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Relationship between mineral magnetic properties and soil textural parameters

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Abstract

The study analyzed the relationship between mineral magnetic properties and particle size in order to determine the suitability of magnetic measurements to serve as particle size proxy for urban top soils samples collected from Jalingo, NE Nigeria. Pearson correlation analyses between mineral magnetic parameters (χlf, χfd%, χARM, SIRM, Soft IRM, ARM/SIRM) and particle size properties (PM2.5, PM10, clay, silt and sand) are reported. Results indicate that each particle size class shows different strength of correlation with magnetic parameters, implying that each particle class contains a proportion of magnetic minerals. For the whole data set ($n = 154$), χfd%, χARM and ARM/SIRM show significant positive correlation with the fine size fractions (PM2.5, PM10, clay and silt) but negatively correlated with the sand proportion, while χlf, SIRM and Soft IRM exhibit contrasting relationship. Of all the magnetic parameters, the magnetic parameters indicating fine-grained ferrimagnetic minerals (ARM/SIRM and χARM) have the strongest and most significant correlations. The nature of the magneto-particle size relationship is different when examined in terms of land use. The fact that magnetic properties and textural parameters have strong relationship indicates that magnetic methods could be considered a potential particle size proxy in Jalingo. However, since the relationship does not follow predictable and consistent patterns of other studies in top soils and sedimentary settings, it brings to fore the non-universality of the method. Hence, the type of relationship existing between magnetic and particle size properties in an environmental setting must be determined before applying the magnetic method as particle size proxy.

Keywords Mineral magnetic · Particle size · Particulate matter · Environmental · Soil

Introduction

The effect of particulate matter (PM) is diverse and has been of great concern to scientist and environmental managers. Particulate matter can threaten human health (Dockery et al. 1993), affects soils, crops (Luo et al. 2011) and visibility (Chen and Xie 2012). Out of these effects, more emphasis is on the health-associated effects since according to WHO (2006) it represents a scientific and social issue. Strong associations have been found to exist between PM and respiratory symptoms and cardiovascular mortality (Burnett et al. 1997; Lippmann et al. 2003; Lippmann 2011). Particulate matter is primarily derived from natural sources derived from soil (wind-blown soils) and particles derived from human activities such as materials used for constructing roads (e.g., paints, cements, asphalt); emissions from vehicles' exhaust pipes, tire and brake linings; inputs from industrial wastes (e.g., coal and oil combustions); biomass burning (natural fires) and long range atmospheric depositions (Adachi and Tainosho 2005; Meza-Figuero et al. 2007; Jordanova et al. 2012).

Particulate matter is ordinarily known as dust. The major classification of particulate matter are PM10 (particles having diameter less than 10 micron, i.e., < 10 µm), PM2.5 (describing concentration of particles having diameter less than 2.5 micron, < 2.5 µm) and PM1 (describing particles smaller than 1 µm). Usually, due to the concentrated traffic density in urban areas, PM2.5 and PM10 concentrations

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increase in urban centers than rural areas (Chen et al. 2007). As a result of the contribution of most pollution by anthropogenic sources, urban centers most often experience spatial and daily fluctuations in the concentration of air pollution (Petrovský et al. 2000; Maher et al. 2008; Brimblecombe 2011; Crosby et al. 2014).

Natural soils are made up of soil particles that vary in size. Soil texture gives information about the relative amount of the different particle sizes such as clay, silt and sand in the soil. It influences the mechanism of flow of water in the soil and the ease at which soil can be worked. Besides its use in agriculture, particle size is also used in measuring the pedogenic and detrital proportions (Zan et al. 2015) and sediment provenance studies (Thompson and Morton 1979; Booth et al. 2005). It has been demonstrated that particle size can greatly affect analytical data related to soils (Booth et al. 2005; Crosby et al. 2014). Pollutants like concentrations of trace metal, radionuclide content and quantity of polychlorinated biphenyls are affected by particle sizes: the concentration increases with decreasing sediment size. Fine-grained sediments usually have larger specific surface areas, cation exchange capacities and surface charges. These increase considerably the extent to which they are adsorbed preferentially (Booth et al. 2005).

Environmental magnetic methods have gained popularity recently as an established proxy method for determining soil heavy metal pollution (Hoffmann et al. 1999; Matzka and Maher 1999; Petrovský et al. 2000; Maher et al. 2008; Basavaiah et al. 2012; Crosby 2012; Jordanova et al. 2012; Kanu et al. 2017), climatic studies (Maxbauer et al. 2016), archaeological studies (Hill et al. 2007), sediment source tracing (Beckwith et al. 1986) and radionuclides concentration (Clifton et al. 1999). These studies utilized the relationships between mineral magnetic parameters and physical and chemical properties of soil, sediments, dusts, etc. The application of environmental magnetic parameters as proxy for particle size is not as established as its use in pollution studies. However, some studies have achieved considerable success in establishing mineral magnetism as particle size proxy (Thompson and Morton 1979; Zheng et al. 1991; Chen et al. 1995; Clifton et al. 1999; Booth et al. 2005, 2007; Crosby et al. 2009, 2014; Oldfield et al. 2009). Most of these studies focused on sedimentary environments, except Booth et al. (2008) and Crosby et al. (2009, 2013, 2014) who focused on roadside soils and Manx top soils from British Isle, respectively. They found that the relationship between magnetic and particle size properties may not be applicable universally; hence, caution must be exercised in its usage. Furthermore, the studies are concentrated in Europe, America and Asia, none so far coming from Africa with tropical climate. Therefore, more case studies are required to understand better and in detail the magnetic proxy method, especially on how it works and under which conditions the technique can be applied in different environments, climates and ecosystems. It must be noted that it is a necessary task to identify the process that drives the magnetic response as magnetic grain size, concentration and mineralogy can respond to changes in geology, size of particle, transport, delivery and flux, anthropogenic pollution and diagenetic and authigenic changes (Hatfield 2014). Hence, magnetic proxies cannot be generalized without prior information on their origin in the samples.

In this study, we intend to achieve the following: (1) examine the level of application of magnetic parameters as reliable proxy for particle size, (2) determine if the relationship between mineral magnetic and textural parameters can be applied universally, that is follow the pattern of other studies and (3) examine if human activities/land use affects the way in which particle size and magnetic properties relate.

Materials and methods

Study area and sample collection strategy

This study was conducted in Jalingo metropolis, the state headquarters of Taraba State, Nigeria. Jalingo is located between latitude 8°50′ and 8°90′N and between longitude 11°17′ and 11°26′E (Fig. 1). Details about the study area can be found in Kanu et al. (2017). The study area is part of the Nigerian Basement Complex rocks and is mainly composed of migmatites, gneisses and the older granites (Obaje 2009).

To investigate the possible links between mineral magnetic and particle size within Jalingo metropolis, a strategy that combines land use pattern and traffic conditions was used. To this end, a number of sampling sites were selected for this study. A total of 154 top soil (0–10 cm) samples were randomly collected from residential areas ($n=25$), roadsides ($n=50$), dumpsites ($n=15$), mechanic workshops and motor park ($n=25$), farm land ($n=20$) and other locations: market/commercial area, sport complex, school environment ($n=19$). The samples were collected between November, 2011 and March, 2012.

Magnetic measurements

The magnetic measurements were performed following the procedure adopted by our previous work (Kanu et al. 2017). Magnetic susceptibility measurements were done using the Agico MFK1-FA Kappabridge instrument. Measurements were carried out at low frequency of 976 Hz and high frequency of 15,616 Hz at an alternating field of 200 A m^{-1}. From these, the frequency-dependent susceptibility (χfd%) parameter that is used to detect the presence of fine-grained (<0.03 um) superparamagnetic (SP) ferrimagnetic minerals in samples (Basavaiah et al. 2012) was calculated. Here,

