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IRON MINERALOGY AND MAGNETIC SUSCEPTIBILITY OF SOILS DEVELOPED ON VARIOUS ROCKS IN WESTERN IRAN

Shamsollah Ayoubi* and Vali Adman

[1]Department of Soil Science, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran

Abstract—The characterization of magnetic minerals and the relationship of these minerals to the magnetic susceptibility of soils that have developed on various parent materials can provide valuable information to various disciplines, such as soil evolution and environmental science. The aim of the study reported here was to investigate variations in the magnetic susceptibility (χ) of soils in western Iran due to differences in lithology and to examine the relationship of χ to ferrimagnetic minerals. Eighty samples were collected from eight parent materials taken from both intact rocks and associated soils. The soil parent materials included a range of igneous and sedimentary rocks, such as ultrabasic rocks (Eocene), basalt (Eocene), andesite (Eocene), limestone (Permian), shale (Cretaceous), marl (Cretaceous), and the Qom formation (partially consolidated fine evaporative materials, early Miocene). The 80 samples were analyzed for χ using a dual-frequency magnetic sensor and for mineralogy using X-ray diffraction (XRD). The highest χ values were found in the ultrabasic rocks and associated soils, while the lowest χ values were observed in the limestone rocks and associated soils. The pedogenic processes significantly enhanced the χ values of soils developed on the sedimentary rocks due to the formation of ferrimagnetic minerals. In contrast, χ values decreased as a result of pedogenic processes in soils developed on igneous rocks due to the dilution effects of diamagnetic materials, such as halite, calcite, phyllosilicates, and organic matter. The significant positive correlation between the XRD peak intensity of the maghemite/magnetite particles and χ values confirmed that χ values in soils are largely controlled by the distribution and content of ferrimagnetic minerals. These results show that χ measurements can be used to quantify low concentrations of ferrimagnetic minerals in the soils of semiarid regions.

Keywords—Ferrimagnetic minerals · Maghemite · Magnetic susceptibility · Soil development · X-ray diffraction

INTRODUCTION

Magnetic susceptibility, a dimensionless proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field, has been applied successfully in various disciplines of geologic and environmental sciences to indicate the presence of ferrimagnetic minerals, such as magnetite and maghemite, in soils (Ayoubi & Mirsaidi 2019). This constant has also been employed effectively in various applications in soil science, such as soil development (Maher & Thompson, 1995; Grimley et al. 2004; Tazikeh et al. 2017), soil contamination by heavy metals (Lu & Bai 2006; Karimi et al. 2011; Dankoub et al. 2012; Naimi & Ayoubi 2013), identification of soil moisture regimes (Valaee et al. 2016), differentiation of soil drainage classes (Mathe & Leveque 2003; Asgari et al. 2018), and soil erosion and deposition processes (Mokhtari Karchegani et al. 2011; Ayoubi et al. 2012; Rahimi et al. 2013).

Soil properties are affected predominantly by the lithology of the rocks and sediments of the soil parent materials. Hence, a characterization of soils developed on various rocks in arid and semiarid regions can inform management practices and environmental science applications (Lu 2000; Rahardjo et al. 2004). Some researchers (*e.g.* Mullins 1977; Karimi et al. 2017) have reported that magnetic susceptibility is one of the most important soil characteristics and that it is affected by lithology (Ayoubi et al. 2018; Ayoubi & Karami 2019).

Magnetite and maghemite are the two main ferrimagnetic minerals that regulate the magnetic susceptibility of soils (Valaee et al., 2016). As such, the magnetic susceptibility technique can be useful for characterizing soil-forming processes (Ayoubi & Mirsaidi, 2019). In recent years, soil scientists and pedologists have employed magnetic susceptibility to broaden their understanding about soil evolution (Sarmast et al, 2017) and soil landscape processes (de Jong et al. 2005; Ayoubi & Mirsaidi 2019). Transformation of maghemite from goethite has also been proposed in acid sulfate soils as the mechanism by which the amounts of magnetic minerals can be increased in soils (Grogan et al. 2003).

Various environmental variables, such as biological activities, topography, pedogenic processes, parent materials, landscape age, physicochemical properties, soil moisture regimes, and human activities, are factors driving the magnetic susceptibility variations observed in soils (*e.g.* Spassov et al. 2004). Grimley & Vepraskas (2000) stated that the magnetic susceptibility is often much greater in soils subjected to a higher rainfall intensity and with better drainage. Favorable soil conditions can enhance the formation of ferrimagnetic minerals and increase the conversion of diamagnetic minerals into magnetite or maghemite.

Dearing (1999) identified five basic types of magnetic behavior which can affect soil magnetic susceptibility; these are:

* E-mail address of corresponding author: ayoubi@cc.iut.ac.ir
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- ferromagnetic materials, including pure iron, that have highly ordered magnetic moments with a similar direction that generate a strong positive magnetic susceptibility;
- ferrimagnetic materials, such as maghemite and magnetite, that similarly exhibit intense magnetic moments and have unbalanced opposing forces;
- antiferromagnetic materials, such as hematite and goethite, that have well associated but opposing moments and generate a moderately positive magnetic susceptibility;
- paramagnetic materials, such as pyrite and biotite, that have weak positive magnetic susceptibility;
- diamagnetic materials, such as gypsum, calcite, quartz, and soil organic carbon, that have a weak negative magnetic susceptibility.

Accordingly, the main minerals that control enhanced magnetic susceptibility in rocks and soils have been identified as magnetite and maghemite (Mullins 1977; Maher 1998; Dearing 1999; Cabello et al. 2009).

