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Physico-Chemical and Magnetic Characterization of Topsoil Influenced by Vehicular Emissions at Padjadjaran University, Jatinangor

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ABSTRACT

This study investigates the impact of vehicular emissions on the physico-chemical properties of topsoil at Padjadjaran University, Jatinangor. Soil samples were analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), magnetic susceptibility (χ_{LF}), magnetic domain properties (χ_{FD} (%)), and heavy metal concentrations using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). The results showed that while pH values remained within the neutral range (6.03–7.40), elevated EC and TDS values were observed at locations with high traffic density, indicating increased ionic content from anthropogenic sources. Magnetic susceptibility values ranged from 506.7 to 1148.7 × 10^{-8} m^3kg^{-1}, with all sites exceeding 10 × 10^{-8} m^3kg^{-1}, confirming the presence of ferrimagnetic minerals, and higher values were found near areas with heavy vehicle activity. The χ_{FD} (%) values, mostly below 4%, suggest a significant contribution from anthropogenic magnetic particles, dominated by stable single domain (SSD) and multi domain (MD) grains. Heavy metal analysis revealed that most elements (Fe, Mn, Cu, Zn, Al, As, Mg, Ca, K, Ni and Cr) were within permissible limits, except cadmium (Cd), which exceeded background crustal levels, suggesting contamination from anthropogenic sources, including vehicle emissions.

1. INTRODUCTION

High vehicle activity can lead to various environmental impacts, one of which is soil pollution. Soil contamination resulting from vehicular emissions is categorized as anthropogenic pollution, as it originates from human activities. Emissions from vehicles including exhaust gases and heavy metal particles, can settle on the soil surface and alter its chemical and physical properties. Heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), manganese (Mn), and nickel (Ni), commonly produced by vehicle emissions, can accumulate in the soil and potentially disrupt its natural condition (Li, 2001). Soil conditions can be assessed through various physico-chemical properties, including pH, electrical conductivity (EC), total dissolved solids (TDS), magnetic susceptibility, and the concentration of heavy metals. These indicators provide insights into the level of pollution and the extent of anthropogenic influence on soil quality.

Soil pH is particularly sensitive to pollutants and may shift due to the deposition of acidic or basic compounds from vehicle emissions. A lower (more acidic) pH generally correlates with higher concentrations of heavy metals, as acidic conditions enhance the mobility and availability of metal ions in the soil. EC reflects the soil's ability to conduct electric current, which is influenced by the presence of conductive mineral ions. Higher concentrations of these ions result in elevated EC values, indicating increased soil salinity (Jordan et al., 2016). Similarly, TDS measure the concentration of dissolved substances such as minerals in the soil solution. TDS is positively correlated with EC, meaning that samples with high EC values typically also exhibit high TDS values (Arlindia & Afdal, 2015). A study by Hanifah et al. (2024) at Situ Cisanti confirmed this correlation through EC and TDS mapping.

In environmental studies, magnetic susceptibility is widely used as a proxy indicator for soil pollution, particularly in areas affected by anthropogenic activities. A study by Lu et al. (2010) demonstrated that surface soils in urban environments typically exhibit elevated magnetic susceptibility values. Similarly, Azizah et al. (2024) observed increased magnetic susceptibility in soils located near steel industry facilities. These findings suggest that magnetic particles originating from human activities are deposited onto the soil surface, potentially accompanied by other pollutants, such as heavy metals.

Heavy metal concentrations in soil can be accurately determined using analytical techniques such as Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). According to Lu et al. (2010), magnetic susceptibility is positively correlated with heavy metal concentration. Soils with higher magnetic susceptibility often contain elevated levels of heavy metals. Comparisons between measured heavy metal concentrations and natural background levels, such as those found in the Earth's crust, can help determine whether a site is contaminated.

