



Magnetic and Morphological Characterization of Magnetic Minerals from Sarimukti Landfill

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Received: March 16, 2025

Revised: May 02, 2025

Accepted: June 25, 2025

Published: June 30, 2025

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DOI: [10.29303/jppipa.v11i6.11229](https://doi.org/10.29303/jppipa.v11i6.11229)

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Abstract: Sarimukti landfill serves as a waste disposal site. Leachate generated from waste accumulation is discharged through pipelines into multiple retention ponds. This study aims to assess contamination levels in leachate deposits by analyzing the magnetic properties and morphology of magnetic minerals collected from four retention ponds, along with measurements of pH, EC, and TDS in the pond water. Magnetic susceptibility values range from 37.4 - 409.5 ($\times 10^{-8}$) m³/kg, indicating ferrimagnetic mineral dominance. The χ_{FD} (%) values range from 0.81% - 5.96%, where χ_{FD} (%) >2% is often associated to pollutant-contaminated soils. A negative correlation between χ_{LF} and χ_{FD} (%) suggests a minor contribution of superparamagnetic grains from pedogenesis. Scanning Electron Microscopy - Energy Dispersive Spectroscopy (SEM-EDS) analysis identifies spherule and hedral magnetic mineral shapes, with O and Fe as dominant elements and minor Ti, indicating magnetite and titanomagnetite presence. Other elements, including C, Mg, Al, Si, K, Ca, and Mn, likely originate from anthropogenic sources.

Keywords: Leachate; Magnetic susceptibility; Minerals.

Introduction

Landfill is a facility provided by the government to accommodate and manage waste on a large scale. In Indonesia, the management of landfills is regulated under Law Number 18 of 2008 on Waste Management, which emphasizes the importance of implementing a sanitary landfill system to mitigate negative environmental impacts. However, in practice, many landfills in Indonesia still operate using an open dumping system, including the Sarimukti Landfill in West Java, located at geographical coordinates 6°48'2.60"S and 107°20'57.51"E. This system poses a significant risk of environmental contamination due to the uncontrolled accumulation of untreated waste (Hanif & Pohan, 2024; Ulfah et al., 2025).

One of the primary challenges of open dumping systems is the formation of leachate a liquid by product of waste decomposition that contains various organic and inorganic pollutants in high concentrations (Astuti

et al., 2025; Fatimah & Budianta, 2021; Khaira & Afdal, 2022). Improperly managed leachate can infiltrate the soil and contaminate groundwater as well as nearby surface water bodies (Jamrah et al., 2024; Said & Hartaja, 2018; Triawan et al., 2020). Therefore, monitoring environmental quality around landfills is essential as a mitigation measure against pollution risks (Huang et al., 2024; Kumar et al., 2019; Rouhani & Hejman, 2024).

This study is crucial in providing a comprehensive overview of potential environmental contamination at the Sarimukti Landfill, employing a multi-method approach that combines magnetic susceptibility analysis, mineral morphology characterization using Scanning Electron Microscopy - Energy Dispersive Spectroscopy (SEM-EDS), and physicochemical parameters (Power of Hydrogen (pH), Total Dissolved Solids (TDS), and Electrical Conductivity (EC)). This approach enables not only the detection of pollution levels but also the identification of contaminant sources,

How to Cite:

Manurung, D. P. K., Fitriani, D., Agustine, E., Kirana, K. H., & Tama, P. A. (2025). Magnetic and Morphological Characterization of Magnetic Minerals from Sarimukti Landfill. *Jurnal Penelitian Pendidikan IPA*, 11(6), 371-382. <https://doi.org/10.29303/jppipa.v11i6.11229>

particularly those of anthropogenic origin (Fitriani et al., 2021; Kirana et al., 2024).

Unlike previous studies, which generally focused on a single method or collected samples only from surface soils, such as research by Bijaksana & Huliselan (2010) entitled “Magnetic properties and heavy metal content of sanitary leachate sludge in two landfill sites near Bandung, Indonesia”, which investigated the magnetic properties and heavy metal content in leachate sludge at two landfill sites but did not comprehensively integrate multidisciplinary approaches, this research specifically targets samples from leachate ponds at the Sarimukti Landfill (including stabilization, anaerobic, aerobic, and sedimentation ponds) as the primary subject of investigation. The novelty of this study lies in the integration of magnetic susceptibility data with magnetic particle morphology and water quality parameters an approach that has rarely been applied comprehensively at active landfill sites in Indonesia.

In general, the findings of this study are expected to contribute to the development of rapid, effective environmental pollution monitoring methods, and to serve as a scientific foundation for evaluating waste management systems and informing environmental policy, particularly in the context of the Sarimukti Landfill.

Method

This study employs a descriptive-quantitative approach to investigate the magnetic mineral properties of solid leachate sediments and the physicochemical characteristics of leachate water in four retention ponds at the Sarimukti landfill. The research involves preparation, sampling and in-situ measurements, magnetic susceptibility analysis, and mineral characterization using SEM-EDS. Figure 1 presents a flowchart outlining the research stages in a concise manner.

Sample Types and Collection Sites

Two types of samples were used: leachate water - for measuring physicochemical parameters (pH, EC, TDS); and leachate sediment - for magnetic susceptibility and SEM-EDS analysis.

Samples were collected from the following four types of retention ponds: stabilization pond (P) - 15 samples; anaerobic pond (R) - 2 samples; aerobic pond (Q) - 6 samples; and sedimentation pond (S) - 4 samples

Sampling locations are shown in Figure 2 with total of 27 sampling points were used. The higher number of samples in the stabilization pond is due to its division by concrete walls into smaller compartments, allowing greater spatial representation.

