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Scanning electron microscopy and magnetic characterization of iron oxides in solid waste landfill leachate

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ABSTRACT

Leachate sludge samples were taken from two municipal solid waste sites of Jelekong and Sarimukti in Bandung, Indonesia. Their magnetic mineralogy and granulometry were analyzed to discriminate the sources of magnetic minerals using X-ray diffraction (XRD), scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (SEM-EDX) and rock magnetism. SEM-EDX analyses infer that the main magnetic minerals in the leachate sludge are iron oxides. In terms of their morphology, the grains from Jelekong are mostly octahedral and angular, which are similar to the general shapes of magnetic grains from the local soils. The grains from Sarimukti, on the other hand, are dominated by imperfect spherule shapes suggesting the product of combustion processes. Hysteresis parameters verify that the predominant magnetic mineral in leachate sludge is low coercivity ferrimagnetic mineral such as magnetite (Fe_3O_4). Furthermore, comparisons of rock magnetic parameters show that the magnetic minerals of soil samples from Jelekong have higher degree of magnetic pedogenesis indicating higher proportion of superparamagnetic/ultrafine particles than those of soil samples from Sarimukti. The plot of susceptibilities ratio versus coercive force has a great potential to be used as a discriminating tool for determining the source of magnetic minerals.

1. Introduction

Iron oxides have been studied intensively in environmental magnetic studies as they constitute the most common magnetic particles on pollutants. In many cases, enhancement or depletion of iron oxides can be used to assess environmental changes as well as to predict the source of pollutants. Such assessments or predictions are possible because anthropogenic or climatic impacts to the environment are often accompanied with alteration of magnetic mineralogy in soils, dusts and sediments. Moreover, identification and measurement of magnetic minerals, such as certain iron oxides, can serve as complementary and alternative tool for chemical analyses of pollutants. Earlier studies showed that magnetic minerals, predominantly iron oxides, were produced by various polluting processes, such as coal-burning power generation [1–4], disposal and incineration of solid waste [5,6], operation of vehicles using fossil fuels [7–10], metal processing [4,11,12] and other industrial activities [4,13].

Identification of magnetic minerals is carried out through a series of magnetic measurements complemented by visual observation and compositional analyses using SEM (scanning electron microscopy) equipped with EDX (energy-dispersive X-ray) spectroscopy. The SEM and EDX techniques were used to provide detailed information on the morphology and composition of magnetic minerals in contaminated sediment and soil [3–5,14–19], in fly ash and dust [20–25], as well as polluting particles deposited on tree leaves [26,27]. Meanwhile, magnetic measurements were also used in the studies of atmospheric particulates and fly ashes [2,23,28], leachate [6], soils [29,30], and sediments [3,31–34]. Moreover, various magnetic parameters were successfully employed to indicate the degree of pedogenesis in soils [35] as well as to verify the presence of anthropogenic pollution in soils [36]. Discrimination of anthropogenic magnetic signals from the background and identification of anthropogenic magnetic particles are conducted based on their distinct magnetic properties as well as their specific morphology.

Leachate is highly contaminated wastewater from a municipal solid waste disposal site. Depending on the design of the site, the leachate can enter groundwater posing environmental as well as health problems. Earlier, it has been shown that leachate sludge from waste disposal sites in Indonesia contains magnetic minerals

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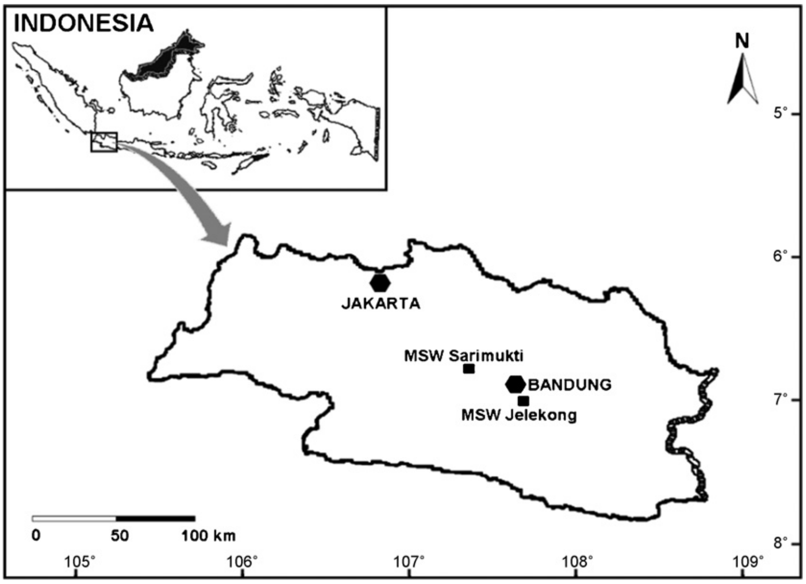

Fig. 1. Map of the study area showing the sampling location of the two municipal solid waste disposal sites (Jelekong and Sarimukti).