Numerous studies have examined the relationship between soil physico-chemical properties and anthropogenic activities. For example, Yulius & Afdal (2014) investigated surface soils near Teluk Bayur Port and found that areas with high traffic intensity exhibited the highest average magnetic susceptibility and heavy metal concentrations. Maharani and Budiman (2018) investigated the topsoil along Bukittinggi highway and reported the accumulation of heavy metals, including Pb, Cu, Zn, Mn, and Ni. These elements are commonly associated with pollutants emitted from motor vehicle activities. Many of those studies, focused primarily on high-traffic urban roads and industrial zones, often overlooking semi-urban or institutional environments like university campuses. Additionally, while the relationship between magnetic susceptibility and heavy metal concentrations has been observed, few studies have integrated multiple physico-chemical parameters, such as pH, EC, and TDS in a comprehensive assessment to evaluate the full extent of soil pollution from vehicular emissions. Therefore, this study aims to fill the gap by conducting an assessment of the physico-chemical properties of topsoil on the Padjadjaran University campus, which has high vehicle activity. The parameters examined include soil pH, EC, TDS, magnetic susceptibility, and heavy metal concentrations. The findings are expected to provide a comprehensive overview of the soil's physico-chemical characteristics and offer new insights into the impacts of vehicle emissions in a less-explored setting.

2. MATERIAL AND METHODS

The materials used in this study consisted of soil samples collected along the outer ring road of the Padjadjaran University, Jatinangor campus. Soil was collected at a distance of approximately one meter from the roadside. A total of 18 sampling points were selected, in addition to one reference point located in an area with low vehicular activity. The topsoil (0–5 cm depth) was collected using a shovel and stored in labeled zipper bags. Sampling locations are presented in **Figure 1**. The collected soil samples were subsequently prepared through a series of steps including air-drying, sieving, and grinding. Sieving was performed using a 10-mesh sieve (2 mm aperture) to remove coarse particles and obtain a homogenized fraction suitable for further analysis.