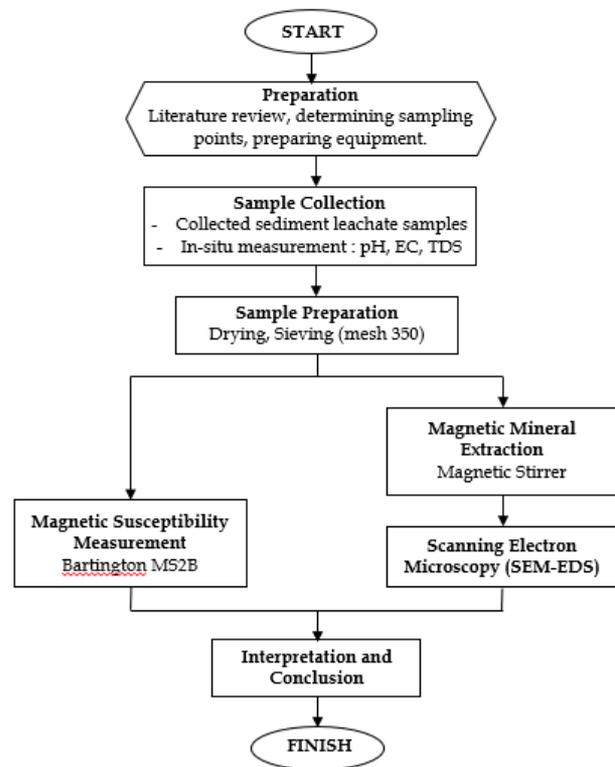


Figure 1. Flowchart of the research process

In-situ Physicochemical Measurements

In-situ measurements of pH, EC TDS were conducted using a HANNA HI 98129 Combo Meter. These measurements were performed directly on leachate water collected from the surface of each retention pond at the time of sampling to reflect the actual water quality.

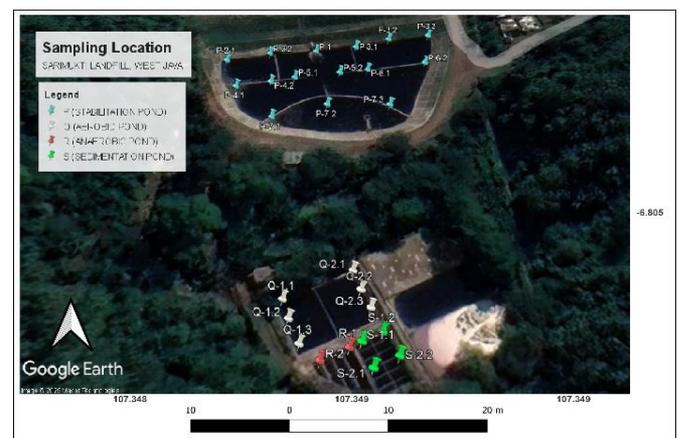


Figure 2. Sampling Locations in Sarimukti Landfill total of 27 sample points in the stabilization pond (P), anaerobic pond (R), aerobic pond (Q), and sedimentation pond (S)

Magnetic Susceptibility Measurement

For magnetic analysis, solid sediment samples were air-dried and sieved through a 325-mesh sieve to obtain

homogeneous particle sizes. Samples were packed tightly into non-magnetic 10 cm³ sized sample holders to avoid air gaps that could interfere with the measurement. Magnetic susceptibility was measured using a Bartington MS2B Susceptibility Meter, at two frequencies:

χ_{LF} (low frequency, 470 Hz) – sensitive to ferrimagnetic and ferromagnetic minerals

χ_{HF} (high frequency, 4700 Hz) – helps estimate the presence of superparamagnetic particles

The frequency-dependent susceptibility $\chi_{FD}(\%)$ was calculated to estimate the proportion of superparamagnetic particles, using the Formula 1.

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

SEM-EDS Measurement

For detailed mineral characterization, magnetic particles were extracted from the dried sediment using manual magnetic separation with a permanent magnet (Adam et al., 2025; Kotta et al., 2025). The extraction process involved dissolving 5 grams of dried sample into 10 mL of distilled water (aquabidest) followed by the extraction of magnetic minerals using a magnetic stirrer. The extracted material was dried again and coated with a conductive layer (carbon or gold) prior to imaging.

SEM-EDS analysis was conducted using a JEOL JSM-6510A instrument to investigate: Morphology of magnetic mineral particles (shape, size, surface texture); and Elemental composition, including iron and other associated elements

Data Analysis

All results were analyzed quantitatively and descriptively. Parameters such as pH, EC and TDS were used to assess the physicochemical conditions. The χ_{LF} value was used to identify ferrimagnetic minerals, while $\chi_{FD}(\%)$ was used to estimate the concentration of superparamagnetic minerals. The correlation between χ_{LF} and $\chi_{FD}(\%)$ provided insight into the dominant magnetic mineral carries, further supported by morphological analysis through SEM-EDS.

Result and Discussion

Physicochemical Analysis

In this study, electrical conductivity (EC) and total dissolved solids (TDS) were initially measured using instruments calibrated in millisiemens per centimeter (mS/cm) and parts per thousand (ppt), respectively. To ensure standardization and facilitate comparison with reference values, the EC data were converted to

microsiemens per centimeter ($\mu\text{S/cm}$), while TDS values were converted to milligrams per liter (mg/L).

Table 1. Values of pH, EC dan TDS

Sample	pH	EC (mS/cm)	TDS (ppt)
P-1	8.06	17.69	8.62
P-2.1	8.2	14.68	7.28
P-2.2	8.09	14.85	7.21
P-3.1	8.13	12.96	6.87
P-3.2	8.13	15.26	7.71
P-3.3	8.01	15.62	7.57
P-4.1	8.25	9.45	4.86
P-4.2	8.33	9.23	4.72
P-5.1	8.17	15.3	7.54
P-5.2	8.2	15.12	7.11
P-6.1	8.11	14.8	7.32
P-6.2	8.11	14.77	7.42
P-7.1	8.18	14.81	7.38
P-7.2	8.23	14.71	7.17
P-7.3	8.18	14.39	7.1
R-1	8.28	14.72	7.15
R-2	8.27	14.85	7.42
Q-1.1	8.23	14.91	7.55
Q-1.2	8.23	15.02	7.45
Q-1.3	8.13	15.01	7.44
Q-2.1	8.26	14.78	6.89
Q-2.2	8.23	14.91	7.31
Q-2.3	8.32	14.75	7.39
S-1.1	8.23	13.43	6.56
S-1.2	8.28	13.36	6.58
S-2.1	8.29	14.11	6.81
S-2.2	8.28	13.74	6.88

Table 1 present the results of pH, EC, and TDS measurements. The pH values of the leachate samples ranged from 8.01 to 8.33, with an average of 8.2. The highest pH value 8.33 was found at the P-4.2 sample, while the lowest value 8.01 was observed at the measurement at P-3.3 sample. The pH values observed are within the standard limit set by the Regulation of the Minister of Environment and Forestry Number P.59 of 2016 (6.0 – 9.0). The relatively alkaline pH is likely due to leachate from household waste, especially from the degradation of organic matter. Lindamulla et al. (2022) noted that tropical landfill leachate typically becomes neutral to alkaline as a result of methanogenic activity and bicarbonate buffering. Similarly, Naveen et al. (2017) reported that reduced VFAs and increased ammoniacal nitrogen in aged leachate contribute to its alkalinity.

