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Magnetic properties, electrical conductivity, and heavy metal contamination of surface soil in agricultural land environments

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ABSTRACT

Agricultural productivity depends on the physical and chemical properties of the soil, thus affecting the level of agricultural soil fertility. However, fertilization activities can increase the amount of pollutants. Environmental risks can affect environmental changes and reduce the fertility of agricultural land. Thus, a study was conducted to analyze magnetic susceptibility, electrical conductivity, and heavy metal contamination of surface soil in agricultural land in the Kumelembuai area, Tomohon City, North Sulawesi, Indonesia. The agromagnetic method with magnetic susceptibility parameters was used and supported by X-ray diffraction (XRD), X-ray fluorescence (XRF), and electrical conductivity. The results showed that a relatively high magnetic susceptibility value (χ_{LF}) indicated the presence of heavy metals resulting from fertilization. The electrical conductivity value of the surface soil obtained was not high enough, meaning that the ability of the surface soil in Kumelembuai to bind water was not strong enough. The lack of soil's ability to bind water can reduce soil fertility. XRD analysis shows the presence of Labradorite, Anorthite, Tridymite, Cristobalite, and Graphite minerals, which are important in providing good soil structure and supporting plant growth. XRF analysis shows high Fe content in the surface soil and the presence of heavy metals such as Ag and Pb. Thus, magnetic susceptibility can be obtained as a proxy indicator of surface soil in agricultural land residues.

Keywords: Magnetic susceptibility, Electrical conductivity, Surface soil, Heavy metals.

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1. INTRODUCTION

Tomohon City, especially in East Tomohon District, is one of the agrotourism areas that produces horticultural agricultural products in North Sulawesi, Indonesia. Geologically, the soil in this area is the result of volcanic tuff weathering, especially from the Tondano Volcano eruption system (Tamuntuan et al., 2023). Agricultural productivity depends on the soil's physical and chemical properties, thus affecting agricultural land fertility. However, human activities such as the use of urea, pesticides, mining activities, and domestic waste can increase the amount of pollutants (Karimi et al., 2011; Taghipour et al., 2011; Dankoub et al., 2012; Azizi et al., 2022). The content of heavy metals in the soil that exceeds the threshold threatens the environment. In agricultural land, heavy metals contained in the soil are residues that interfere with plant growth (Sulistiawaty et al., 2021).

Environmental risks can affect environmental changes and reduce the fertility of agricultural land. Agricultural land can bring environmental changes (Anis et al., 2023; Fitriani et al., 2024). Environmental risks such as pollution, erosion, and climate change can drive environmental changes such as land degradation, agricultural degradation, and ecosystem degradation, which directly reduce land fertility through nutrient loss, damage.to soil structure, and decreased activity of soil organisms. Conversely, unsustainable agriculture triggers these environmental risks and environmental changes, creating a cycle that undermines land fertility and agricultural productivity (Moritsuka et al., 2021).

Assessment of environmental changes can be traced through soil magnetic minerals. Magnetic minerals are influenced by the element Fe. Even though the Fe content is low, its magnetic susceptibility is high enough to be detected. The method that can be used for this purpose is the rock magnetism method. The rock magnetism method is one of the geophysical methods developed to study the magnetic properties of rocks, iron sand, river sediments, and soil. In environmental magnetic studies, magnetic minerals are associated with a number of heavy metals. Thus, magnetic properties can be used as a proxy indicator of the presence of heavy metals in agricultural soils (Ayoubi and Karami, 2018; Ayoubi and Mirsaidi, 2018; Azizi et al., 2023; Amirmohammadi et al., 2024).

Environmental magnetic methods offer significant advantages, as they are fast and non-destructive. This makes them an easy and efficient soil and environmental studies tool in the agricultural sector (Tiwow et al., 2018; Tiwow et al., 2019). Changes in the magnetic properties of a material are related to changes in the characteristics of magnetic mineral concentration, mineralogy, grain size, and magnetic domains (Ayoubi and Adman, 2019). The application of environmental magnetic methods, especially magnetic susceptibility parameters, has been explored in various environments, such as river environments (Tiwow and Rampe, 2022; Tiwow et al., 2022), landfills (Mulyana et al., 2022; Boroallo et al., 2023), cave sediment (Tiwow et al., 2024; Tiwow et al., 2025) and coastal environments (Tiwow et al., 2023). These findings indicate a promising future for environmental magnetic methods in soil and environmental studies in the agricultural sector.

Applying environmental magnetic methods to agricultural soils is a newly developed rock magnetism method, and soil and environmental studies in the agricultural sector are very important (Kruglov et al., 2023; Malyshev and Alekseev, 2023). The role of environmental magnetic methods in analyzing agricultural soils' physical and chemical properties is crucial in describing the presence of heavy metal contamination in agricultural soils. The application of environmental magnetic methods to agricultural soil in the Rurukan area, East Tomohon, has obtained information on magnetic susceptibility, geochemistry, and electrical conductivity (Tamuntuan et al., 2023). Meanwhile, similar environmentally friendly studies have never been conducted in the Kumelembuai area, East Tomohon.

Environmental magnetic case studies on agricultural land in the Kumelembuai area, East Tomohon, are important because they can provide information on soil quality, fertility potential, and environmental conditions and help identify and monitor pollution. Soil magnetic properties, such as magnetic susceptibility, can indicate the content of magnetic minerals related to soil fertility and plant growth. In addition, magnetic studies can be used to identify and monitor pollutants in the soil (Fitriani et al., 2024). This information can help farmers and scientists understand soil conditions better, identify fertility and pollution problems, and take appropriate actions to improve soil quality and agricultural land productivity. Thus, the Kumelembuai area, East Tomohon, as an agrotourism area, will maintain soil quality to increase horticultural crop production for farmers.