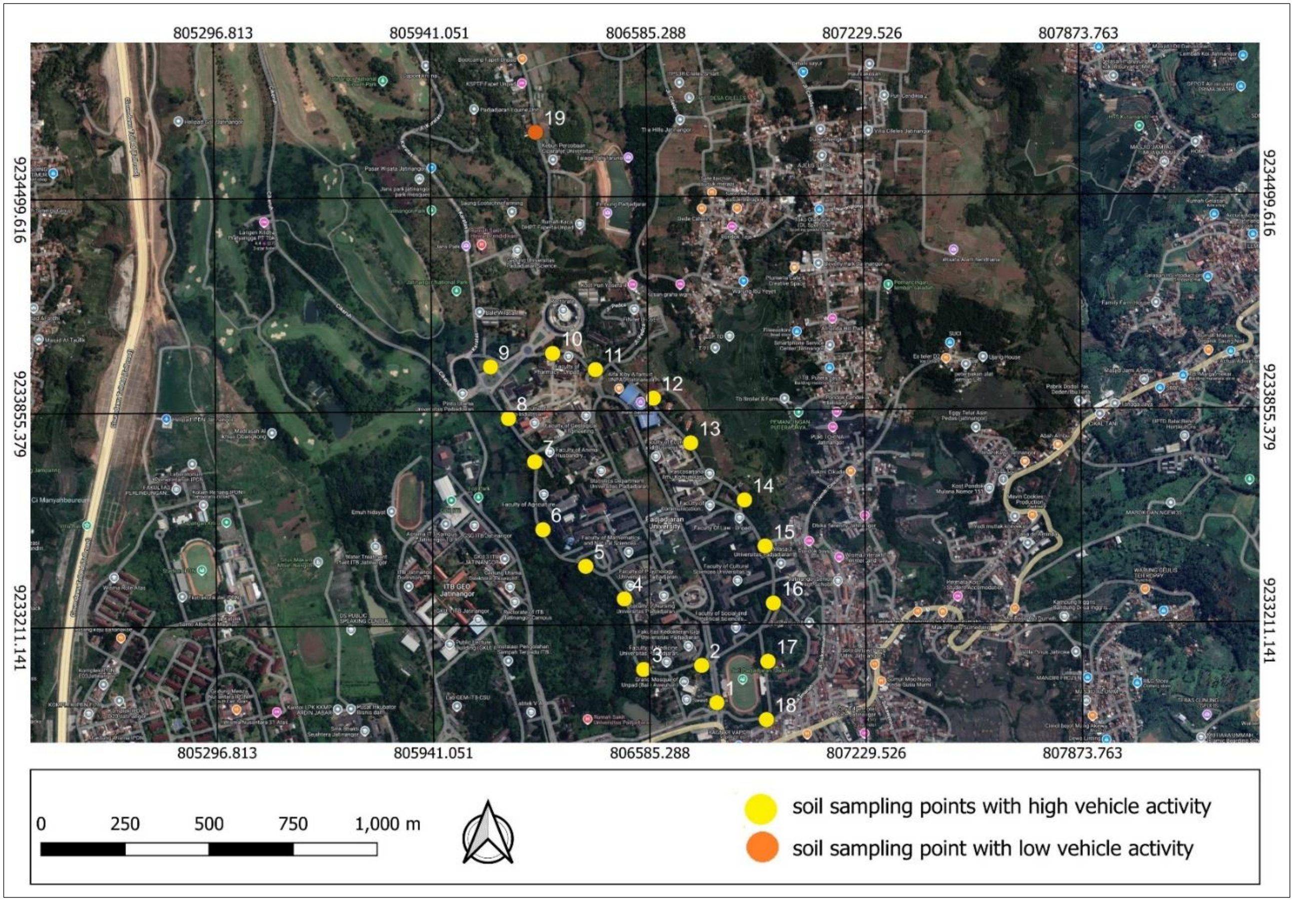


Figure 1. Sampling location points. Yellow round marks are soil sampling points with high vehicle activity and orange round mark is soil sampling point with low vehicle activity.

Measurements of pH, electrical conductivity (EC), and total dissolved solids (TDS) were conducted using a Hanna Combo Meter (model HI-9813). Each soil sample was prepared by mixing with aquabidest at a 1:2 ratio. The probe was immersed in the suspension, and readings were recorded after stabilizing for 1–2 minutes. Each sample was measured in triplicate to ensure accuracy and reproducibility

Magnetic susceptibility measurements were carried out using a Bartington Susceptibility Meter (model MS2B). Each sample was measured at two frequencies: low frequency (χ_{LF}) at 0.47 kHz and high frequency (χ_{HF}) at 4.7 kHz. Five replicate measurements were performed per sample to ensure precision. The frequency dependent susceptibility ($\chi_{FD}(\%)$) was calculated to assess the presence of superparamagnetic (SP) grains, as proposed by Dearing (1999). $\chi_{FD}(\%)$ represents the relative difference between χ_{LF} and χ_{HF}, and is calculated using **Equation (1)** below:

$$\chi_{FD}\ (\%) = \frac{\chi_{LF} - \chi_{HF}}{\chi_{LF}}\ x\ 100\% \tag{1}$$

Heavy metal analysis was performed using an Agilent 725 Series ICP-OES. Soil samples for analysis were selected based on their representative high and low magnetic susceptibility values. The elements analyzed included Fe, Mn, Cu, Zn, Cd, Al, As, Mg, Ca, K, Ni, and Cr. The measured concentrations were subsequently compared with natural background values, specifically the average elemental abundances in the Earth's crust as reported by Turekian and Wedepohl (1961), presented in **Table 1**.

