The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Magnetic Susceptibility Approach for Detecting Heavy Metal Pollution (Fe, Co, Cu, and Zn) in Coastal Sediments of Kendari Bay, Southeast Sulawesi, Indonesia

Irawati[1]✉ | Asmadin[1] | Syamsul Razak Haraty[2] | Al Rubaiyn[2]

1. Department of Oceanography, Halu Oleo University, Kendari, Indonesia
2. Department of Geophysical Engineering, Halu Oleo University, Kendari, Indonesia

Article Info

Article type:
Research Article

Article history:
Received: 28 May 2025
Revised: 31 August 2025
Accepted: 28 January 2026

Keywords:
Magnetic susceptibility
Heavy metals
anthropogenic activity
Coastal sediments
Kendari Bay

ABSTRACT

Heavy metal pollution in coastal areas is a serious environmental issue driven by intensive anthropogenic activities. This study aims to assess the potential heavy metal contamination in coastal sediments of Kendari Bay, Southeast Sulawesi, Indonesia, using magnetic susceptibility and X-ray fluorescence (XRF) approaches. A total of 20 sediment samples were collected from three different zones based on anthropogenic activities: port, roadside, and residential areas. Magnetic susceptibility (χlf) was measured using a Bartington MS2 meter with an MS2D sensor, while concentrations of heavy metals (Fe, Co, Cu, Zn) were analyzed using XRF. The χlf values ranged from 4×10^{-5} to 1265×10^{-5} SI, with the highest values observed in the port zone. Iron (Fe) concentrations ranged from 25020 to 57490 mg/kg, cobalt (Co) from 150 to 280 mg/kg, copper (Cu) from 10 to 20 mg/kg, and zinc (Zn) from 40 to 800 mg/kg. A weak positive correlation was found between χlf and Fe ($r \approx 0.21$), while weak to moderate negative correlations were observed with Co, Cu, and Zn (r ranging from –0.15 to –0.38). These findings indicate that some heavy metals are deposited alongside magnetic minerals derived from industrial and transportation activities. Magnetic susceptibility is proven to be a rapid, non-destructive, and cost-effective method, making it highly suitable as a preliminary screening tool for monitoring sediment pollution in coastal environments.

Cite this article: Irawati, Asmadin, Razak Haraty, S., & Rubaiyn, A. (2026). Magnetic Susceptibility Approach for Detecting Heavy Metal Pollution (Fe, Co, Cu, and Zn) in Coastal Sediments of Kendari Bay, Southeast Sulawesi, Indonesia. *Pollution*, 12(1), 180-189.
https://doi.org/10.22059/poll.2025.396143.2959

Publisher: The University of Tehran Press.
DOI: https://doi.org/10.22059/poll.2025.396143.2959

INTRODUCTION

Environmental pollution in coastal areas has become a growing global concern due to the increasing pressure from anthropogenic activities that threaten marine ecosystems. Kendari Bay in Southeast Sulawesi, Indonesia, is a strategic area experiencing rapid growth in industrial, port, maritime transportation, and coastal settlement sectors (Damayanty et al., 2020). These activities contribute to the release of heavy metals into aquatic environments, which subsequently accumulate in sediments. Previous studies in Kendari Bay have reported the presence of heavy metals such as Pb, Cu, and Zn in sediments, indicating that their concentrations have not yet exceeded environmental quality standards based on national regulations. Although heavy metal concentrations in Kendari Bay generally remain below national and USEPA thresholds, long-term accumulation still poses potential ecological risks through bioaccumulation and sublethal effects on marine biota (Indriyani et al., 2020; Yap & Al-Mutairi, 2022)

Studies in tropical and coastal regions show that χlf can serve as an effective early indicator

---

*Corresponding Author Email: *irawatijumaidin@gmail.com* for detecting heavy metal pollution, even when concentrations are below quality thresholds (Karbassi & Shankar, 1994; Anis et al., 2023; Rong et al., 2023). Sediments play a crucial role in aquatic systems as both repositories and secondary sources of contaminants such as heavy metals and organic compounds (Zhang & Liu, 2002; Eggleton & Thomas, 2004). Heavy metals from anthropogenic sources are known to be toxic, persistent, and capable of biological accumulation. Geochemical analysis of sediments can reveal pollution histories, identify sources, and assess the mobility potential of heavy metals linked to redox conditions, organic content, and the presence of metal-binding oxides (Stamatis et al., 2019; Xu et al., 2020; Bai et al., 2024).

Over the past decades, magnetic susceptibility has been increasingly applied as an alternative method for detecting heavy metal pollution (Orosun et al., 2020; Hasberg et al., 2020; Rong et al., 2023). This method measures a material's ability to respond to an external magnetic field and is effective in detecting ferromagnetic minerals such as magnetite, which are often associated with anthropogenic activities, including vehicle emissions and industrial waste (Slotznick et al., 2020).