This report combines environmental magnetic methods applied to surface soil in the Kumelembuai agricultural land, East Tomohon, with X-ray fluorescence (XRF), X-ray diffraction (XRD), and electrical conductivity. The information obtained can describe magnetic susceptibility as a proxy indicator of surface soil residues in agricultural land. The correlation between magnetic and geochemical parameters of agricultural soil can describe the process of environmental change and sources of contamination (Arsyad et al., 2022; Ghobadi et al., 2024; Guda et al., 2024). The availability of the above information is invaluable in agricultural management and optimization of agricultural production in the East Tomohon area. Therefore, this study aims to analyze the magnetic susceptibility, electrical conductivity, and heavy metal contamination of the surface soil of Kumelembuai agricultural land, Tomohon City, North Sulawesi, Indonesia.

2. MATERIALS AND METHODS

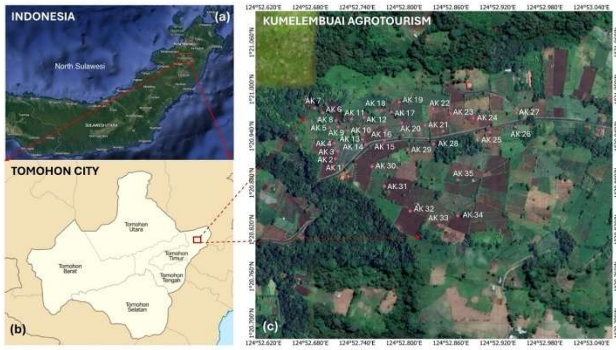

Fig. 1. (a) Map of North Sulawesi Province, which is one of the provinces in Indonesia, (b) Map of Tomohon City, one of the cities in North Sulawesi Province, (c) Kumelembuai agrotourism, location of the study area and sampling points

This study was conducted in Kumelembuai, East Tomohon District, Tomohon City, North Sulawesi, Indonesia. Kumelembuai area, East Tomohon District is located at 1° 21' 1.15" N and 124° 53' 24.32" E. The sampling points are shown in Fig. 1. The sampling coordinates were determined using a Global Positioning System (GPS) tool. Sampling points were determined randomly on agricultural land in the Kumelembuai agrotourism area. Samples were taken at 35 points, at as

Table 1. Descriptive statistics of magnetic susceptibility of agricultural land in the Kumelembuai area, Tomohon City (n = 35)

Variable	Unit	Descriptive statistics					
		Minimum	Maximum	Range	Mean	SD	CV (%)
χ_{LF}	$\times 10^{-8}$ m^3/kg	521.9	955.6	521.9–955.6	684.3	96.11	14
χ_{HF}	$\times 10^{-8}$ m^3/kg	512.4	936.6	512.4–936.6	667.3	95.16	14
χ_{FD}	%	1.82	3.15	1.82–3.15	2.5	0.38	15

much as 500 g at each point and put into plastic bags for temporary storage. Samples were prepared using the powder method to obtain samples of two categories: samples without extraction and extraction samples. The samples were dried at room temperature to remove water content, and the samples were ground and sieved using a 100-mesh sieve. Furthermore, each sample was weighed as much as 15 g and tested (Tiwow et al., 2021).

Magnetic susceptibility testing using the Bartington Susceptibility Meter equipped with an MS2B sensor. Measurements were made at low frequencies (470 Hz) and high frequencies (4700 Hz) (Tiwow et al., 2023). Measurements at two frequencies to obtain frequency-dependent magnetic susceptibility using the equation χ_{FD} (%) = $[(\chi_{LF} - \chi_{HF})]/\chi_{LF} \times 100\%$. This method determines the mineral content in soil samples based on magnetic mineral classification. Frequency-dependent magnetic susceptibility to obtain information on the presence of superparamagnetic (SP) minerals, magnetic grain size, and magnetic domains (Kirana et al., 2021; Tiwow et al., 2025). Plot the frequency-dependent magnetic susceptibility graph against magnetic susceptibility at low frequencies to interpret the surface soil residue sources. Electrical conductivity measurements used the Hanna Groline HI 98331 Soil Test direct Electrical Conductivity tool for analyzing the soil's ability to bind water (Murthuza et al., 2023; Tamuntuan et al., 2023; Kirana et al., 2024).

The results of the magnetic susceptibility study were strengthened by XRF measurements using the PANalytical Epsilon 3 XRF tool for testing heavy metal content in agricultural soil (Mulyana et al., 2022). XRF testing was carried out on ten selected samples having the highest and lowest magnetic susceptibility values. In addition, XRD measurements used the XRD Xpert Pro PANalytical PW3040/60 tool to test the surface soil mineral type. This tool works at a wavelength of 0.154 Å, copper anode, 40 kV voltage, 30 mA current, 0.02° scan step, and diffraction angle (10–100)°. Interpretation of surface soil residue sources using magnetic susceptibility was strengthened by statistical analysis, namely the correlation of magnetic parameters (magnetic susceptibility) with Fe elements and the correlation of Fe elements with other identified heavy metal elements (Arsyad et al., 2022).

3. RESULTS AND DISCUSSION

3.1 Magnetic Susceptibility

Magnetic susceptibility measurements were conducted on 35 samples from the Kumelembuai agricultural land, East Tomohon, North Sulawesi, Indonesia. Table 1 shows a statistical description of the magnetic susceptibility of surface soil samples in Kumelembuai agricultural land, East Tomohon. The magnetic susceptibility values at low frequencies (χ_{LF}) varied 521.9–955.6 × 10^{-8} m^3/kg with an average value of 684.3 × 10^{-8} m^3/kg. The magnetic susceptibility values at high frequencies (χ_{HF}) also varied 512.4–936.6 × 10^{-8} m^3/kg with an average value of 667.3 m^3/kg. Meanwhile, the frequency-dependent magnetic susceptibility value obtained 1.82%–3.15% with an average value of 2.54%.

