies of rock magnetism-chemical parameters taking into account the abundance of magnetic minerals in topsoil of urban areas in the peatland of South Kalimantan have never been carried out before. The primary goal of this research is to validate the application of physical properties, specifically the magnetic characteristics of rocks, to the presence of anthropogenic material in the topsoil of urban areas located in peatlands. This research is useful in determining the relationship between magnetic characteristics and anthropogenic materials in topsoil from urban areas.

This study will report the first magnetic susceptibility survey of the topsoil of residential areas in Banjarmasin, as well as evaluate the spatial distribution of heavy metals. Representative topsoil samples were analyzed using several fast and non-destructive techniques, including X-ray (XRF) fluorescence, X-ray (XRD) diffraction, and the scanning of electron microscopes (SEM), to identify existing minerals, characterize magnetic minerals, and ensure the morphology of magnetic minerals in topsoil samples. This study will look at the possibility of magnetic measurements as a proxy indicator for anthropogenic material pollution in urban topsoil in tropical peat environments, especially in South Kalimantan. We have used the Igeo pollution index to determine the level of contamination in the topsoil of this urban area. These findings provide an alternative strategy for measuring urban topsoil contamination of peat areas with toxic anthropogenic materials. Monitoring polluted areas is important and beneficial to ensure that pollution prevention and management efforts will be successful in the long term.

2. Methods

As shown in **Figure 1**, the city of Banjarmasin can be found in a latitude of 3°16’46 “up to 3°22’54” South Latitude and 114°31’40 “up to 114°39’55” East Longitude. There are five sub-districts that make up Banjarmasin city, and one of them is the North Banjarmasin District. 17.75 square kilometers make up the North Banjarmasin District. According to **Sikumbang and Heryanto (1994)**, the alluvium formation (QA) in Banjarmasin is composed of gravel, sand, silt, clay, and mud by composition. Within a particular depth, there are also a great number of plant and peat fragments that have been left behind.

Thirty samples of topsoil were collected from three locations (see **Figure 1**). Ten topsoil samples were collected from residential areas near rivers and main roads (BA), settlements close to rivers (KU), and residential areas near green spaces (KT). To create homogeneous particles, the topsoil was sieved through a 10 mesh (2 mm diameter) screen. Sample preparation were carried out following the detailed techniques outlined by **Lu et al. (2007)**.

Rock magnetism analysis consists of magnetic susceptibility measurements and magnetic mineral morphology measurements. Measurement of the magnetic susceptibility of the sample was carried out by measuring mass-specific magnetic susceptibility at two different frequencies (low frequency at 470 Hz and high frequency at 4700 Hz). Padang University conducted magnetic susceptibility measurements using the Bartington MS-2B magnetic susceptibility system (Bartington Ltd., Oxford, UK). The results are called low-frequency mass-specific susceptibility (χ_{LF}) and high-frequency mass-specific susceptibility (χ_{HF}). The frequency-dependent magnetic susceptibility ($\chi_{FD}\%$) is calculated as **Equation 1** as follows:

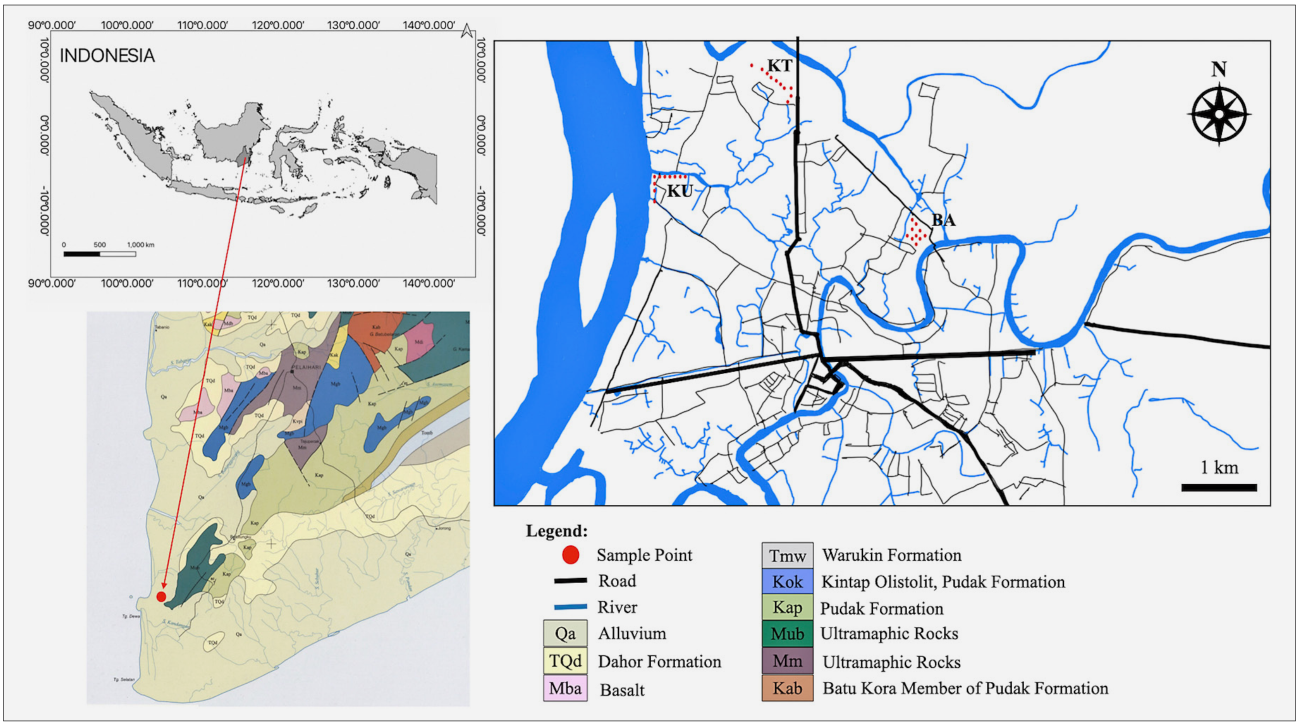

Figure 1. Geological map of the research area shows the sampling sites (red dots) (modified from **Heryanto and Sikumbang, 1999**).