[6]. Moreover, if the quantity of magnetic minerals in the leachate sludge is sufficient, then the magnetic susceptibility correlates well with heavy metal content. However, magnetic minerals in leachate sludge could be derived from various sources, including the local soil and the waste. In this study we examine the origin of magnetic minerals in leachate using SEM-EDX and magnetic analyses to discriminate the predominant contributors to leachate magnetic signature. This information is expected to enhance our understanding in the use of magnetic analyses for pollutant identification and quantization.

2. Materials and methods

Samples in the form of leachate sludge were taken from two municipal solid waste (MSW) disposal sites near the city of Bandung, Indonesia in 2007 (Fig. 1). The first site, Jelekong, is located in the southern part of the city, approximately 19 km from city center. This site was opened up in 1991 and after 15 years of operation, it was closed in 2006. It is located at S 7°01′54.8″; E 107°40′13.6″. The second site, Sarimukti, located 25 km west of city center, is a new site opened only in 2006. Its geographic location is S 6°48′19.7″; E 107°20′55.9″. Samples were taken using a specially designed coring device made of PVC pipes that are 3 in. in diameter. Apart from leachate samples, soils samples were also taken from the vicinity of leachate ponds for comparison. The same soils, taken from horizon A, were used in the landfill. Detailed information regarding the sites, soil geology background, soil types and sampling methodology was published elsewhere [6]. The selected samples represent the same low and high magnetic susceptibility value for SEM and EDX analyses. To determine the magnetic morphology and composition in the samples, two leachate sludge and two soil samples from each site were extracted.

Magnetic minerals were extracted from leachate sludge and soil samples dispersed in ethanol using a strong neodymium hand magnet. The extracted magnetic grains were then gold–palladium coated for SEM analyses. A JSM 6360LA (JEOL, Tokyo, Japan) was used for SEM analyses. This instrument is also equipped with EDX system for semi-quantitative compositional analyses. To complement the SEM analyses, non-extracted samples of leachate sludge and soil were subjected to X-ray diffraction (XRD) analyses using a Philips X'Pert PRO MRD PW3050/60 (Philips, Eindhoven, The Netherlands) with a CuKα radiation.

For magnetic measurements, 30 leachate sludge samples from Jelekong (20 samples) and Sarimukti (10 samples) were prepared by taking a portion of residual solid of leachate sludge and placing it inside a tightly secured plastic cylindrical holder (2.54 cm in diameter and 2.2 cm in height). Similarly, 30 soil samples from Jelekong (15 samples) and Sarimukti (15 samples) were also prepared by taking about 10 g of soil and placing it inside plastic holder of the same type. The samples were then subjected to volumetric magnetic susceptibility, κ measurement using an MS2 Susceptibility Meter (Bartington Instrument, Oxford, UK) operating at 470 Hz. The mass-specific low frequency susceptibility, χ, was calculated using the formula $\chi = \kappa\ [10^{-5}\ \mathrm{SI}] \times 10\,\mathrm{cm}^3$/mass in grams. This parameter is used frequently because it approximates (is dominated by) concentration of magnetite in the sample. Later, an anhysteretic remanent magnetization (ARM) was imparted by AF demagnetization with the initial peak amplitude of 70 mT while at the same time applying bias DC field of 0.05 mT. The ARM is given inside a Molspin AF (alternating field) demagnetizer, while the ARM intensity is measured using a Minispin magnetometer (both instruments are products of Molspin, Newcastle upon Tyne, UK). The susceptibility of ARM (χ_{ARM}) was determined by dividing the ARM intensity by the steady biasing field.

Leachate sludge and soil samples were also subjected to analyses of IRM (isothermal remanent magnetization) acquired at room temperature by applying incrementally increasing field to initially demagnetized samples. The IRM acquired at 1000 mT is referred to as the saturation isothermal remanent magnetization (SIRM). The IRM measurements were carried out using a Minispin magnetometer. SIRM could be used as approximates to the total magnetic mineral concentration with grain size larger than the superparamagnetic (SP)/single domain (SD) threshold. At room temperature, magnetite particles with grain sizes in the range of ~0.030–0.070 μm are single domain while grains in the size range ~0.07–~2 μm are pseudosingle domain (PSD). Multidomain (MD) grains with grain sizes is >~2 μm while superparamagnetic particles, typically <~30 nm in magnetite [37]. Lastly, the samples were also subjected to the measurement of magnetic hysteresis curve as well as the determination of the four hysteresis parameters (saturation magnetization, M_{s}, saturation remanence, M_{rs}, coercive force, B_{c}, and coercivity of remanence, B_{cr}) using the 1.2H/CF/HT vibrating sample magnetometer (Oxford Instruments, Oxfordshire, UK).