The advantages of the magnetic susceptibility method lie in its ability to perform rapid, low-cost, and non-destructive detection. However, this method has limitations, such as the inability to directly distinguish between magnetic minerals originating from natural (geogenic) versus anthropogenic sources and its low sensitivity to non-magnetic heavy metals. Therefore, further analyses such as SEM-EDX, XRD, or isotopic studies are required to more accurately identify the sources of magnetic minerals.

Despite these limitations, the magnetic susceptibility approach remains highly promising for the early detection of heavy metals in sediments. Its rapid, non-destructive, and cost-effective nature makes it a relevant screening method for broad environmental quality monitoring. Applications of this method in various coastal areas have shown correlations between magnetic susceptibility values and heavy metal concentrations (D'Emilio et al., 2007; Pan et al., 2019; Yang et al., 2019). However, such correlations in tropical regions, especially Indonesia, are still rarely reported in scientific literature.

This study provides new insight by applying magnetic susceptibility to detect heavy metal contamination in a tropical coastal environment of Indonesia, where such applications remain limited and underreported in the scientific literature. This research aligns with Indonesia's national agenda for marine and coastal pollution control, as stipulated in Government Regulation No. 32 of 2019 concerning the Environmental Protection and Management Plan.

Therefore, this study aims to apply the magnetic susceptibility approach to detect heavy metal contamination in the coastal sediments of Kendari Bay. This method offers a solid scientific foundation to support sustainable coastal environmental management strategies aligned with national policy frameworks (Devanesan et al., 2020).

MATERIALS AND METHODS

Sampling Location and Procedure

This study was conducted in October 2024 in Kendari Bay, Southeast Sulawesi, Indonesia. A total of 20 sediment sampling stations were selected based on land use variation and anthropogenic activity intensity. These stations were categorized into three main zones: roadside area (Stations 1–8), harbor and fisheries area (Stations 9–17), and residential area (Stations 18 20). The locations were chosen based on the intensity of potential pollution sources such as transportation, port industries, and coastal settlements. The geographic coordinates of each station were recorded using GPS and mapped with ArcGIS software. The spatial distribution of the stations is presented in Fig.1.

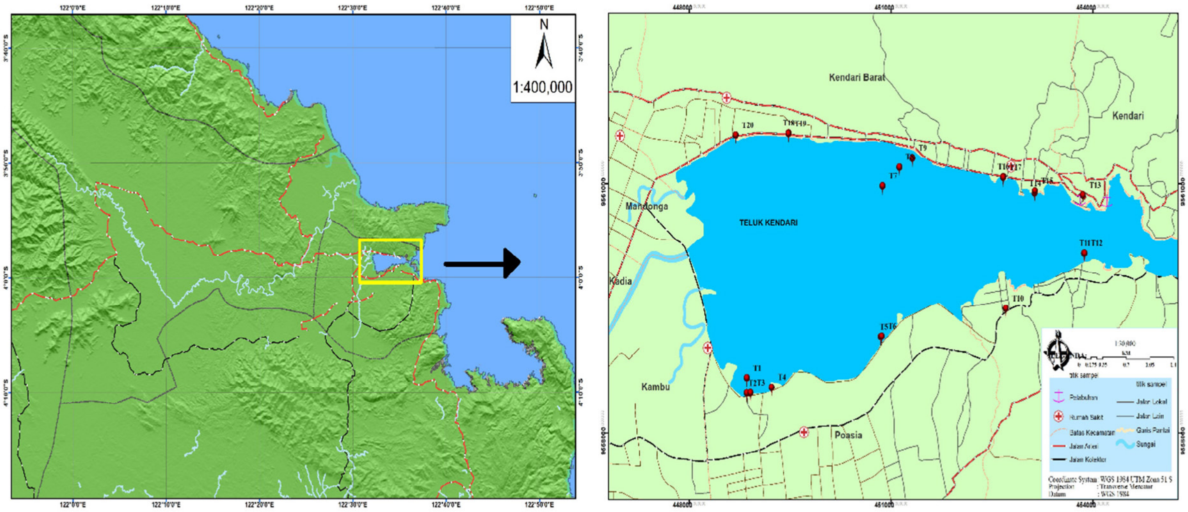

Fig. 1. Map of Kendari Bay

Magnetic Susceptibility Measurement

Magnetic susceptibility values (χlf) were measured using the Bartington MS2 meter with an MS2D surface sensor. This sensor is designed for field measurements on surface sediments and is capable of detecting magnetic signals from the upper sediment layer (~0–5 cm). In situ measurements were conducted by placing the sensor horizontally on undisturbed sediment surfaces. The magnetic susceptibility values are expressed in SI units (10^{-5} SI). To ensure accuracy, each measurement was repeated three times and averaged. The device was calibrated before and after field measurements using a factory magnetic standard. Quality control procedures were carried out in accordance with the protocol of the Ozarks Environmental and Water Resources Institute (OEWRI, 2020).