$$\chi_{FD}\% = 100\%\left(\frac{\chi_{LF} - \chi_{HF}}{\chi_{LF}}\right) \quad (1)$$

At Institut Teknologi Sepuluh Nopember in Surabaya, Indonesia, the representative samples (BA 07, KU 07, and KT 06) were measured for magnetic mineral morphology using a Hitachi Flexsem 100, equipped with EDS (Energy Dispersive X-Ray Spectroscopy). At Malang State University, Indonesia, the samples were subjected to geochemical analysis to identify the main elements and trace elements using a MiniPal 4 EDXRF type (PANalytical, Netherlands), equipped with a 9 W X-ray tube Rh (max 1 mA, max 30 kV), 5 tube filters, a high-resolution Silicon Drift Detector, and a 12-position. The Bandung Institute of Technology in Indonesia then examined the magnetic grains using a Rigaku Smartlab XRD (X-Ray Diffraction) (Rigaku Corp., Tokyo, Japan). Representative samples for SEM-EDS and XRD analysis use specimens that have been extracted using a magnetic stirrer. Magnetic extraction was performed on these samples following the procedure described in **Novala et al. (2019)**. The program SPSS Statistics 20.0 for Windows (SPSS Inc., Chicago, IL, USA) was used to analyze the correlation between magnetic and geochemical characteristics using Pearson correlation. Analysis of pollution levels using the Igeo pollution index is calculated using the following **Equation 2**:

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \quad (2)$$

Igeo can evaluate research samples for heavy metal contamination by comparing them to a reference metal content. **Müller (1969)** states that **Equation 2** determines Igeo. Cn is the metal concentration of the research sample, Bn is the background value of the metal under consideration, and 1.5 is the background matrix correction factor that generates lithogenic influence. **Müller (1981)** classified Igeo into seven classes: first (Igeo ≤ 0; Class 0) for uncontaminated categories, second (Igeo 0–1; Class 1) for uncontaminated to moderately contaminated categories, third (Igeo 1–2; Class 2) for moderately contaminated categories, fourth (Igeo 2–3; Class 3) for moderate to highly contaminated categories, fifth (Igeo 3–4; Class 4) for highly to very highly contaminated categories, and sixth (Igeo 4–5; Class 5) for very highly contaminated categories.

3. Results

Table 1 shows the results of magnetic susceptibility measurements, which show that all samples have magnetic susceptibility that is not much different. The average value of χ_{LF} in the BA sample is 2.54×10^{-6} m^3/kg, while the average value in the KU sample is 2.54×10^{-6} m^3/kg, and the KT sample is 2.26×10^{-6} m^3/kg. However, these samples have different χ_{LF} ranges. BA samples have a χ_{LF} range between $(0.79–13.60) \times 10^{-6}$ m^3/kg, KU samples have a χ_{LF} range between $(0.22–7.91) \times 10^{-6}$ m^3/kg, and KT samples have a χ_{LF} range between $(0.40–3.46) \times 10^{-6}$ m^3/kg. Based on this, it can be seen that the BA sample has the strongest range of χ_{LF} values. Like-

Table 1. Summary of magnetic susceptibility value on topsoil samples of this study.

Sample	χ_{LF} (10^{-6} m^3/kg)	χ_{HF} (10^{-6} m^3/kg)	χ_{FD}%
BA 01	2.56	2.50	2.25
BA 02	2.88	2.87	0.42
BA 03	0.79	0.78	0.52
BA 04	1.60	1.59	0.66
BA 05	5.40	5.34	1.21
BA 06	1.15	1.15	0.83
BA 07	13.60	12.50	7.75
BA 08	4.09	4.07	0.48
BA 09	3.28	3.27	0.30
BA 10	2.25	2.24	0.33
Min	0.79	0.78	0.30
Max	13.60	12.50	7.75
Average	3.76	3.63	1.48
Std. Dev	3.72	3.40	2.28
KU 01	0.22	0.22	0.72
KU 02	0.69	0.68	1.44
KU 03	0.80	0.79	1.27
KU 04	1.19	1.19	0.71
KU 05	0.45	0.45	2.21
KU 06	3.96	3.93	0.95
KU 07	7.91	7.89	0.25
KU 08	1.96	1.96	0.51
KU 09	2.10	2.08	0.69
KU 10	1.08	1.07	0.51
Min	0.22	0.22	0.25
Max	7.91	7.89	2.21
Average	2.04	2.03	0.93
Std. Dev	2.33	2.33	0.58
KT 01	2.29	2.28	0.47
KT 02	3.20	3.17	0.82
KT 03	1.64	1.63	0.56
KT 04	3.46	3.44	0.77
KT 05	0.40	0.39	3.33
KT 06	2.41	2.40	0.49
KT 07	1.64	1.63	0.39
KT 08	2.88	2.83	1.63
KT 09	2.08	2.06	0.81
KT 10	2.59	2.57	0.94
Min	0.40	0.39	0.39
Max	3.46	3.44	3.33
Average	2.26	2.24	1.02
Std. Dev	0.89	0.88	0.89

wise with the χ_{FD}% value, the BA sample has the highest average value, namely 1.48, with the highest value range, namely 0.30–7.75. Meanwhile, the KU sample has the lowest average χ_{FD}% value, namely 0.93, with a value range that is also the lowest, 0.25–2.21. A standard deviation of more than 100% of the average occurs because this research data has large variations (both in absolute values and in distribution) (**Johnson et al., 1994**). This can be seen from the BA samples which have a range of χ_{LF} values, (13.60–0.79) $\times10^{-6}$ m^3/kg; χ_{HF}, (12.50–0.78) $\times10^{-6}$ m^3/kg; χ_{FD}%, 7.75–0.30. Likewise with the KU sample, where the χ_{LF} value has a value range of (7.91–0.22) $\times 10^{-6}$ m^3/kg; χ_{HF}, (7.89–0.22) $\times10^{-6}$ m^3/kg); χ_{FD}%, 2.21–0.25. The same is true for the KT sample, where the χ_{LF} value has a value range of (3.46–0.40) $\times10^{-6}$ m^3/kg; χ_{HF}, (3.44–0.39) $\times10^{-6}$ m^3/kg); χ_{FD}%, 3.33–0.39.