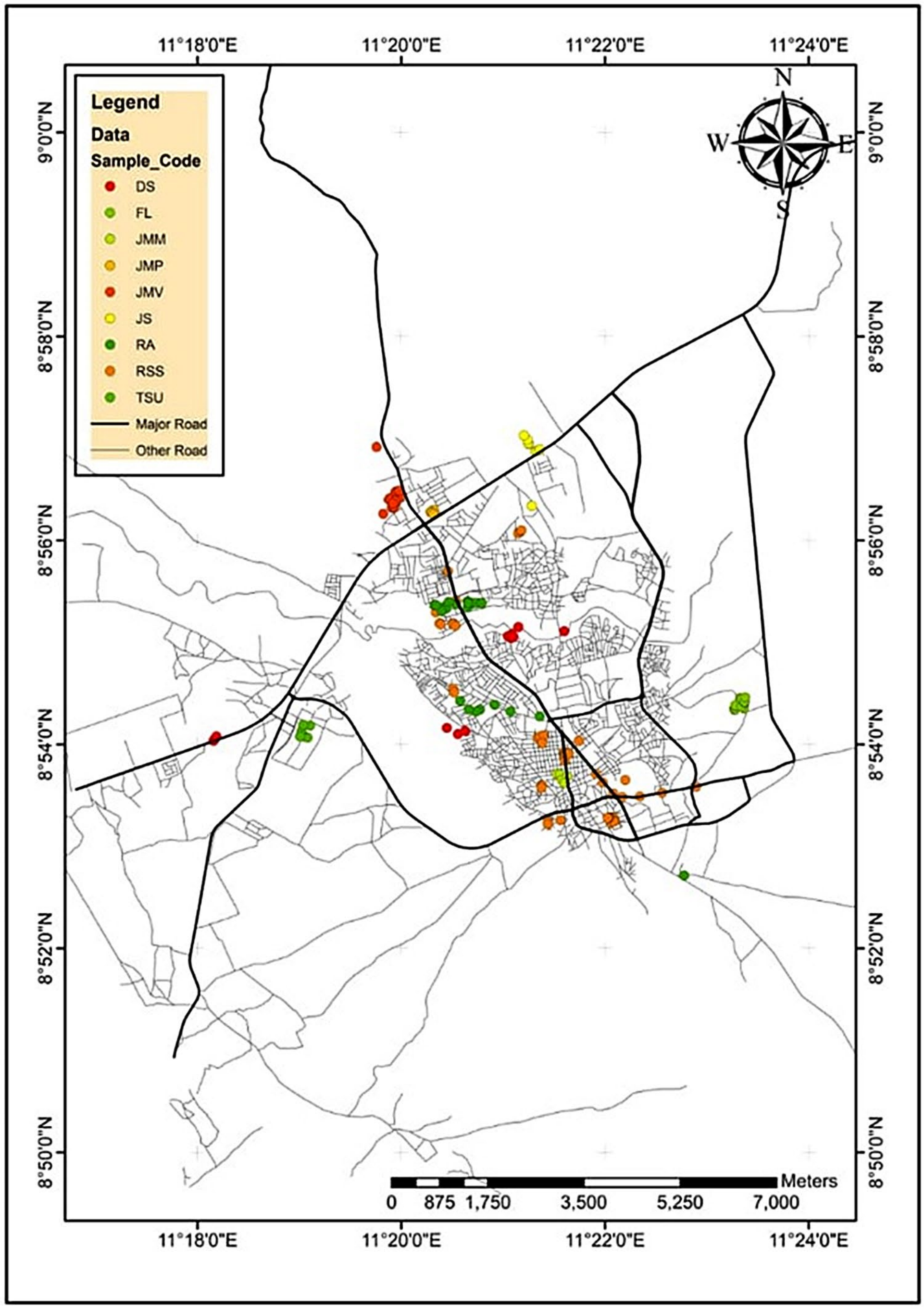

Fig. 1 Map of Jalingo showing sample points

χfd% was calculated; thus, $\chi fd(\%) = \frac{\chi lf - \chi hf}{\chi lf} \times 100\%$, where χlf and χhf are low- and high-frequency magnetic susceptibility, respectively.

Anhysteretic remanent magnetization (ARM) was induced with peak alternating magnetic field of 100 mT and a constant DC bias field of 0.05 mT using a D-2000 AF demagnetizer (ASC scientific). The remanence acquired is measured using a Molspin spinner magnetometer, and the values were converted to give the mass specific susceptibility of ARM (χARM).

In order to determine the isothermal remanent magnetization (IRM), the samples were exposed to a forward field of 0.02 T and 1 T in a Molspin pulse magnetizer and the IRM was measured using the spinner magnetometer. The highest field that can be measured by the Molspin pulse magnetizer is 1 T and is used as saturation isothermal remanent magnetization (SIRM). Thereafter, back field demagnetization in steps of 20, 30, 100 and 300 mT was applied. The soft isothermal remanent magnetization (Soft IRM) and *S*-ratio was then calculated from the following relations, respectively,

$$\text{Soft IRM} = \left(\frac{\text{SIRM} - \text{IRM}_{-30\text{ mT}}}{2}\right), \quad S_{\text{ratio}} = \frac{|\text{IRM}_{-300\text{ mT}}|}{\text{SIRM}}.$$

Particle size/textural analyses

Particle size analyses were performed using a CILAS 1064 particle size analyzer with a detection range from 0.03 to 500 µm. Prior to measurement, the soil and dust samples were sieved using a sieve merge and the < 125 µm size fractions were used for the particle size analysis. Approximately 200 mg of samples was dispersed in sodium hexametaphosphate [$Na(PO_3)_6$] solution and is poured to the sample chamber and laser analyzed for the grain size spectrum for a 10 min program. For data reproducibility, three runs per sample were conducted. The results obtained from the laser granulometry were separated into different grades of fractions following Wentworth (1922) classification scheme; thus, clay ≤ 4 µm, silt = 4–63 µm and sand ≥ 63 µm. Other finer particles classes are PM2.5 ≤ 2.5 µm and PM10 ≤ 10 µm.

Results and discussion

Mineral magnetic properties of the different sampling sites in Jalingo are shown in Table 1. The magnetic susceptibility values varied considerably from a low value of 0.21×10^{-8} m^3 kg^{-1} to a high value of 912.56×10^{-8} m^3 kg^{-1}. The highest mean χlf values are obtained in roadside soil (219.13×10^{-8} m^3 kg^{-1}) followed by residential area (166.32×10^{-8} m^3 kg^{-1}) and dumpsites (131.43×10^{-8} m^3 kg^{-1}). SIRM varied between 40.81×10^{-5} A m^2 kg^{-1} and 4010.76×10^{-5} A m^2 kg^{-1}, with highest mean values obtained in dumpsites followed by roadside soils and residential areas. The values of χlf and SIRM in all the locations are high indicating abundance of ferrimagnetic and remanence carrying magnetic minerals. In all the sampling sites, high mean values of χARM are obtained, implying high concentration of stable single-domain magnetite in the soils. Generally, the mean values of χARM varied in the order farmland (0.30×10^{-5} m^3 kg^{-1}) > dumpsites (0.27×10^{-5} m^3 kg^{-1}) > residential area (0.20×10^{-5} m^3 kg^{-1}) > roadside (0.17×10^{-5} m^3 kg^{-1}) > other locations (0.15×10^{-5} m^3 kg^{-1}) > mechanic workshop/motor park (0.12×10^{-5} m^3 kg^{-1}). Usually, χlf and SIRM are regarded as approximate estimates of

Table 1 Summary statistics of magnetic parameters (*n* = 154)

Sampling locations	χlf (×10^{-8} m^3 kg^{-1})	χfd (%)	χARM (×10^{-5} m^3 kg^{-1})	SIRM (×10^{-5} A m^2 kg^{-1})	ARM/SIRM (dimensionless)	*S*-ratio (dimensionless)	Soft IRM (×10^{-5} A m^2 kg^{-1})
Road side soil (*n* = 50)							
Range	21.17–614.89	1.50–7.68	0.01–0.32	63.45–2009.72	0.003–0.02	0.88–1.00	28.23–924.84
Mean ± SD	219.13 ± 138.80	2.98 ± 1.42	0.17 ± 0.07	1026.83 ± 528.50	0.008 ± 0.004	0.96 ± 0.03	466.93 ± 238.63
Residential area (*n* = 25)							
Range	16.08–912.56	0.30–14.72	0.05–0.45	113.53–4010.76	0.004–0.03	0.80–0.97	40.78–1598.98
Mean ± SD	166.32 ± 251.63	6.70 ± 3.67	0.20 ± 0.12	979.28 ± 1187.61	0.01 ± 0.01	0.91 ± 0.05	390.22 ± 447.29
Dump sites (*n* = 15)							
Range	53.82–352.34	4.01–9.76	0.12–0.57	358.81–3192.96	0.01–0.02	0.93–0.99	127.87–1529.71
Mean ± SD	131.43 ± 93.89	6.74 ± 1.84	0.27 ± 0.13	1138.52 ± 859.10	0.01 ± 0.01	0.97 ± 0.02	521.71 ± 411.74
Mechanic workshop and motor park (*n* = 25)							
Range	0.21–375.90	2.24–12.91	0.001–0.53	40.81–3967.96	0.00–0.03	0.84–0.99	10.54–1833.40
Mean ± SD	79.67 ± 97.28	5.60 ± 3.02	0.12 ± 0.12	663.98 ± 866.71	0.01 ± 0.01	0.95 ± 0.05	297.43 ± 399.91
Farm land (*n* = 20)							
Range	35.04–160.75	4.88–19.38	0.14–0.95	251.55–872.94	0.01–0.71	0.68–0.99	94.53–360.23
Mean ± SD	75.26 ± 37.41	12.52 ± 3.18	0.30 ± 0.23	412.80 ± 138.95	0.03 ± 0.02	0.90 ± 0.07	166.02 ± 67.90
Other locations (*n* = 19)							
Range	18.80–351.03	1.61–15.14	0.08–0.32	108.38–1110.82	0.004–0.03	0.69–1.00	42.29–485.56
Mean ± SD	88.93 ± 82.03	9.56 ± 5.19	0.15 ± 0.06	435.31 ± 266.71	0.02 ± 0.01	0.91 ± 0.07	191.60 ± 124.50
Total (*n* = 154)							
Range	0.21–912.56	0.30–19.38	0.001–0.945	40.81–4010.76	0.00–0.07	0.68–1.00	10.54–1833.40
Mean ± SD	143.99 ± 150.63	6.45 ± 4.37	0.19 ± 0.13	815.93 ± 758.25	0.01 ± 0.01	0.94 ± 0.06	354.34 ± 328.32

