



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

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Article Info	ABSTRACT
<p>Article type: Research Article</p> <p>Article history: Received: 28 May 2025 Revised: 31 August 2025 Accepted: 28 January 2026</p> <p>Keywords: <i>Magnetic susceptibility</i> <i>Heavy metals</i> <i>anthropogenic activity</i> <i>Coastal sediments</i> <i>Kendari Bay</i></p>	<p>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 (χ_{lf}) 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 χ_{lf} 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 25.02 to 57.49 mg/kg, cobalt (Co) from 150 to 280 mg/kg, copper (Cu) from 10 to 20 mg/kg, and zinc (Zn) from 40 to 120 mg/kg. A weak positive correlation was found between χ_{lf} 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.</p>

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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 χ_{lf} can serve as an effective early indicator

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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.

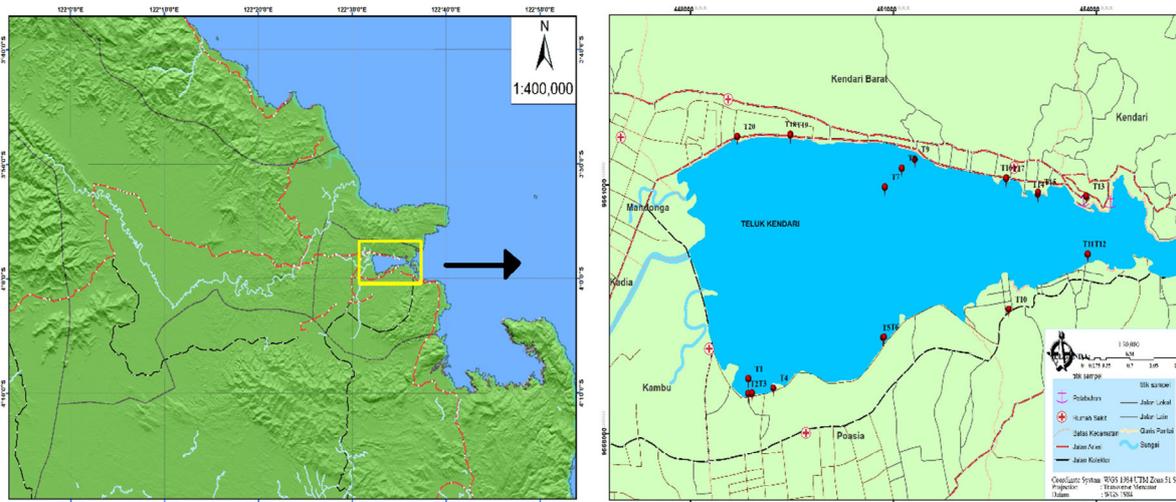


Fig. 1. Map of Kendari Bay

Magnetic Susceptibility Measurement

Magnetic susceptibility values (χ_{lf}) 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 ($\sim 0\text{--}5$ 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 (χ_{lf}) values measured at 20 stations in Kendari Bay exhibited

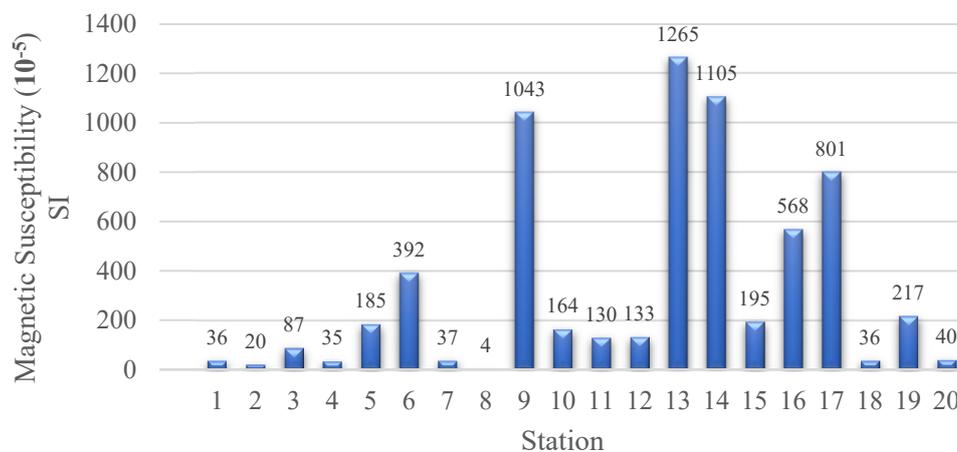


Fig. 2. Distribution graph of sediment magnetic susceptibility values

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 χ_{lf} values and the presence of heavy metal pollutants in industrial coastal environments (Hanesch & Scholger, 2002; Łęczyński et al., 2018; Kusza et al., 2023). Therefore, χ_{lf} 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 χ_{lf} values (Table 1). Fe concentrations ranged from 25.02–57.49 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 χ_{lf} 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, χ_{lf} values tend to be high at stations with high Fe content, such as Station 13 ($\chi_{lf} = 1265 \times 10^{-5}$ SI, Fe = 40 mg/kg) and Station 14 ($\chi_{lf} = 1105 \times 10^{-5}$ SI, Fe = 47.28 mg/kg).

In general, it is observed that χ_{lf} values tend to be high at stations with elevated iron (Fe) content, such as at Station 13 ($\chi_{lf} = 1265 \times 10^{-5}$ SI, Fe = 40 mg/kg) and Station 14 ($\chi_{lf} = 1105 \times 10^{-5}$ SI, Fe = 47.28 mg/kg).