Sediment Sampling and Analysis

Surface sediment samples were collected from a depth of 0–10 cm using a stainless steel grab sampler. Samples were stored in sterile polyethylene plastic bags, labeled, and kept in an icebox during transport to the laboratory. At the Geo Gea Laboratory, samples were dried, ground, and sieved prior to analysis. Heavy metal concentrations (Fe, Co, Cu, Zn) and major oxide compounds were analyzed using X-ray Fluorescence (XRF) with the X-MET3000TXS instrument. Detection and quantification followed OEWRI standard operating procedures and were calibrated using certified standard materials. Each sample was analyzed three times to ensure data reproducibility.

The oxide compounds analyzed included: sodium oxide (Na_2O), magnesium oxide (MgO), aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), phosphorus pentoxide (P_2O_5), sulfur trioxide (SO_3), potassium oxide (K_2O), calcium oxide (CaO), titanium dioxide (TiO_2), chromium trioxide (Cr_2O_3), and manganese oxide (MnO). The analysis of these oxides aimed to understand both geogenic and anthropogenic contributions to sediment composition and their roles in binding heavy metals.

Data obtained from magnetic susceptibility and XRF measurements were used in correlation analysis, spatial distribution mapping, and evaluating the relationships between magnetic minerals, heavy metal concentrations, and sediment oxide content.

RESULTS AND DISCUSSION

Magnetic Susceptibility Patterns and Anthropogenic Influence

The magnetic susceptibility (χlf) values measured at 20 stations in Kendari Bay exhibited

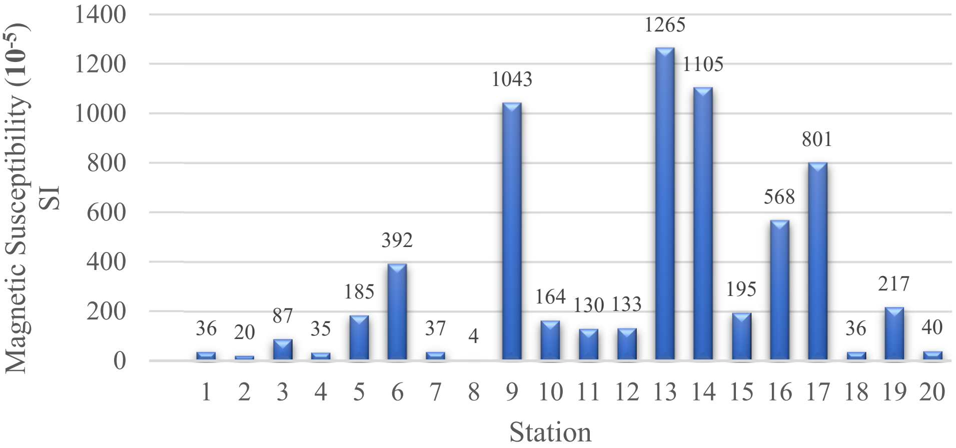

Fig. 2. Distribution graph of sediment magnetic susceptibility values

significant spatial variation, ranging from 4 × 10^{-5} SI to 1265 × 10^{-5} SI. The highest values were recorded at Stations 13, 14, and 17 located in the harbor and industrial zones, while the lowest values were found at Stations 2 and 8 in the residential and roadside zones, as shown in Fig 2.

This distribution pattern indicates a strong relationship between intensive anthropogenic activity and the increased presence of ferromagnetic minerals in sediments. Activities such as vessel operation, port maintenance, fossil fuel combustion, and industrial runoff are potential sources of magnetic particles (e.g., magnetite) that accumulate in sediments.

Previous studies have also reported a correlation between high χlf values and the presence of heavy metal pollutants in industrial coastal environments (Hanesch & Scholger, 2002; Łęczyński et al., 2018; Kusza et al., 2023). Therefore, χlf measurements serve as an effective early indicator for detecting areas with high pollution potential.

Heavy Metal Distribution

The concentrations of heavy metals (Fe, Co, Cu, Zn) in sediments showed spatial variations consistent with χlf values (Table 1). Fe concentrations ranged from 25020–57490 mg/kg, with the highest concentration at Station 15 and other significant values at Stations 13 and 14. Co concentrations ranged from 150–280 mg/kg, with the highest levels at Stations 2 and 7. Cu ranged from 10–20 mg/kg, and Zn from 40–120 mg/kg, peaking at Station 12.