ferrimagnetic minerals contents in the samples (Shen et al. 2008). Specifically, SIRM is generally used as approximation of the total magnetic mineral concentration with grain size larger than SP/single-domain (SD) threshold. Unlike χlf, SIRM is not influenced by para- and diamagnetic minerals (Thompson and Oldfield 1986; Zhang et al. 2007). χARM can give information about the amount of ferrimagnetic minerals in stable single-domain (SSD) region (Kanu et al. 2017). χlf, SIRM and χARM are regarded as concentration-dependent magnetic parameters, while χfd% and ARM/SIRM are parameters that depend on grain size. *S*-ratio and Soft IRM are indicative of magnetic mineralogy. From the χfd% results, the mean values indicate that the roadside soil is overshadowed by coarse multidomain (MD) magnetic particles, while samples from farmland are dominated by SP grains. Other locations are composed of admixture of SSD and SP grains. High *S*-ratio (average, 0.94) and Soft IRM suggest the dominance of low coercivity soft magnetic minerals like magnetite and/or maghemite in the samples.

The results of particle size analysis by laser granulometry are presented in Table 2. The concentration of individual particle size classes is compared using box plots shown in Fig. 2. Results show that the concentration of sand fractions dominated the assemblage (51.76%) followed by the silt fraction (41.14%) and clay fraction (7.10%). However, based on individual land use, the silt fraction dominated the soils from dumpsites and farm land, while sand fractions dominated the roadside soil, residential areas and mechanic workshop and motor park. In other locations, the ratio of silt to sand is very close (46.08%: 47.45%). High sand fractions in road side soils have also been observed in Southport, Merseyside, UK (Booth et al. 2007), Scunthorpe, North Lincolnshire, UK (Crosby et al. 2009) and Wolverhampton, UK (Crosby et al. 2013).

In terms of the respiratory health size classes, PM10 grains represent ~ 9%, while PM 2.5–4% of the sediments. The PM 2.5 and PM 10 are seen to be highly variable and have the highest values in the farmland. This may be attributed to accumulation of combustion products from bush burning and long distance travel vehicular emissions and even fertilizer application. The least values of the respiratory health-related sizes PM 2.5 and PM 10 are found in roadside soils (Table 2, Fig. 2), while the highest values are obtained in the farmland.

Correlation between magnetic properties and particle size classes

The values of the Pearson correlation coefficient (*r*) between magnetic concentration, mineralogical and grain and particle size parameters for Jalingo soils ($n = 152$) were computed using SPSS 20 statistical software and are presented in Table 3. Each magnetic parameter correlates significantly (at either $P < 0.01$ or $P < 0.05$) either positively or negatively with one particle size class or the other. It

Table 2 Summary statistics of textural parameters ($n = 154$)

Sampling locations	PM 2.5 (%)	PM10 (%)	Clay (%)	Silt (%)	Sand (%)
Road side soil ($n = 50$)					
Range	1.38–4.1	2.22–7.53	2.21–7.53	14.18–61.45	31.02–83.61
Mean ± SD	2.36 ± 0.68	4.73 ± 1.90	4.10 ± 1.31	27.95 ± 10.64	67.95 ± 11.81
Residential area ($n = 25$)					
Range	2.01–6.35	4.17–16.65	3.54–12.26	20.71–72.08	17.73–74.90
Mean ± SD	3.34 ± 1.31	7.72 ± 3.89	6.06 ± 2.67	39.99 ± 12.69	53.95 ± 14.50
Dump sites ($n = 15$)					
Range	2.72–5.75	6.38–16.92	4.83–11.08	48.22–77.37	11.55–46.95
Mean ± SD	3.96 ± 0.90	10.32 ± 3.05	7.24 ± 1.86	61.89 ± 7.91	30.87 ± 9.57
Mechanic workshop and motor park ($n = 25$)					
Range	1.45–10.39	1.63–21.55	2.11–18.85	14.96–79.18	9.61–82.32
Mean ± SD	4.02 ± 3.22	8.21 ± 7.18	7.09 ± 6.04	39.96 ± 19.81	52.95 ± 25.01
Jalingo farm land ($n = 20$)					
Range	2.19–23.00	3.20–42.04	3.41–41.04	35.23–71.90	0.00–57.63
Mean ± SD	8.80 ± 6.93	18.60 ± 13.23	16.19 ± 12.78	56.09 ± 11.66	27.71 ± 21.99
Other locations ($n = 19$)					
Range	1.47–5.90	2.11–17.31	2.19–11.68	19.03–69.03	20.65–78.78
Mean ± SD	3.56 ± 1.46	8.54 ± 4.01	6.48 ± 2.84	46.08 ± 15.69	47.45 ± 18.37
Total ($n = 154$)					
Range	1.38–23.00	1.63–42.02	2.11–41.04	14.18–79.18	0.00–83.61
Mean ± SD	3.94 ± 3.53	8.62 ± 7.43	7.10 ± 6.58	41.14 ± 17.54	51.76 ± 22.22

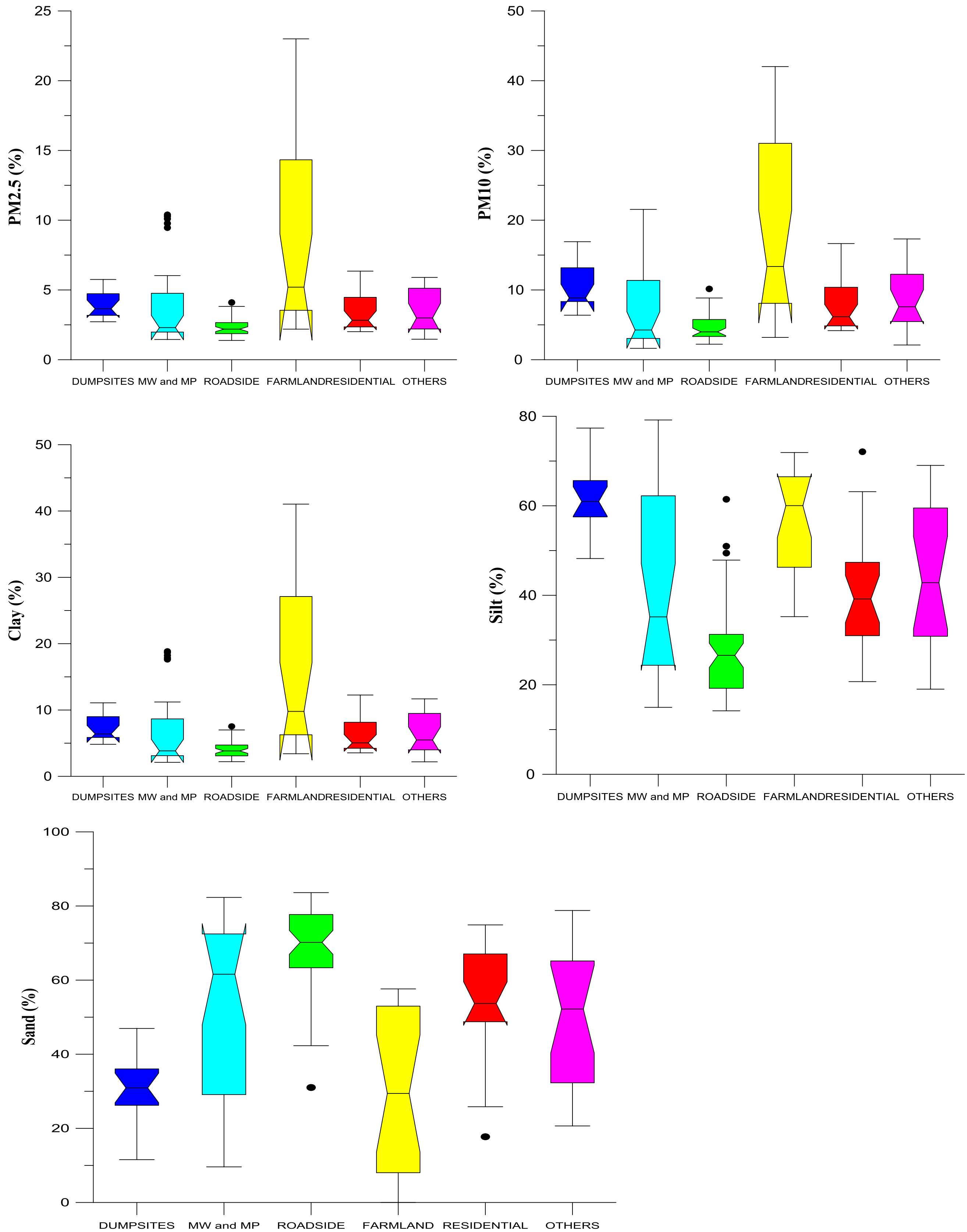

Fig. 2 Notched boxplots showing the variation of the particle size classes in the sampling locations