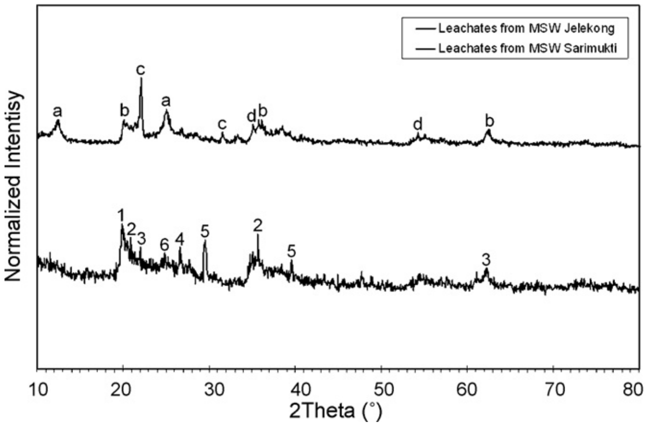

Fig. 2. X-ray diffractograms of leachate sludge samples from Jelekong and Sarimukti ((a) chamosite ($Fe_3Si_2O_5(OH)_4$); (b) kaolinite ($Al_2Si_2O_5(OH)_4$); (c) cristobalite (SiO_2); (d) montmorillonite ($Na_{0.3}(Al, Mg)_2Si_4O_{10}(OH)_{2.8}\cdot H_2O$); (1) chromium(II) chloride ($CrCl_2$); (2) mercury sulfate (Hg_2SO_4); (3) iron phosphate ($Fe(PO_4)$); (4) magnesium nitrate ($Mg(NO_3)_2$); (5) calcite ($CaCO_3$); (6) zirconium hydrogen phosphate hydrate ($Zr(HPO_4)_2\cdot H_2O$)).

For given mineralogy, the ratios of the above magnetic parameters are sensitive to magnetic mineralogy and granulometry. Therefore a combination of parameters sensitive to composition, concentration and grain-size distribution of iron oxides can be used to reveal their source [2,6,38–40].

3. Results and discussion

3.1. X-ray diffraction and scanning electron microscopy

Mineralogical study on raw leachate sludge samples was performed by means of X-ray diffraction of powdered samples. The results for both leachate sludge samples from Jelekong and Sarimukti are shown in Fig. 2. The minerals in sample from Jelekong are all naturally derived (cristobalite, chamosite, kaolinite, and montmorillonite) from soils and rocks. In contrast, apart from calcite, the minerals in sample from Sarimukti are anthropogenic (chromium chloride, magnesium nitrate, mercury sulfate, iron phosphate, zirconium hydrogen phosphate hydrate). This discrepancy in mineral composition is likely due to the fact that Sarimukti in an active site, while Jelekong has been in closed in 2006. The decomposed solid wastes in Jelekong are no longer releasing anthropogenic chemical compounds into the environment. Condition in Jelekong is similar to that in Mornag, Tunisia [41] where XRD analyses of soils that were partly amended by compost from MSW site shows that compost amendments would not affect the mineralogical composition of the soil. Despite its minimum contribution to the overall composition of leachate sludge, the solid waste might contribute significantly to the magnetic mineralogy of the sludge.

To further investigate this, SEM-EDX analyses were conducted on extracted magnetic grains from leachate sludge and soil samples. SEM analyses on extracted magnetic grains provide the detail morphology and texture of such grains. This is important since anthropogenic magnetic particles can be distinguished from pedogenic particle, among others, by their specific morphology. Fig. 3a–c show typical magnetic grains extracted from leachate sludge from Jelekong, while Fig. 3d–f show typical magnetic grains from Sarimukti. Based on their morphology the magnetic grains from Jelekong can be classified as octahedral and angular, with fractured edges and corners. The magnetic grains from Sarimukti, on the other hand, have imperfect spherical shapes. In terms of the grain size, the grains from Jelekong are significantly smaller (~5–25 μm) than those from Sarimukti (~50–100 μm). EDX analyses on magnetic grains from both sites showed that the grains are mainly iron oxides. EDX analyses on selected grains in Fig. 3a–c show that main elements are Fe and Ti with C, Al, and Si as minor elements. Similar analyses on grains in Fig. 3d–f, on the other hand, show that the main element is Fe with C, Na, Mg, Al, Ti, and Cr as minor elements (Table 1).

The above results of SEM and EDX analyses suggest that magnetic grains from Jelekong and Sarimukti were derived from different sources. Based on their morphology, the magnetic grains from Jelekong are very likely of pedogenic origin. Their octahedral and angular shapes with fractured edges and corners are typical of titanomagnetite fragments. Compared to those of grains from Sarimukti, their relatively small grain sizes also confirm that the grains from Jelekong have distinct origin. On the contrary, the imperfect spherule shape of grains from Sarimukti infers that the grains were anthropogenic in origin, *i.e.*, they were derived from the solid waste burning at the Sarimukti site. A number of studies have showed that magnetic spherules are common in fly ashes, roadside dusts and sediments, which are mainly derived from fossil fuel combustions from vehicles or furnaces at high temperatures [25,42–45]. The sizes of magnetic grains from Sarimukti (~50–100 μm) are also comparable to that of magnetic spherules in roadside dusts [25], fly ashes [46], and soils [47].