According to the World Health Organization (2011), the water quality threshold for Electrical Conductivity (EC) should not exceed 1500 $\mu\text{S/cm}$. The EC values measured in mS/cm were converted to $\mu\text{S/cm}$, showing a range between 9230 $\mu\text{S/cm}$ and 17690 $\mu\text{S/cm}$, with an average of 14340 $\mu\text{S/cm}$. The highest value was recorded at point ST-1 (17690 $\mu\text{S/cm}$), taken

from the pipe before the leachate entered the collection pond, while the lowest value was found at P-4.2 sample (9230 $\mu\text{S}/\text{cm}$). All of these values exceed the water quality threshold, indicating high electrical conductivity (salinity) in the leachate. Measurement samples P-4.1 and P-4.2 showed relatively lower EC values, indicating differences in electrical conductivity at those locations.

Meanwhile, Total Dissolved Solids (TDS) measured in ppt were converted to mg/L, with values ranging from 4720 mg/L to 8620 mg/L. The highest TDS value was also found at P-1 sample (8620 mg/L), while the lowest was at P-4.2 sample (4720 mg/L). All TDS values exceeded the wastewater quality standard, which is 2000 mg/L according to Regulation of the Minister of Environment and Forestry No. P.68/MENLHK/SETJEN/KUM.1/8/2016 concerning Domestic Wastewater Quality Standards, indicating a

high concentration of dissolved substances in the leachate. Samples P-4.1 and P-4.2 again showed lower TDS values compared to other samples, reflecting differences in dissolved solids concentration. The graph of EC and TDS values for each measurement point is shown in Figure 3. The TDS values at the measurement points are directly proportional to the EC values; the higher the EC value at a measurement point, the higher the TDS value, and vice versa. This linear relationship between EC and TDS has also been confirmed by Arlindia & Afdal (2015); Barroso et al. (2023); Meiramkulova et al. (2022); Saghi et al. (2024), who reported a strong correlation between electrical conductivity and total dissolved solids in wastewater samples, supporting the use of EC as a reliable proxy for estimating TDS concentrations.

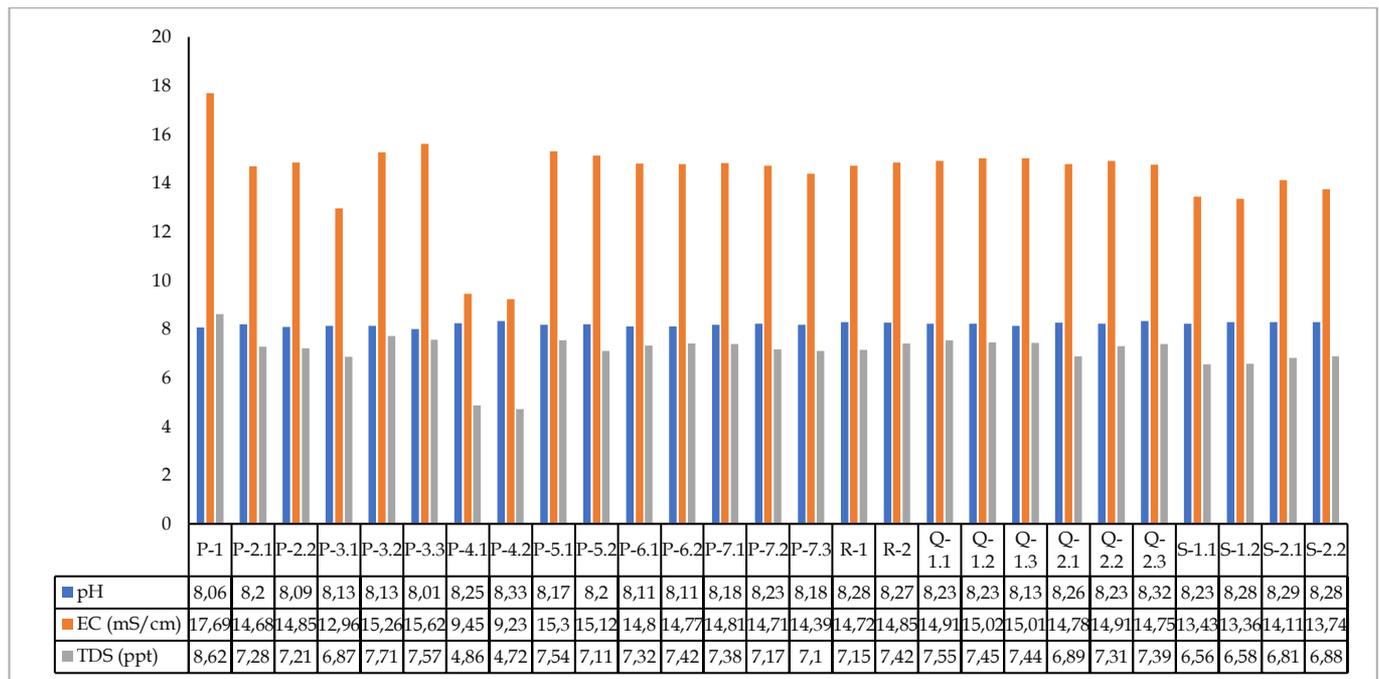


Figure 3. The graph of pH, EC, TDS in the stabilization pond (P), anaerobic pond (R), aerobic pond (Q), and sedimentation pond (S)

Magnetic Susceptibility Analysis

The result of magnetic susceptibility measurement are presented in Table 2 and the graph of susceptibility magnetic values is shown in Figure 4. Based on the measurement results, the values of magnetic susceptibility (χ_{LF}) ranged from 37.40 to $409.50 \times 10^{-8} \text{ m}^3/\text{kg}$. These values were obtained from various samples within the leachate treatment pond system, including the stabilization, anaerobic, aerobic and sedimentation ponds. Specifically, the χ_{LF} value ranges in each pond are as follows: the stabilization pond (P) ranged from 37.40 to $409.50 \times 10^{-8} \text{ m}^3/\text{kg}$, the anaerobic pond (R) ranged from 222.40 to $245.60 \times 10^{-8} \text{ m}^3/\text{kg}$, the

aerobic pond (Q) ranged from 63.10 to $110.90 \times 10^{-8} \text{ m}^3/\text{kg}$, and the sedimentation pond (S) ranged from 57.40 to $189.80 \times 10^{-8} \text{ m}^3/\text{kg}$.