As revealed by a literature review conducted prior to undertaking the study reported here, little attempt has been made to explore the relationships between magnetic susceptibility in various rocks and soil parent materials in arid and semiarid regions and the concentrations of magnetite and maghemite in those regions. Therefore, the main objectives of the present study were to: (1) characterize variations in the magnetic susceptibility of various igneous and sedimentary rocks; (2) determine the variations in the contents of ferrimagnetic minerals in rocks and the soils developed on the rocks using X-ray diffraction (XRD); and (3) evaluate the relationships between mineral presence/content and magnetic susceptibility in a semiarid region located in western Iran.

METHODS AND MATERIALS

Description of the study area

The study area is located in the Maku region, western Azerbaijan province, of northwestern Iran (approximately 45.5°E, 39.21°N) (Fig. 1). The average elevation of the selected area is 1634 m a.s.l. The average annual temperature and mean annual precipitation are 10°C and 270 mm, respectively. Pastures, irrigated farming, and dry land cropping are the major land uses in the study area. The predominant parent materials in the region are Eocene igneous rocks, Cretaceous sedimentary rocks, Permian sedimentary rocks (limestone), and Ordovician metamorphic rocks. The soil moisture regime in the study area is xeric and the temperature regime is mesic according to the Soil Survey Staff (2014).

Soil sampling

Field studies were conducted and eight parent materials were collected from the study area (Fig. 1). The selected parent materials were igneous rocks that included granite, andesite, basalt, and ultrabasic and sedimentary rocks and deposits that included shale, limestone, marl, and the Qom formation. The Qom formation consists of partly consolidated, finely evaporated materials, including calcite, gypsum, and halite belonging to the early Miocene. Sampling sites were chosen for their similar geographical characteristics in terms of environmental features and nature, as well as similar vegetation cover, land use, elevation, slope, and slope aspect. All samples were collected from the back-slope landscape positions of pasture land that had 10–20% slope gradients with eastern slope aspects. Of the collected parent materials, ten samples were taken from the underlying parent materials along with the soils developed from the parent materials, with a total of 80 intact rock samples and 80 soil samples.

Laboratory analysis

The soil samples collected were air dried, crushed, and passed through a 2-mm sieve to remove coarse materials and plant litter prior to the laboratory analyses. Soil electrical conductivity (EC) of the saturated paste extracts was determined using an EC meter, and soil pH was measured in saturated soil pastes using a pH meter (Rhoades 1982). The soil texture and particle-size distribution were determined using the pipette method (Gee & Bauder 1986). The soil organic material (SOM) content was determined by wet oxidation using chromic acid (K_2CrO_7–H_2SO_4) (Nelson & Sommers 1982), and acid dissolution followed by back-titration was employed to measure calcium carbonate ($CaCO_3$) equivalents (CCE) (Black et al. 1965).

A Bartington MS2 dual-frequency sensor (Bartington Instrument Ltd., Oxon, UK) was employed to measure magnetic susceptibility (χ) at low (0.47 kHz; χ_{lf}) and high frequencies (4.7 kHz, χ_{hf}). For these analyses, all soil and rock samples were crushed and passed through a 2 mm sieve, following which ~10 g of the soil or crushed rock was placed into a 4-dram clear plastic vial (diameter 2.3 cm) (Dearing et al. 1996). The following equation was used to calculate the mean magnetic susceptibility of the dependent frequency (χ_{fd}):

$$\chi_{fd} = \left[\left(\chi_{lf} - \chi_{hf}\right)/\chi_{lf}\right] \times 100 \quad (1)$$

XRD analysis was performed on crushed soils and rock samples using a Bruker AXS D8 Advance X-ray diffractometer (Bruker, Billerica, Massachusetts, USA) with Cu-Kα radiation. XRD measurements were performed using a step size of 0.022°2θ and a step time of 1 s. A scanning range of 10 to 80°2θ was used to obtain X-ray patterns. Relative peak positions were used to identify minerals, and peak intensities were used for semi-quantitative estimates of the ferrimagnetic mineral (magnetite and maghemite) contents (Soil Survey Staff 2014).

Statistical analysis

Descriptive statistics, which included range (minimum, maximum), mean, skewness, kurtosis, standard deviation, and coefficients of variation (CVs) were calculated using *SPSS* software version 19.0 (IBM Corp., Armonk, New York, USA). The correlations between soil magnetic susceptibility and soil properties were obtained also using *SPSS* version 19.0 (Swan & Sandilands 1995), as were the correlations between ferrimagnetic mineral peak intensities and magnetic susceptibility in the soil samples.

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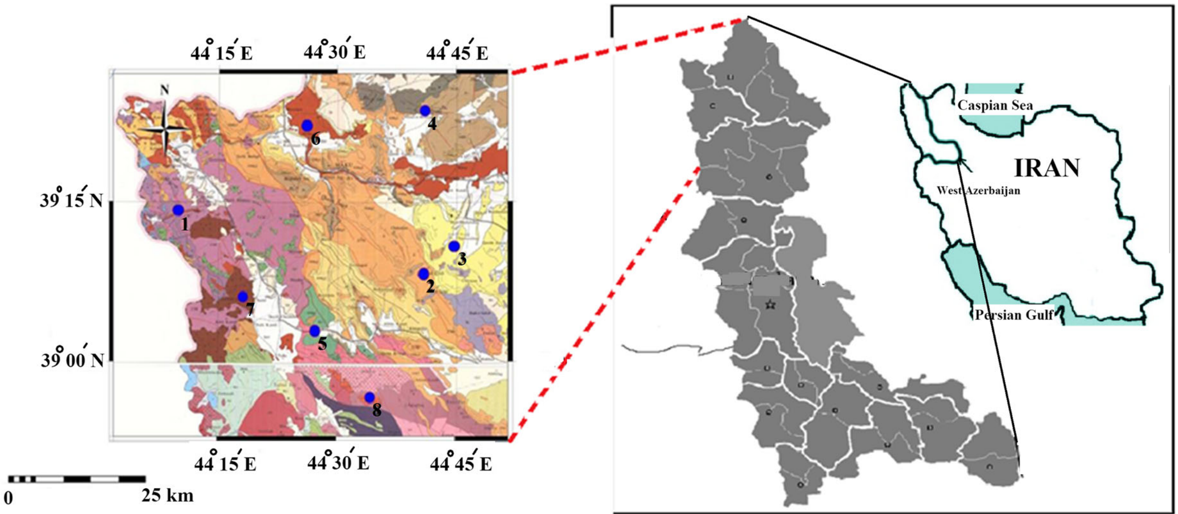