Figure 2 shows a plot of χ_{FD}% versus χ_{LF} values for thirty samples. The samples can be seen grouped together, but there are also samples scattered in different directions representing each sample. This concludes that there are magnetic susceptibility values that have different affinity values. As shown in **Table 1**, the KT sample is magnetically stronger than the KU sample but not as strong as the BA sample. **Figure 2** also shows that there are different groupings of the three samples.

The results of XRF analysis for thirty topsoil samples are listed in **Table 2**. The average contents of Mn, Fe, and Ni in BA samples are higher than in KU and KT samples. The average contents of Ti, V, and Zn in KU samples were higher than BA and KT samples, while Cr and Cu were highest in KT samples. The Fe content in the BA sample was 28.33 × 10^3 mg/kg, while in the KU sample the average Fe content was 24.18 × 10^3 mg/kg, and in the KT sample the average Fe content was 23.43 × 10^3 mg/kg. The average Ti content in the KU sample is 2.19 × 10^3 mg/kg, the average Ti content in the KT sample is 1.76 × 10^3 mg/kg, while in the BA sample it is only 1.74 × 10^3 mg/kg.

4. Discussion

This discussion section presents three parts. The first part will present a discussion of the identification of magnetic minerals, the second part will discuss heavy metal content and the risk of pollution, and the third part will discuss the relationship between magnetic parameters and heavy metal content.

4.1. Magnetic Mineral Identification in Topsoil

The average value of χ_{LF} of topsoil from this research area is higher when compared with research in other areas such as in Shanghai, China (148 × 10^{-8} m^3/kg) (**Jaffar et al., 2017**), residential in Hangzhou city, China (35 to 218 × 10^{-8} m^3/kg) (**Lu and Bai, 2006**), and Khvalynsk, Saratov Region, Russian Federation (1.81 to 77.2 × 10^{-7} m^3/kg) (**Reshetnikov et al., 2020**). The high average value of magnetic susceptibility in this research area can be caused by the type and abundance of magnetic minerals contained in the samples. Based on the XRD results, it can be confirmed that the samples from this research

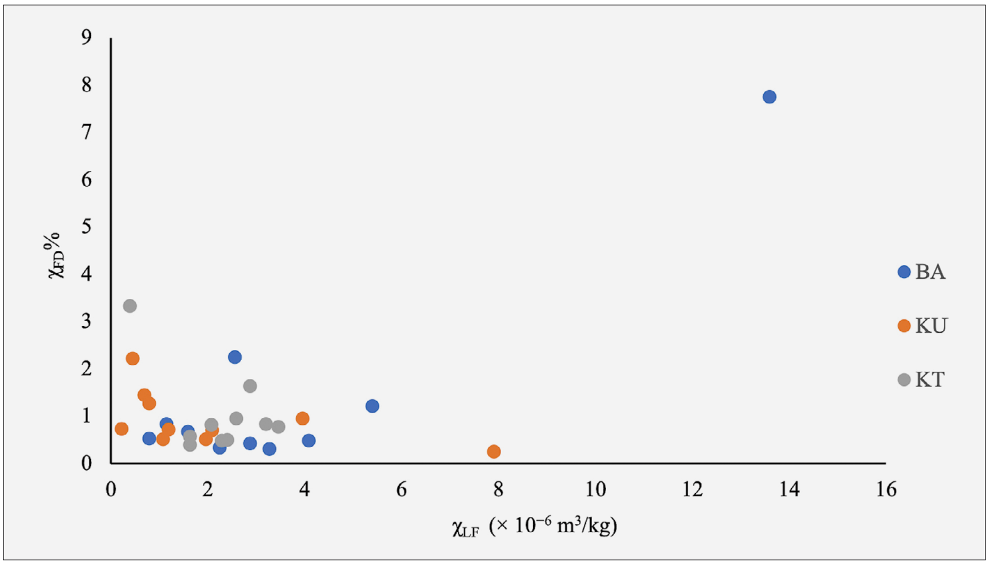

Figure 2. Distribution of magnetic susceptibility for BA, KU, and KT.

area contain the magnetic mineral, namely magnetite (see **Figure 3**). Magnetite is a ferrimagnetic mineral that has very strong magnetic susceptibility (**Kletetschka et al., 2000**). This was also confirmed by **Dearing (1999)**, who stated that ferrimagnetic minerals usually show magnetic susceptibility values higher than 10×10^{-8} m³/kg. Meanwhile, paramagnetic minerals have magnetic susceptibility below this threshold. The presence of magnetite in topsoil samples in this research area can also be confirmed from the SEM EDS results of selected samples (see **Figure 4**). Several previous researchers have confirmed that the shape of the magnetite mineral in topsoil samples is spherule (**Kirana et al., 2021; Huliselan et al., 2010; Quoc, 2022**), octahedral (**Kirana et al., 2021; Huliselan et al., 2010**), and irregular (**Kirana et al., 2021**).

The susceptibility value for BA07 is significantly higher (nearly three times) than the other BA samples. This is because sample BA07 contains the dominant mineral magnetite. The XRD and SEM EDS results clearly demonstrate the dominance of the mineral magnetite in the sample. This magnetite mineral originates from anthropogenic activities, as evidenced by its spherule shape. It is thought to be the result of combustion at high temperatures, both from motor vehicle exhaust and from household and industrial activities in the surrounding area (**Razzaq and Gautam, 2001**). The BA07 sampling location is right next to a busy highway in this residential area. It also contributes greatly to the enrichment of magnetic minerals in the topsoil.

The sample has a minor proportion of superparamagnetic (SP) grains, as indicated by the average χ_{FD}% value of all samples, which is less than 2%. In contrast, a mixture of SP and non-SP coarse grains is indicated by a χ_{FD}% value between 2% and 10% (**Dearing, 1999**). The presence of anthropogenic material in the sample is indicated by the χ_{FD}% value, which varies between 1 and 4% (**Bijaksana and Huliselan, 2010**). According to the study's findings, anthropogenic material influenced some topsoil samples in the investigated area, whereas pedogenic material influenced others.