According to Dearing (1999), χ_{LF} values greater than $10 \times 10^{-8} \text{ m}^3/\text{kg}$ indicate the dominance of ferrimagnetic minerals in the sample, while lower values suggest the presence of paramagnetic minerals. Since all χ_{LF} values exceeded this threshold, it can be concluded that the samples are predominantly composed of ferrimagnetic minerals.

The highest χ_{LF} value was observed at P-1 sample, which recorded $409.50 \times 10^{-8} \text{ m}^3/\text{kg}$. This sample is located at the pipeline before the leachate enters the

treatment pond. The high susceptibility value at this location indicates that the leachate, originating directly from the landfill, contains a high concentration of magnetic minerals that have not yet undergone treatment. As the leachate moves through the various treatment stages (anaerobic, aerobic, and sedimentation), the χ_{LF} values tend to decrease, suggesting that magnetic minerals are either being deposited or transformed during the treatment process. Nevertheless, relatively high χ_{LF} values were still found in the sedimentation pond, likely due to the accumulation of magnetic mineral deposits. This is consistent with the findings of Fitriani et al. (2019); Zulaikah et al. (2022), who stated that magnetic mineral accumulation over a long period can lead to higher magnetic susceptibility values in leachate sediments.

The $\chi_{FD}\%$ values in leachate deposits across all treatment ponds ranged from 0.80% to 5.92%. In the stabilization pond (P), $\chi_{FD}\%$ values ranged between 0.81% and 4.17%, with the highest value observed at P-5.2 sample (4.17%) and the lowest at P-3.2 sample (0.81%). In the anaerobic pond (R), values ranged from 2.36% to 3.24%, with the highest value at R-1 sample. The aerobic pond (Q) displayed a wider range, from 1.52% to 5.92%, with the highest value at Q-2.3, which was also the highest among all ponds. Meanwhile, the sedimentation pond (S) had $\chi_{FD}\%$ values between 2.96% and 4.00%, with the peak value recorded at S-1.2.

Table 2. Magnetic susceptibility (χ_{LF} and χ_{HF}) and frequency-dependent susceptibility ($\chi_{FD}\%$)

Sample	χ_{LF} ($\times 10^{-8}$ m ³ /kg)	χ_{HF} ($\times 10^{-8}$ m ³ /kg)	$\chi_{FD}\%$
P-1	409.50	401.80	1.88
P-2.1	265.10	257.70	2.79
P-2.2	163.80	157.70	3.72
P-3.1	133.10	129.60	2.63
P-3.2	360.00	357.10	0.81
P-3.3	297.20	294.00	1.08
P-4.1	312.50	307.80	1.50
P-4.2	319.80	315.40	1.38
P-5.1	114.10	110.90	2.80
P-5.2	129.40	124.00	4.17
P-6.1	322.50	316.50	1.86
P-6.2	306.30	303.00	1.08
P-7.1	82.40	80.70	2.06
P-7.2	69.90	67.40	3.58
P-7.3	96.10	93.40	2.81
R-1	222.40	215.20	3.24
R-2	245.60	239.80	2.36
Q-1.1	63.10	60.00	4.91
Q-1.2	110.90	109.20	1.53
Q-1.3	37.40	36.80	1.60
Q-2.1	98.60	94.80	3.85
Q-2.2	58.90	56.30	4.41
Q-2.3	40.30	37.90	5.96
S-1.1	176.70	171.10	3.17
S-1.2	189.80	182.20	4.00
S-2.1	57.40	55.70	2.96
S-2.2	171.40	165.70	3.33