Table 3 Mineral magnetic and textural properties correlation for Jalingo metropolis ($n=152$)

	PM 2.5 (%)	PM (10%)	Clay (%)	Silt (%)	Sand (%)
χlf	− 0.179	**− 0.183***	**− 0.176***	**− 0.288****	**0.279****
χfd%	**0.549****	**0.572****	**0.551****	**0.570****	**− 0.613****
χARM	**0.498****	**0.523****	**0.503****	**0.349****	**− 0.424****
SIRM	**− 0.190***	**− 0.167***	**− 0.185***	**− 0.177***	**0.195***
ARM/SIRM	**0.727****	**0.716****	**0.726****	**0.519****	**− 0.625****
S-ratio	**− 0.345****	**− 0.360****	**− 0.349****	**− 0.325****	**0.360****
Soft IRM	**− 0.189***	**− 0.167***	**− 0.184***	**− 0.179***	**0.196***

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

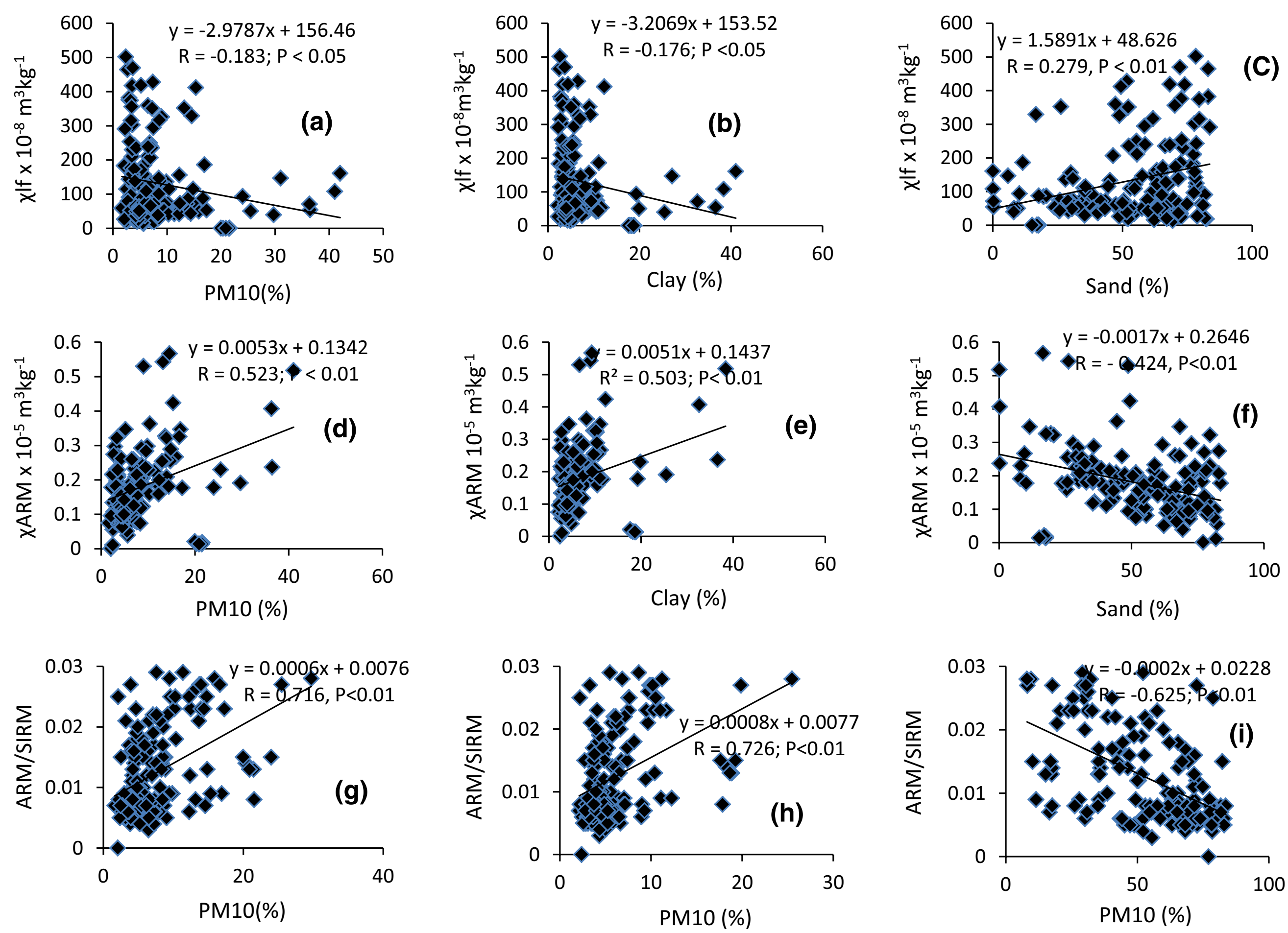

Fig. 3 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (PM 10, clay and sand)

is also observed that each particle size class shows different strengths of correlation with the magnetic parameters. This implies that all particle size fractions contain a proportion of magnetic minerals, but the proportion varies with particle size (Oldfield et al. 2009). For the magnetic concentration parameters (χlf, SIRM and χARM), weak negative correlations are observed between χlf and SIRM and PM2.5, PM10, clay and silt fractions. The sand proportion shows positive and stronger association with χlf (0.279, $P<0.01$) and SIRM (0.195, $P<0.05$), suggesting that differences in the ferrimagnetic components could be used as proxy for the concentration of sand. In contrast to χlf and SIRM, χARM exhibit stronger significant positive correlation with PM2.5 ($r=0.498$, $P<0.01$), PM10

Table 4 Mineral magnetic and textural properties correlation for dumpsites ($n=15$)

	PM 2.5 (%)	PM (10%)	Clay (%)	Silt (%)	Sand (%)
χlf	**0.591***	**0.705****	**0.609***	**0.699****	**−0.696****
χfd%	0.045	0.046	0.056	−0.016	0.003
χARM	**0.600***	**0.726****	**0.618***	**0.773****	**−0.759****
SIRM	0.528	**0.659***	**0.548***	**0.662****	**−0.653***
ARM/SIRM	−0.154	−0.253	−0.175	−0.201	0.200
S-ratio	0.235	0.017	0.156	0.041	−0.063
Soft IRM	**0.537***	**0.670****	**0.562***	**0.646***	**−0.642***

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

Table 5 Mineral magnetic and textural properties correlation for road side soils ($n=50$)

	PM 2.5 (%)	PM (10%)	Clay (%)	Silt (%)	Sand (%)
χlf	−0.067	−0.067	−0.071	−0.113	0.110
χfd%	0.288	**0.313***	**0.294***	**0.418****	**−0.410****
χARM	−0.014	0.028	0.000	−0.069	0.062
SIRM	−0.178	−0.152	−0.173	−0.224	0.221
ARM/SIRM	**0.293***	**0.334***	**0.309***	**0.423****	**−0.416****
S-ratio	**−0.358***	**−0.345***	**−0.357***	**−0.398****	**0.400****
Soft IRM	−0.201	−0.179	−0.197	−0.243	0.241

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

($r=0.523$, $P<0.01$), clay ($r=0.503$, $P<0.01$) and silt ($r=0.349$, $P<0.01$) fractions and negative association with sand ($r=-0.424$, $P<0.01$). This result indicates that the maximum contribution of SD ferrimagnetic grains comes from the finer size classes. In Wolverhampton (UK) soils, Crosby et al. (2013) also obtained negative correlation between χlf, SIRM and χARM for lower size fractions and positive correlation with the medium and coarse sand fractions. The magnetic grain size indicators (χfd% and ARM/

Table 7 Mineral magnetic and textural properties correlation for farm land ($n=20$)

	PM 2.5	PM 10	Clay	Silt	Sand
χlf	**0.457***	**0.444***	**0.451***	0.131	−0.332
χfd%	**0.731****	**0.702****	**0.725****	**0.459***	**−0.665****
χARM	**0.686****	**0.670****	**0.680****	0.367	**−0.590****
SIRM	0.127	0.125	0.125	−0.039	−0.051
ARM/SIRM	**0.800****	**0.769****	**0.794****	0.444	**−0.696****
S-ratio	−0.047	−0.023	−0.042	0.122	−0.040
Soft IRM	0.346	0.331	0.343	0.054	−0.228

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

Table 8 Mineral magnetic and textural properties correlation for residential areas ($n=24$)

	PM 2.5 (%)	PM (10%)	Clay (%)	Silt (%)	Sand (%)
χlf	0.301	0.263	0.319	−0.214	0.127
χfd%	0.065	0.116	0.054	**0.465***	−0.417
χARM	**0.643****	**0.652****	**0.661****	0.245	−0.339
SIRM	0.137	0.117	0.154	−0.267	0.204
ARM/SIRM	0.235	0.316	0.228	**0.689****	**−0.646****
S-ratio	−0.253	−0.245	−0.273	0.195	−0.119
Soft IRM	0.204	0.172	0.219	−0.252	0.180