Several researchers have reported magnetic susceptibility values in the soil around the research area. Magnetic susceptibility measurements carried out on peat soil in the Pulang Pisau to Brengkel area, Central Kalimantan, Indonesia, obtained values in the range of -0.9×10^{-10} m³/kg – 0.712×10^{-6} m³/kg (**Budi et al., 2017**). Meanwhile, soil on agricultural land in Banjarbaru, South Kalimantan, Indonesia has a magnetic susceptibility value in the range of $(1.10–136.50) \times 10^{-8}$ m³/kg (**Sudarningsih et al., 2022**), in other surrounding areas, it has magnetic susceptibility values of $(31.03–12{,}082.77) \times 10^{-8}$m³/kg (**Sudarningsih et al., 2024**), and $(24.40–538.40) \times 10^{-8}$m³/kg (**Putri et al., 2024**). Referring to the results of this research, the area studied has a higher magnetic susceptibility value.

Meanwhile, geologically, the city of Banjarmasin is located in an alluvium formation which, based on its composition, consists of gravel, sand, silt, clay and mud. It is very difficult to understand if this high magnetic susceptibility value comes from these alluvial materials. Apart from being influenced by the formation of the research area, the magnetic susceptibility value in this research area is also influenced by the magnetic properties of a combination of lithogenic and anthropogenic materials (**Hanesch et al., 2007**). The lithogenic material contained in topsoil samples in this research area is thought to originate from landfill material originating from the area around the research, which has basalt, gabbro, and ultramafic formations (**Sikumbang and Heryanto, 1994**). This is in accordance with the XRD results, which show that the minerals contained in the samples apart from magnetite are also saponite, dickite, sodalite, and pyroxene minerals, which are minerals originating from rocks high in magnesium (Mg) that are worn down by basic or ultrabasic acids or when fluids and igneous

Table 2. Measured content of major and minor elements in the surface soil samples (n.d means not detected).

Sample	(× 10^3 mg/kg)							
	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn
BA 01	1.82	0.06	0.65	0.47	35.30	0.65	0.24	0.65
BA 02	1.24	0.04	0.93	0.30	26.10	0.67	0.18	0.20
BA 03	2.91	0.11	0.67	0.12	18.90	0.19	0.16	0.03
BA 04	1.52	0.04	0.76	0.31	22.70	0.43	0.19	0.16
BA 05	1.77	0.11	0.91	0.37	34.60	0.74	0.27	1.00
BA 06	2.52	0.11	0.47	0.24	25.20	0.29	0.26	0.28
BA 07	2.47	0.06	0.20	0.33	37.80	0.06	0.14	n.d.
BA 08	0.62	0.04	0.85	0.57	38.70	2.20	0.18	0.14
BA 09	1.03	0.06	0.65	0.44	26.80	1.00	0.21	0.22
BA 10	1.45	0.07	0.59	0.28	17.20	0.32	0.17	0.27
Min	0.62	0.04	0.20	0.12	17.20	0.06	0.14	0.03
Max	2.91	0.11	0.93	0.57	38.70	2.20	0.27	1.00
Average	1.74	0.07	0.67	0.34	28.33	0.66	0.20	0.33
Std. Dev	0.72	0.03	0.22	0.13	7.79	0.61	0.04	0.30
KU 01	1.58	0.03	1.00	0.21	7.16	0.06	0.13	0.17
KU 02	2.37	0.11	0.14	0.18	30.20	0.09	0.17	0.29
KU 03	2.09	0.09	0.54	0.30	21.50	0.12	0.19	0.40
KU 04	1.81	0.08	0.37	0.32	31.90	0.10	0.23	1.22
KU 05	3.67	0.18	0.12	0.12	22.40	0.08	0.15	0.25
KU 06	1.52	0.07	0.68	0.38	31.80	0.52	0.25	0.98
KU 07	n.d	n.d	0.82	0.65	45.15	2.67	n.d	0.05
KU 08	1.83	0.04	0.51	0.24	18.20	0.38	0.15	0.39
KU 09	2.22	0.06	0.70	0.17	14.60	0.15	0.19	0.40
KU 10	2.64	0.11	1.01	0.23	18.90	0.23	0.17	0.30
Min	1.52	0.03	0.12	0.12	7.16	0.06	0.13	0.05
Max	3.67	0.18	1.01	0.65	45.15	2.67	0.25	1.22
Average	2.19	0.09	0.59	0.28	24.18	0.44	0.18	0.45
Std. Dev	0.66	0.05	0.32	0.15	10.80	0.80	0.04	0.37
KT 01	1.13	0.04	0.81	0.21	16.60	0.38	0.15	0.43
KT 02	1.17	0.04	0.57	0.35	22.70	0.54	0.17	0.12
KT 03	1.28	0.04	0.82	0.37	20.40	0.54	0.17	0.20
KT 04	1.58	0.07	0.87	0.56	30.60	0.89	0.30	1.20
KT 05	2.61	0.11	0.73	0.12	21.60	0.07	0.12	n.d
KT 06	1.56	0.08	0.74	0.33	26.60	0.58	0.18	0.11
KT 07	2.44	0.09	0.09	0.29	20.20	0.42	0.16	0.09
KT 08	1.78	0.09	0.85	0.44	29.30	0.53	0.37	0.28
KT 09	2.09	0.07	0.77	0.39	27.90	0.44	0.28	0.30
KT 10	1.95	0.08	1.05	0.28	18.40	0.49	0.16	0.09
Min	1.13	0.04	0.09	0.12	16.60	0.07	0.12	0.09
Max	2.61	0.11	1.05	0.56	30.60	0.89	0.37	1.20
Average	1.76	0.07	0.73	0.33	23.43	0.49	0.21	0.31
Std. Dev	0.51	0.02	0.25	0.12	4.85	0.20	0.08	0.35
Earth crust (Turekian et al., 1961)	4.60	0.13	0.09	0.85	47.20	0.07	0.05	0.10

materials interact hydrothermally (**Tao et al., 2019**). Sodalite is a mineral that comes from the weathering of igneous rocks (**Dumańska-Słowik et al., 2015**), and the mineral pyroxene comes from ultramafic or serpentinite rock (**Fajar et al., 2022; Yang et al., 2022a**).