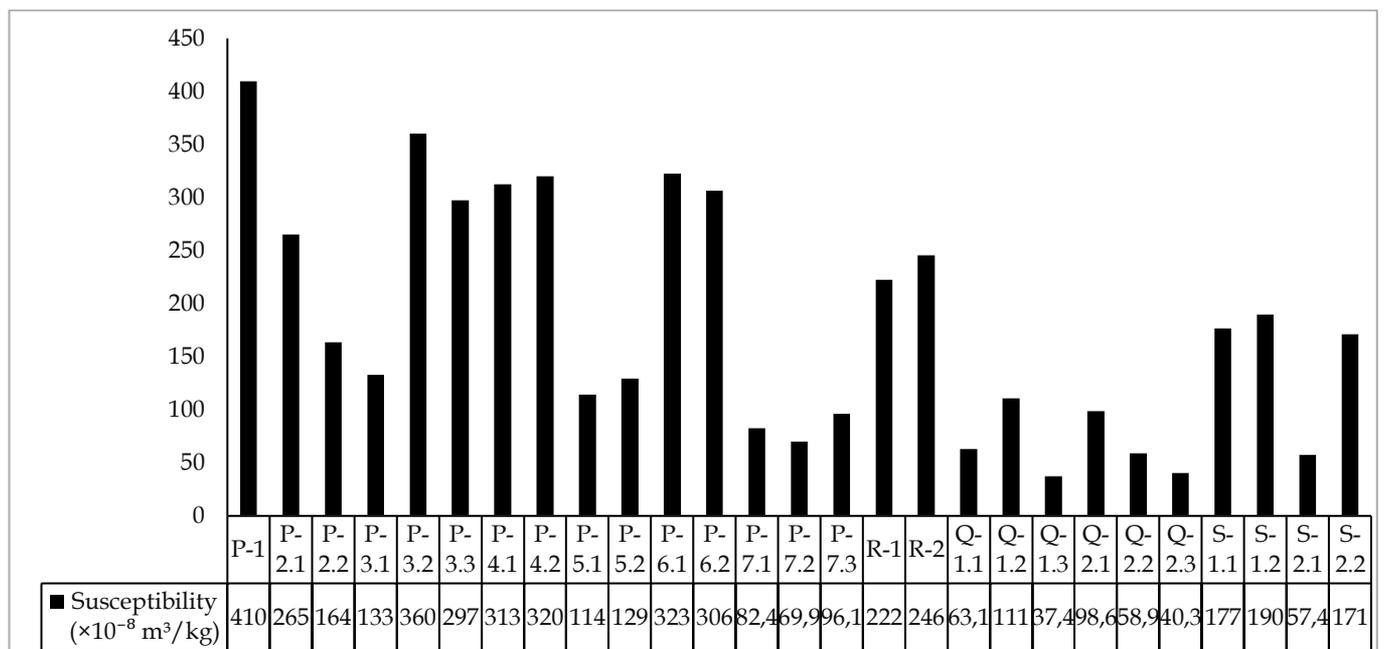


Figure 4. The graph of the variation in magnetic susceptibility values in the stabilization pond (P), anaerobic pond (R), aerobic pond (Q), and sedimentation pond (S)

Most $\chi_{FD}\%$ values were above 2%, which according to the classification by Dearing (1999), falls

into the category of medium $\chi_{FD}\%$. This suggests that the samples contain a mixture of superparamagnetic and

non-superparamagnetic grains, with the superparamagnetic grains typically being smaller than $0.005 \mu\text{m}$. High values at samples like P-5.2 and Q-2.3 indicate a significant presence of superparamagnetic grains, possibly resulting from the accumulation of metal waste or fine ferromagnetic particles originating from anthropogenic activities.

The other hand, several samples such as P-1, P-6.2, and P-3.2 exhibited low $\chi_{FD}\%$ values (less than 2%), indicating a low concentration of superparamagnetic grains in the sediment, as similarly reported by Kirana et al. (2020); Tiwow & Rampe (2022), who found that $\chi_{FD}\%$ values below 2% indicate the near absence of superparamagnetic grains in river sediments. The observed negative correlation between χ_{LF} and $\chi_{FD}\%$ in Figure 5 further supports the conclusion that the magnetic minerals in the leachate sediment do not originate from natural pedogenic processes, but rather from anthropogenic sources, such as activities at the landfill and the degradation of domestic or industrial waste over time.

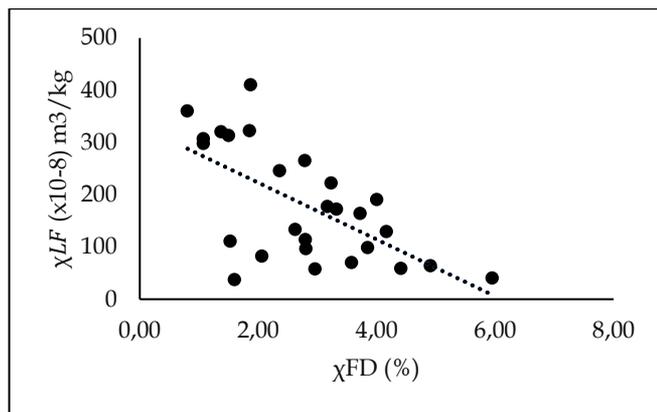


Figure 5. Graph showing the correlation $\chi_{LF} - \chi_{FD}(\%)$ across samples from the four ponds

Figure 6, which schematically represents χ_{LF} and $\chi_{FD}(\%)$, shows that the distribution of the sample data points lies within the transitional zone between acid igneous sources and the SSD/MD (Stable Single Domain/Multidomain) magnetic grain domain. Most of the samples tend to cluster closer to the SSD/MD field, indicating a predominance of multidomain (MD) magnetic minerals. This pattern is consistent with findings by Solomon et al. (2017), who demonstrated that magnetic susceptibility characteristics in urban sediments can reflect contributions from anthropogenic metallic pollutants. The low $\chi_{FD}(\%)$ values observed in this study generally below 4% suggest that the magnetic minerals in the leachate sediment are primarily derived from natural igneous materials (Novala et al., 2016), but have undergone alteration due to environmental contamination, likely influenced by human activities.

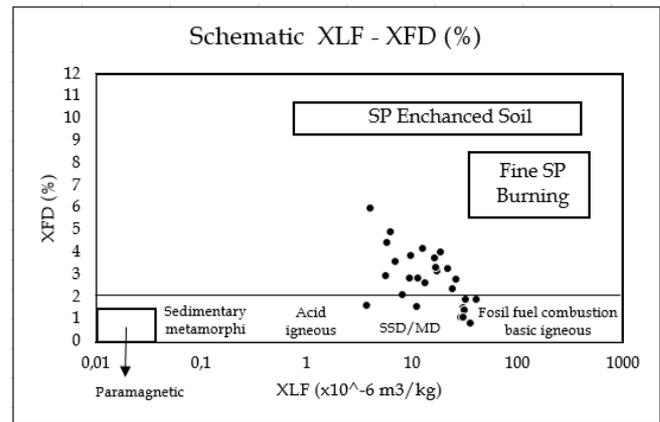


Figure 6. A schematic scattergram of $\chi_{LF} - \chi_{FD}(\%)$

SEM-EDS analysis

SEM-EDS analysis was conducted to further investigate the characteristics of magnetic minerals that had been identified through magnetic susceptibility measurements (χ_{LF} , χ_{HF} , $\chi_{FD}\%$) and physico-chemical parameters (pH, EC, and TDS). Based on previous measurements, all sampling points exhibited very high EC and TDS values, significantly exceeding the thresholds set by Regulation of the Minister of Environment and Forestry Number P.59 of 2016, WHO (2022), Regulation of the Minister of Environment and Forestry No.P.68/MENLHK/SETJEN/KUM.1/8/2016. This indicates a considerable concentration of dissolved substances and salinity, which are closely associated with the potential for magnetic contamination resulting from anthropogenic activities. SEM-EDS analysis was conducted on samples P-1, P-3.2, R-1, Q-1.2, and S-1.2.