Correlation between Magnetic Susceptibility (χ_{lf}) and Heavy Metals

To evaluate the relationship between magnetic susceptibility values (χ_{lf}) 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 (χ lf) (10^{-5}) SI	Heavy metal (mg/kg)			
		Fe	Co	Cu	Zn
1	36	49,64	210	10	800
2	20	26,84	280	10	50
3	87	25,02	260	10	50
4	35	29,51	250	20	40
5	185	27,51	230	20	40
6	392	25,02	260	10	50
7	37	28,96	280	20	70
8	4	26,99	260	20	70
9	1043	25,16	240	20	70
10	164	31,18	240	10	50
11	130	29,06	220	10	50
12	133	30,54	270	10	120
13	1265	40	210	10	70
14	1105	47,28	200	10	70
15	195	57,49	170	10	90
16	568	53,59	160	10	80
17	801	49,95	150	10	70
18	36	40,1	210	10	80
19	217	37,38	200	10	70
20	40	34,84	190	10	70

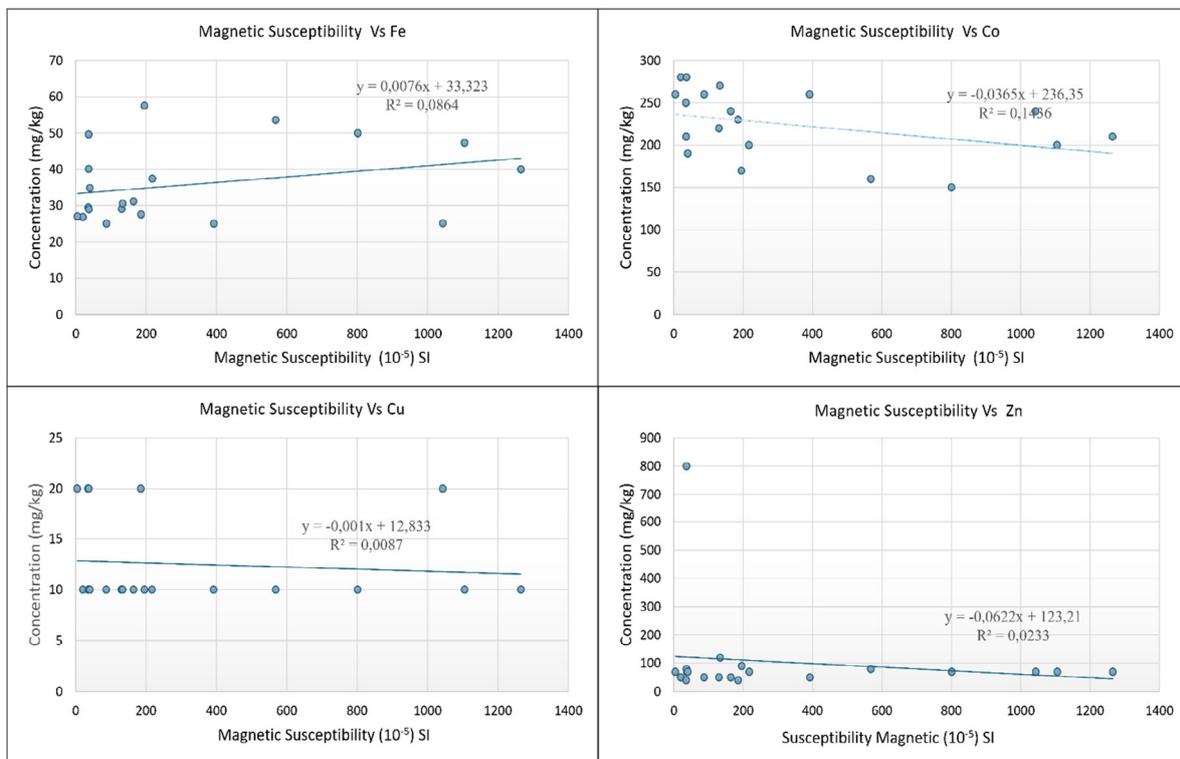


Fig. 3. Correlation Analysis between Magnetic Susceptibility (χ lf) and Heavy Metal Concentrations (Fe, Co, Cu, and Zn)

The correlation between magnetic susceptibility (χ_{lf}) and iron (Fe) concentrations exhibited a weak positive relationship. This suggests that increasing χ_{lf} 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 χ_{lf} (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 χ_{lf} .

In contrast, χ_{lf} and cobalt (Co) showed a weak negative correlation, indicating that higher χ_{lf} 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 χ_{lf} , 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 χ_{lf} . In addition, Sudarningsih et al., (2023) observed that χ_{lf} 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 χ_{lf} 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 χ_{lf} -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, χ_{lf} 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 χ_{lf} is more responsive to ferromagnetic metals but less sensitive to non-magnetic metals. The negative correlations between χ_{lf} 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 χ_{lf} 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 χ_{lf} 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 SiO₂ dominates the composition, indicating geogenic input from silicate rock weathering. Elevated levels of Al₂O₃, CaO, and MgO further support the presence of natural minerals such as carbonates and feldspars (Al-Saady et al., 2016). However, increased concentrations of TiO₂, MnO, and SO₃

Table 2. Composition of oxide compounds in sediments

Station	Okside (mg/kg)										
	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	K ₂ O	CaO	TiO ₂	Cr ₂ O 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 χ_{lf} values alongside elevated TiO₂ 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 χ_{lf} 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 χ_{lf} 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 (χ_{lf}) 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 TiO₂ 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.

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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

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