Table 1 also shows a high percentage of coefficient of variation, which is more than 10%. If the coefficient of variation is high, then the magnetic susceptibility values between samples or measurements differ greatly. This may indicate differences in the content of magnetic minerals between samples. Samples may have different mixtures of magnetic minerals, or there may be differences in the size and orientation of the minerals (Byrne et al., 2019). In addition, variations in magnetic susceptibility can be influenced by environmental factors such as temperature, pressure, or water content that can affect the magnetic properties of minerals (Moritsuka et al., 2021).

Compared with the research results of Fitriani et al. (2021), the χ_{LF} of agricultural soil near the Cikijing River, which was obtained at 28.3–374.1 × 10^{-8} m^3/kg, this value is lower than the χ_{LF} of surface soil in the Kumelembuai agricultural area. However, both the χ_{LF} of agricultural soils near the Cikijing River and the Kumelembuai area exceeding 10 × 10^{-8} m^3/kg are significant findings. This high value indicates the dominance of ferrimagnetic mineral groups in all agricultural soil samples, a crucial factor in understanding the soil's behaviour (Tiwow et al., 2019; Arsyad et al., 2022; Anis et al., 2023). According to the location of this agricultural land, it is also an agrotourism area that is often visited, so anthropogenic activity factors and vehicle emissions are thought to influence the high magnetic susceptibility value. In addition, the activity of changing crops after harvesting is planted on agricultural land so that fertilizer is often applied to the same land. These results are in accordance with research reported by Brempong et al. (2016) and Ameen (2024) that the high magnetic susceptibility value in agricultural land is enriched by ferrimagnetic material as a result of anthropogenic activities and repeated fertilizer applications in the soil.

The magnetic susceptibility value χ_{LF} is greater than χ_{HF} (Fig. 2). This occurs because when measuring with high frequency, SP grains do not contribute to determining the susceptibility value, so the changes in the external magnetic field produced are faster than the relaxation time required for SP grains (Tiwow et al., 2018; Tiwow and Rampe, 2022). In addition, the wavelength produced by χ_{LF} is greater than χ_{HF}, so when the measurement is carried out, the low-frequency magnetic susceptibility value of χ_{LF} is more optimal in analyzing SP grains (Fauzan et al., 2024; Sambolangi et al., 2024; Tiwow et al., 2024). The high magnetic susceptibility value of χ_{LF} is indicated by heavy metals resulting from fertilization. Fertilization that is carried out continuously will lower the pH of the soil, which will contain heavy metals. Fitriani et al. (2024) explained that heavy metals in the soil will cause a higher magnetic susceptibility value. In addition, according to Tamuntuan et al. (2023) stated that soil type and land topography can also affect the magnetic susceptibility value in the soil. Agricultural land in Kumelembuai has a topography; some are hilly, some are flat, and some are alluvial and loose soil types.

Meanwhile, the χ_{FD} value obtained was dominant in the medium category, namely 2%–10%. This means that the sample contains 10%–75% SP grains, a mixture of fine and coarse SP grains (Dearing, 1999). High SP grains in the soil indicate that the soil in Kumelembuai has a high nutrient absorption capacity. The presence of SP grains in the surface soil suggests that the entire surface soil in Kumelembuai has refined grains. The number of refined grains in the surface soil in Kumelembuai agricultural land is indicated to cause high nutrient absorption. This result also follows the findings obtained by Rangkuti and Budiman (2019), which showed that the more SP grains the surface soil contains, the more fine mineral grains the surface soil has.

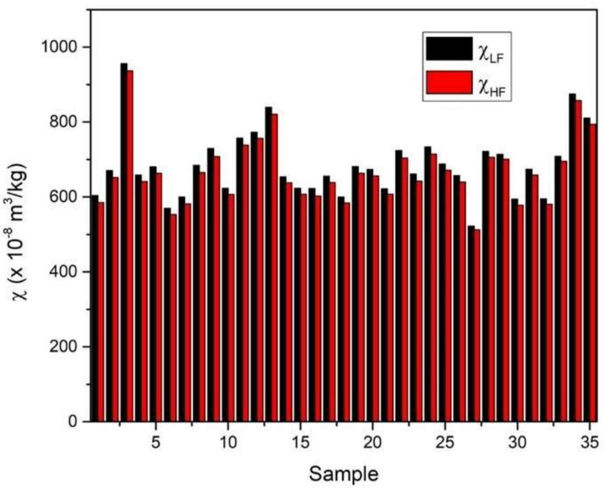

Fig. 2. Comparison of χ_{LF} and χ_{HF} of agricultural land in the Kumelembuai area, Tomohon city

Previous studies have explained that fine-grained magnetic minerals SP indicate that the character of agricultural soil is more controlled by natural or lithogenic components (Evans and Heller, 2003). Even the findings reported by Cao et al. (2015) found high concentrations of magnetic minerals with fine grain sizes of SP single domain (SD) domains in areas far from settlements and near forests with fresh and clean environmental conditions. These magnetic mineral properties are only influenced by natural properties or only come from the source of weathering of the original rock (lithogenic components) (Evans and Heller, 2003).

The average χ_{FD} value in the sample is around 2.5%, which is included in the medium χ_{FD} category. This means that the magnetic minerals in the sample tend to be dominated by non-SP magnetic minerals with coarse grain sizes (< 0.005 µm) (Dearing, 1999). This finding can be further strengthened by the plot diagram between χ_{LF} and χ_{FD} (Fig. 3), which shows the grain size and domain status of magnetic minerals, indicating the source of magnetic minerals in the sample.