Samples P-1 and P-3.2, which exhibited the highest χ_{LF} values (409.50 and $360 \times 10^{-8} \text{ m}^3/\text{kg}$, respectively), revealed the morphology of magnetic minerals with spherulitic and hedral forms that had undergone degradation. The imperfectly rounded spherulitic shapes, as shown in Figures 7(a) and 8(a), are characteristic of anthropogenic particles formed through rapid condensation during high-temperature combustion processes, as described by Fitriani et al. (2019) observed similar spherical morphologies in leachate sludge, indicating the presence of magnetite particles resulting from anthropogenic thermal processes such as waste incineration. Similarly, Choisez et al. (2022) noted that such spherulitic particles often originate from combustion-derived emissions and are typically composed of iron oxides, reflecting their formation under rapid cooling conditions following high-temperature exposure. Such processes commonly occur at sites like the Sarimukti Landfill, which handles municipal and domestic solid waste. Meanwhile, the octahedral forms with damaged edges and corners, as seen in Figures 7(b) and 8(b), indicate the presence of titanomagnetite that has undergone weathering or

corrosion due to exposure to acidic substances or other chemical contaminants. This observation is consistent with the findings reported by Chen et al. (2017), who noted that such morphological alterations are characteristic of titanomagnetite particles that have experienced surface degradation through prolonged interaction with chemically aggressive environments, such as acid leachates or industrial waste. Elemental composition from EDS analysis (Tables 3 and 4) shows a dominance of Fe and O, with traces of Ti, confirming the presence of titanomagnetite derived from metallic or ceramic materials in household waste.

where reductive reactions and acidity can accelerate the fragmentation of magnetic grains (Zhou et al., 2018).

Table 3. EDS analysis result showing the elemental composition of magnetic grains extracted from the P-1 sample.

Elements	%Mass P-1	
	Hedral	Spherule
C	4.86	4.17
O	42.59	29.29
Mg	0.88	1.35
Al	0.86	1.29
Si	0.34	0.39
Ti	-	-
Mn	-	-
Fe	8.90	9.10
Total	0.16	0.66

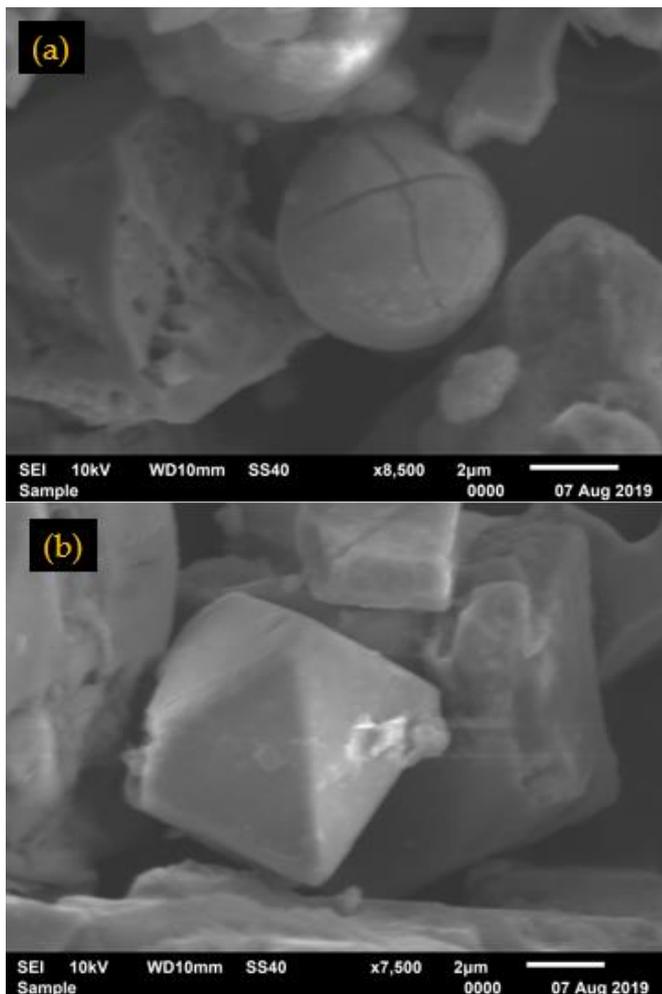


Figure 7. Identification P-1 sample using SEM (a) spherule shape (b) hedral shapes with damaged.

The sample from the anaerobic pond (R-1) exhibited spherulitic 9(a) and hedral 9(b) forms with relatively small sizes and damaged surfaces. The high χ_{LF} value ($222.40 \times 10^{-8} m^3/kg$) and chemical composition indicating the presence of Fe, O, and Ti support the identification of the mineral as titanomagnetite as shown in table 5. The fragmented hedral shapes with surface degradation are likely the result of chemical stress in the anaerobic environment,