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

Table 6 Mineral magnetic and textural parameters correlation for Jalingo mechanic village (JMV) and Jalingo central motor park (JMP) ($n=25$)

	PM 2.5 (%)	PM10 (%)	Clay (%)	Silt (%)	Sand (%)
χlf	**−0.584****	**−0.569****	**−0.586****	−0.358	**0.425***
χfd%	0.112	0.173	0.120	0.311	−0.275
χARM	−0.376	−0.275	−0.367	0.134	−0.017
SIRM	**−0.564****	**−0.539****	**−0.568****	−0.241	0.329
ARM/SIRM	0.307	0.373	0.318	**0.451***	**−0.434***
S-ratio	**−0.909****	**−0.890****	**−0.905****	**−0.743****	**0.807****
Soft IRM	**−0.607****	**−0.584****	**−0.611****	−0.293	0.380

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

Table 9 Mineral magnetic and textural properties correlation for other locations ($n = 19$)

	PM 2.5	PM 10	Clay	Silt	Sand
χlf	−0.272	−0.159	−0.237	−0.111	0.132
χfd%	0.444	0.347	0.413	0.337	−0.352
χARM	**0.666****	**0.654****	**0.661****	**0.696****	**−0.697****
SIRM	−0.245	−0.146	−0.214	−0.101	0.119
ARM/SIRM	**0.470***	0.412	0.450	0.375	−0.390
S-ratio	−0.241	−0.176	−0.221	−0.313	0.302
Soft IRM	−0.233	−0.134	−0.203	−0.067	0.089

Significant correlation values are bolded

**Implies significant correlation at the 0.01 level (2-tailed), while * implies significant correlation at the 0.05 level (2-tailed)

SIRM) show stronger relationship with the particle sizes than the concentration-dependent parameters. χfd% and ARM/SIRM reveal strong positive association with PM2.5, PM10, clay and silt fractions and negative correlation with sand. The *S*-ratio and Soft IRM which indicate abundance of soft coercive magnetic minerals (e.g., magnetite, maghemite) are negatively correlated with PM2.5, PM10, clay and silt fractions and positively correlated with sand fraction. This may indicate that the concentration of higher coercivity minerals increases with finer size fractions, but magnetite/maghemite increases in the coarse sand fraction.

In general, it is worth noting that the magnetic particle size relationship is divided into two broad categories: those that correlated positively with the fine size classes (PM2.5, PM10, clay and silt) but negatively with the proportion of sand (i.e., χfd%, χARM and ARM/SIRM) and others that correlated negatively with the fine fractions but positively correlated with sand (χlf, SIRM, *S*-ratio and Soft IRM). This further indicates that χfd%, χARM and ARM/SIRM which respond to fine-grained minerals are strongly positively correlated with fine size classes and negatively correlated with the coarse sand fraction. Also, for this study area, ARM/SIRM proved to be the most suitable proxy for estimating particle size fractions in Jalingo top soils, since it showed the highest significant correlation values with all the size classes. This is closely followed by χARM and χfd%.

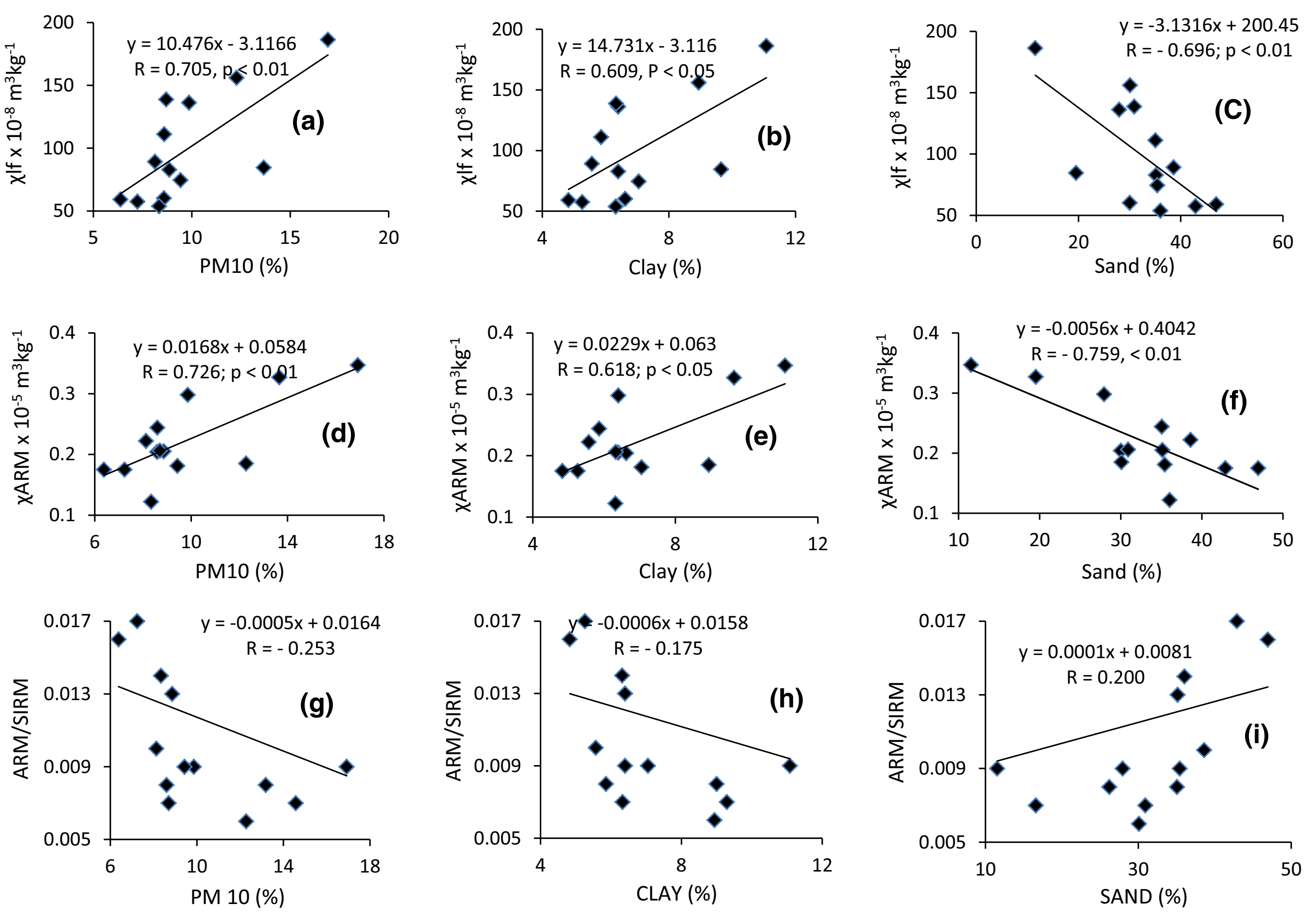

Fig. 4 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (PM 10, clay and sand) for dumpsites sample

In comparison with previous studies, significant relationship between χlf, SIRM and χARM and particle size classes has been found. Measurement of ARM is used to determine the amount of magnetite in fine textured (less than 0.1 μm) clay size fraction, while χlf could be a useful indication of the quantity of coarse MD magnetite in large textured (> 1 μm) fractions (Oldfield et al. 1993). Clifton et al. (1999) found that χlf had strong correlation with sands and medium silts fractions, χARM had strong association with clay and fine silts, while SIRM had strong association with very fine to medium silts. According to Zhang et al. (2001), χfd% and χARM could be used as a proxy for clay content. In terms of the potential of mineral magnetic measurements as a proxy for urban PM, Booth et al. (2005, 2007) found that χlf, χARM and SIRM parameters correlated with all class sizes and suggested that χlf, χARM and SIRM have potential as particle size proxies for several sedimentary environments. They, however, noted the importance of fully determining the nature of the relationship between sediment particle size and magnetic properties before applying mineral magnetic data as a size proxy. More recently, this was further explored by Booth et al. (2008) who discussed potential problems of employing this technique. Crosby et al. (2009) found that in urban road-deposited sediment, χARM and SIRM were strongly related to all the different PM classes (PM1.0, PM2.5 and PM10), but χlf did not. Saragnese et al. (2011) reported variable degree of correlation between the contents of PM 10 and various magnetic properties and attributed this variation to the diverse sources of origin of PM 10. The trends observed in the present study are not totally consistent with these earlier investigations, though significant similarities are evident. For example, while sand correlated negatively with χlf, χARM and SIRM (Booth et al. 2005, 2007), it is positively correlated with χlf and SIRM and negatively associated with χARM in this study. Also, while Crosby et al. (2013) obtained significant moderate negative correlation between χlf, χARM and SIRM and clay, silt and sand contents, this study found significant ($P < 0.05$) but weak negative correlation between χlf and SIRM and clay and silt contents, and positive correlation with sand content. χARM rather shows stronger significant but contrasting relationship.

