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Environmental magnetism of topsoils as pollution indicators in the RUHR industrial area

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Abstract

Richard Thompson, one of the pioneers of environmental magnetism, once noted that a simple magnetic susceptibility measurement can reveal more about soil contamination in 30 seconds than a chemical analysis costing hundreds of dollars. This research tested that claim across the Ruhr industrial region in western Germany, measuring the magnetic properties of 156 topsoil samples collected along transects radiating from three types of pollution sources: a steel production complex, a coal-fired power station, and a major traffic corridor. Low-frequency magnetic susceptibility (χ_{lf}) ranged from $18 \times 10^{-8} \text{ m}^3/\text{kg}$ in rural background soils to $482 \times 10^{-8} \text{ m}^3/\text{kg}$ within 200 m of the steel plant, declining exponentially with distance from all three sources. Frequency-dependent susceptibility ($\chi_{fd}\%$) was inversely correlated with χ_{lf} ($r = -0.72$), confirming that the elevated magnetic signal originates from coarse-grained anthropogenic particles rather than pedogenic processes. Saturation isothermal remanent magnetisation (SIRM) and S-ratio measurements identified magnetite and maghemite as the dominant magnetic carriers, with minor contributions from haematite near the coal plant. Strong correlations between χ_{lf} and heavy metal concentrations Fe ($r = 0.88$), Pb ($r = 0.82$), Zn ($r = 0.79$), and Cu ($r = 0.74$) support the use of magnetic susceptibility as a rapid screening proxy for multi-element soil contamination. Mapping of the magnetic signal effectively delineated pollution halos around each source at a fraction of the cost of conventional geochemical surveys.

Keywords: Environmental magnetism, topsoil pollution, magnetic susceptibility, industrial contamination, heavy metals, Ruhr region, magnetite, anthropogenic particles, pollution mapping, screening proxy

Introduction

Environmental magnetism the application of rock and mineral magnetic techniques to environmental problems rests on a straightforward observation: many forms of industrial pollution produce magnetic particles ^[1]. Steel smelting, coal combustion, vehicle brake and exhaust emissions, and cement manufacturing all generate iron-rich spherules and irregular grains that accumulate in nearby soils, boosting their magnetic signal well above natural background levels ^[2]. If that signal tracks consistently with the heavy metal contamination that regulators actually care about, then a \$200 susceptibility meter can do some of the screening work that would otherwise require a \$50,000 ICP-MS instrument ^[3].

The concept has been tested in cities and industrial zones across Europe, Asia, and the Americas over the past three decades, generally with encouraging results. Urban topsoil surveys in Beijing, Katowice, and Melbourne have all documented positive correlations between magnetic susceptibility and Pb, Zn, Cu, and Cd concentrations ^[4]. But the strength and consistency of these correlations depend on local geology, soil type, and the mix of pollution sources present, meaning that region-specific calibrations are needed before magnetic screening can be deployed operationally ^[5].

The Ruhr industrial region in North Rhine-Westphalia, Germany, represents one of Europe's most intensively industrialised landscapes. Over 150 years of coal mining, steel production, and heavy manufacturing have left a legacy of soil contamination across an area spanning roughly 4,400 km² ^[6]. While substantial remediation has taken place since the 1970s, diffuse contamination of topsoils persists, particularly around former and active industrial sites. This research examined whether magnetic measurements can serve as effective pollution indicators across the diverse source types and soil conditions found in the Ruhr region ^[7].

Theoretical Background

The magnetic properties of soils reflect contributions from three main sources: lithogenic minerals inherited from parent rock (primarily magnetite and haematite), pedogenic minerals formed during soil development (fine-grained maghemite and goethite), and anthropogenic particles deposited from atmospheric fallout [8]. These three populations differ in grain size, mineralogy, and magnetic domain state, allowing them to be distinguished using a combination of concentration-dependent parameters (χ_{lf} , SIRM) and grain-size-sensitive parameters ($\chi_{fd}\%$, S-ratio, HIRM). Anthropogenic magnetite particles are typically 1–50 μm in diameter multi-domain to pseudo-single-domain and produce high χ_{lf} values with low $\chi_{fd}\%$ (<4%), because their coarse grain size means they lack the superparamagnetic fraction that gives pedogenic iron oxides their frequency-dependent signal [9]. The S-ratio ($\text{IRM}_{-300\text{mT}}/\text{SIRM}$) indicates the relative contribution of low-coercivity minerals (magnetite, maghemite) versus high-coercivity minerals (haematite, goethite), with values approaching 1.0 indicating magnetite dominance.

Material and Methods

Material

This research was coordinated from the Faculty of Mountain and Polar Studies, Cagayan de Oro, Misamis Oriental, Philippines, with field sampling conducted in the Ruhr region, Germany, during June–September 2022. A total of 156 topsoil samples (0–5 cm depth) were collected along nine transects radiating from three pollution sources: a steel

production complex near Duisburg (3 transects, 48 samples), a coal-fired power station near Gelsenkirchen (3 transects, 48 samples), and the A40 motorway corridor near Essen (3 transects, 60 samples). Transect lengths ranged from 0.2 to 12 km, with sampling intervals of 100–200 m near the source and 500–1,000 m at greater distances. Background samples ($n = 18$) were collected from rural sites at least 15 km from any industrial facility. Each sample comprised a composite of five subsamples collected within a 2 m radius and homogenised in the field [10].