Indication that magnetic grains from Sarimukti are anthropogenic in origin is also supported by the EDX results that show the presence of Fe with C, Na, Mg, Al, Ti, and Cr as minor elements (Table 1). Earlier study [25] showed that iron-oxides spherules with Al, Ca, Na and Si as minor elements were derived from anthropogenic sources, such as combustion of fossil fuels in power plants, industries and domestic heating systems. The presence of C in magnetic grains, however, could be caused by organic processes, biological weathering as well as solid waste burning. Solid waste burning which is common practice in Indonesian solid waste disposal sites is expected to produce magnetic spherules found in the leachate sludge from Sarimukti. Solid waste burning is still occurring in the active Sarimukti site but is no longer occurred in Jelekong since its closure in 2006. The presence of Cr in magnetic grains was probably generated by abrasion/corrosion of metal waste. This presence of this element has been reported from other studies of anthropogenic magnetism in sediment [14] and in soil [19].

In comparison, SEM analyses on magnetic grains extracted from soil samples at the two sites show that the grains are either octahedral or angular in shapes (Fig. 4a–f). Some grains have fractured edges and corners. The surfaces of some grains, for example in Fig. 4b and e, are rough and full of cracks suggesting the trace of weathering processes. The morphology of magnetic grains in soils is similar to that in leachate sludge from Jelekong, suggesting that the magnetic grains in the leachate sludge are pedogenic in origin. This is also supported by the EDX analyses on magnetic grains in soil samples. This semi-quantitative compositional analyses show that the elemental composition of magnetic grains in soils is comparable to that in the leachate sludge from Jelekong.

3.2. Magnetic parameters and determination of the source of magnetic minerals in leachate sludge

Although environmental samples might contain more than one kind of magnetic minerals, their overall magnetic properties are often determined by a single predominant mineral. Magnetic parameters, including, hysteresis loop often reflect the behavior of this predominant mineral. Furthermore, hysteresis parameters such as coercive force (B_c), coercivity of remanence (B_{cr}), as well as the ratios B_{cr}/B_c and M_{rs}/M_s, to obtain information about the particle size and magnetic characteristics [20]. Fig. 5 shows the hysteresis loops for representative leachate sludge and soils samples. All samples exhibit thin hysteresis loops which are almost saturated