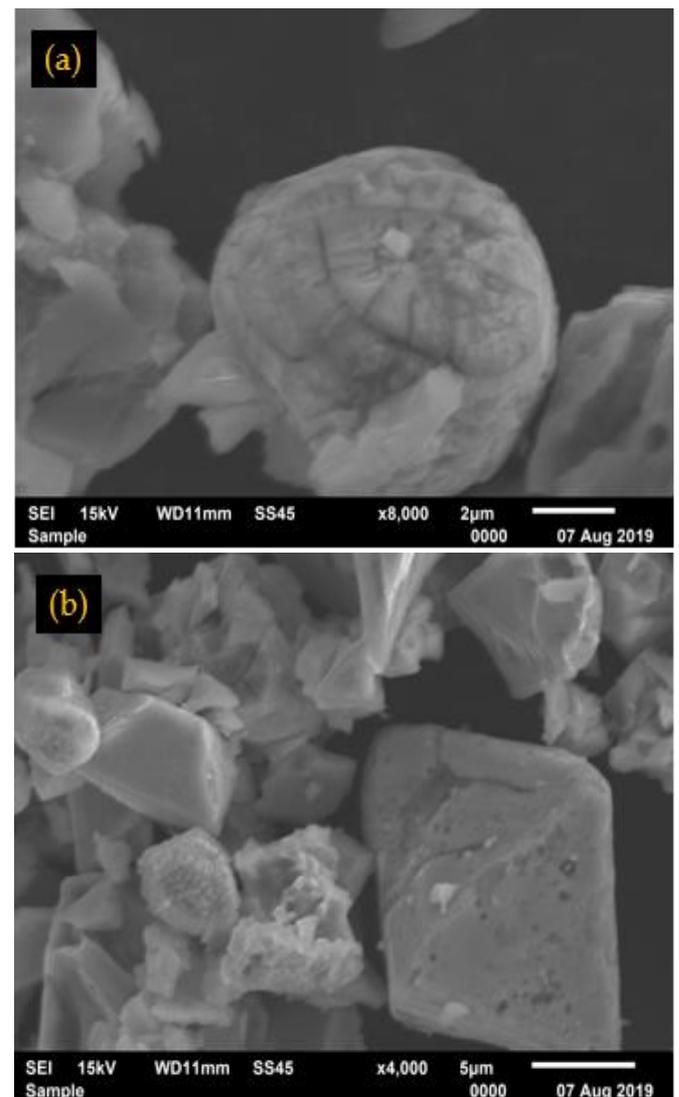


Figure 8. Identification P-3.2 sample using SEM (a) spherule with imperfect surfaces shape (b) hedral shape.

Table 4. EDS analysis result showing the elemental composition of magnetic grains extracted from the P-3.2 sample.

Elements	%Mass P-3.2	
	Hedral	Spherule
C	6.29	4.16
O	50.92	37.62
Mg	0.24	0.86
Al	0.71	1.66
Si	0.64	0.12
Ti	-	-
Mn	-	-
Fe	6.83	5.56
Total	0.42	0.32

interactions with oxygen and chemical substances from waste. The high Ti content in the hedral grains in table 6 (13.4%) suggests a potential source from pigments or alloy materials in household industrial waste (Matzka & Maher, 1999).

Table 5. EDS analysis result showing the elemental composition of magnetic grains extracted from the R-1 sample

Elements	%Mass R-1	
	Hedral	Spherule
C	6.09	6.07
O	49.78	52.8
Mg	1.34	1.89
Al	2.30	6.45
Si	0.20	7.54
Ca	-	-
Ti	-	2.35
Mn	3.07	0.66
Fe	0.21	0.20
Total	37.01	22.04

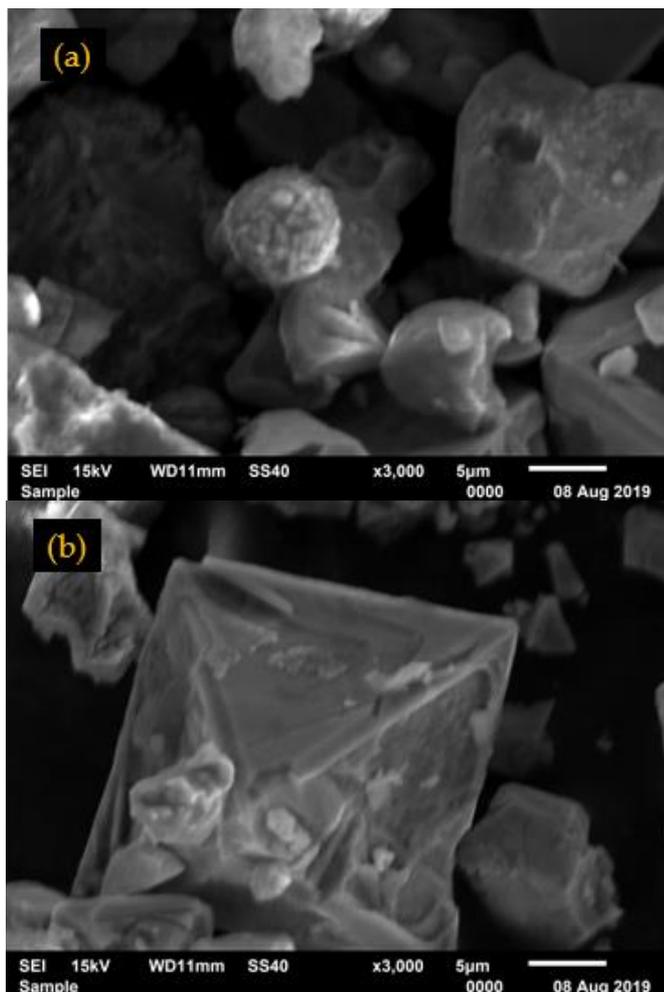


Figure 9. Identification R-1 sample using SEM (a) spherule shape (b) hedral shape.

In the aerobic pond, sample Q-1.2 exhibited a lower χ_{LF} value ($110.90 \times 10^{-8} m^3/kg$) and a slightly higher $\chi_{FD}(\%)$ compared to the stabilization pond (P), indicating a mixture of ferrimagnetic minerals and contributions from superparamagnetic grains. Figure 10 shows anthropogenic spherules 10(a) and cracked hedral 10(b) fragments, which serve as indicators of mechanical or chemical degradation of particles due to