Table 1. Reference values for crustal heavy metal concentrations (Turekian & Wedepohl, 1961)

Reference Values of Elements in the Earth's Crust														
Element	Fe	Mn	Pb	Cu	Zn	Cd	Co	Al	As	Mg	Ca	K	Ni	Cr
Concentration (ppm)	47200	850	20	45	95	0.3	19	80000	13	15000	22100	26600	68	90

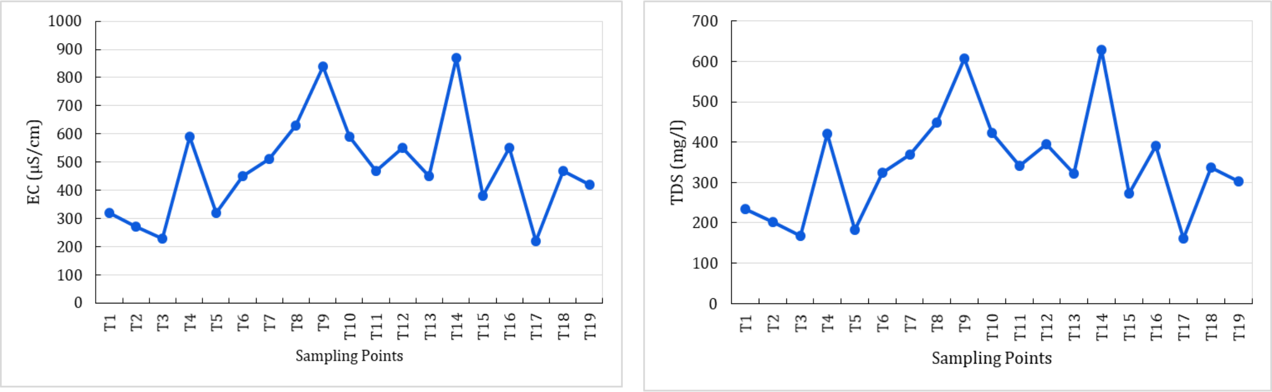
3. RESULT AND DISCUSSION

Table 2 presents the variations in soil pH, EC, and TDS across all sampling points. The soil pH values ranged from 6.03 to 7.40, indicating neutral conditions. Neutral pH implies that the soil is neither significantly acidic nor alkaline. Since acidic soils tend to contain more hydrogen ions (H^+), a more acidic environment would typically enhance the mobility of heavy metals. However, the relatively stable and neutral pH values observed across all points suggest that there has not yet been a significant impact from vehicular emissions. Minor differences in pH may be attributed to local environmental variability at each sampling site.

Table 2. pH, EC, and TDS values at each sampling point

Point	pH	EC (μS/cm)	TDS (mg/l)
T1	6.27	320	234.33
T2	6.03	270	202.67
T3	6.60	230	167.67
T4	6.50	590	420.00
T5	6.80	320	182.00
T6	6.27	450	325.33
T7	7.40	510	369.33
T8	6.07	630	448.33
T9	6.83	840	607.33
T10	6.73	590	423.33
T11	7.23	470	341.33
T12	7.13	550	394.00
T13	7.27	450	321.33
T14	7.00	870	629.33
T15	6.73	380	272.33
T16	7.33	550	391.67
T17	6.33	220	161.33
T18	6.33	470	336.33
T19	6.57	420	302.67

Electrical conductivity (EC) values ranged from 220 to 870 μS/cm, as shown in **Figure 2(a)**. The highest EC values were recorded at T9 (840 μS/cm) and T14 (870 μS/cm), both of which are located in areas with high vehicle activity. In contrast, the lowest EC values were observed at T3 (230 μS/cm) and T17 (220 μS/cm), corresponding to areas with lower traffic density. The elevated EC values at traffic-intensive points may be caused by the accumulation of dissolved ions from vehicular emissions. Despite these variations, all EC values remain within the low to moderate range, considered non-hazardous to soil health (Muliawan et al., 2016). Nevertheless, excessive EC levels can damage soil structure and impair nutrient absorption.