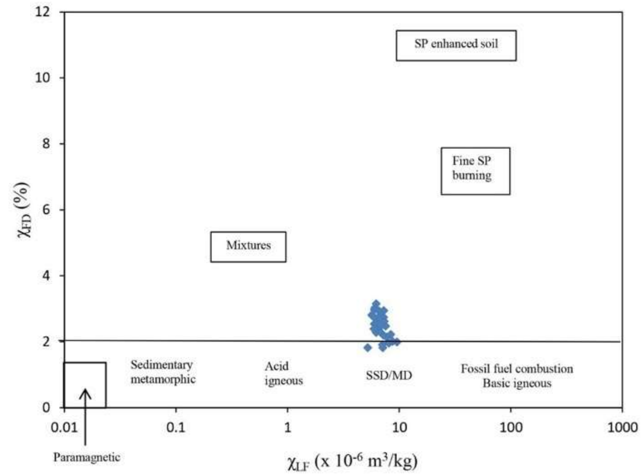

Fig. 3. Relationship between χ_{LF} and χ_{FD} of agricultural land in the Kumelembuai area, Tomohon city

Fig. 3 shows that ferrimagnetic minerals more influence the χ_{LF} value but has a medium χ_{FD} (2%–10%, except points 3, 27, 29, 33, and 35). This indicates that the type of magnetic minerals in the sample is more dominated by fine-grained supermagnetic and non-supermagnetic mixed ferrimagnetic minerals and tends to occupy the SP and stable single domain (SSD) domains (Fig. 4). This finding is similar to the results of studies such as Kirana et al. (2020) and Wnuk et al. (2020), which have found the properties of magnetic minerals originating from polluted agricultural soils that tend to be dominated by fine-grained (< 0.005 µm) mixed SP and non-SP ferrimagnetic magnetic minerals and have SP and SSD domains.

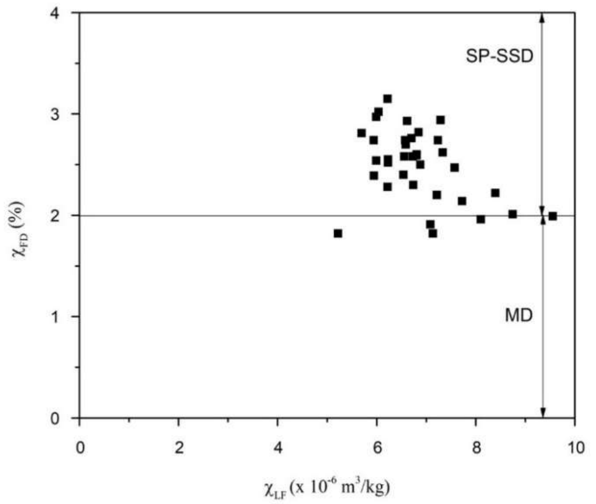

Fig. 4. A schematic $\chi_{LF} - \chi_{FD}$ scattering diagram showing typical positions of samples

The concentration of magnetic minerals increased in surface soil samples affected by anthropogenic activities. According to data from the Agrotourism location as of June 2025, the number of visitors to the Kumelembuai Agrotourism site is 100–150 people per day on Mondays through Fridays and 200–300 people per day on Saturdays and Sundays. Meanwhile, on national holidays or collective leave, the number of visitors can exceed 300. This is one factor contributing to the increased concentration of magnetic minerals introduced by human activity. These results are in line with several previous studies reported by Brempong et al. (2016), Fitriani et al. (2021), and Ameen (2024). Identification in the field that the spot is located on a sloped area whose lower part is bordered by a vegetated area. It is suspected that magnetic material, which usually has a higher density, is eroded and deposited at the spot in the rainy season. In contrast, lighter nonmagnetic material is carried by water flow and deposited in the lowlands. Tamuntuan et al. (2023) stated that the combination of topographic conditions and vegetation cover can affect the magnetic properties of surface soil.

Even some other researchers Kirana et al. (2020) and Wnuk et al. (2020), found a good correlation between the χ_{LF} value and the concentration of heavy metals, which indicates that the high concentration of magnetic minerals in the sample is influenced by magnetic minerals originating from anthropogenic components. The results of this study are supported by the mapping of magnetic susceptibility values of surface soil in the Kumelembuai agricultural area, East Tomohon district, Tomohon city, shown in Fig. 5. The magnetic susceptibility value depends on the Fe content in the surface soil sample, so it can be said that the southeast and northwest of the study area are zones with relatively high Fe content. The correlation between the Fe (iron) value