Stations in the harbor zone (Stations 13–17) generally exhibited high χlf values and heavy metal concentrations. Conversely, residential and roadside zones showed lower values, supporting the assumption that heavy metals are deposited from human activities. In general, χlf values tend to be high at stations with high Fe content, such as Station 13 (χlf = 1265 × 10^{-5} SI, Fe = 40000 mg/kg) and Station 14 (χlf = 1105 × 10^{-5} SI, Fe = 47280 mg/kg).

In general, it is observed that χlf values tend to be high at stations with elevated iron (Fe) content, such as at Station 13 (χlf = 1265 × 10^{-5} SI, Fe = 40000 mg/kg) and Station 14 (χlf = 1105 × 10^{-5} SI, Fe = 47280 mg/kg).

Correlation between Magnetic Susceptibility (χlf) and Heavy Metals

To evaluate the relationship between magnetic susceptibility values (χlf) and heavy metal concentrations (Fe, Co, Cu, and Zn), a correlation analysis was conducted based on data obtained from 20 observation stations in the coastal sediments of Kendari Bay, as presented in Fig 3. This analysis revealed that the strength and direction of the correlations varied depending on the type of heavy metal.

Table 1. Magnetic susceptibility values and heavy metal concentrations (Fe, Co, Cu, Zn)

Station	Susceptibility Magnetic (χlf) (10^{-5}) SI	Heavy metal (mg/kg)			
		Fe	Co	Cu	Zn
1	36	49640	210	10	800
2	20	26840	280	10	50
3	87	25020	260	10	50
4	35	29510	250	20	40
5	185	27510	230	20	40
6	392	25020	260	10	50
7	37	28960	280	20	70
8	4	26990	260	20	70
9	1043	25160	240	20	70
10	164	31180	240	10	50
11	130	29060	220	10	50
12	133	30540	270	10	120
13	1265	40000	210	10	70
14	1105	47280	200	10	70
15	195	57490	170	10	90
16	568	53590	160	10	80
17	801	49950	150	10	70
18	36	40100	210	10	80
19	217	37380	200	10	70
20	40	34840	190	10	70

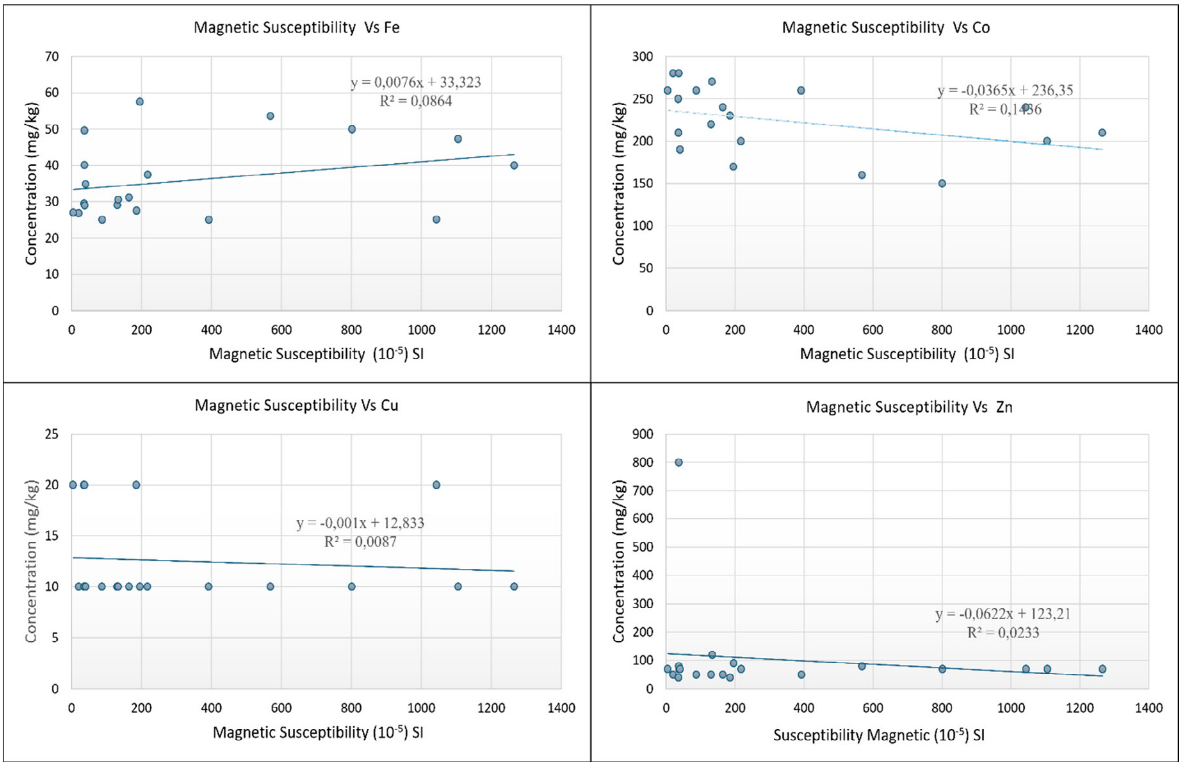

Fig. 3. Correlation Analysis between Magnetic Susceptibility (χlf) and Heavy Metal Concentrations (Fe, Co, Cu, and Zn)