Number of Location	Symbol	GPS	Lithology
1		39° 12′E, 44° 9′N	Ultrabasic rocks
2		39° 19′E, 44° 21′N	Qom formation
3		39° 12′E, 44° 50′N	Marl
4		39° 24′E, 44° 38′N	Shale
5		39° 02′E, 44° 26′N	Limestone
6		39° 22′E, 44° 23′N	Basalt
7		39° 12′E, 44° 15′N	Andesite
8		38° 59′E, 44° 37′N	Granite

Fig. 1 Location of the study area in northwestern Iran, Azerbaijan province, Maku district, and locations of the study sites with respect to the various parent rock and soil materials

RESULTS AND DISCUSSION

Variability in χ_{lf} in the studied parent materials

The results of the analysis of variance indicated significant differences ($P < 0.05$) between the χ_{lf} values of the rocks examined. Of all rock samples, the highest mean χ_{lf} values were found in ultrabasic rocks (2066.90×10^{-8} m^3 kg^{-1}) (Fig. 2a). Overall, igneous rocks (ultrabasic, basalt, andesite, and granite) had greater χ_{lf} values than the sedimentary parent materials (Qom formation, shale, marl, and limestone). The lowest χ_{lf} (1.17×10^{-8} m^3 kg^{-1}) value was observed in the Qom formation samples which were enriched in the diamagnetic minerals calcite, gypsum, and halite (Mullins 1977).

The mean χ_{lf} values in the ultrabasic and basalt rocks were much greater (>1700-fold) than those in the other rocks studied. Among the igneous rocks, the ultrabasic and basic rocks, which contained much greater amounts of ferrimagnetic minerals such as magnetite, had the highest χ_{lf} values. Mooney & Bleifuss (1953) also compared the χ_{lf} values in igneous rocks and, similar to the present findings, observed that the basalt samples had the highest χ_{lf} value (1260×10^{-8} m^3 kg^{-1}), while granite had the smallest χ_{lf} (220×10^{-8} m^3 kg^{-1}). Mullins (1977) stated that the magnetic susceptibility of igneous rocks is mainly correlated to the magnetite content in these rocks.

Aydin et al. (2007) stated that the predominant source of magnetic susceptibility was ferromagnesian silicates plus ilmenite in an ilmenite-series of granites, and titanomagnetite in a magnetite-series of granites. These authors reported that the chemical composition (Fe/Mg ratio) and the abundance of constituent minerals controlled the magnetic susceptibility values of the rocks.

In the present study, the sedimentary rocks with large concentrations of diamagnetic minerals (halite, gypsum, and calcite) and paramagnetic minerals (*e.g.* aluminosilicate clays) had low magnetic susceptibility values that varied from 1.17×10^{-8} m^3 kg^{-1} in the Qom formation to 6.26×10^{-8} m^3 kg^{-1} in the shale deposits. These findings are similar to the observations of other researchers on sedimentary rocks and deposits throughout the world (de Jong et al. 1999; Ranganai et al. 2015; Karimi et al. 2017).

Magnetic susceptibility in soils and the contributions of parent materials

Descriptive statistics of the χ_{lf} values of the various soils developed on selected parent materials in the study area are given in Table 1. The χ_{lf} values in the soils developed on the ultrabasic rocks were the highest (range 1274.81×10^{-8} m^3 kg^{-1} to 948.15×10^{-8} m^3 kg^{-1}) with a CV value of 23.38%. The lowest χ_{lf} values (~71.95×10^{-8} m^3 kg^{-1}) were observed in the soils developed on the limestone rocks (71.09×10^{-8} m^3 kg^{-1}), with a CV value of 33.21%. The mean χ_{lf} values in the studied soils are given in Fig. 2b. The mean magnetic susceptibility values in the studied rocks compared using the least significant difference statistical test revealed no significant differences ($P < 0.05$) between