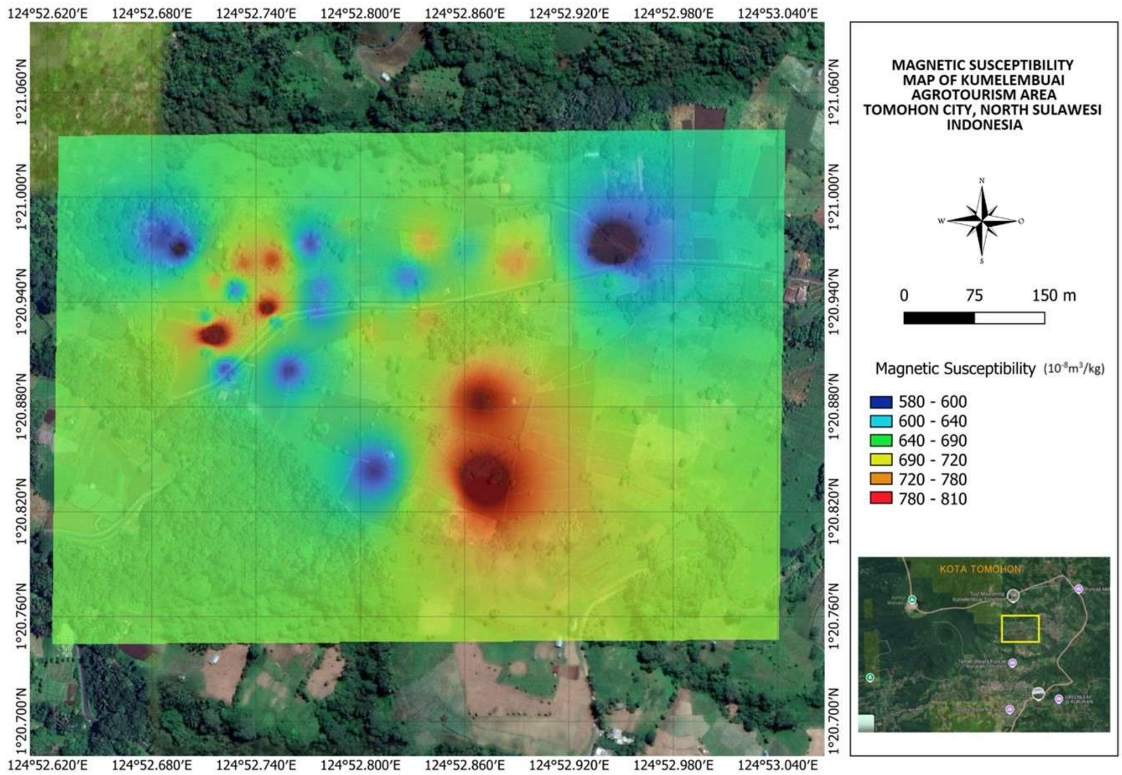

Fig. 5. Spatial distribution map of magnetic susceptibility values of surface soil in the Kumelembuai agricultural area, Tomohon city

and the magnetic susceptibility value further underscores the importance of this research (Kruglov et al., 2023; Malyshev and Alekseev, 2023; Ameen, 2024; Ghobadi et al., 2024).

3.2 Electrical Conductivity

Standard electrical parameters measured in soil samples are electrical conductivity or its inverse, electrical resistivity. Electrical conductivity depends on humidity content, pH and temperature. Electrical conductivity in soil and soil-water mixtures combines surface, particle, and pore fluid conduction. Therefore, the interaction between the two dramatically determines the measured global electrical conductivity (Tamuntuan et al., 2023).

Theoretically, pore fluid conduction depends on the availability and mobility of ions in the pore fluid. Surface conduction depends on the concentration of ions in the pore fluid, porosity, and the specific surface of the particles. The soil's water content level greatly influences soil electrical conductivity. The greater the water content in the soil, the higher the conductivity value. Each type of soil has a different water-binding ability, and each region has a different type of soil. Agricultural land productivity is greatly influenced by the soil's nutrients and the soil's ability to bind water (Tamuntuan et al., 2023).

Agricultural soil fertility is also influenced by chemical properties, namely electrical conductivity values. Soil electrical conductivity interprets the ability of agricultural soil to bind water. Through in-situ measurements, the electrical conductivity values of surface soil in Kumelembuai agricultural land were obtained differently and varied, ranging from 1×10^{-2} mS/cm to 8×10^{-2} mS/cm (Fig. 6). The smallest electrical conductivity value was 1×10^{-2} mS/cm in sample 23, while the largest was 8×10^{-2} mS/cm in samples 17, 27, and 34.

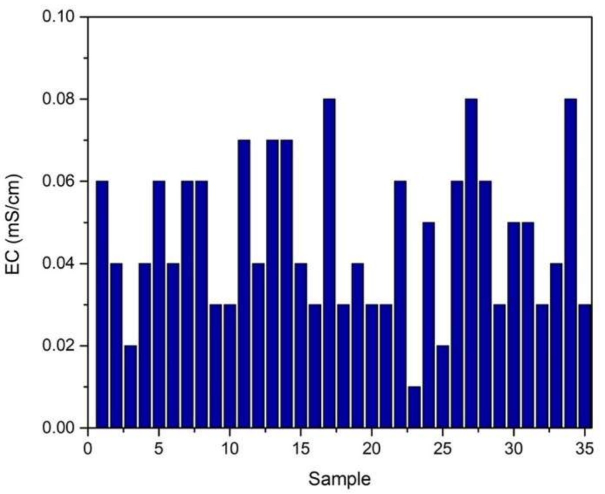

Fig. 6. Electrical conductivity value of agricultural land in the Kumelembuai area, Tomohon city

The results were not high enough, meaning that the ability of the surface soil in Kumelembuai agricultural land to bind water is not strong enough. It also appears that the electrical conductivity values of the surface soil in the Kumelembuai agricultural area vary. Several causes result in different surface soil conductivity values, including the rock grains' size, the rock's mineral composition, water content, and porosity. Porosity is the ratio between the space of a rock and the volume of the rock itself. On the other hand, Kekane et al. (2015) stated that strong soil electrical conductivity values indicate high salt ion content and soil salinity, which pollutants can cause. Soil that has been contaminated with pollutants can cause changes in the electrical properties of the soil. These changes are determined by the initial soil composition, chemical and physical properties of the contaminant, concentration, duration of interaction between the soil and the contaminant, temperature, and pressure (Borner et al. 1993).

Fig. 7 shows the distribution of electrical conductivity values against the magnetic susceptibility values of surface soil in the Kumelembuai agricultural area, East Tomohon. It can be seen that the third sample (K3), which has a small conductivity value of 2×10^{-2} mS/cm, exhibits a high magnetic susceptibility. On the other hand, the 27th sample (K27), which has a reasonably significant conductivity value of 8×10^{-2} mS/cm, exhibits a small magnetic susceptibility value. For samples with medium magnetic susceptibility values, medium electrical conductivity values are also obtained, as seen in sample K16. The relative positions of samples K3, K16, and K27 based on magnetic susceptibility values can be seen in Fig. 2. The susceptibility values of the three samples are shown in Table 2. These results indicate that the higher the surface soil electrical conductivity, the higher the abundance of magnetic minerals in the surface soil. The results obtained are the same as those reported by Kirana et al. (2024). In addition, the increase in soil electrical conductivity is influenced by the high number of hydrogen ions or alkaline pH. Hydrogen ions can affect soil salinity and water content (Aizat et al., 2014).