Figure 3a–i shows bivariate scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) versus selected textural parameters (clay, sand and PM10). The

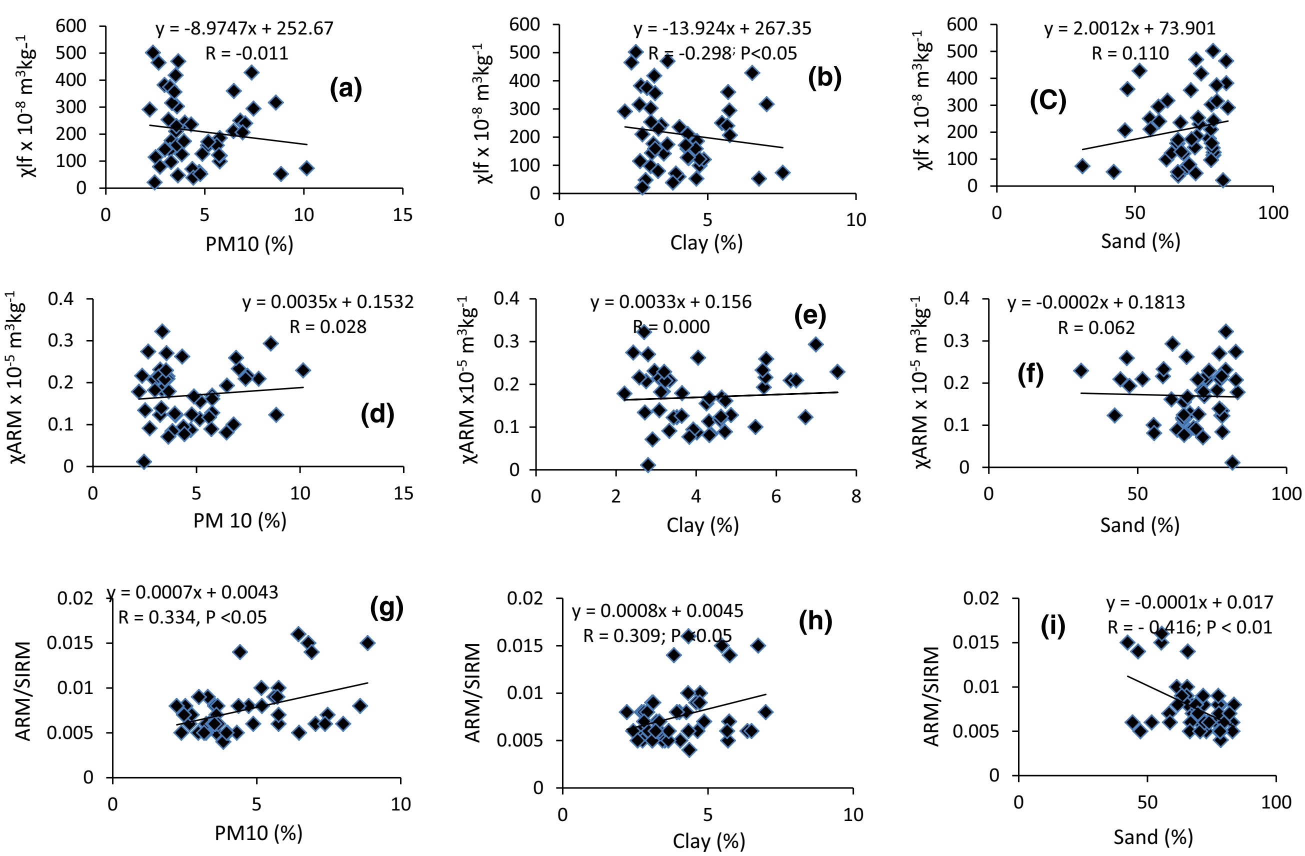

Fig. 5 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (PM 10, clay and sand) for road side soils samples

plots of χlf and clay, sand and PM10 (Fig. 3a–c) show that the sample points are distributed all over the plot area, suggesting that the relationship does not give enough confidence to conclude that magnetic susceptibility could be a particle size proxy in the study area. Figure 3d–i shows relatively good degrees of scatter around the trend line, suggesting that χARM and ARM/SIRM might be a good proxy for the contents of the textural parameters.

The study further assessed the dependence of the magnetic parameters and particle size relationship on land use (road side soils, dumpsites, mechanic workshops/motor parks, farmland, etc.). Results are presented in Tables 4, 5, 6, 7, 8 and 9. The results indicate that the strength and significance of the association between magnetic parameters and textural parameters can be different for specific environments within the same geological settings. Similar observation was found by Booth et al. (2008) within a sedimentary setting. The potential application of magnetic methods as proxy for particle size on dumpsites yielded interesting results shown in Table 4. Unlike the general case, χlf, χARM, SIRM and Soft IRM are significantly positively associated with the proportions of PM2.5, PM10, clay and silt and negatively correlated with sand fractions consistent with Booth et al. (2005, 2007). This suggests that in the dumpsites, χlf, χARM, SIRM and Soft IRM could be effective particle size proxy. The grain size-dependent magnetic parameters (χfd% and ARM/SIRM) show contrasting trend, though with very weak correlation coefficient that is not significant at $P<0.01$ and $P<0.05$. Figure 4a–i shows scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) versus selected textural parameters (clay, sand and PM10) for the dumpsites samples. The plots show good relationship between the particle sizes and χlf and χARM (Fig. 4a–f), but not with ARM/SIRM (Fig. 4g–i). ARM/SIRM plots show greater scatter with the particle size and might not be a suitable particle size proxy for the dumpsites.

In Table 5, the Pearson correlation coefficients for Jalingo roadside soils are presented. The result indicate that χlf, SIRM and Soft IRM are poorly and negatively correlated with all the particle sizes except sand fraction. χfd% and ARM/SIRM show significant positive relationship with PM10, clay and silt, and negative correlation with sand

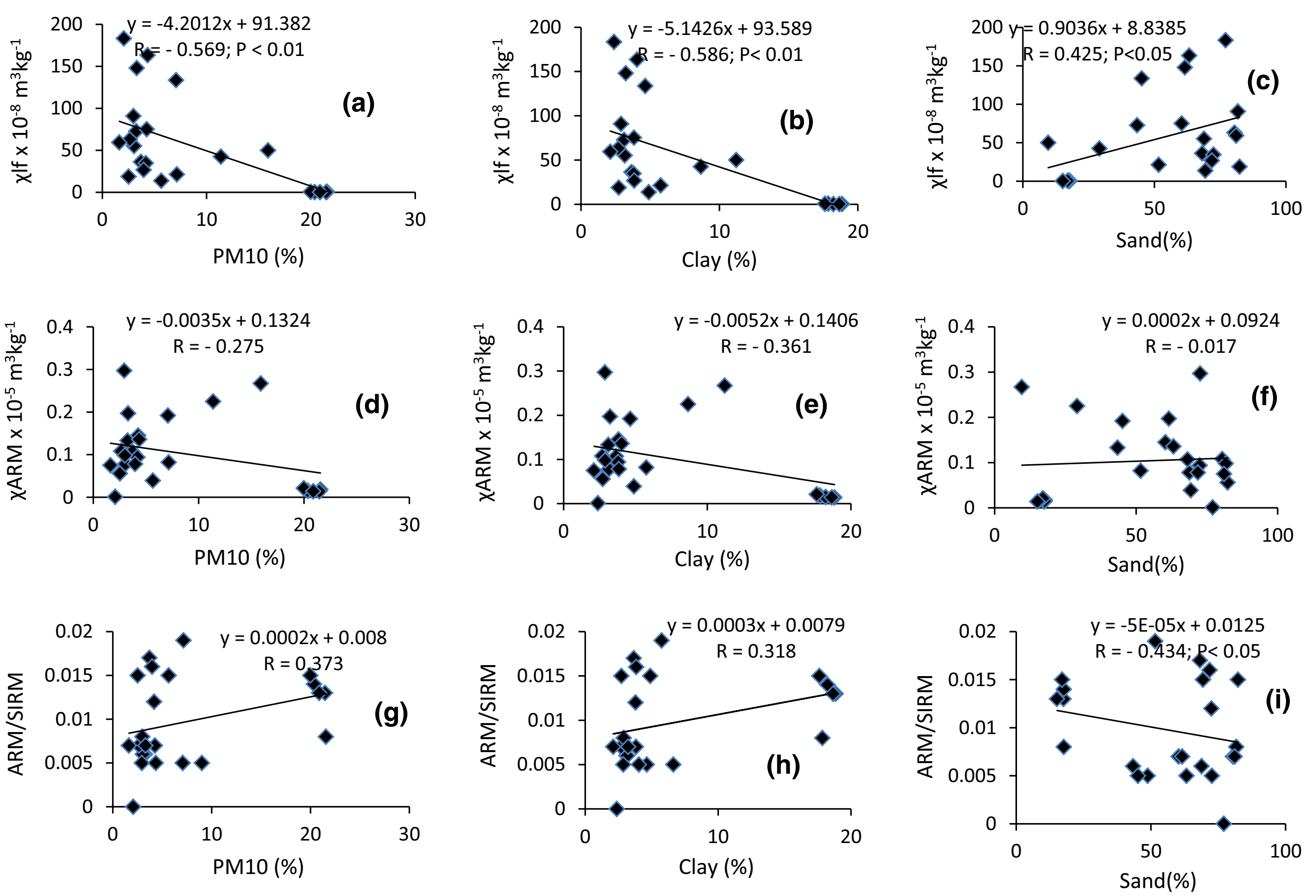

Fig. 6 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (clay, sand and PM 10) for JMP and JMV soils samples