Meanwhile, the presence of anthropogenic material can also influence the high magnetic susceptibility of topsoil. As reported by **Dankoub et al. (2012)**, dust containing magnetic particles, such as dust originating from traffic vehicle emissions (traffic) and dust from industri-

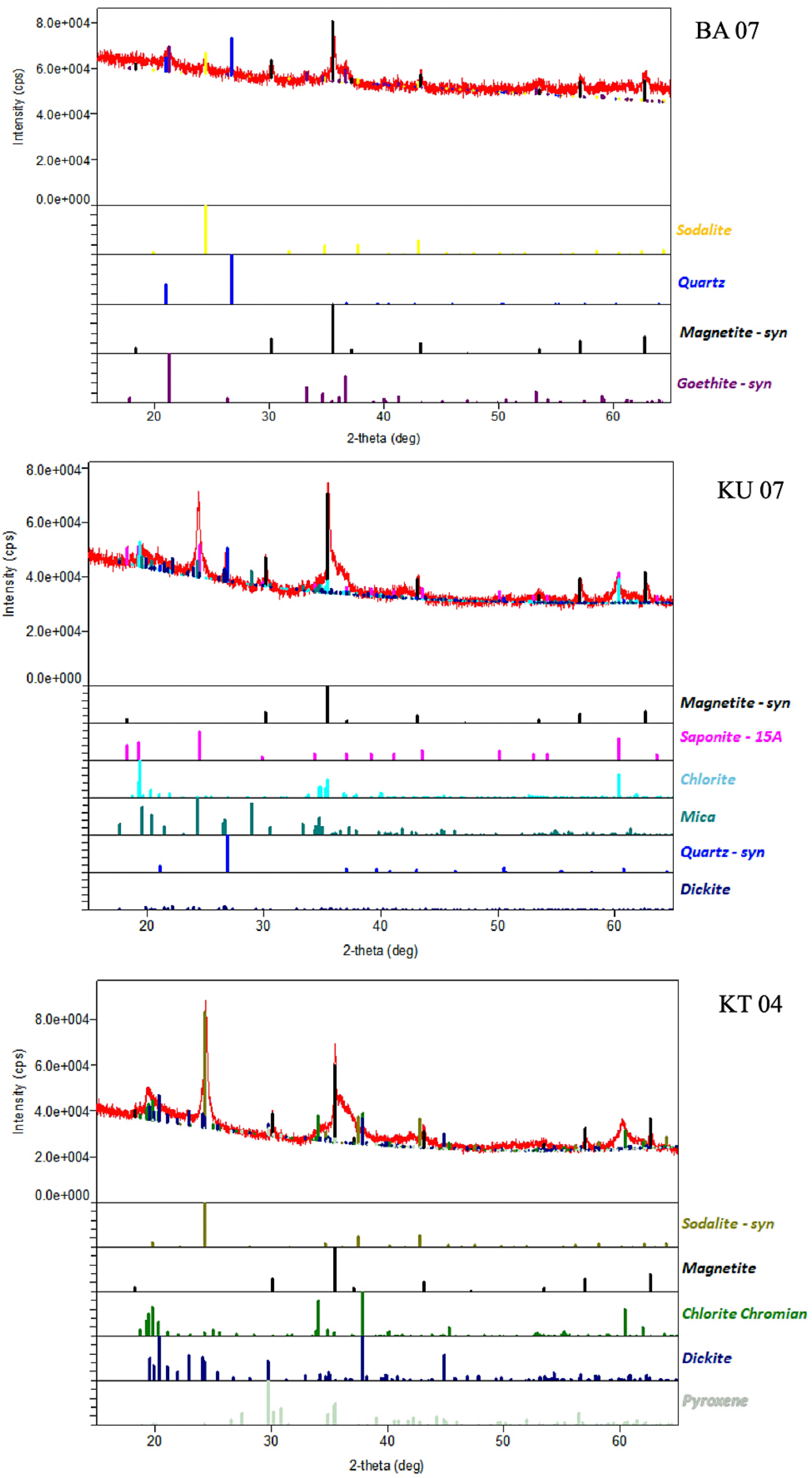

Figure 3. XRD measurement result for surface soil samples (BA 07, KU 07, and KT 04). There are differences in mineral content for each sample. BA 07 is composed of the sodalite, quartz, magnetite, and goethite minerals. KU 07 contains magnetite, saponite, chlorite, mica, quartz, and dickite minerals. KT 04 consist of sodalite, magnetite, chlorite chromium, dickite, and pyroxene minerals.