The correlation between magnetic susceptibility (χlf) and iron (Fe) concentrations exhibited a weak positive relationship. This suggests that increasing χlf values tend to be accompanied by higher Fe levels, albeit not in a linear fashion. This phenomenon can be explained by the ferromagnetic characteristics of Fe, especially in the form of minerals such as magnetite and hematite, which significantly influence χlf (Karbassi & Shankar, 1994; Anis et al., 2023). However, the weak correlation also indicates that much of the Fe may be present as diamagnetic or paramagnetic compounds, such as goethite and limonite, which contribute minimally to χlf.

In contrast, χlf and cobalt (Co) showed a weak negative correlation, indicating that higher χlf values do not necessarily reflect increased Co concentrations. This suggests that Co may originate from geogenic or non-magnetic anthropogenic sources and is not directly associated with magnetic minerals (Ziwa et al., 2021).

Similarly, copper (Cu) demonstrated a weak negative correlation with χlf, suggesting that variations in Cu levels are not well reflected by magnetic susceptibility. As reported by Hung et al. (2024), Cu tends to bind with organic matter fractions such as AEOM and DOM rather than magnetic minerals. Schilling & Cooper (2004) also highlighted Cu strong affinity for carboxyl and hydroxyl groups in organic matter, which further weakens its association with χlf. In addition, Sudarningsih et al., (2023) observed that χlf often has weak or insignificant correlations with Cu, Zn, and Hg in coastal sediments.

Zinc (Zn) followed a similar trend, with weak negative correlations observed across sampling stations. Notably, some stations exhibited high Zn concentrations but low χlf values, indicating that Zn contamination likely originates from non-magnetic anthropogenic sources, such as domestic or industrial waste. Studies in the Yellow River Estuary and Citarum River also reported weak or insignificant χlf–Zn correlations, reinforcing the idea that Zn is more frequently bound to non-magnetic or organic fractions (Rong et al., 2023)(Sudarningsih et al., 2023).

Overall, χlf exhibited a weak positive correlation with Fe and a weak to moderate negative correlation with non-magnetic metals such as Co, Cu, and Zn. These findings suggest that χlf is more responsive to ferromagnetic metals but less sensitive to non-magnetic metals. The negative correlations between χlf and Co, Cu, and Zn indicate that these metals may originate from non-magnetic anthropogenic sources such as domestic wastewater, antifouling paints, and industrial effluents rather than from ferromagnetic mineral carriers. In addition, the coastal sediments of Kendari Bay are dominated by fine-grained alluvium, which tends to retain higher concentrations of heavy metals due to its large specific surface area. This characteristic may enhance metal accumulation independently of magnetic mineral content. The weak correlations may also be influenced by other factors, including sediment grain size, organic matter content, and redox conditions, which collectively affect the distribution and retention of heavy metals (Łęczyński et al., 2018; Rong et al., 2023).

The application of magnetic susceptibility in coastal studies has consistently shown correlations between χlf and heavy metal contents. Hanesch & Scholger (2002) demonstrated that magnetic signals increase significantly in industrial zones, making them useful as early indicators of heavy metal loads. A similar study by Abbasi et al. (2010) showed that increasing χlf values were consistently associated with Fe and Cu metal concentrations in industrial and urban areas, supporting the finding that magnetic parameters are a reliable proxy for detecting heavy metal pollution.

Oxide Composition and Environmental Implications

Analysis of sediment oxide compounds (Table 2) revealed that SiO_2 dominates the composition, indicating geogenic input from silicate rock weathering. Elevated levels of Al_2O_3, CaO, and MgO further support the presence of natural minerals such as carbonates and feldspars (Al-Saady et al., 2016). However, increased concentrations of TiO_2, MnO, and SO_3