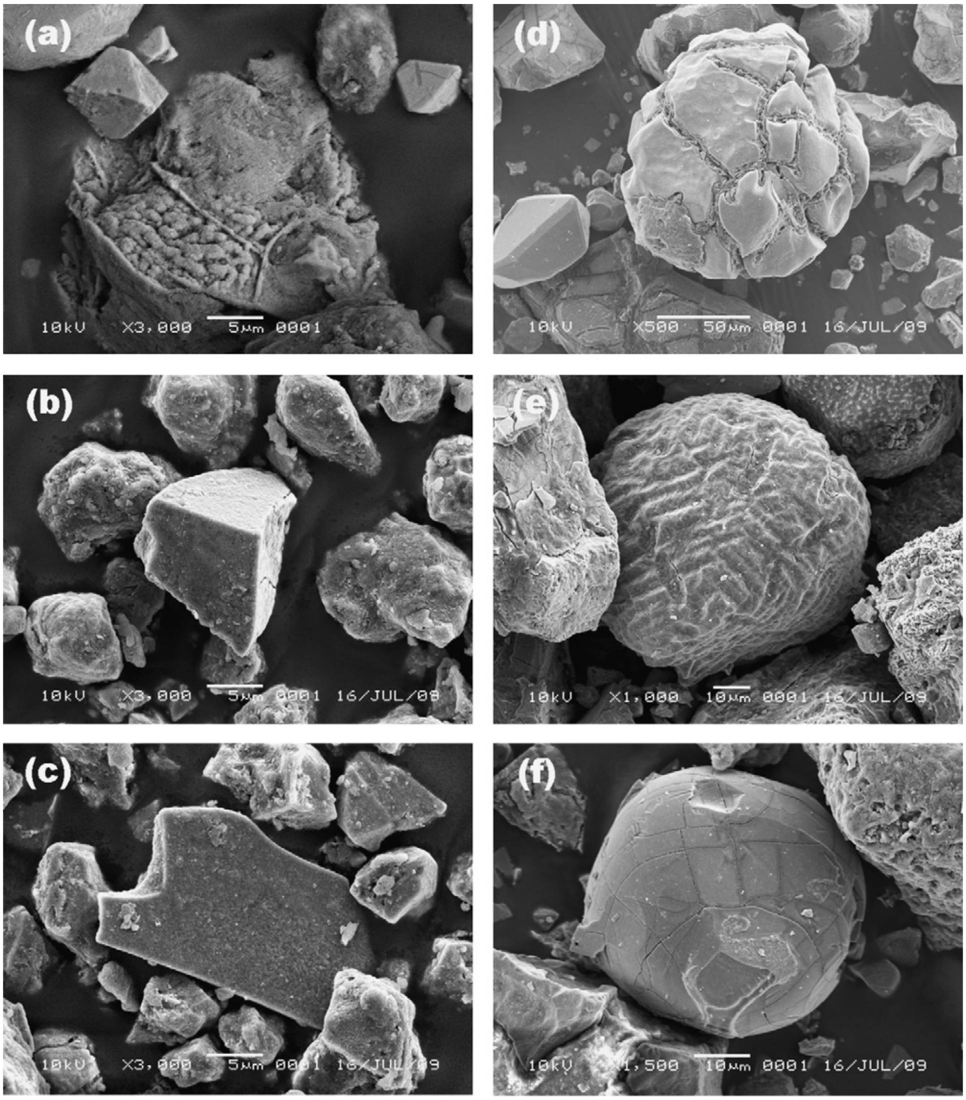

Fig. 3. Scanning electron microscopy (SEM) images of the magnetic extracts in leachate sludge samples: (a–c) magnetic particles from Jelekong and (d–f) magnetic particles from Sarimukti. Based on EDX analyses, the particles shown on the picture are iron oxides, probably magnetite and titanomagnetite. In (a–c), the grains are predominantly octahedral and angular in shapes. The grains in (d–f) are imperfect magnetic spherules. The grain in (d) exhibits framboid-like surface, while the grain in (e) exhibits brain-like surface. The grain in (f) shows pattern of cracks in its surface.

in the ambient field of less than 300 mT indicating the predominant contribution of low coercivity ferrimagnetic minerals, such as magnetite (Fe_3O_4). This is also supported by the mean values of coercivity (B_c) and coercivity of remanence (B_{cr}) in leachate and soil samples (Table 2). Referring to the earlier study [4,38,48], the mean values of B_c and B_{cr} in leachate sludge and soils from Jelekong and Sarimukti fall within the range of low coercivity ferrimagnetic mineral such as magnetite (Fe_3O_4) as the predominant magnetic phase. In the earlier study [6], IRM acquisition curves for leachate sludge and soil from MSW Jelekong and Sarimukti confirmed the

Table 1
Energy dispersion analytical data (mass%) on magnetic grains in leachate and soil sample from MSW Jelekong and Sarimukti.

Element	MSW Jelekong						MSW Sarimukti					
	Leachate			Soil			Leachate			Soil		
	Grain a	Grain b	Grain c	Grain a	Grain b	Grain c	Grain d	Grain e	Grain f	Grain d	Grain e	Grain f
C	6.20	4.64	14.08	13.00	30.17	9.60	3.03	14.23	12.81	6.44	11.57	8.08
O	28.86	29.81	25.62	22.99	22.49	25.30	26.82	24.56	21.95	25.57	25.86	26.28
Na	–	–	–	–	–	–	0.57	–	0.08	–	–	–
Mg	–	–	–	1.32	–	1.08	0.96	1.49	0.97	–	1.47	–
Al	1.85	1.79	2.74	1.85	3.06	4.02	2.34	4.42	1.51	4.01	4.88	0.95
Si	1.69	0.76	1.80	–	1.73	2.26	–	–	–	1.74	2.95	1.54
Ti	20.18	24.33	13.52	7.98	14.70	4.96	12.89	9.38	5.04	5.75	5.08	14.67
Cr	–	–	–	–	–	–	0.02	1.27	0.31	–	–	–
Fe	41.23	38.65	42.24	52.86	27.86	52.78	53.36	44.64	57.33	56.48	48.20	48.48
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

predominance of magnetite (Fe_3O_4). These results are in agreement with that of other pollution studies in sediment [4], pine needles samples [48] and topsoil [49].

As listed in Table 2, the mean values of B_c and B_{cr} in leachate sludge samples are slightly higher than those in soil samples. In Jelekong, the mean value of B_c for leachate is 7.14 mT compared to 6.41 mT for soil. Similarly, in Sarimukti, the mean value of B_c is 6.51 mT for leachate compared to 4.39 mT for soil. Moreover, coercivity of remanence (B_{cr}) of leachate is also higher than that of the soils. In Jelekong, the mean value of B_{cr} for leachate is 23.64 mT compared to 22.67 mT for soil. Similarly, in Sarimukti, the mean value of B_{cr} is 25.19 mT for leachate compared to 16.25 mT for soil. These differences in the mean values of B_c and B_{cr} suggest that the magnetic grain sizes in leachate samples are finer than those in soil samples [39]. In addition, leachate sludge samples from Sarimukti have higher ratio of B_{cr}/B_c than those from Jelekong. This means that the magnetic grain sizes in leachate sludge samples from Sarimukti are coarser than those from Jelekong.

Furthermore, information about the presence and the relative proportion of superparamagnetic ultrafine particles could also be inferred from ratios of other magnetic parameters, such as the ratio of χ_{ARM}/χ and of SIRM/χ. The low value of χ_{ARM}/χ indicates relatively higher contribution of ultrafine particles (SP) [2], while the low value of SIRM/χ infers higher proportion of SP and/or SD grains in the samples [40]. The soil samples from Jelekong have lower mean values of χ_{ARM}/χ and of SIRM/χ compared to the soil samples from Sarimukti indicating that the soil samples of Jelekong have higher proportion of SP particles. Since ferrimagnetic minerals produced in soils during pedogenesis are mainly fine-grained [50–52], this means that the soil samples from the older site Jelekong have higher degree of magnetic pedogenesis compared to the soil samples from the younger site Sarimukti. Moreover, magnetic extracts at the soil samples from MSW Jelekong contained significant portions of pedogenic horizons A [17]. Meanwhile, according the similarity in their mean values of χ_{ARM}/χ and of SIRM/χ, the proportion of SP grains in leachate sludge samples from Jelekong is comparable to that in samples from Sarimukti.