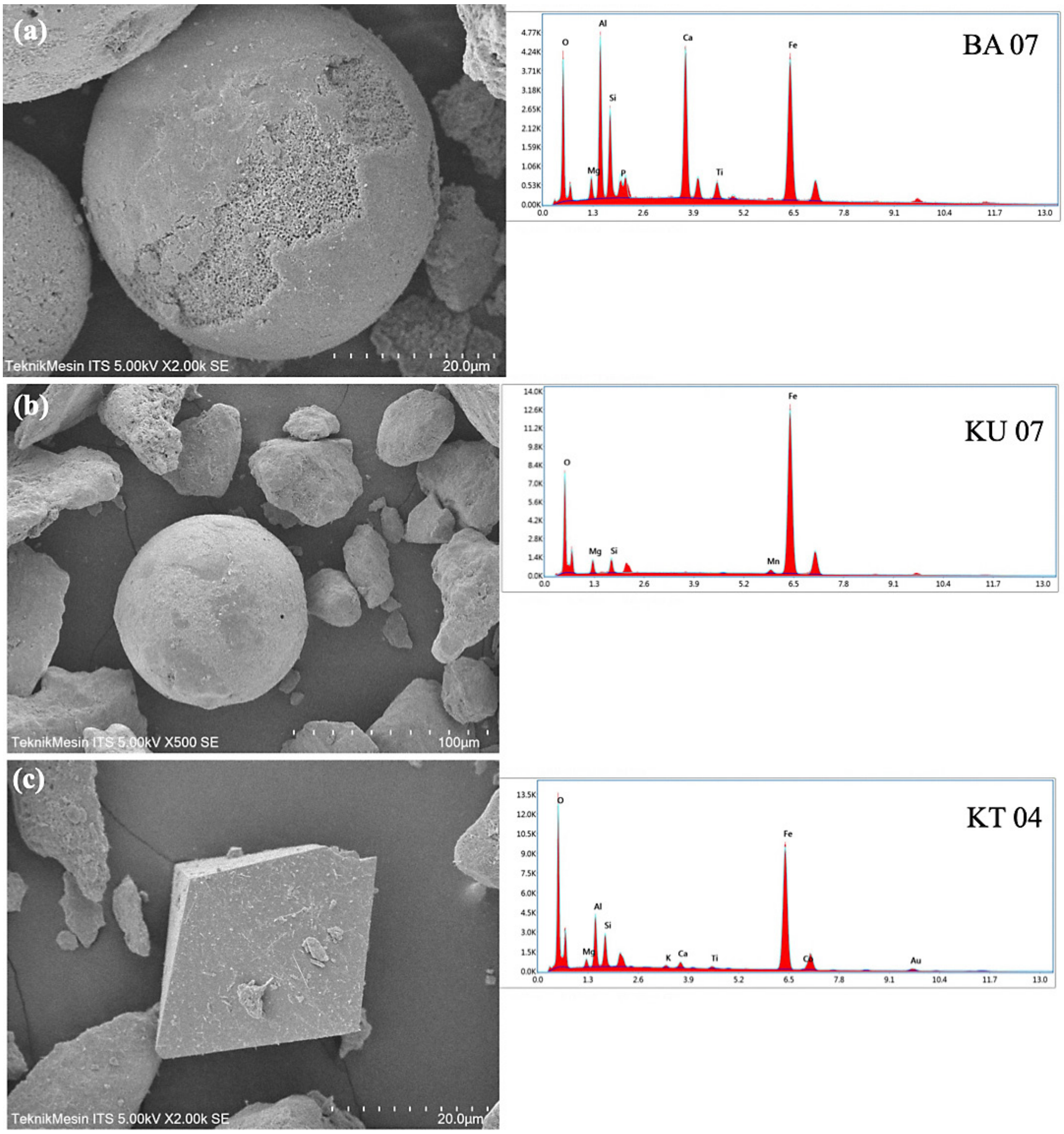

Figure 4. SEM-EDS measurement result for surface soil samples (a) BA 07, (b) KU 07, and (c) KT 04). There are differences in shaped-magnetite grains for each sample.

al activities. The presence of anthropogenic material in topsoil samples can be seen from the shape of the magnetic grains. The different morphologies of magnetic grains may indicate that the grains were formed from different sources. The octahedral shape indicates magnetic minerals originating from pedogenic processes, while the spherule shape indicates magnetic minerals originating from anthropogenic processes (**Shafaria et al., 2023**). The spherule shape indicates a change in the shape of the magnetic mineral caused by oxidation or burning and diagenesis processes (**Franke et al., 2007**). SEM EDS results of topsoil samples in this research area show the presence of spherule, octahedral, and irregular magnetic minerals (see **Figure 4**). This can confirm that the topsoil in the research area contains magnetic materials that are the result of the lithogenic process, namely originating from bedrock weathering or anthropogenic weathering such as traffic vehicle emissions.

4.2. Heavy Metal Content in Topsoil and Pollution Risks

Table 2 displays descriptive statistics for the eight elements used in this study, including minimum, mean, maximum, and standard deviation. This table also includes reference values, which represent the earth's crustal averages for the metals studied (**Turekian et al., 1961**). The average metal content in the research area that exceeds the content in the earth's crust is Cr, Ni, Cu, and Zn. Several other studies have looked at heavy metal levels in urban areas. Heavy metal levels in this research area are relatively high compared to surface soils

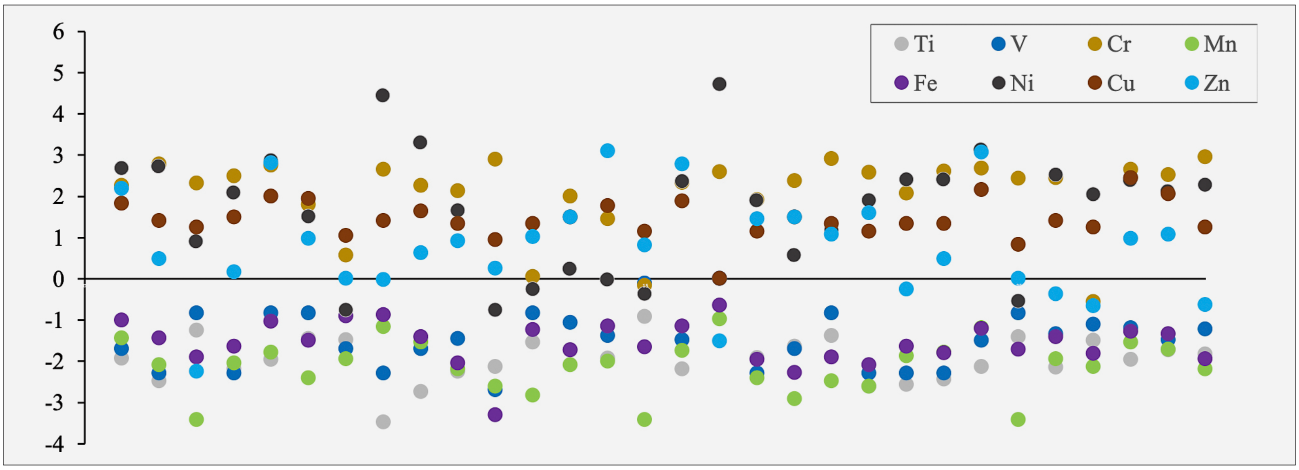

Figure 5. Evaluation of heavy metals in topsoil of research area using Igeo analysis

in urban areas such as Ufa city, Russia (**Goncharov et al., 2024**), the city of Lisbon, Portugal (Cr and Ni) (**Silva et al., 2021**), and cities in India (**Adimalla, 2020**). Igeo results also confirm this, revealing Cr, Ni, Cu, and Zn contamination in almost every sample (see **Figure 5**).