Table 2. Composition of oxide compounds in sediments

Station	Okside (mg/kg)										
	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO
1	0,26	38	67,41	279,42	0,5	2,93	3,97	256,17	5,23	0,44	0,95
2	0,25	26,89	50,58	418,87	0,16	1	1,86	213,12	1,47	0,35	0,45
3	0,23	25,06	47,15	390,43	0,15	0,93	1,73	238,65	1,37	0,33	0,42
4	0,38	18,77	54,75	259,51	0,22	1,69	2,74	304,72	1,72	0,24	0,44
5	0,35	17,5	51,03	243,25	0,21	1,58	2,55	334,71	1,6	0,22	0,41
6	0,23	25,06	47,15	390,43	0,15	0,93	1,73	248,65	1,37	0,33	0,42
7	0,25	25,85	31,29	277,67	0,24	0,98	3,35	316,09	2,12	0,22	0,47
8	0,23	24,09	39,17	288,82	0,22	0,91	3,12	294,63	1,98	0,21	0,44
9	0,21	32,45	27,19	241,25	0,21	0,85	2,91	324,62	1,85	0,2	0,41
10	0,25	34,02	68,38	384,63	0,1	25,05	4,31	198,68	4,74	0,15	0,39
11	0,23	22,39	83,74	435,8	0,09	23,35	4,02	169,94	4,42	0,14	0,36
12	0,32	25,46	79,14	562,22	0,23	2,9	5,67	110,66	3,28	0,2	0,53
13	0,26	34,75	121,32	481,26	0,14	1,46	10,02	118,3	4,67	0,18	0,51
14	0,24	43,07	113,08	458,58	0,13	1,36	9,34	131,63	4,35	0,17	0,48
15	0,26	49,05	71,26	477,64	0,16	8,13	4,33	128,57	4,27	0,91	0,99
16	0,24	55,72	66,42	405,89	0,15	7,58	4,04	171,2	3,98	0,85	0,92
17	0,22	42,62	61,91	406,29	0,14	7,07	3,77	184,33	3,71	0,79	0,86
18	0,28	25,52	117,19	545,77	0,16	1,08	11,07	96,47	3,82	0,11	0,36
19	0,26	23,79	109,23	508,71	0,15	1,01	10,32	122,64	3,56	0,1	0,34
20	0,24	22,17	101,81	474,17	0,14	0,94	9,62	149,07	3,32	0,09	0,32

in industrial stations suggest anthropogenic contributions, including industrial waste and fossil fuel combustion (Kimeli et al., 2021). These oxides play a significant role in binding heavy metals through adsorption and complexation processes, especially iron and manganese oxides, which act as major scavengers for metals such as Pb, Cd, and Zn (Buccione et al., 2021; Li et al., 2024). The spatial pattern showing high χlf values alongside elevated TiO_2 and MnO concentrations reinforces the hypothesis that magnetic minerals may carry associated heavy metal contaminants (Ismail et al., 2008).

Synthesis and Environmental Considerations

These findings emphasize that the combination of magnetic susceptibility and sediment geochemistry data provides a comprehensive understanding of pollution distribution in Kendari Bay. The port and industrial zones are identified as priority areas for monitoring and mitigation due to the high χlf values and heavy metal concentrations. Moreover, the potential remobilization of heavy metals under anoxic conditions highlights the importance of early pollution control. The use of χlf as a preliminary screening method is highly relevant for sustainable coastal management strategies in tropical coastal regions such as Indonesia.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that the level of heavy metal contamination in coastal sediments of Kendari Bay is closely related to anthropogenic activities, particularly in the port and industrial zones. High magnetic susceptibility (χlf) values were detected in areas with intensive human activities, and they were correlated with increased concentrations of heavy metals, especially iron (Fe) and zinc (Zn), as well as oxide compounds such as TiO_2 and MnO.

Magnetic susceptibility has proven effective as a preliminary screening approach to detect pollution potential in coastal areas. This method is fast, non-destructive, and cost-effective. The integration of magnetic and geochemical data provides comprehensive information to support sustainable coastal environmental management.

Recommendations

1. Integrate magnetic susceptibility measurements into routine sediment quality monitoring systems in Indonesia's coastal areas.
2. Conduct long-term monitoring in port and industrial zones to detect temporal changes and prevent hazardous heavy metal accumulation.
3. Develop further studies using multivariate approaches and heavy metal bioavailability assessments to strengthen the validity of the relationship between magnetic parameters and ecological risks.

These findings are expected to serve as a scientific foundation for the formulation of data-driven and context-specific coastal environmental management policies, especially for tropical regions like Kendari Bay.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research

REFERENCES

Abbasi, S., Atekeh, A., Mohammadian, H. A., Hosseini, S. M., Khorasani, N., & Karbassi, A. (2010). Magnetic Properties of Air Polluting Suspended Particles Deposited on the Leaves of Platanus Orientalis to Monitor Air Pollution in Tehran. *Environmental Researches*, *11*(21), 219–232.