(a) (b)

Figure 2. (a) Graph of EC values based on sampling points, (b) Graph of TDS values based on sampling points

TDS values ranged from 161.33 to 629.33 mg/l. Similar to the EC values, high TDS levels were observed at sampling points T9 and T14, while lower values were found at T3 and T17, as illustrated in **Figure 2(b)**. A strong positive correlation between EC and TDS is confirmed in **Figure 3**, with an R^2 value of 0.99. According to Choo-in (2019), an R^2 within 0.91–1.00 indicates a very strong correlation. This strong relationship arises because the concentration of total dissolved solids in a sample directly influences the total amount of conductive ions or minerals present in the solution. As the concentration of dissolved solids increases, the number of conductive minerals also increases, thereby enhancing the solution's electrical conductivity.

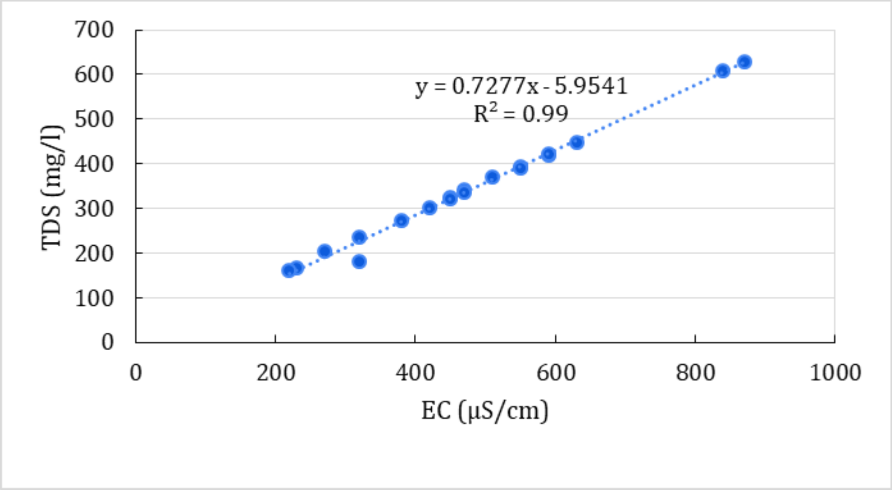


Figure 3. Correlation graph of EC and TDS values

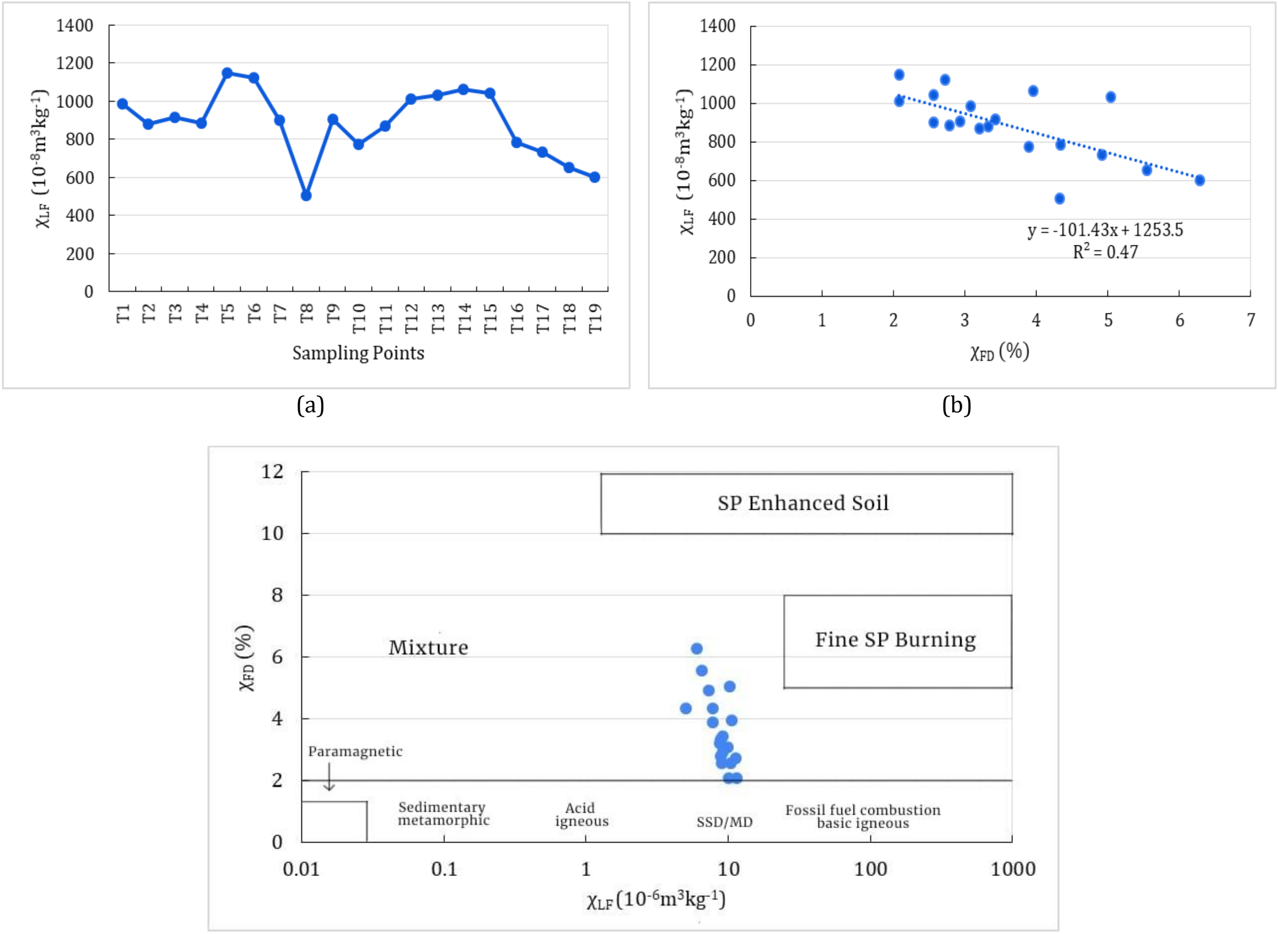
Table 3 presents the magnetic susceptibility (χ_{LF}) values, ranging from 506.7 to 1148.7 × 10^{-8} m^3kg^{-1}. The highest χ_{LF} value was found at T5 and the lowest at T8, as shown in **Figure 4(a)**. These values suggest the presence and accumulation of ferrimagnetic minerals in all samples, as values exceeding 10 × 10^{-8} m^3kg^{-1} are typically attributed to ferrimagnetic phases (Dearing, 1999). The elevated magnetic susceptibility values may be attributed to the increased deposition of magnetic particles from vehicular emissions on the soil surface. For instance, sample point T19, located far from traffic activity, showed a lower χ_{LF} value of 601.9 × 10^{-8} m^3kg^{-1} compared to T5, situated near a high-traffic area, which recorded 1148.7 × 10^{-8} m^3kg^{-1}.