Based on the analysis of the pollution index Igeo>1, it can be seen that the heavy metals Cr, Ni, Cu, and Zn in all samples have values above zero, which indicates that almost all samples have been contaminated with these heavy metals. Even for Cr, Ni, and Zn, samples were found that had reached Igeo = 3, which indicates that they were highly polluted to very highly polluted (Igeo > 4) for Ni. These results indicate that the heavy metals Cr, Ni, Cu, and Zn come not only from bedrock but also from anthropogenic sources. These results indicate that the heavy metals Cr, Ni, Cu, and Zn come not only from bedrock but also from anthropogenic sources. The elements Cr, Ni, Cu, and Zn can be found in igneous rocks from the surrounding area, as reported by **Soeria-Atamadja et al. (1999), Sudarningsih et al. (2023), Sudarningsih et al. (2012)**, and **Sudarningsih et al. (2024)**. However, the concentration of these heavy metals surpasses that of the earth's crust (**Turekian et al., 1961**), indicating their enrichment. This enrichment of heavy metals can occur due to anthropogenic processes, such as combustion products in vehicle engines, industry, and household waste (**Zhang et al., 2012**).

Based on previous research that identified pollution levels using the Igeo index, several studies had average Igeo values for Cr, Ni, Cu, and Zn, which were lower than the results of this study, such as in several cities in China (**Su et al., 2014**) and several metropolitan cities in Pakistan (**Ayaz et al., 2023**). Previous research shows that from road construction to the summit, it is a significant source of Cu, Zn, and Cr entering the environment. Cu and Zn are mostly transported by atmospheric deposition, while Cr is mainly transported by direct deposition from traffic sources (**Bartkowiak, 2020; Gunawardena et al., 2015**). The high Igeo value in this research indicates the presence of heavy metal contamination, especially Cr, Ni, Cu, and Zn.

4.3. Correlation between heavy metals and magnetic susceptibility

Table 3 shows the correlation coefficients of various heavy metals in topsoil at the research location. Strong and significant relationships indicate the existence of comparable underlying factors responsible for their origin and deposition. Significant positive correlation between magnetic parameters (χ_{LF}) and metals V, Fe, Mn, and Ni. **Lu et al. (2007)** reported a positive and significant correlation between χ_{LF} and Cr, Cu, and Zn in topsoil samples from the urban area of the city of Luoyang, China. Positive correlation between LnPb, V, and LnCu and χ_{LF} in samples from urban areas in the arid region of Isfahan, central Iran (**Karimi et al., 2011**). These studies show that similar geological processes give rise to the positive correlation values between χ_{LF} and the metals V, Fe, Mn, and Ni (**Li et al., 2012**). Researchers found similar correlations in other areas with different backgrounds. This indicates that the correlation is strongly supported by anthropogenic process factors. The outer surface of ferrimagnetic grains can absorb heavy metal elements, or they can penetrate the lattice structure of ferrimagnetic materials (**Karimi et al., 2011**). The SEM EDS results reveal that anthropogenic processes associated with several heavy metals, including Mn, account for the majority of the magnetite in the samples (see **Figure 4b**). Cr, Ni, Cu, and Zn, which have high correlation values, indicate that the cause of topsoil pollution can come from motor vehicle pollution and industrial activities in the area around the research area, which can cause topsoil pollution (**Khalid et al., 2018; Zhao et al., 2014**).

χ_{FD}(%) is the potential for the presence of superparamagnetic (SP) mineral fractions according to **Dearing (1999)**. According to **Maher (1988)**, a low χ_{FD}(%) value indicates that the small amount of SP material from the topsoil contributes to the development of topsoil vulnerability in this research area. The results of this study indicate that χ_{LF} can be used to estimate the content of heavy metals (V, Mn, Fe, and Ni) in the topsoil, as well

Table 3: Pearson relationship between magnetic characteristics (χ_{LF}, χ_{HF}, and χ_{FD}(%)), and heavy metals of topsoil in research location; significant at the p < 0.05 level; significant at the p < 0.01 level, bold is correlation value >0.60.

	Ti	**V**	**Cr**	**Mn**	**Fe**	**Ni**	**Cu**	**Zn**	**χ_{LF}**	**χ_{HF}**	**χ_{FD}%**	**Igeo (Ti)**	**Igeo (V)**	**Igeo (Cr)**	**Igeo (Mn)**	**Igeo (Fe)**	**Igeo (Ni)**	**Igeo (Cu)**	**Igeo (Zn)**
Ti	1.00	0.47	0.09	-0.28	0.10	-0.08	0.45	-0.20	-0.10	0.05	0.27	**0.89**	**0.67**	-0.37	-0.22	-0.08	-0.28	-0.31	-0.33
V		1.00	0.09	0.45	0.46	0.69	**0.99**	-0.17	**0.65**	0.39	-0.11	0.52	0.42	0.14	0.33	0.18	0.41	-0.46	-0.39
Cr			1.00	0.29	-0.11	0.33	0.13	0.02	0.36	-0.04	-0.37	-0.24	-0.24	**0.93**	0.21	-0.09	0.39	0.03	-0.03
Mn				1.00	**0.72**	**0.81**	0.53	0.23	**0.78**	0.52	-0.11	-0.15	0.04	0.38	**0.89**	0.59	**0.73**	0.20	0.09
Fe					1.00	0.62	0.51	0.32	**0.63**	**0.65**	0.29	0.14	0.33	0.01	**0.63**	**0.86**	0.04	0.01	0.14
Ni						1.00	-0.22	-0.08	**0.85**	0.43	-0.28	-0.01	0.13	0.34	**0.67**	0.41	**0.80**	-0.20	-0.24
Cu							1.00	-0.09	**0.70**	0.41	-0.13	0.48	0.41	0.20	0.40	0.25	0.47	-0.36	-0.32
Zn								1.00	0.18	0.17	-0.07	-0.20	0.12	0.06	0.24	0.37	0.04	**0.66**	0.88
χ_{LF}									1.00	0.57	-0.24	-0.05	0.19	0.41	**0.63**	0.49	**0.82**	-0.01	0.02
χ_{HF}										1.00	0.57	0.16	-0.02	0.10	0.44	0.57	0.43	0.41	0.02
χ_{FD}%											1.00	0.29	-0.05	-0.27	-0.09	0.15	-0.51	0.00	0.00
Igeo (Ti)												1.00	0.58	-0.26	-0.04	-0.03	-0.18	-0.32	-0.39
Igeo (V)													1.00	-0.25	0.08	0.28	0.09	-0.01	-0.01
Igeo (Cr)														1.00	0.29	0.03	0.41	0.08	0.05
Igeo (Mn)															1.00	0.54	**0.70**	0.20	0.09
Igeo (Fe)																1.00	0.41	0.49	0.33
Igeo (Ni)																	1.00	0.06	-0.05
Igeo (Cu)																		1.00	**0.72**
Igeo (Zn)																			1.00

as χ_{HF} to Fe, particularly in this research area. In the research area, χ_{LF} and χ_{HF} are indicators of heavy metal pollution (V, Mn, Fe, and Ni) in topsoil originating from anthropogenic sources.