Al-Saady, Y. I., Al-Tawash, B. S., & Al-Suhail, Q. A. (2016). Effects of Land Use and Land Cover on Concentrations of Heavy Metals in Surface Soils of Lesser Zab River Basin, NE Iraq. *Iraqi Journal of Science*, *57*(2), 1484–1503. https://ijs.uobaghdad.edu.iq/index.php/eijs/article/view/7149

Anis, N., Kumar, A., & Kumar Arya, A. (2023). Assessment of concentration and distribution of contaminants using magnetic susceptibility measurements. *Pollution*, *9*(1), 139–149. https://doi.org/10.22059/poll.2022.341263.1488

Bai, H., Liu, G., Chen, D., Xing, Z., Wang, Y., Wang, J., & Zhao, Y. (2024). Heavy Metal Pollution in Sediments of the Yu River in a Polymetallic Ore Concentration Area: Temporal–Spatial Variation, Risk Assessment, and Sources Apportionment. *Sustainability (Switzerland)*, *16*(3), 1–14. https://doi.org/10.3390/su16031154

Buccione, R., Fortunato, E., Paternoster, M., Rizzo, G., Sinisi, R., Summa, V., & Mongelli, G. (2021). Mineralogy and heavy metal assessment of the Pietra del Pertusillo reservoir sediments (Southern

Italy). *Environmental Science and Pollution Research*, *28*(4), 4857–4878. https://doi.org/10.1007/s11356-020-10829-6

D'Emilio, M., Chianese, D., Coppola, R., Macchiato, M., & Ragosta, M. (2007). Magnetic susceptibility measurements as proxy method to monitor soil pollution: development of experimental protocols for field surveys. *Environmental Monitoring and Assessment*, *125*, 137–146.

Damayanty, S., Kamal, M., & Pawennari Muhammad, A. (2020). Identification of causes and the existence of Mercury and Chromium in sediment and sea water in Kendari Bay. *Jurnal Kesehatan Masyarakat*, *15*(3), 344–355. https://doi.org/10.15294/kemas.v15i3.21871

Devanesan, E., Chandrasekaran, A., Sivakumar, S., Freny Joy, K. M., Najam, L. A., & Ravisankar, R. (2020). Magnetic Susceptibility as Proxy for Heavy Metal Pollution Detection in Sediment. *Iranian Journal of Science and Technology, Transaction A: Science*, *44*(3), 875–888. https://doi.org/10.1007/s40995-020-00865-9

Eggleton, J., & Thomas, K. V. (2004). A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environment International, 30(7), 973–980.*, *30*(7), 973–980.

Hanesch, M., & Scholger, R. (2002). Mapping heavy metal loadings in soils by means of Magnetic Susceptibility measurements. *Environmental Geology, 42, 857–870*, *42*, 857–870.

Hasberg, A., Bijaksana, S., Held, P., Just, J., Melles, M., Morlock, M. A., Opitz, S., Russell, J. M., Vogel, H., & Wennrich, V. (2020). *Magnetic susceptibility measurements from different surface sediment samples of Lake Towuti, Indonesia*. PANGAEA. https://doi.org/10.1594/PANGAEA.914836

Hung, M. Y., Huang, W. H., Tsai, H. C., Hsieh, C. Y., & Chen, T. C. (2024). Copper Distribution and Binding Affinity to Size-Fractioned Dissolved and Particulate Organic Matter in River Sediment. *Environments - MDPI*, *11*(6), 1–13. https://doi.org/10.3390/environments11060129

Indriyani, L., Deniyatno, Bana, S., Surya, R. A., & Teke, J. (2020). Environmental quality analysis in Kendari Bay in terms of heavy metal pollutants : Pb. Cu, and Zn. *GeoEco Journal*, *6*(1), 12–27.

Ismail, A. A., El-Midany, A. A., Ibrahim, I. A., & Matsunaga, H. (2008). Heavy metal removal using SiO2-TiO2 binary oxide: experimental design approach. *Adsorption*, *14*(1), 21–29. https://doi.org/10.1007/s10450-007-9042-4

Karbassi, A. R., & Shankar, R. (1994). Magnetic susceptibility of bottom sediments and suspended particulates from Mulki-Pavanje River, estuary, and adjoining shelf, west coast of India. *Journal of Geophysical Research*, *99*(C5). https://doi.org/10.1029/93jc02001

Kimeli, A., Ocholla, O., Okello, J., Koedam, N., Westphal, H., & Kairo, J. (2021). Geochemical and petrographic characteristics of sediments along the transboundary (Kenya-Tanzania) Umba River as indicators of provenance and weathering. *Open Geosciences*, *13*(1), 1064–1083. https://doi.org/10.1515/geo-2020-0275

Kusza, G., Kubowicz, A., Kłostowska, Ż., Łuczak, K., Łęczyński, L., & Hulisz, P. (2023). Environmental effects of potentially toxic elements and the magnetic susceptibility distribution in the surface bottom sediments in the Vistula estuary (Gulf of Gdańsk, Poland). *Journal of Soils and Sediments*, *23*(9), 3499–3512. https://doi.org/10.1007/s11368-023-03595-8