proportion. *S*-ratio is significantly negatively correlated with PM2.5, PM10, clay and silt fractions and positively correlated with sand. For this data set (road side soils), χlf, SIRM, χARM and Soft IRM may not be reliable particle size proxies as they display minimal/poor relationship with particle sizes. In comparison with road-deposited sediment from Scunthorpe, North Lincolnshire, UK, Crosby et al. (2009) found that moderate significant relationships exist between clay content, PM10, PM2.5 and PM1.0 and χARM and SIRM with χARM displaying the strongest correlation. In this study, the strongest correlation is found between χfd%, ARM/SIRM and *S*-ratio and PM2.5, PM10, silt and sand, suggesting that these magnetic parameters (χfd%, ARM/SIRM and *S*-ratio) could be considered as potential proxy for PM2.5, PM10 and silt in the road side soil. Figure 5 clearly summarizes these observations. Data points are highly scattered in the χlf, χARM versus particle size plots as opposed to the ARM/SIRM versus particle size plots which indicates existence of better relationships (Fig. 5g–i).

For the Jalingo mechanic village (JMV) and Jalingo central motor park (JMP), *S*-ratio displays the strongest relationship with particle size classes. It is significantly negatively correlated with PM2.5 ($r = -0.909$, $P < 0.01$), PM10 ($r = -0.890$, $P < 0.01$), clay ($r = -0.905$, $P < 0.01$), silt ($r = -0.743$, $P < 0.01$) and positively correlated with fraction of sand ($r = 0.807$, $P < 0.01$) (Table 6). This indicates the abundance of soft magnetic mineral (e.g., magnetite) in the coarse fraction and the hard component (e.g., hematite) in the finer fractions. PM2.5, PM10 and clay are observed to relate significantly negatively with χlf, SIRM and Soft IRM, while ARM/SIRM shows significant positive relationship with silt ($r = 0.451$, $P < 0.05$) and negative correlation with sand ($r = -0.434$, $P < 0.05$) only. The poor correlation observed between χARM and ARM/SIRM textural parameters in JMV and JMP (Table 6) may suggest the dominance of MD grains in the magnetic fraction over the finer SD and/or SP grains. This is because MD grains in most cases originate from polluted sources (Kanu et al. 2017). The data spread in Fig. 6 indicates that high level of confidence will not be given to χlf, χARM and ARM/SIRM as particle size normalization parameters. Although χlf relationship with particle sizes is promising, the data are clearly not distributed normally.

The relationship between some mineral magnetic and textural parameters for a farmland in Jalingo is presented in Table 7 and Fig. 7. Here, significant negative correlations

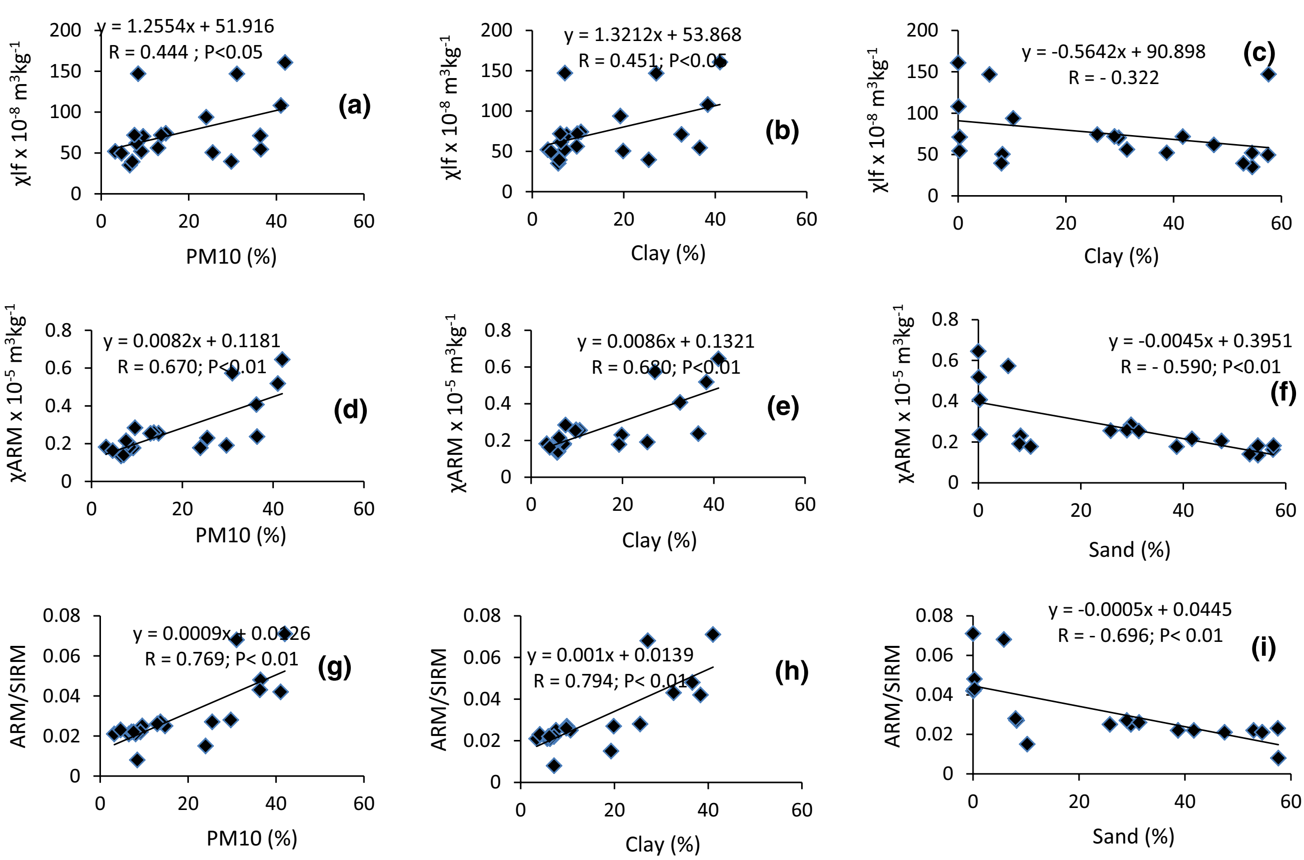

Fig. 7 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (clay, sand and PM 10) for Jalingo farmland soils samples

are found between χlf, χfd%, χARM and ARM/SIRM and fine fractions (PM2.5, PM10 and clay). These magnetic parameters are, however, found to exhibit significant negative correlation with sand fraction. Silt content is found to be related to χfd% only. The data distribution is concentrated around the regression line (Fig. 7) compared to the situation in the JMP and JMV samples (Fig. 6). In this site, the χfd%, χARM and ARM/SIRM displayed the strongest relationship and could be used as potential particle size proxy.

The situation in residential area is different from the other sites. In the Jalingo residential areas, χARM significantly correlated positively with the fine size fractions (PM2.5, PM10 and clay), while ARM/SIRM displayed significant and positive correlation with silt and negative correlation with sand (Table 8 and Fig. 8). This implied that χARM and ARM/SIRM could be considered appropriate particle size proxy in the residential area. Weiguo and Lizhong (2003) also obtained χARM to be highly correlated with fine fraction (< 4 μm) for tidal flat sediments from Yangtze River, China.

Results of magnetic-particle size relationships for combination of other locations in Jalingo such as school environment, market place, sports complex, etc., are shown in Table 9 and Fig. 9. In this case, χARM appears to be the most efficient particle size proxy. It shows significant positive correlation at 1% confidence level with PM2.5 ($r = 0.666$), PM 10 ($r = 0.654$), clay ($r = 0.661$) and Silt ($r = 0.696$) and negative correlation with sand ($r = -0.697$). Also, ARM/SIRM exhibits moderate positive correlation which is significant at $P < 0.05$ with PM2.5 ($r = 0.470$).