Table 3. Values of χ_{LF} and χ_{FD}(%) at each sampling point

Point	χ_{LF}	χ_{FD}
	× ($10^{-8}m^3kg^{-1}$)	(%)
T1	985.5	3.08
T2	879.3	3.33
T3	918.1	3.43
T4	886.2	2.78
T5	1148.7	2.08
T6	1120.9	2.72
T7	899.3	2.56
T8	506.7	4.32
T9	908.2	2.93
T10	772.8	3.89
T11	870.6	3.20
T12	1010.7	2.08
T13	1031.0	5.04
T14	1063.0	3.96
T15	1041.9	2.56
T16	782.9	4.34
T17	733.8	4.92
T18	652.1	5.55
T19	601.9	6.28

The variation in χ_{FD}(%) is also presented in **Table 3**, with values ranging from 2.08% to 6.28%. In the studied samples, χ_{FD}(%) values fall within the medium category (2–10%), indicating the presence of SP grains with diameters <0.005 μm, typically representing a mixture of fine superparamagnetic and coarser non-superparamagnetic grains. According to Bijaksana and Huliselan (2010), contaminated samples tend to exhibit low χ_{FD}(%) values (1–4%), whereas samples dominated by naturally occurring magnetic minerals generally show higher values, around 10%. This statement is also supported by the findings of Ulfah et al. (2016), Fitriani et al. (2021), and Fitriani et al. (2023), Novala et al., 2016, who reported similar results in their respective studies. In this study, the majority of χ_{FD}(%) values are below 4%, suggesting that the magnetic minerals present in the samples are primarily of anthropogenic origin.