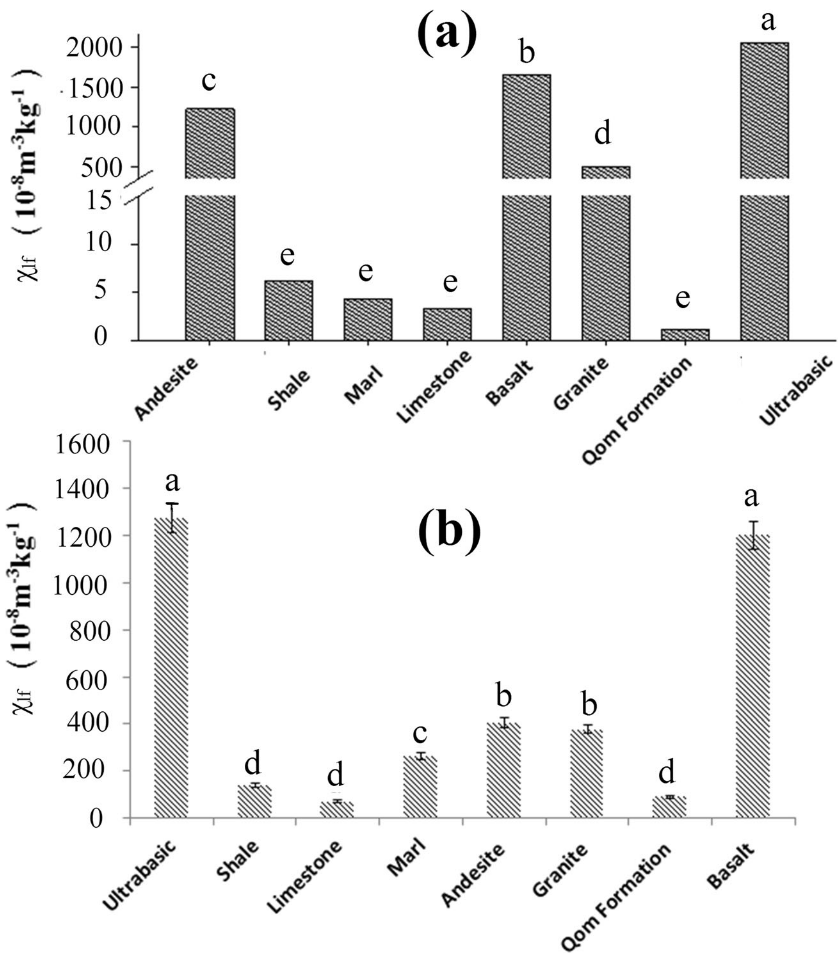

Fig. 2 Comparison of magnetic susceptibility values measured at low frequency (0.47 kHz; χ_{lf}) in samples from the studied parent materials (**a**) and the magnetic susceptibility values of the soils developed on them (**b**) in the study area. Different letters on the bars in each figure indicate a significant difference at the $P < 0.05$ probability level

ultrabasic and basalt rocks. The LSD values obtained for granite and andesite, however, differed from those of the ultrabasic and basalt rocks. Among the sedimentary rocks, no significant differences were found, with the exception of marl which had the highest value (Fig. 2b). These results are consistent with the findings of other researchers in Iran and other countries (de Jong et al., 1999; Ranganai et al., 2015; Karimi et al., 2017). Mokhtari Karchegani et al. (2011) reported a mean χ_{lf} value of 62.59×10^{-8} m^3 kg^{-1} for the sedimentary deposits in western Iran. Karimi et al. (2017) indicated that the soils developed on limestone and gypsiferous marls had a mean χ_{lf} value of 69.5×10^{-8} m^3 kg^{-1} and that the soils developed on ultramafic rocks had a mean χ_{lf} value of 197.6×10^{-8} m^3 kg^{-1}.

The χ_{lf} values in the soils were compared to the soil parent materials, and the results indicated that the χ_{lf} values changed significantly after soil formation. A number of theories have been advanced to explain this increase in χ_{lf} values in the soils in comparison to the soil parent materials. One of the earliest theories, *i.e.*, the effects of heat during fires, proposed by Le Borgne (1955), was rejected here because no trace of fires in the study area was found. A second theory that has been put forward in recent decades is that of the accumulation of particles of material from atmospheric pollution (Blundell et al. 2009; Karimi et al. 2011; Naimi & Ayoubi 2013) as a result of fossil fuel burning. However, this possiblity was also rejected because no urbanization or industrial activities have occurred near the studied soils. Two remaining processes which could account for the results include inheritance from parent materials and pedogenic processes (Mullins 1977; Blundell et al. 2009).

In the soils developed on igneous rocks, magnetic susceptibility originated mainly from the parent materials that had relatively higher χ_{lf} values in comparison to the sedimentary rocks. In the soils developed on the igneous rocks, dilution effects led to decreases in the χ_{lf} values in comparison to the parent rocks (Lu et al. 2008a,b). It is possible that the formation of a number of diamagnetic minerals (*e.g.* calcite) and

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Table 1 Descriptive statistics for magnetic susceptibility measured at low frequency and the mean magnetic susceptibility of the dependent frequency of soils developed on the various parent materials studied

Parent material	Magnetic susceptibility/ dependent frequency	Number of samples	Minimum value	Maximum value	Mean value	CV%	Skewness	Kurtosis	Range
Granite	χ_{lf}	10	285.70	617.95	376.90	20.81	2.2	6.39	332.25
	χ_{fd}	10	0.39	2.45	1.45	46.60	0.11	1.30	2.06
Ultrabasic	χ_{lf}	10	886.75	1834.90	1274.81	23.38	0.49	−0.64	948.15
	χ_{fd}	10	0.10	3.44	1.47	35.30	1.20	−1.56	3.34
Basalt	χ_{lf}	10	922.75	1510.55	1201.39	16.81	0.08	−1.43	587.80
	χ_{fd}	10	1.67	3.04	2.66	13.72	0.99	0.33	1.37
Andesite	χ_{lf}	10	285.70	533.95	404.39	21.49	−0.01	−1.63	248.25
	χ_{fd}	10	0.87	2.25	1.67	23.46	−0.21	−0.037	1.38
Shale	χ_{lf}	10	72.40	213.70	138.72	31.79	0.64	−0.55	141.30
	χ_{fd}	10	2.23	5.45	4.84	52.33	−0.89	−1.01	3.22
Marl	χ_{lf}	10	168.10	350.10	264.76	21.66	−0.10	−1.20	182.00
	χ_{fd}	10	2.34	6.50	4.56	45.99	1.01	0.89	4.16
Limestone	χ_{lf}	10	40.65	112.60	71.09	33.21	0.40	−1.16	71.95
	χ_{fd}	10	2.56	6.07	5.01	67.89	1.10	2.34	3.51
Qom formation	χ_{lf}	10	36.95	154.65	90.71	36.08	0.76	−0.08	117.00
	χ_{fd}	10	3.76	6.70	5.02	78.09	0.09	0.08	2.94