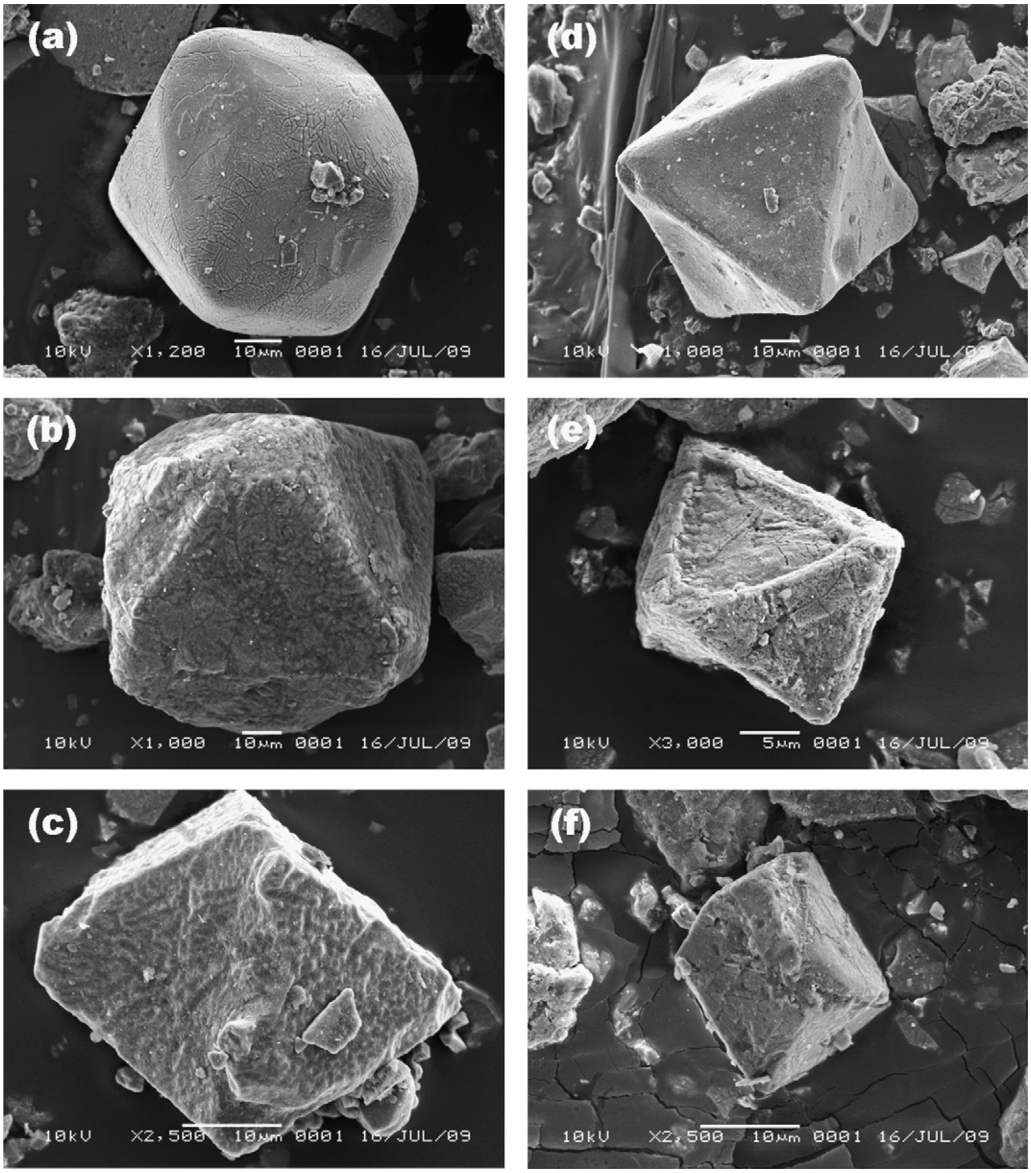

Fig. 4. Scanning electron microscopy (SEM) images of the magnetic extracts in soil samples showing magnetic grains that are likely to be magnetite and titanomagnetite. The grains in (a–c) are from Jelekong, while the grains in (d–f) are from Sarimukti. The grains from the two sites are comparable to each other. Grains in (a–b) and in (d–e) are octahedral in shapes with varying surface textures. Grains in (c) and in (f) are angular in shapes.