Figure 4(b) presents a correlation graph between χ_{LF} and χ_{FD}(%), indicating a negative correlation. This negative relationship suggests a dominant contribution of multi domain (MD) grains over superparamagnetic (SP) grains (Lu & Bai, 2008). Furthermore, the schematic diagram proposed by Dearing (1999), which plots χ_{FD}(%) versus χ_{LF}, can be utilized to assess the magnetic domain state and potential sources of magnetic minerals in soil samples. The schematic diagram for the study samples is shown in **Figure 4(c)**, indicating that the soil samples predominantly exhibit a mixed domain type, comprising stable single domain (SSD) and MD grains. Magnetic particles originating from anthropogenic sources can vary in origin; however, existing studies generally report a dominance of MD and SSD grains (Hu et al., 2007). Based on this, the abundance of magnetic minerals at the study site is likely influenced by anthropogenic contamination, particularly from vehicular emissions.



(a)

(b)

(c)

Figure 4. (a) Graph of χ_{LF} values based on sampling points, (b) Correlation graph of χ_{LF} versus χ_{FD}(%), (c) Schematic diagram of χ_{FD}(%) versus χ_{LF}

To evaluate heavy metal contamination, two soil samples were selected: T5 (high χ_{LF}) and T19 (low χ_{LF}). The results of the ICP-OES analysis are presented in **Table 4**, indicate the presence of several heavy metals in the samples, including Fe, Mn, Cu, Zn, Cd, Al, As, Mg, Ca, K, Ni, and Cr. Based on the data, the T19 sample exhibited higher concentrations of heavy metals compared to T5. Despite the observed differences, the concentrations of Cu, Zn, As, and Cr in both samples generally remained within the maximum permissible limits set by the World Health Organization (WHO), which are 36 mg/kg for Cu, 50 mg/kg for Zn, 20 mg/kg for As, and 100 mg/kg for Cr. However, cadmium (Cd) in the T19 sample exceeded the WHO threshold of 0.8 mg/kg, reaching 1.06 mg/kg, indicating localized contamination. When compared to the soil concentration ranges proposed by Brady and Weil (1996) (200–2000 mg/kg for Mn, 10,000–100,000 mg/kg for Fe, and 10–1000 mg/kg for Ni), the values measured in both T5 and T19 remained below these reference thresholds, further supporting the conclusion that while some elements show enrichment, widespread contamination may not yet be critical.

Table 4. Concentrations of some heavy metals and comparison with crustal heavy metal concentrations in samples T5 and T19

Element	Concentrations (mg/l)		Soil sample/earth's crust	
	T5	T19	T5	T19
Fe (Iron)	1273.81	9102.22	0.03	0.19
Mn (Manganese)	384.48	594.09	0.45	0.70
Cu (Copper)	17.85	18.40	0.40	0.41
Zn (Zinc)	14.11	24.17	0.15	0.25
Cd (Cadmium)	0.53	1.06	1.77	3.53
Al (Aluminum)	28027.14	26658.75	0.35	0.33
As (Arsenic)	1.53	6.21	0.12	0.48
Mg (Magnesium)	252.81	633.51	0.02	0.04
Ca (Calcium)	214.01	218.70	0.01	0.01
K (Potassium)	289.80	323.72	0.01	0.01
Ni (Nickel)	6.79	6.36	0.10	0.09
Cr (Chromium)	0.73	11.26	0.01	0.13

Further analysis compared measured concentrations to natural background levels in the Earth's crust. Most heavy metals showed concentration ratios <1, indicating that they do not exceed background levels. However, Cd had elevated ratios at both T5 (1.77) and T19 (3.53), suggesting potential anthropogenic enrichment. According to Palar (1994), Cd may originate from both natural sources, such as rock weathering and volcanic activity, as well as anthropogenic activities. Alloway (1995) adds that common anthropogenic sources of Cd include mining, agricultural waste, and vehicle emissions.