The results indicated that when magnetic concentration parameters are employed as estimate for pollutant content, it is important to look into the changes caused by composition of particle size and possibly reduce such effects. Significant correlations between the magnetic parameters and the respiratory health-related size classes have shown the potential of using the technique as a possible alternative tool for monitoring PM, which could be linked to both health and pollution studies. It can be said that magnetic measurements have high possibility to be a reliable proxy for particle size. However, when data presented here are compared between different sampling sites and previous investigations, it is clear that there is no general trend that could be adduced. For example, one cannot conclude that χARM is a clay size proxy or χlf is used as a sand proxy. Therefore, more case studies are needed to arrive at a conclusion; otherwise,

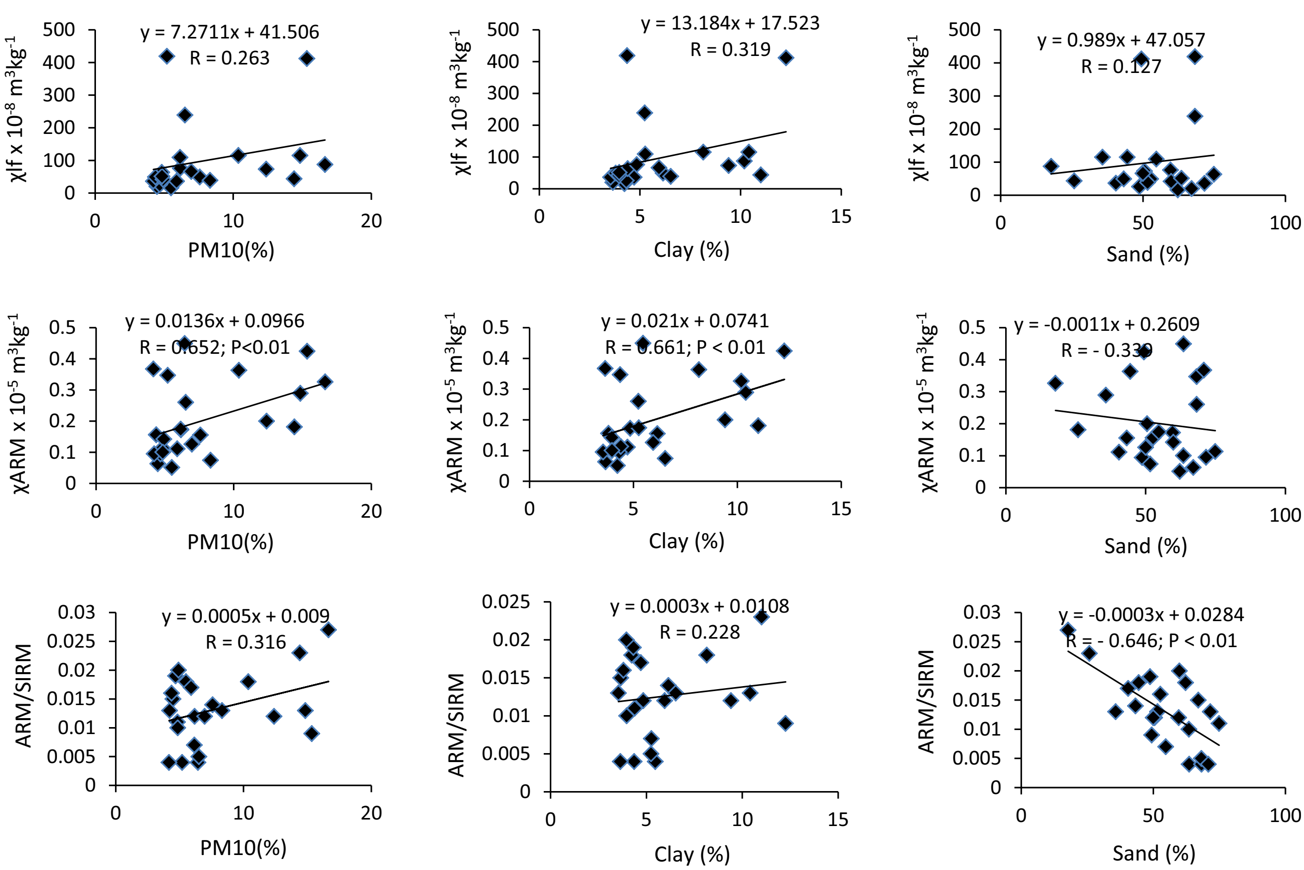

Fig. 8 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (clay, sand and PM 10) for soils from Jalingo residential areas samples

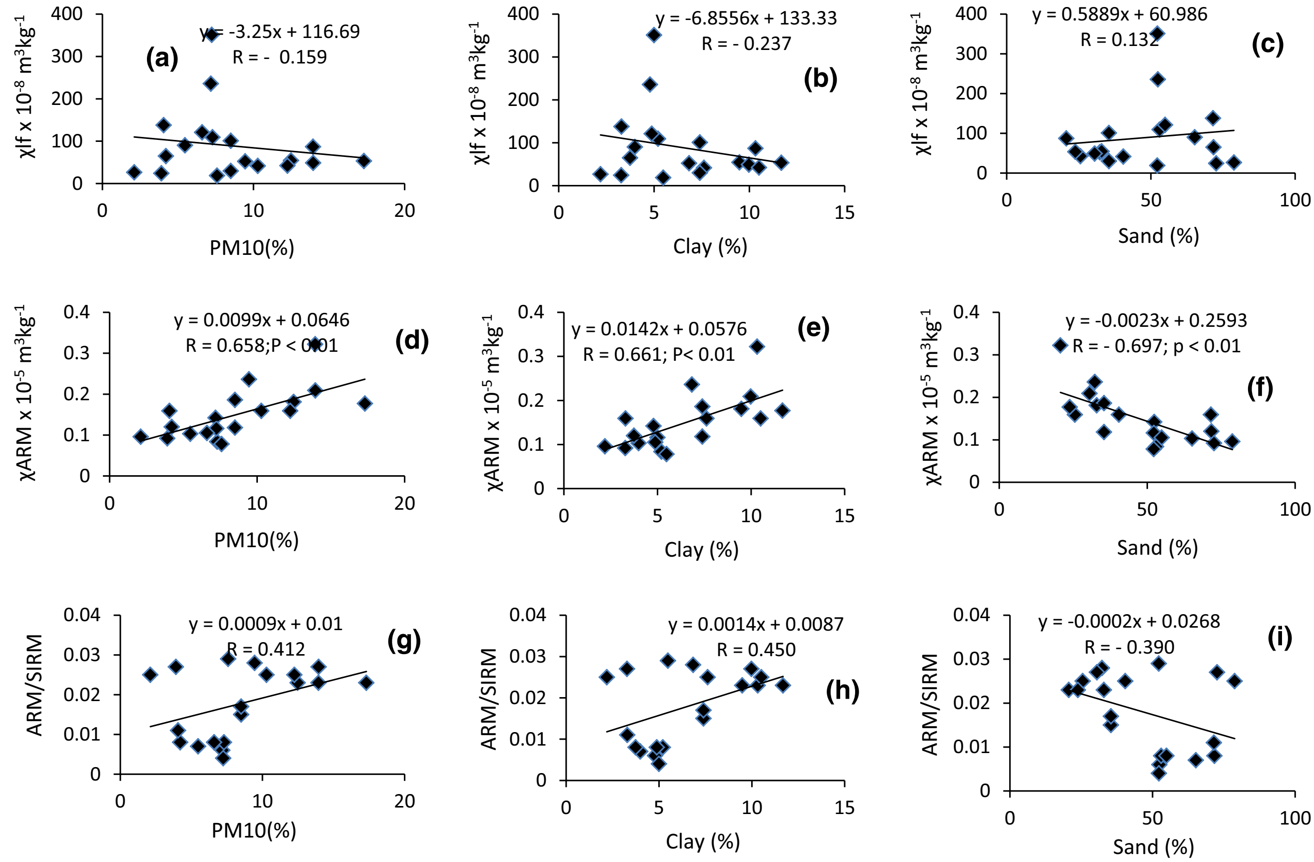

Fig. 9 Scatter plots of some magnetic parameters (χlf, χARM and ARM/SIRM) and particle size classes (clay, sand and PM 10) for soils from other locations

caution should be exercised when using mineral magnetic methods as particle size proxy.

Conclusions

- Results obtained indicate that each particle size class shows different strengths of correlation with magnetic parameters, implying that each particle size class contains a proportion of magnetic minerals.
- Some magnetic properties (χfd%, χARM and ARM/SIRM) are positively correlated with finer fractions (PM2.5, PM10, clay and silt) but negatively correlated with sand proportion, while χlf, SIRM and Soft IRM reveal opposite trend of correlation.
- Land use affects the manner in which magnetic parameters relate with particle size. It varies from one land use pattern to another.
- Assessment of all selected magnetic parameters used for the study shows that the magnetic parameters that indicate fine-grained ferrimagnetic minerals (ARM/SIRM and χARM) have the strongest and most significant correlation values and most consistently significant ($P < 0.01$) relationship with most particle size classes and could be considered most suitable particle size proxy for the study area. Thus, magnetic techniques have the potential to be considered as proxy for particle size.
- Although significant relationship between magnetic and particle size parameters has been obtained, the trend does not follow predictable pattern of other studies. This implies that the application of magnetic data as proxy for particle size may not be universal; hence, for a particular soil or environmental setting, the nature of the association should be examined before attempting to use magnetic properties as particle size proxy.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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