Tabel 2. Magnetic susceptibility values of three representative samples.

Sample	χ_{LF} ($\times 10^{-8}$ m^3/kg)
K3	955.6
K16	622.1
K27	521.9

On the other hand, this indicates that surface soil samples with small conductivity values have excessive Fe content, so it is feared that plants will absorb too much Fe, inhibiting the absorption of other nutrients and vice versa. Therefore, urea fertilizer is needed to provide macro elements such as N, P, and K so that plants absorb balanced nutrients. The higher the susceptibility value, the higher the Fe content in the surface soil. Repeated use of land with the same plants causes nutrient absorption by plants to always be the same, likewise with the absorption of Fe in soil planted with plants that are always the same (Rangkuti and Budiman, 2019). This also makes the Fe content in each land different, even though the land is close together.

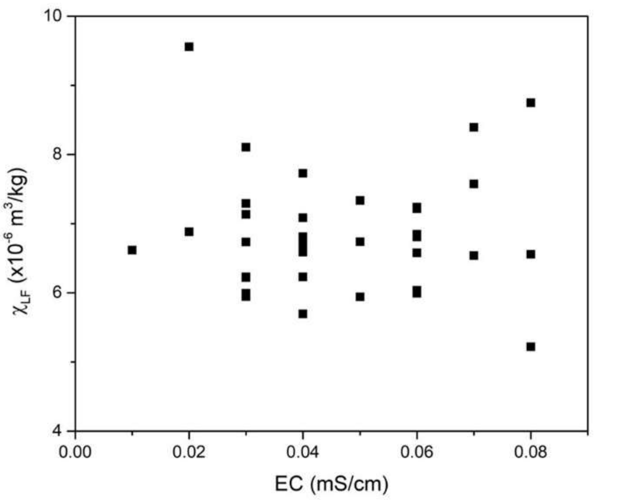

Fig. 7. Distribution of electrical conductivity values against magnetic susceptibility values of agricultural land in the Kumelembuai area, Tomohon city

3.3 Mineral Characterization

The XRD analysis, a critical method in our research, was employed to accurately identify the mineral content in surface soil samples. Three samples were selected for XRD analysis based on their magnetic susceptibility values. Samples K3, K16, and K27 represent high, medium, and low magnetic susceptibility values, respectively. These samples represent the entire experimental series, exhibiting identical preparation conditions, consistent physical parameters (sample quantity, particle size, particle size distribution), and samples taken from the same area but at different points. This strengthens the interpretation of the XRD mineralogical analysis, demonstrating the representativeness of the selected samples.

Fig. 8 illustrates the XRD diffractogram of surface soil samples from the Kumelembuai agricultural area, Tomohon City. The results obtained through the search and match method indicate that the AK3 sample contains the minerals Labradorite (PDF 00-003-0499), Tridymite (ICSD 01-086-0681), Anorthite (ICSD 01-089-1459), and Graphite (ICSD 01-089-8487). The AK16 sample contains the minerals Cristobalite (PDF 00-011-0695), Anorthite (ICSD 01-075-1587), and Labradorite (ICSD 01-083-1370). Meanwhile, the sample AK27 contains the minerals Cristobalite (PDF 00-039-1425), Anorthite (ICSD 01-073-1435), and Labradorite (ICSD 01-083-1368). These minerals, identified as the dominant ones in the samples, play a significant role in the surface soil's composition.

Labradorite and Anorthite minerals are plagioclase minerals rich in Ca elements, which are thought to originate from the weathering of igneous rocks. Likewise, Tridymite and Cristobalite minerals, which are rich in Si elements and Graphite minerals, which are rich in C elements, are also thought to originate from the formation of igneous rocks. These results are based on the geology of the research location, namely from the weathering of rocks from volcanic eruptions (Tamuntuan et al., 2023).

Graphite and other minerals, such as soil minerals, are not directly needed by plants as nutrients. Graphite, which is composed of carbon, is not absorbed by plants like other nutrients. However, graphite is important in providing good soil structure, which supports plant growth. Soil minerals, on the other hand, contain various nutrients that are important for plants, such as N, P, K, and various other microelements that are absorbed by plants through the roots and used for photosynthesis and growth (Singh and Schulze, 2015).

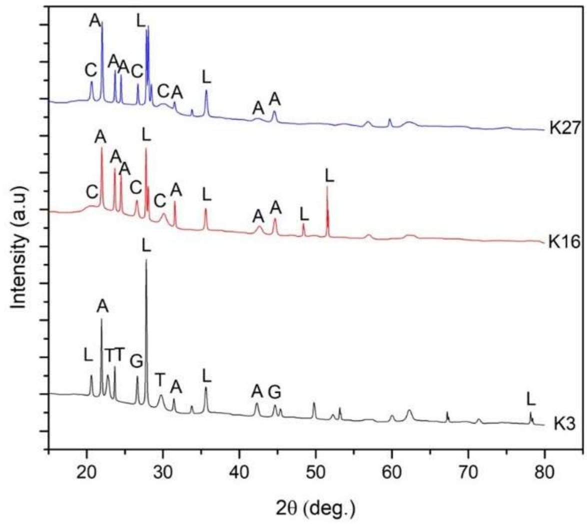

Fig. 8. XRD diffractogram of surface soil samples in the Kumelembuai agricultural area, Tomohon city where L = Labradorite [$(Na_{0.4}Ca_{0.6})\,Al_{1.6}Si_{2.4}O_8$], T = Tridymite ($SiO_2$), A = Anorthite [$Ca\ (Al_2Si_2O_8)$], G=Graphite (C), C = Cristobalite (SiO_2)