The highest and most significant correlation coefficient between χ_{LF} and Ni metal was found in topsoil samples in the research area. This significant relationship indicates that ferrimagnetic minerals are the main factor determining topsoil magnetic susceptibility (**Ayoubi and Adman, 2019**). There is a strong relationship between χ_{LF}, χ_{HF}, and χ_{FD}(%) and Mn metal. This may occur because Mn is added to the lattice structure of ferrimagnetic minerals during the formation and release processes, or because ferrimagnetic minerals in the environment absorb it (**Kukier et al., 2003**). Several studies found a strong relationship between χ_{LF} and heavy metals in topsoil samples. This indicates that man-made pollution is the main cause of changes in χ_{LF} in the topsoil (**El Hamzaoui et al., 2020; Yang et al., 2022b**). Therefore, this study shows that the high correlation coefficient between χ_{LF} with heavy metals (V, Mn, Fe, and Ni), and χ_{HF} with Fe can be used as an indicator of pollution, especially in areas with the same profile as this study.

5. Conclusions

Using topsoil samples from the urban area of Banjarmasin city in South Kalimantan, Indonesia, relationships between certain heavy metal concentrations and magnetic susceptibility, as well as pollution studies, have been obtained. Measurements of magnetic properties and geochemical tests show that the research location has certain amounts of heavy metals that exceed different thresholds and magnetic susceptibility values. In this study, χ_{LF} and χ_{HF} of the studied topsoil showed a significant correlation with the contents of V, Mn, Fe, and Ni. Meanwhile, the four heavy metals studied in the research area have an abundance that exceeds their presence in the earth's crust, as evidenced by the Igeo pollution index, which shows moderate to high pollution. The interesting thing that can be seen from this research is that the lithology and mineralogy of the parent material in the research area have a small influence, but the lithology and mineralogy of the parent material in the area around the research have a fairly large role in these values. χ_{LF} and χ_{HF} in the topsoil because the research area is a swamp area that has been filled using soil material from the area around the research. The enrichment of χ_{LF} and χ_{HF} values, as well as heavy metal content, is also thought to come from vehicle traffic, both land and river, and it is thought that some also comes from industrial areas around the research location. Based on the findings of this research, it is known that the magnetic parameter (χ_{LF}) can be used to determine whether there are heavy metals V, Mn, Fe, and Ni, while χ_{HF} is for Fe at the research location or in similar places.

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SAŽETAK

Identifikacija antropogenih materijala u površinskome sloju tla iz urbanoga područja Banjarmasina u Indoneziji korištenjem geokemijskih i magnetskih svojstava stijena

Grad Banjarmasin nalazi se na tresetištu i ima tropsku klimu. Iako su tresetna područja jedinstvena i gradom prolaze mnogi pritoci, on se vrlo rijetko istražuje, posebno u vezi s korištenjem magnetizma stijena. Ovo je istraživanje važno jer istražuje izvedivost korištenja magnetskih tehnika za identifikaciju antropogenih materijala proizvedenih ljudskim aktivnostima, koristeći se magnetizmom stijena, geokemijskom analizom i izračunima indeksa onečišćenja. U usporedbi s pozadinskim vrijednostima magnetski signal urbanoga gornjeg sloja tla znatno je pojačan, s magnetskom susceptibilnošću (χLF) od (0,22 – 13,60) × 10^{-6} m^3/kg. Međutim, urbani površinski sloj tla sadržava samo mali broj pedogenih superparamagnetskih (SP) zrna, na što upućuje niska prosječna vrijednost χFD % (< 2 %). Geokemijska svojstva magnetske frakcije u urbanome površinskom sloju tla znatno se razlikuju od onih površinskoga sloja tla koji se općenito nalazi u tresetištu. Ovo dodatno pokazuje da magnetski minerali koji se akumuliraju u urbanome površinskom sloju tla ne potječu samo od pedogenih procesa, već i od materijala matičnoga tla iz okolnoga područja istraživanja. U ovome slučaju površinsko tlo istraživačkoga područja služi kao nasip za izgradnju naselja, prometnica i druge infrastrukture. Znatne korelacijske magnetske tehnike mogu uputiti na onečišćenje površinskoga sloja tla u ovome području, što dokazuje znatna korelacija između χLF s V, Mn, Fe i Ni, kao i χHF s Fe. Igeo indeks onečišćenja označava blagu do visoku razinu onečišćenja Cr, Ni, Cu i Zn.

Ključne riječi:
tresetište, pedogeno, magnetska osjetljivost, indeks onečišćenja, magnetizam stijena, korelacija

Author's contribution

Sudarningsih Sudarningsih (PhD, Associate Professor in Physics) performed the topsoil sample data collection, magnetic and geochemistry measurements and processing, performed data interpretation, composed the original and final manuscripts, and performed project administration. **Tetti Novalina Manik** (PhD, Associate Professor in Physics) provided statistical analysis of the data and their interpretation and composed the original and final manuscripts. **Fahruddin Fahruddin** (PhD, Lecturer, with a research interest in rock magnetism, especially in soil) performed topsoil sample data collection, magnetic and geochemistry data measurements and processing, provided the data interpretation, and composed the original and final manuscripts. **Gerald Tamuntuan** (PhD, Associate Professor in Physics) provided statistical analysis of the data and their interpretation and composed the original and final manuscripts. **Fahrun Razi** (S. Sci., Student) performed the topsoil sample data collection, samples preparation and performed visualisation and also composed the original and final manuscript. **Dzikri Dzikri** (S. Sci., Student) performed the topsoil sample data collection, samples preparation and performed visualisation and also composed the original and final manuscript.
All authors have read and agreed to the published version of the manuscript.