χ_{lf}, magnetic susceptibility measured at low frequency (units: 10^{-8} m^{-3} kg^{-1}); χ_{fd}, mean magnetic susceptibility of the dependent frequency (unit: %); CV, coefficient of variation

alterations to ferrimagnetic minerals (*i.e.* to paramagnetic minerals) during soil-forming processes are the main causes of decreased χ_{lf} values in the soils. In a study conducted on various igneous and metamorphic rocks in northwestern Iran, Yousefifard, Ayoubi, Jalalian, Khademi, & Makkizadeh (2012) demonstrated that χ_{lf} values declined in all igneous rocks relative to the parent materials.

In the sedimentary parent materials, χ_{lf} values increased significantly in the soils in comparison to the parent materials. The χ_{lf} values in all soils developed on sedimentary parent materials were significantly enhanced, with values ranging from 1500% greater in limestone to >7000% greater in marl and the Qom formation. The enhanced χ_{lf} values in the sedimentary rocks are mainly attributable to soil-formation processes in the semiarid climate of the study area. These findings are consistent with those reported by Lu (2000) and indicate that the soils developed on igneous rocks had high magnetic susceptibility values, high absolute χ values, and markedly decreased χ values in comparison to the χ values of the parent materials. They also reported an increase in χ values in the upper soil horizons of the soils developed on sedimentary rocks in comparison to the χ values of the parent materials.

In the soils formed on sedimentary rocks, the χ_{fd} was > 4%. (see Table 1), indicating that super-paramagnetic particles were the prevalent magnetic minerals in these soils and that the χ_{fd} values could regulate the magnetic signal (Dearing 1994; Ng et al. 2003; Jordanova et al. 2008). Highly positive significant correlations ($P < 0.05$) were obtained between the χ_{lf} and χ_{fd} values in the sedimentary rocks (Fig. 3), confirming that the χ_{lf} in these rocks increased through pedogenic processes that resulted in the formation of super-paramagnetic particles (Hu et al. 2007). Low χ_{fd} values were found in the soils that formed on the andesite, granite, basalt, and ultrabasic rocks (range 1.45–2.66%; Table 1), and no significant relationships were found between χ_{lf} and χ_{fd} in these soils (Fig. 3). These results confirmed that most of the ferrimagnetic minerals in the soils that formed on the andesite, granite, basalt, and ultrabasic rocks was inherited from the parent rocks. In contrast, the dilution influences that resulted from soil development led to a reduction in the χ_{lf} value in comparison with the respective parent rocks.

Correlation between soil properties and χ_{lf}

The observed relationships between magnetic susceptibility and soil properties (Fig. 4) revealed that all of the measured soil properties, including pH, EC, SOM, CCE, and clay content, were significantly and negatively correlated with χ_{lf}. The presence of SOM and calcite, both diamagnetic materials, reduced χ_{lf} values by weakening the effects of the magnetic materials (Marwick 2005). These findings are consistent with the results of other researchers, such as Naimi and Ayoubi (2013) who conducted a study in central Iran. Similar to the present findings, Dankoub et al. (2012) observed significant and negative relationships between χ_{lf} and EC in the arid regions of Iran. These authors attributed this phenomenon to the dilution effects of soluble salt minerals on the magnetic minerals in the bulk soils.

A positive significant correlation ($r = 0.55$, $P < 0.01$) was observed between χ_{lf} and sand content. This positive

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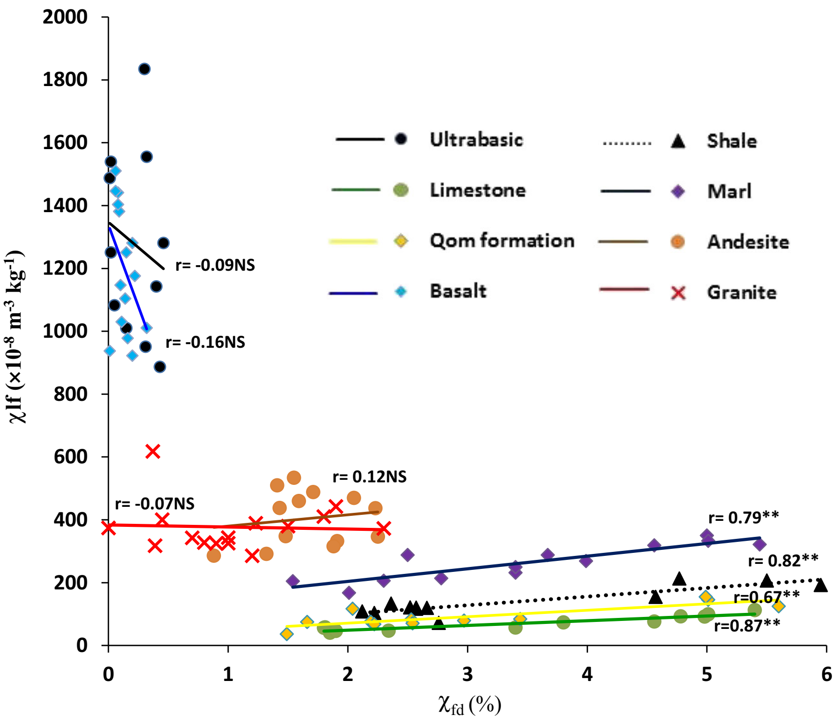

Fig. 3 Relationships between χ_{lf} and mean magnetic susceptibility of the dependent frequency (χ_{fd}) of soils that developed on various parent materials in the study area. The double asterisk indicates a significant difference at the $P < 0.01$ probability level. NS Not significant at $P < 0.05$

correlation confirmed the inheritance of magnetic minerals from the parent materials, especially in the igneous rocks. Yousefifard et al. (2012) examined the relationship between magnetic susceptibility and soil properties in the igneous rocks of northwestern Iran and found positive and significant relationships ($r = 0.66$, $P < 0.05$) between sand content and χ_{lf} values. de Jong et al. (1999) stated that magnetic susceptibility was more highly correlated with the subsurface soils when the distance from the parent materials was shorter .