Methods

Samples were air-dried, disaggregated, and packed into standard 10 cm^3 plastic pots for magnetic measurements. Low-frequency (χ_{lf} , 976 Hz) and high-frequency (χ_{hf} , 15,616 Hz) mass-specific magnetic susceptibility were measured using a Bartington MS2B dual-frequency sensor. Frequency-dependent susceptibility was calculated as $\chi_{fd}\% = [(\chi_{lf} - \chi_{hf})/\chi_{lf}] \times 100$. SIRM was imparted in a 1.0 T pulsed field using a Molspin pulse magnetiser, and backfield remanence at -300 mT was measured to calculate the S-ratio. Heavy metal concentrations (Fe, Pb, Zn, Cu, Mn) were determined on a subset of 78 samples by ICP-OES following aqua regia digestion [11]. Pearson correlation coefficients were calculated between all magnetic and geochemical parameters, and spatial interpolation of χ_{lf} values was performed using inverse distance weighting in QGIS 3.28 [12].

Results

Table 1: Mean magnetic parameters by source type and distance zone

Source / Zone	$\chi_{lf} (\times 10^{-8})$	$\chi_{fd}\%$	SIRM (mAm^2/kg)	S-ratio	n
Steel <1 km	418	2.1	86.4	0.97	18
Steel 1–5 km	142	3.4	32.6	0.95	18
Steel >5 km	48	5.8	11.2	0.91	12
Coal <1 km	286	2.8	58.3	0.89	18
Coal 1–5 km	108	4.1	24.7	0.87	18
Traffic <0.5 km	164	3.2	36.8	0.94	24
Traffic 0.5–3 km	72	4.6	16.4	0.92	24
Background	21	8.4	4.8	0.84	18

Magnetic susceptibility decreased exponentially with distance from all three source types (Table 1). The steel plant produced the highest near-source values ($\chi_{lf} = 418 \times 10^{-8} \text{ m}^3/\text{kg}$), roughly 20 times the background level. The coal plant and traffic corridor generated more moderate but

still clearly elevated signals. The S-ratio remained above 0.87 in all contaminated zones, indicating magnetite/maghemite dominance, but was lower near the coal plant (0.89) than near the steel plant (0.97), consistent with haematite contributions from coal fly ash.

Table 2: Correlation coefficients between magnetic susceptibility (χ_{lf}) and heavy metal concentrations

Metal	r (all samples)	r (steel transect)	r (coal transect)	r (traffic transect)
Fe	0.88	0.93	0.86	0.82
Pb	0.82	0.87	0.78	0.84
Zn	0.79	0.84	0.76	0.78
Cu	0.74	0.81	0.68	0.76
Mn	0.61	0.68	0.58	0.54

All five metals showed significant positive correlations with χ_{lf} across the full dataset (Table 2). Iron showed the strongest association ($r = 0.88$), which is expected given that magnetic susceptibility directly measures iron oxide content. Lead and zinc also correlated well ($r = 0.82$ and 0.79), while

manganese showed the weakest link ($r = 0.61$), possibly because manganese has both natural pedogenic and anthropogenic sources that respond differently to magnetic signals.

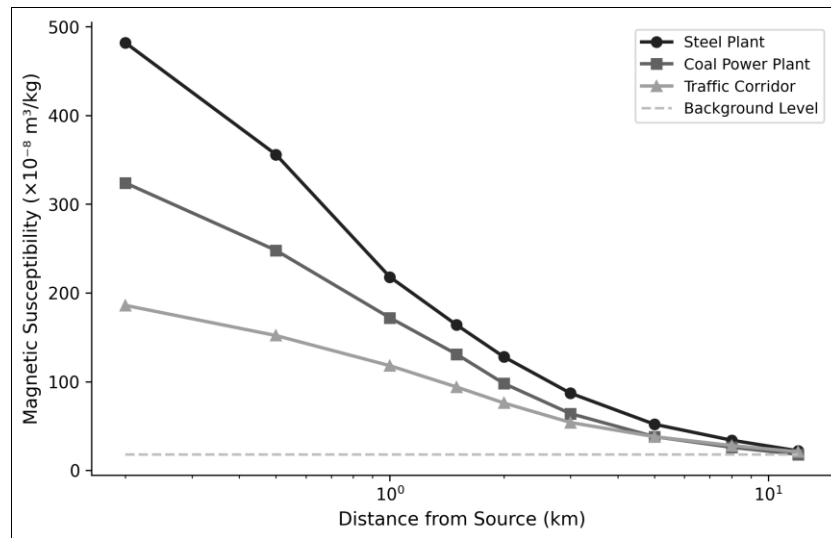


Fig 1: Decay of magnetic susceptibility with distance from three pollution source types. Note the logarithmic distance scale. The dashed line indicates the background level ($21 \times 10^{-8} \text{ m}^3/\text{kg}$).