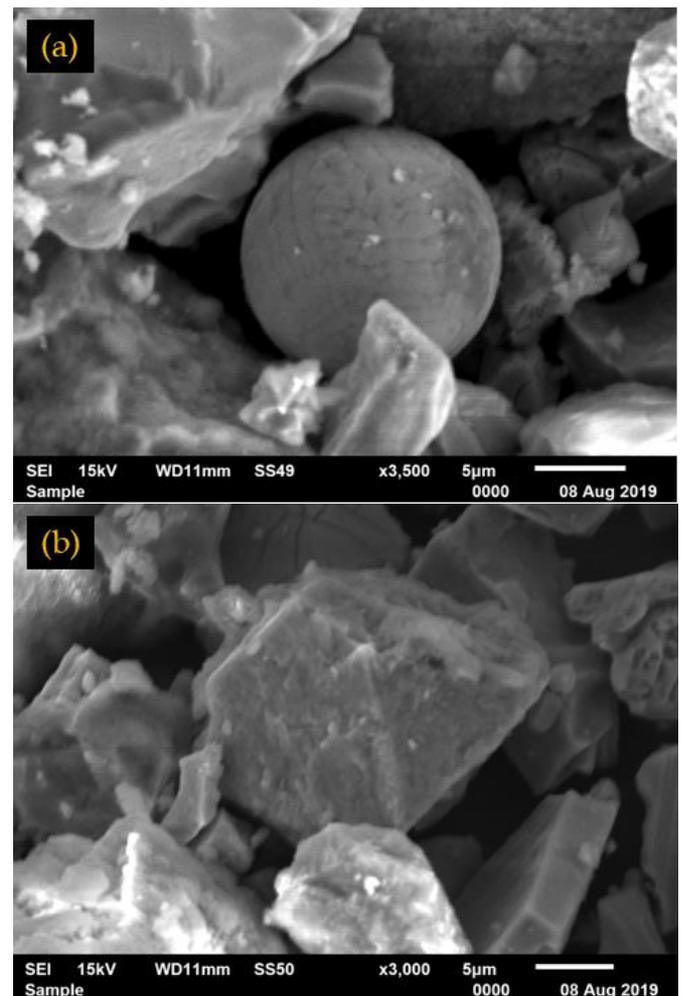


Figure 10. Identification Q-1.2 sample using SEM (a) spherule shape (b) hedral shape.

Table 6. EDS analysis result showing the elemental composition of magnetic grains extracted from the Q-1.2 sample.

Elements	%Mass Q-1.2	
	Hedral	Spherule
C	3.44	4.30
O	39.97	40.77
Mg	1.94	-
Al	2.28	-
Si	6.90	-
K	0.74	-
Ca	0.38	-
Ti	13.40	0.46
Fe	-	-
Total	30.95	54.47

Ca and Al, which may originate from coagulants or flocculating agents used in the wastewater treatment process. The Fe and O content remains high, suggesting that magnetic minerals persist through to the final treatment stage despite having undergone sedimentation.

Table 7. EDS analysis result showing the elemental composition of magnetic grains extracted from the S-1.2 sample.

Elements	%Mass S-1.2	
	Hedral	Spherule
C	7.95	6.75
O	41.37	50.97
Mg	1.53	2.35
Al	2.24	5.43
Si	0.70	9.17
Ca	-	-
Ti	0.16	4.64
Mn	5.86	0.49
Fe	-	-
Total	40.19	20.21

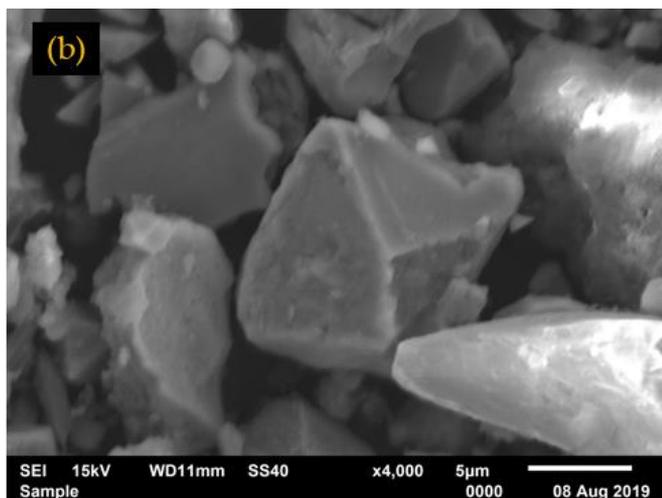


Figure 11. Identification S-1.2 sample using SEM (a) spherule shape (b) hedral shape.

The sample from the sedimentation pond (S-1.2) exhibited spherulitic and hedral morphologies (Figure 11 (a&b)), with a moderate χ_{LF} value ($189.80 \times 10^{-8} m^3/kg$) and a $\chi_{FD}(\%)$ value of 4%. The particle morphology and EDS results (Table 7) indicate a dominance of magnetite/titanomagnetite, with trace elements such as

Overall, the results indicate that the magnetic minerals in leachate from the Sarimukti landfill are predominantly anthropogenic in nature, mainly composed of magnetite and titanomagnetite formed through the combustion and weathering of municipal solid waste. The high concentrations of EC and TDS support the presence of dissolved substances accumulation, while the χ_{LF} values and SEM-EDS analysis confirm that magnetic particles serve as important indicators of heavy metal pollution. This study is consistent with the findings Ibrahim (2022), who reported that ferromagnetic materials in landfill environments tend to originate from human activities and reflect high levels of contamination. The presence of hedral particles with damaged surfaces and imperfect spherules provides visual evidence of the degradation and contamination experienced by magnetic materials.

Conclusion

This study concludes that the magnetic minerals found in the leachate deposits of the Sarimukti landfill are predominantly anthropogenic in origin, characterized mainly by magnetite and titanomagnetite. These minerals likely result from the combustion and degradation of urban solid waste. High values of magnetic susceptibility (χ_{LF}) across all sampling points confirm the dominance of ferrimagnetic minerals, while low $\chi_{FD}(\%)$ values and a negative $\chi_{LF} - \chi_{FD}(\%)$ correlation indicate a minimal contribution from superparamagnetic grains typically formed through natural pedogenic processes. SEM-EDS analysis

supports these findings by revealing magnetic particles with spherule and degraded euhedral morphologies, composed primarily of Fe and O, with minor Ti and traces of other anthropogenic elements. The persistence of these particles even in the final sedimentation pond highlights their stability and potential role as indicators of heavy metal contamination. These findings emphasize the utility of magnetic and SEM-EDS analyses as effective tools in environmental monitoring of leachate pollution, particularly in identifying the presence and anthropogenic sources of magnetic contaminants in landfill retention systems.

Acknowledgments

The authors would like to thank Departement of Geophysics, FMIPA, Universitas Padjadjaran for the support during the research.

Author Contributions

Conceptualization; methodology; validation; formal analysis; data curation, D.P.K.M, D.F, E.A, K.H.K, P.A.T.; writing-original draft preparation, D.P.K.M.; writing-review and editing, D.F. and D.P.K.M.; supervision, D.F, E.A, K.H.K.; project administration, D.P.K.M, D.F, E.A, K.H.K, P.A.T. All authors have read and agreed to the published version of the manuscript.

Funding

The research was carried out without any external funding

Conflicts of Interest

The authors declare no conflicts of interest in this research.

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