Fe-oxide mineralogy and relationship to magnetic susceptibility

X-ray diffractometry is one of the principal techniques used to characterize the crystalline mineral phases (Whitting & Allardice 1986; Cervi et al. 2014) and ferrimagnetic minerals in soils and sediments (da Costa et al. 1999; Cervi et al. 2014). Distinguishing magnetite from maghemite using the XRD technique is difficult because magnetite and maghemite have similar crystalline structures and the small grain size of typical maghemite broadens the X-ray peaks (Carlson & Schwertmann 1981). Therefore, in the present study, the shared XRD peaks were considered to indicate the co-occurrence of maghemite and magnetite. Previous researchers used XRD successfully to identify maghemite and magnetite in soils developed on igneous and volcanic rocks (da Costa et al. 1999; Cervi et al. 2014).

The XRD patterns of the crushed rock samples are representative of igneous (ultrabasic and granite) and sedimentary (limestone) rocks. XRD analysis of the fine earth samples taken from the developed soils revealed mineralogical differences between the igneous and sedimentary rocks (Fig. 5). Specifically, Fe-oxide minerals, magnetite/maghemite (*d* spacing of 0.1488, 0252, and 0.296 nm), and hematite (*d* spacing 0.368 nm) were identified in the ultrabasic, basalt, granite, and andesite rock samples while, in contrast, no evidence was found to indicate the presence of these minerals in the sedimentary rock samples (Fig. 5e). Goethite (*d* spacing 0.418 nm), an Fe-oxide mineral, was also found in the granite (Fig. 5c).

The mineralogy of soils developed on the igneous rocks was also studied, and the results showed similar patterns of Fe-oxide mineral occurrence in the soils developed as in the parent igneous rocks (Fig. 5b, d, vs. 5a, c), with maghemite/magnetite being the main mineral fraction in the soils. This result is similar to those of da Costa et al. (1999) and Cervi et al. (2014), both of which studies reported that maghemite/magnetite constituted the main Fe-oxide fraction in the soils developed on basalt. An interesting observation in the present study was detection of the existence of Fe-oxide minerals, mainly maghemite/magnetite, in limestone (Fig. 5f), while no trace of iron oxide was found in the parent rock.

Exploration here of the contribution of Fe-oxide minerals to magnetic susceptibility in various soils revealed the presence of linear relationships between the peak intensity of

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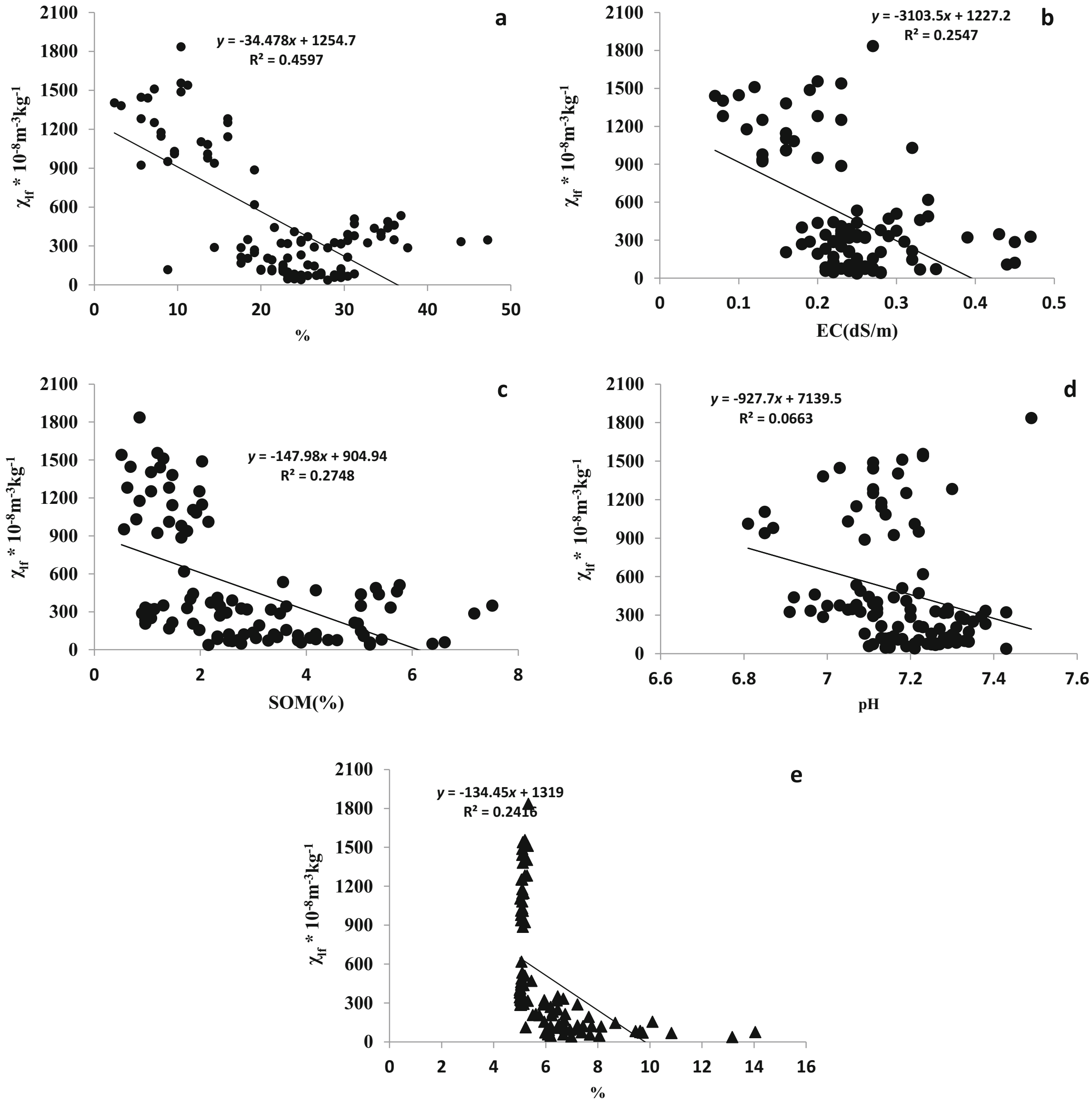