The presence of Labradorite, Anorthite, Tridymite, Cristobalite, and Graphite minerals are categorized as paramagnetic and diamagnetic materials. Minerals that are paramagnetic and diamagnetic include minerals with weak magnetic properties, so according to the magnetic susceptibility value of the surface soil samples obtained, it is also not too high. In addition, according to the XRD interpretation related to the source of magnetic minerals in agricultural soil samples (Tiwow et al., 2018; Kirana et al., 2021). Fig. 8 is an XRD diffractogram where the selected sample was not subjected to extraction treatment, so ferrimagnetic minerals such as magnetite were not obtained. Although XRD did not identify ferrimagnetic minerals in selected samples (Fig. 8), χ_{LF} measurements (Table 1) showed their presence in surface soils in the Kumelembuai agricultural area. This indicates that χ_{LF} measurements are more sensitive to detecting ferrimagnetic minerals than

Table 3. Heavy metal composition of surface soil in the Kumelembuai agricultural area, Tomohon city (unit, ppm)

Elemental	Elemental composition (ppm)									
	AK3	AK6	AK9	AK13	AK16	AK18	AK23	AK27	AK30	AK34
Cr	110	140	0	130	90	150	110	0	110	0
Mn	4020	4670	5540	3430	4800	3440	5540	5180	4860	5450
Fe	289020	317060	309720	283750	287300	323040	314280	297270	291680	286680
Cu	800	1180	1200	940	1170	1100	1310	1220	1160	930
Zn	1310	820	1080	740	980	690	1140	1060	910	1070
As	70	70	50	60	70	120	50	80	70	30
Zr	1500	1770	1440	1330	1400	1690	1440	1690	1400	1570
Ag	6610	5970	6170	6180	5820	7350	4510	6440	5670	4140
In	1270	0	910	1210	1160	0	1680	1600	1310	2730
Pb	200	270	210	190	190	270	210	200	180	200

XRD measurements when default equipment settings are used (Camelo et al., 2018).

3.4 Heavy Metal Contamination

Measurement of surface soil residue content in the Kumelembuai agricultural area, Tomohon City, using the XRF PANalytical Epsilon 3 instrument. The measurement results are on ten selected samples from 35 samples. Ten samples were selected to represent a wide range of magnetic susceptibility values (low, medium, and high), allowing for a clear understanding of the relationship between chemical composition and magnetic properties. Furthermore, the results of the XRF analysis identified elements that included heavy metals. Heavy metals have high atomic numbers and densities of more than 5 g/cm^3 (Eso et al., 2024; Wardhani et al., 2024; Widyastuti et al., 2024). Table 3 shows the heavy metal composition of the surface soil in the Kumelembuai agricultural area, Tomohon City. The heavy metal content in surface soil is Cr, Mn, Fe, Cu, Zn, As, Zr, Ag, In, and Pb. The surface soil samples predominantly contain heavy metal Fe. The samples were also found to contain heavy metal Pb.

The element Pb is dangerous. Compared with the results obtained by Anis et al. (2023), the heavy metal content in agricultural soil in Lucknow, India, was obtained as Pb, Zn, Co, Ni, Cu, Fe, and Cr. Meanwhile, Zhao et al. (2024) reported a meta-analysis based on published data that generally heavy metals Cr, Cu, Zn, Pb, Ni, As, Cd, Mn, and Fe are contained in agricultural soil.

The XRF test results show that the magnetic minerals contained in the sample are only Fe_2O_3 (hematite), by estimates based on the magnetic susceptibility value of the sample. The magnetic susceptibility value of minerals in a rock is controlled by the properties of the minerals, namely ferrimagnetic and paramagnetic (Tarling and Hrouda, 1993). This is evidenced by the results of the XRF test that in addition to ferrimagnetic minerals, the sample also contains paramagnetic minerals such as Al_2O_3, CaO, TiO_2, K_2O and diamagnetic such as SiO_2 and P_2O_5. The presence of diamagnetic minerals will not affect the susceptibility value because they have a negative susceptibility value.

Our investigation of the physical and chemical properties is significantly enhanced by the use of statistical analysis. We have established a correlation between the magnetic susceptibility parameter data at low frequencies and Fe elements (Ghobadi et al., 2024; Noya et al., 2024). Furthermore, we have identified a correlation between surface soil residues, identified as heavy metals, and Fe elements. In materials, Fe is often associated with other elements, and its concentration directly impacts the magnetic susceptibility value (Kirana et al., 2024; Nikat and Munfarikha, 2024). We have interpreted contaminant sources based on the plot of magnetic susceptibility graphs at low frequencies with frequency-dependent magnetic susceptibility (Arsyad et al., 2022; Anis et al., 2023). This statistical approach has greatly contributed to our understanding of the data.

The Pearson correlation coefficient between χ_{LF} and heavy metals in the surface soil of the Kumelembuai agriculture area, East Tomohon District, Tomohon City, is shown in Table 4. It appears that the Pearson correlation coefficient with magnetic parameters obtained a positive correlation of $r = 0.42$, p-value < 0.05 (χ_{LF} vs Zn), $r = 0.43$, p-value < 0.05 (χ_{LF} vs In), $r = 0.40$, p-value < 0.05 (χ_{FD} vs Fe), and $r = 0.62$, p-value < 0.01 (χ_{FD} vs Cu). At the same time, a negative correlation was obtained for χ_{LF} vs. Fe ($r = -0.51$, p-value < 0.01). The plot of the magnetic parameters graph with heavy metal content (Zn, In, Fe, and Cu) is shown in Fig. 9. Furthermore, the graph plot between Fe and other heavy metals, namely Cu, Zr, As, and Pb, is shown in Fig. 10. Result shows that a positive correlation was obtained based on the Pearson coefficient. This means that ferromagnetic Fe is associated with other metal elements, indicating an effect on the magnetic susceptibility value (Santoso et al., 2024; Wang et al., 2024).