Despite T5 having high χ_{LF}, its Cd concentration was lower than T19. T19 is an area with low vehicular activity but is situated near agricultural operations, whereas T5 is located in a high-traffic zone frequently traversed by motor vehicles. Based on magnetic susceptibility measurements, which indicate a dominance of multi domain (MD) and stable single domain (SSD) magnetic particles typically associated with anthropogenic sources, it can be inferred that the heavy metal accumulation at T5 is likely attributed to agricultural waste (Handayani et al., 2022). In contrast, the accumulation of heavy metals at T19 is presumed to result from vehicular emissions.

The concurrence of magnetic and chemical indicators across this study highlights the potential of both combination as a proxy for tracing contamination pathways and distinguishing between natural and anthropogenic sources of soil pollution. Elevated EC, TDS, χ_{LF}, and Cd values at traffic-dense sites indicate that even moderate vehicular activity can influence surface soil quality. The findings of this study are consistent with and reinforce previous research on soil pollution in urban environments and high-traffic areas. For example, Jumianti & Afdal (2010) reported elevated magnetic susceptibility χ_{LF} values in roadside soils within Indonesian urban settings. Similarly, our study observed significantly higher χ_{LF} values at locations with dense traffic, supporting the notion that vehicle emissions are a major contributor to surface soil contamination.

Kanu et al. (2014) further emphasized the reliability of magnetic parameters as proxy indicators of pollution, particularly in scenarios where direct chemical analysis is constrained by cost or limited accessibility. Their study demonstrated notable increases in magnetic susceptibility at industrial sites in Nigeria. A pattern also evident in our results, where elevated χ_{LF} values were recorded near zones of intense anthropogenic activity, such as vehicular traffic. This suggests that the relationship between magnetic signals and metal pollution is not geographically confined, but rather reflects a broader environmental phenomenon linked to human activities.

Additional support comes from Christoforidis and Stamatis (2009), who identified substantial heavy metal concentrations in roadside soils. Their findings revealed that urban and industrial road dust samples contained high levels of Pb, Cu, Zn, and As, along with exceptionally elevated concentrations of

Cd and Hg, with local traffic identified as the primary source. Our results similarly showed elevated Cd concentrations, aligning with these observations.

Collectively, these prior studies provide a robust empirical foundation for validating our findings. The convergence of magnetic and physico-chemical data across diverse research contexts, including those with differing soil types, climates, and urban densities, demonstrates the reproducibility and generalizability of these patterns. In alignment with previous works, this study not only supports their conclusions but also extends their applicability to new environments, such as university campus settings.

4. CONCLUSION

The analysis of physico-chemical properties of topsoil at Padjadjaran University revealed that vehicular emissions have a measurable impact on soil quality, particularly in areas with high traffic intensity. Although pH values remained within neutral ranges, EC and TDS levels showed notable increases at traffic-dense points, indicating the accumulation of dissolved ions likely derived from vehicle emissions. Magnetic susceptibility data further confirmed the presence of ferrimagnetic particles, with elevated values and a predominance of MD and SSD grains suggesting anthropogenic origins, particularly from vehicle emissions. The heavy metal analysis revealed that while most metal concentrations were within permissible limits, cadmium (Cd) exceeded crustal background thresholds, pointing to pollution from vehicular activity. These findings emphasize the importance of continuous monitoring of soil health in institutional environments, which is often overlooked in comparison to industrial zones. The use of magnetic susceptibility as a rapid screening tool, combined with physico-chemical analysis, offers a cost-effective approach to the early detection of soil pollution hotspots.

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