Fig. 4 Relationships between magnetic susceptibility and some soil properties in the studied soils: (**a**) Clay content, (**b**) electrical conductivity (*EC*), (**c**) soil organic matter (*SOM*), (**d**) pH, **e**calcium carbonate ($CaCO_3$)

maghemite/magnetite (*d* spacing 0.252 nm) and the χ_{lf} values. These relationships are presented in Figs 6 and 7 for igneous rocks and sedimentary parent materials, respectively. A positive and significant relationship was observed between peak intensity and χ_{lf} values in the soils developed on ultrabasic rocks ($r = 0.60$, $P < 0.05$), basalt ($r = 0.71$, $P < 0.05$), andesite ($r = 0.74$, $P < 0.05$), and granite ($r = 0.75$, $P < 0.05$). Significant and positive correlations were also found between peak intensity and χ_{lf} values in the soils developed on limestone ($r = 0.82$, $P < 0.01$), marl ($r = 0.80$, $P < 0.01$), shale ($r = 0.83$, $P < 0.01$), and the Qom formation $r = 0.80$, $P < 0.01$). da Costa et al. (1999) examined Brazilian soils and reported a significant and positive relationship ($Rm^2 = 0.89$) between the maghemite content and magnetic susceptibility of the clay fractions. These significant correlations confirmed that ferrimagnetic minerals were the most important components that control magnetic susceptibility in the soils. These results also revealed that magnetic susceptibility measurements could provide valuable information to quantify ferrimagnetic minerals in semiarid regions with low concentrations of magnetic minerals.

CONCLUSIONS

(1) A comparison of the mean χ_{lf} values showed significant variations in the rock samples subjected to analysis. The highest χ_{lf} values were observed in the basalt and ultrabasic rocks that had the highest ferrimagnetic mineral contents,

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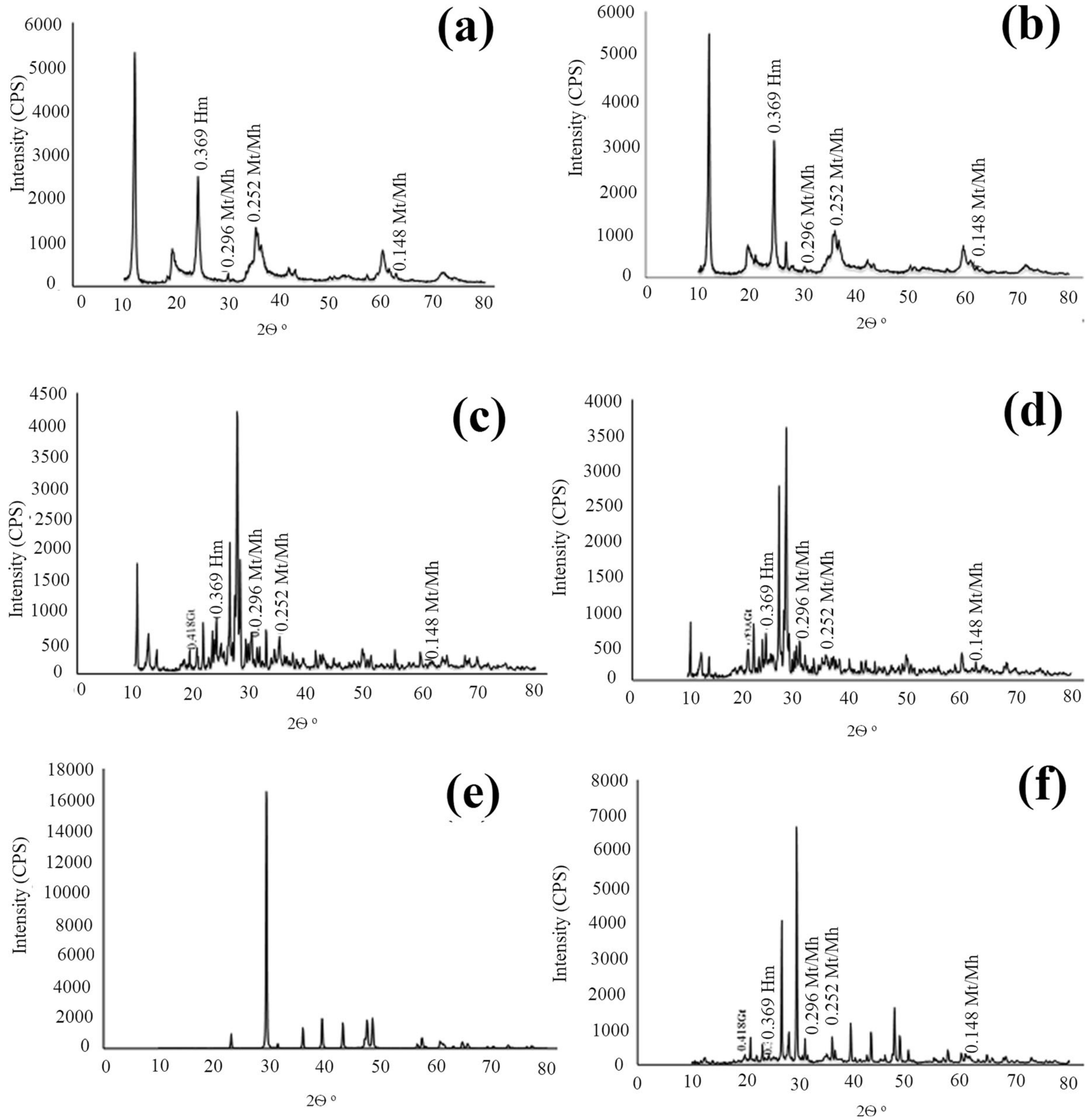