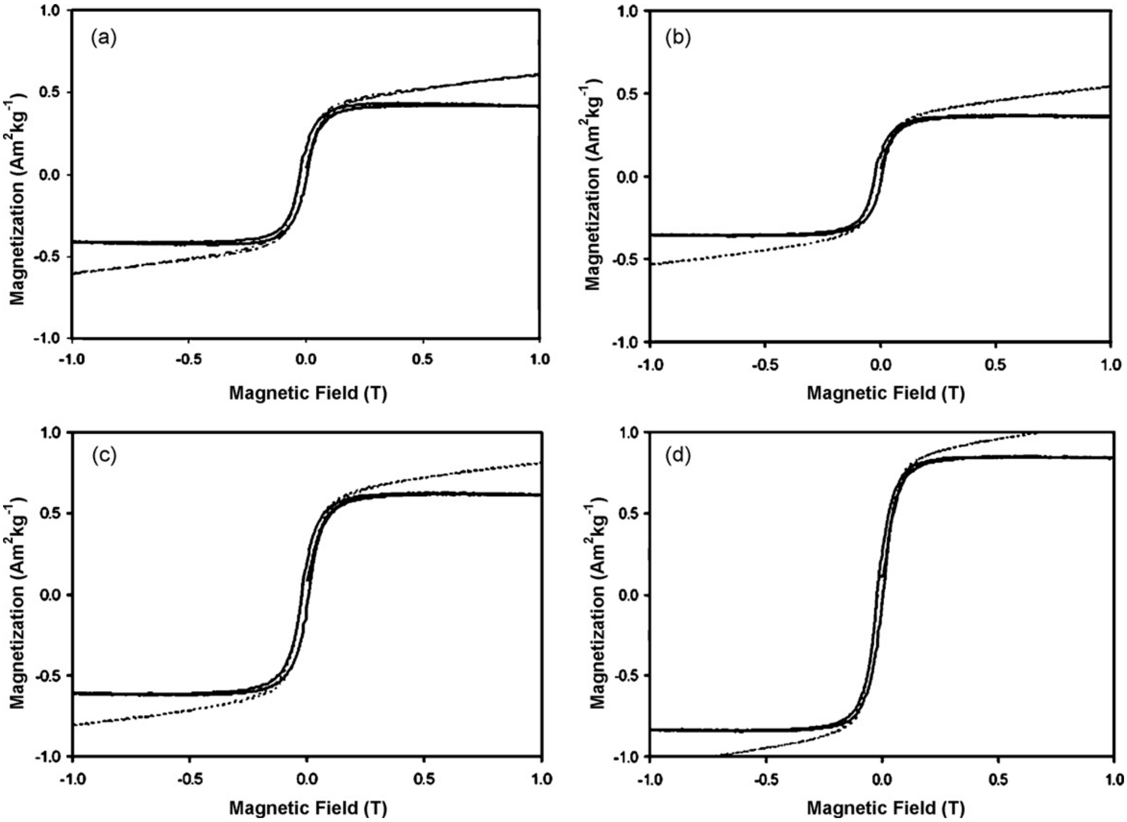

Fig. 5. Magnetic hysteresis loops for typical samples before (dashed lines) and after (solid lines) correction for the paramagnetic contributions. (a) Leachate sludge sample Jelekong; (b) leachate sludge sample from Sarimukti; (c) soil sample from Jelekong and (d) soil sample from Sarimukti.

Magnetic mineralogy and magnetic granulometry of leachate sludge reflect the possible sources of their magnetic minerals. In leachate sludge, the magnetic minerals are likely to originate from two distinct sources, namely the anthropogenic source of solid waste dissolution, mechanical decomposition and burning-induced transformation, and the lithogenic sources through processes such as weathering and/or erosion. If the magnetic minerals in leachate were originated mainly from the soils then the magnetic mineralogy and granulometry of leachate samples should be similar to that of soils. Based on SEM analyses, the magnetic grains in leachate sludge samples from Jelekong are very likely to be pedogenic in origin. In Jelekong, the magnetic grain morphologies of leachate samples are similar to that of soil samples. This indication is also supported by the results of EDX analyses that show similar elemental composition between magnetic grains in leachate samples and the grains in soil samples. Magnetic analyses show that the soils in Jelekong have higher proportion of ultrafine magnetic grains that could be easily transported into leachate

Table 2
Magnetic parameters of leachate sludge and soil sample from Jelekong and Sarimukti. For each site, 10 leachate sludge and soil samples were used, respectively.

Parameters	Leachate			Soil		
	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
Jelekong						
χ_{LF} ($\times 10^{-8}$ m^3 kg^{-1})[a]	198.8–349.0	262.1	36.0	450.2–970.3	629.7	138.3
χ_{ARM} ($\times 10^{-6}$ m^3 kg^{-1})[a]	14.8–23.0	19.2	2.6	19.4–56.2	32.3	9.7
SIRM ($\times 10^{-6}$ A m^2 kg^{-1})[a]	14023.1–25806.8	20416.2	3568.3	14025.0–40233.7	30360.7	6843.0
B_c (mT)	4.91–9.21	7.14	1.37	4.29–8.26	6.41	1.42
B_{cr} (mT)	20.81–27.90	23.64	2.11	19.50–27.20	22.67	2.47
M_{rs}/M_s (dimensionless)	0.29–0.39	0.34	0.03	0.29–0.37	0.34	0.03
B_{cr}/B_c (dimensionless)	2.51–4.37	3.42	0.69	2.62–4.55	3.66	0.67
χ_{ARM}/χ (dimensionless)	5.43–10.28	7.41	1.29	3.18–6.91	5.14	0.99
SIRM/χ (kA m^{-1})	6.60–8.86	7.76	0.58	2.99–6.88	4.91	1.87
Sarimukti						
χ_{LF} ($\times 10^{-8}$ m^3 kg^{-1})[a]	64.8–223.0	155.3	50.2	138.3–915.3	485.4	279.9
χ_{ARM} ($\times 10^{-6}$ m^3 kg^{-1})[a]	4.6–17.4	11.5	3.9	12.3–66.1	44.1	16.6
SIRM ($\times 10^{-6}$ A m^2 kg^{-1})[a]	4189.1–17697.6	12538.7	4155.0	13948.2–70094.6	47547.9	17258.1
B_c (mT)	3.64–8.08	6.51	1.23	2.11–6.88	4.39	1.60
B_{cr} (mT)	21.74–33.73	25.19	3.35	12.10–21.09	16.25	2.63
M_{rs}/M_s (dimensionless)	0.32–0.40	0.36	0.03	0.20–0.30	0.25	0.03
B_{cr}/B_c (dimensionless)	2.98–6.64	4.06	1.20	2.56–5.73	4.02	1.05
χ_{ARM}/χ (dimensionless)	6.91–7.80	7.38	0.31	3.52–38.68	13.97	11.84
SIRM/χ (kA m^{-1})	6.47–8.91	8.01	0.68	3.85–43.14	15.33	12.86