Similar to the findings obtained by Anis et al. (2023) related to the level of pollution, there is a strong correlation with heavy metals such as Pb, Zn, Co, and Ni and a weak correlation with Cu and Cr. Zhao et al. (2024) also reported that Pearson's correlation analysis showed significant positive correlations of Pb, Zn, and Cu with χ_{LF} ($r = 0.51$-0.53, $p < 0.001$) and Mn and Fe with χ_{FD} ($r = 0.50$–0.53, $p < 0.001$). The correlation between magnetic susceptibility and

Table 4. Pearson correlation coefficient between χ_{LF} and heavy metals in the surface soil of the Kumelembuai area, Tomohon City (n = 10)

	Cr	Mn	Fe	Cu	Zn	Zr	As	Ag	In	Pb
Cr	1									
Mn	-0.70	1								
Fe	0.26	0.05	1							
Cu	-0.09	0.53	0.56*	1						
Zn	-0.49	0.55	-0.27	-0.14	1					
Zr	-0.02	-0.01	0.56*	0.13	-0.17	1				
As	0.51	-0.64	0.43**	0.10	-0.49	0.42	1			
Ag	0.33	-0.68	0.24	-0.13	-0.34	0.26	0.83	1		
In	-0.62	0.52	-0.64	-0.22	0.56	-0.36	-0.72	-0.74	1	
Pb	0.39	-0.28	0.84*	0.18	-0.46	0.77	0.53	0.36	-0.73	1
χ_{LF}	-0.09	-0.19	-0.51	-0.84	0.42**	-0.41	-0.48	-0.19	0.43**	-0.34
χ_{FD}	0.29	0.23	0.40**	0.62*	-0.20	-0.27	0.01	-0.11	-0.41	0.17

Bold values represent correlation with significance.
* Correlation with significance at the 0.01 probability level.
** Correlation with significance at the 0.05 probability level.

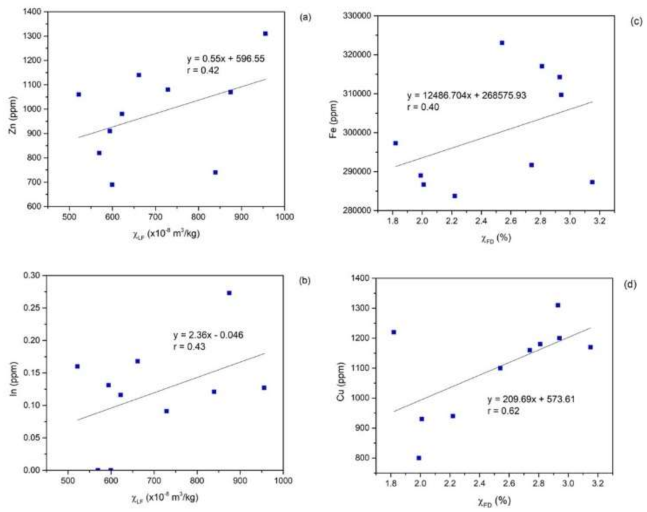

Fig. 9. Graphical plot of (a) χ_{LF} vs Zn; (b) χ_{LF} vs In; (c) χ_{FD} vs Fe; and (d) χ_{FD} vs Cu

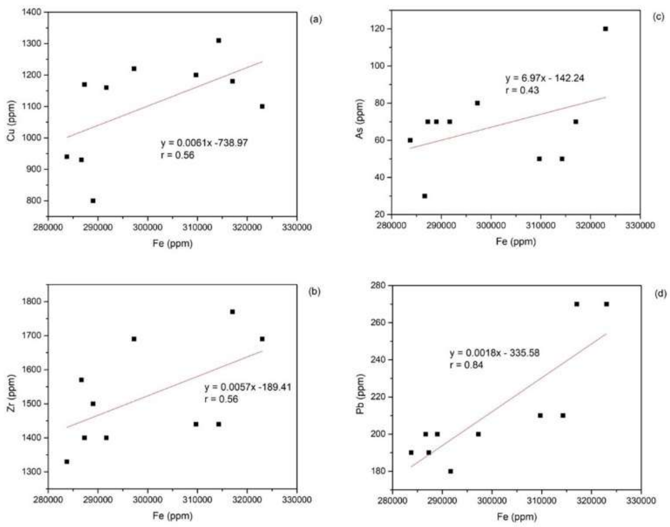

Fig. 10. Plot of heavy metal content (a) Fe vs Cu; (b) Fe vs Zr; (c) Fe vs As; and (d) Fe vs Pb

heavy metal content shows the correlation between iron oxide and heavy metals in the surface soil. The χ_{LF} value assessed with higher heavy metal content in surface soil samples has consistently been a good indicator of anthropogenic contributions to the surface soil residue in the Kumelembuai agricultural area, Tomohon City.

4. CONCLUSION

The magnetic susceptibility value (χ_{LF}) varies 521.9–955.6 × 10^{-8} m^3/kg. The reasonably high magnetic susceptibility value (χ_{LF}) indicates the presence of heavy metals resulting from fertilization. The χ_{FD} value obtained is dominant in the medium category, namely 2%–10%, which means that the sample contains SP grains between 10%–75%, a mixture of fine and coarse SP grains. High SP grains in the surface soil indicate that the overall surface soil has a decreased fertility level. The surface soil electrical conductivity value obtained ranges from 1–8 × 10^{-2} mS/cm. The surface soil electrical conductivity value obtained is not high enough, meaning the surface soil's ability to bind water is not strong enough. The lack of surface soil's ability to bind water can reduce soil fertility. XRD analysis shows the presence of Labradorite, Anorthite, Tridymite, Cristobalite, and Graphite minerals as paramagnetic and diamagnetic materials. These minerals are the source of nutrients plants need in the surface soil. XRF analysis showed high Fe content in the surface soil, and heavy metals such as Ag and Pb were found. Heavy metal contamination was shown based on the correlation of magnetic susceptibility with heavy metal content, which showed a positive correlation. Thus, magnetic susceptibility can be obtained as a proxy indicator of surface soil residue in agricultural land.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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