Łęczyński, L., Kłostowska, Ż., Kusza, G., Ossowski, T., Arciszewski, B., & Koza, R. (2018). *The Impact of Grain Size Composition and Organic Matter Content on Magnetic Susceptibility of Anthropogenically Transformed Bottom Sediments, as Exemplified by the Former Naval Harbour in Hel BT - Magnetometry in Environmental Sciences: Studying Environm* (M. Jeleńska, L. Łęczyński, & T. Ossowski (eds.); pp. 91–102). Springer International Publishing. https://doi.org/10.1007/978-3-319-60213-4_7

Li, F., Yin, H., Zhu, T., & Zhuang, W. (2024). Understanding the role of manganese oxides in retaining harmful metals: Insights into oxidation and adsorption mechanisms at microstructure level. *Eco-Environment and Health*, *3*(1), 89–106. https://doi.org/10.1016/j.eehl.2024.01.002

OEWRI. (2020). *Standard Operating Procedure for : X-MET3000TXS + Handheld XRF Analyzer*.

Orosun, M. M., Oniku, S. A., Peter, A., Orosun, R. O., Salawu, N. B., & Hitler, L. (2020). Magnetic susceptibility measurement and heavy metal pollution at an automobile station in ilorin, north-central nigeria. *Environmental Research Communications*, *2*(1). https://doi.org/10.1088/2515-7620/ab636a

Pan, H., Lu, X., Lei, K., Shi, D., Ren, C., Yang, L., & Wang, L. (2019). Using magnetic susceptibility to evaluate pollution status of the sediment for a typical reservoir in northwestern China. *Environmental Science and Pollution Research*, *26*, 3019–3032.

Rong, S., Wu, J., Liu, J., Li, Q., Ren, C., & Cao, X. (2023). Environmental Magnetic Characteristics and

Heavy Metal Pollution Assessment of Sediments in the Le’an River, China. *Minerals*, *13*(2). https://doi.org/10.3390/min13020145

Schilling, M., & Cooper, W. (2004). Identification of Copper Binding Sites in Soil Organic Matter through Chemical Modifications and 13 C CP-MAS NMR Spectroscopy. *Environmental Science & Technology*, *38*, 5059–5063. https://doi.org/10.1021/es049653w

Slotznick, S. P., Sperling, E. A., Tosca, N. J., Miller, A. J., Clayton, K. E., van Helmond, N. A. G. M., Slomp, C. P., & Swanson-Hysell, N. L. (2020). Unraveling the Mineralogical Complexity of Sediment Iron Speciation Using Sequential Extractions. *Geochemistry, Geophysics, Geosystems*, *21*(2). https://doi.org/10.1029/2019GC008666

Stamatis, N., Kamidis, N., Pigada, P., Sylaios, G., & Koutrakis, E. (2019). Quality indicators and possible ecological risks of heavy metals in the sediments of three semi-closed East Mediterranean Gulfs. *Toxics*, *7*(2). https://doi.org/10.3390/TOXICS7020030

Sudarningsih, S., Pratama, A., Bijaksana, S., Fahruddin, F., Zanuddin, A., Salim, A., Abdillah, H., Rusnadi, M., & Mariyanto, M. (2023). Magnetic susceptibility and heavy metal contents in sediments of Riam Kiwa, Riam Kanan and Martapura rivers, Kalimantan Selatan province, Indonesia. *Heliyon*, *9*(6), e16425. https://doi.org/10.1016/j.heliyon.2023.e16425

Xu, Y., Lin, X., & Wang, Z. (2020). Magnetic susceptibility as a proxy for assessing industrial pollution in coastal sediments. *Environmental Geochemistry and Health*, *42*, 2335–2349.

Yang, D., Wang, M., Lu, H., Ding, Z., Liu, J., & Yan, C. (2019). Magnetic properties and correlation with heavy metals in mangrove sediments, the case study on the coast of Fujian, China. *Marine Pollution Bulletin*, *146*, 865–873. https://doi.org/https://doi.org/10.1016/j.marpolbul.2019.07.035

Yap, C. K., & Al-Mutairi, K. A. (2022). Ecological-health risk assessments of heavy metals (Cu, pb, and zn) in aquatic sediments from the asean-5 emerging developing countries: A review and synthesis. *Biology*, *11*(1). https://doi.org/10.3390/biology11010007

Zhang, J., & Liu, C. L. (2002). Riverine composition and estuarine geochemistry of particulate metals in China, weathering features, anthropogenic impact and chemical fluxes. *Estuarine, Coastal and Shelf Science*, *54*(6), 1051–1070.

Ziwa, G., Crane, R., & Hudson-Edwards, K. A. (2021). Geochemistry, mineralogy and microbiology of cobalt in mining-affected environments. *Minerals*, *11*(1), 1–20. https://doi.org/10.3390/min11010022