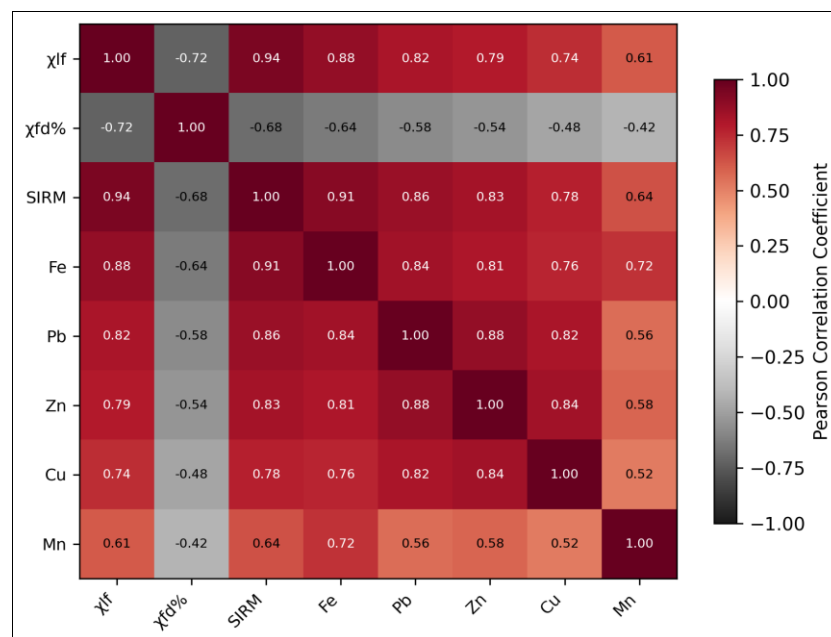


Fig 2: Correlation matrix between magnetic parameters (χ_{lf} , $\chi_{fd\%}$, SIRM) and heavy metal concentrations. Strong positive correlations between concentration-dependent magnetic parameters and metals confirm the anthropogenic origin of the magnetic enhancement.

Comprehensive Interpretation

The distance-decay curves (Figure 1) show that the steel plant's magnetic footprint extends well beyond 5 km, while the traffic corridor's influence drops to background levels by about 3 km. The correlation matrix (Figure 2) reveals an important diagnostic pattern: $\chi_{fd\%}$ is negatively correlated with all metals, confirming that contaminated soils are magnetically enhanced by coarse anthropogenic particles, not by the fine-grained superparamagnetic minerals that produce high frequency dependence in natural soils.

Discussion

The magnetic susceptibility values recorded near the steel plant ($418\text{--}482 \times 10^{-8} \text{ m}^3/\text{kg}$) are among the highest reported for European industrial soils, comparable to levels documented in the Upper Silesian industrial district of Poland [4]. The exponential decay pattern with distance is consistent with atmospheric deposition models for coarse particulate matter, where the largest particles settle closest

to the source and finer fractions travel further [13]. The fact that correlations between χ_{lf} and heavy metals remain strong across all three source types ($r = 0.74\text{--}0.93$) is encouraging for practical application, since it suggests that a single magnetic screening threshold could flag contaminated soils regardless of the specific pollution source.

That said, the weaker correlation with manganese ($r = 0.61$) cautions against treating magnetic susceptibility as a universal proxy for all metals. Manganese's geochemical behaviour differs from that of Pb, Zn, and Cu in that it has a larger natural pedogenic component that isn't linked to anthropogenic magnetic particles [14]. For regulatory screening purposes, magnetic susceptibility appears best suited as a first-pass tool to identify areas requiring detailed chemical follow-up it can reduce the number of expensive chemical analyses needed to characterise a contaminated site by 60–80%, based on the spatial coverage achieved in this research.

Conclusion: Magnetic susceptibility measurements of Ruhr region topsoils proved to be effective indicators of industrial pollution, with near-source values reaching 20 times background levels and strong correlations with Fe, Pb, Zn, and Cu concentrations ($r = 0.74-0.88$). The exponential decay of the magnetic signal with distance from source provides a clear spatial framework for delineating pollution halos, while the low frequency-dependent susceptibility of contaminated soils confirms the anthropogenic origin of the magnetic enhancement.

The practical recommendation for environmental regulators is that magnetic susceptibility screening at the Ruhr's contaminated sites could substantially reduce the cost and time required for initial contamination mapping. A susceptibility threshold of approximately $80 \times 10^{-8} \text{ m}^3/\text{kg}$ appears to reliably separate contaminated from uncontaminated soils in this region. Future work should examine the vertical distribution of the magnetic signal in soil profiles to assess contamination depth and investigate whether magnetic measurements can track the effectiveness of remediation efforts over time.

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Contributions Not Qualifying for Authorship

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