[a] These data have been published earlier elsewhere [6].

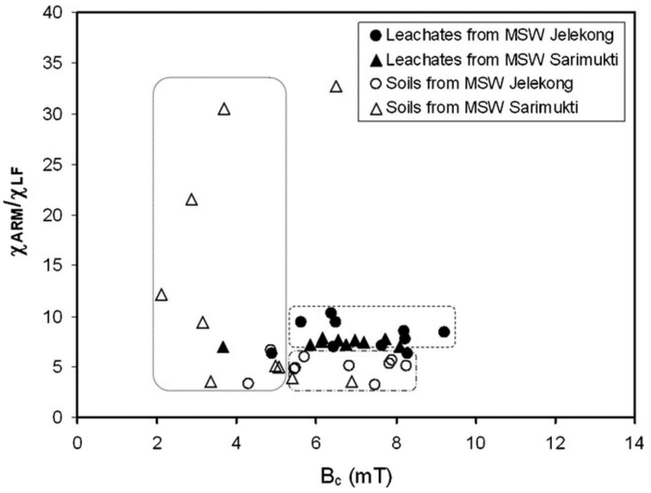

Fig. 6. Bi-plots of χ_{ARM}/χ versus B_c for leachate sludge and soil samples from Jelekong (circles) and Sarimukti (triangles) showing that the leachate sludge samples from Sarimukti are generally distinguishable from the leachate sludge from Jelekong as well as from soil samples. Such plots have great potential to be used as discriminating tools for determining the source of magnetic minerals in pollutant.

pond. Since the Jelekong site is now closed, it is understandable that the magnetic grains in leachate sludge are originated only from the nearby soils. The situation is very different in Sarimukti. Based on SEM analyses, the magnetic grains in leachate are very like to be anthropogenic in origin as shown by their distinct imperfect spherule shapes and their relatively larger grain sizes. This indication is also supported by the results of EDX analyses that show the presence of certain minor elements produced during burning or combustion process. The burning processes in Sarimukti were done casually and sporadically throughout the site rather than in a specific chamber. Therefore, the estimate temperature during the solid waste burning at the site would not exceed 275 °C, which is the maximum temperature of soil during natural fires [53].

These differences between leachate sludge samples from Jelekong and that from Sarimukti can be inferred also from the plot of χ_{ARM}/χ versus B_c as shown in Fig. 6. In such plot, most data for soil samples from both Jelekong and Sarimukti are clustered around $\chi_{ARM}/\chi \sim 5$–10. The data for leachate samples from Jelekong are also clustered together next to the data for soil samples suggesting the magnetic minerals in leachate samples from Jelekong are indeed similar to the minerals in soil samples. The data for leachate samples from Sarimukti, on the contrary, have wider range of χ_{ARM}/χ suggesting that the magnetic minerals in leachate samples from Sarimukti are different from that in soil samples.

4. Conclusions

Detailed morphology and mineralogy analyses were performed on leachate sludge and soils from two municipal solid waste disposal sites near Bandung, Indonesia. SEM observation identified that the magnetic grains in leachate sludge from Jelekong are predominantly octahedral and angular in shapes suggesting their lithogenic origin, while such grains from Sarimukti are imperfect spherules, suggesting their anthropogenic origin. Based on hysteresis analyses, magnetic grains in leachate sludge are predominantly low coercivity ferrimagnetic mineral such as magnetite (Fe_3O_4). The situation is very different in the active disposal site of Sarimukti where soil waste dumping as well as soil waste burning is common practice producing anthropogenic magnetic minerals eventually transported into leachate pond. The plots of χ_{ARM}/χ versus B_c have been shown to be effective as discriminating tool for sources of magnetic minerals. Data for leachate sludge samples from Jelekong are clustered very close to those for soils confirming the anthropogenic origin of magnetic minerals. Data for leachate sludge samples from Sarimukti stand out differently suggesting that the magnetic minerals come from different sources.

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