Fig. 5 XRD patterns of some of the soil samples used to identify iron minerals. (**a**) Ultrabasic rocks, (**b**) ultrabasic soil samples, (**c**) granite rock, (**d**) granite soil sample, (**e**) limestone rock, (**f**) limestone soil sample. Mt: magnetite, Mh: maghemite, Hm: hematite, Gt: geothite, CPS: counts per second

while the lowest χ_{lf} values were observed in the Qom formation deposits that were enriched with diamagnetic minerals (*i.e.* calcite, gypsum, and halite) and lacked ferrimagnetic minerals.

(2) The highest and lowest χ_{lf} values were observed in the soils developed on the ultrabasic and limestone rocks, respectively. In comparison to the respective soil parent materials, the χ_{lf} values in the soils decreased in the igneous rocks and increased in the sedimentary rocks. Increased χ_{lf} values in the sedimentary rocks were mainly due to soil-formation processes in the semiarid climate of the study area. Decreased χ_{lf} values were observed in the soils developed on the igneous rocks. This decrease was mainly attributed to the dilution effects induced by the soil-formation processes.

(3) The negative and significant relationships between magnetic susceptibility and soil properties, which included EC, SOM, CCE, and clay content were ascribed to the dilution effects of diamagnetic minerals, such as halite, organic matter, calcite, and phyllosilicates, respectively.

(4) The positive and significant relationships between maghemite/magnetite XRD peak intensity and χ_{lf} values confirmed that ferrimagnetic minerals were the most important components that control χ_{lf} values in the soils. These results

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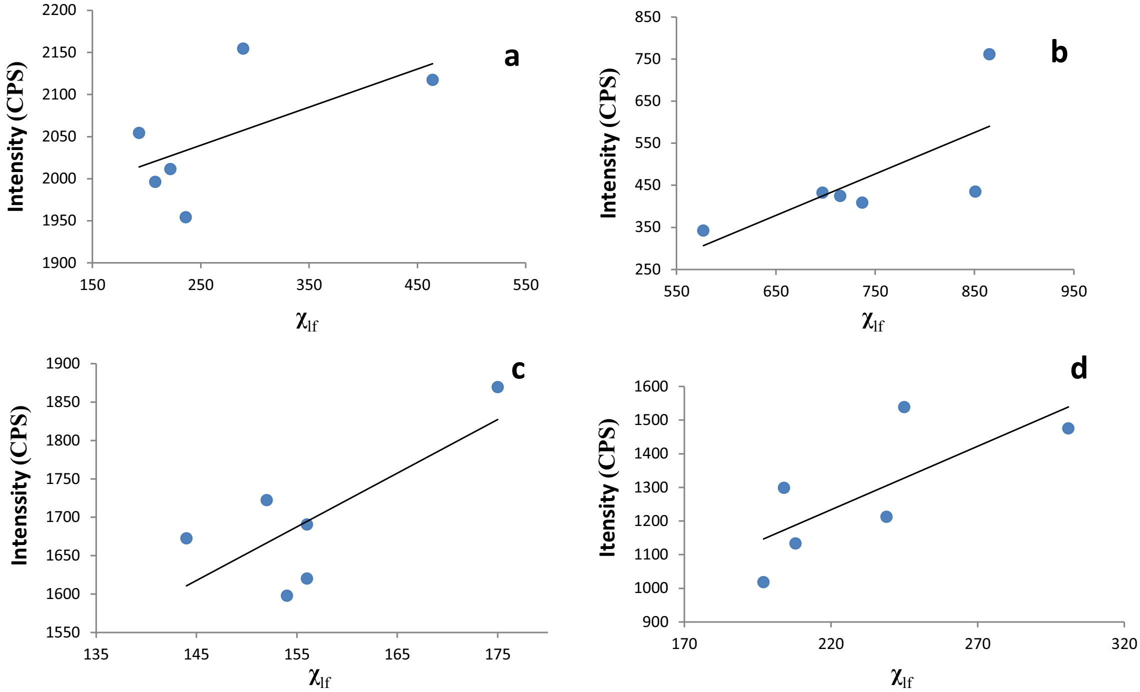

Fig. 6 Relationships between χ_{lf} values and X-ray peak intensity for magnetite/maghemite in various soils developed on igneous rocks. (**a**) Ultrabasic, (**b**) basalt (**c**) granite, (**d**) andesite

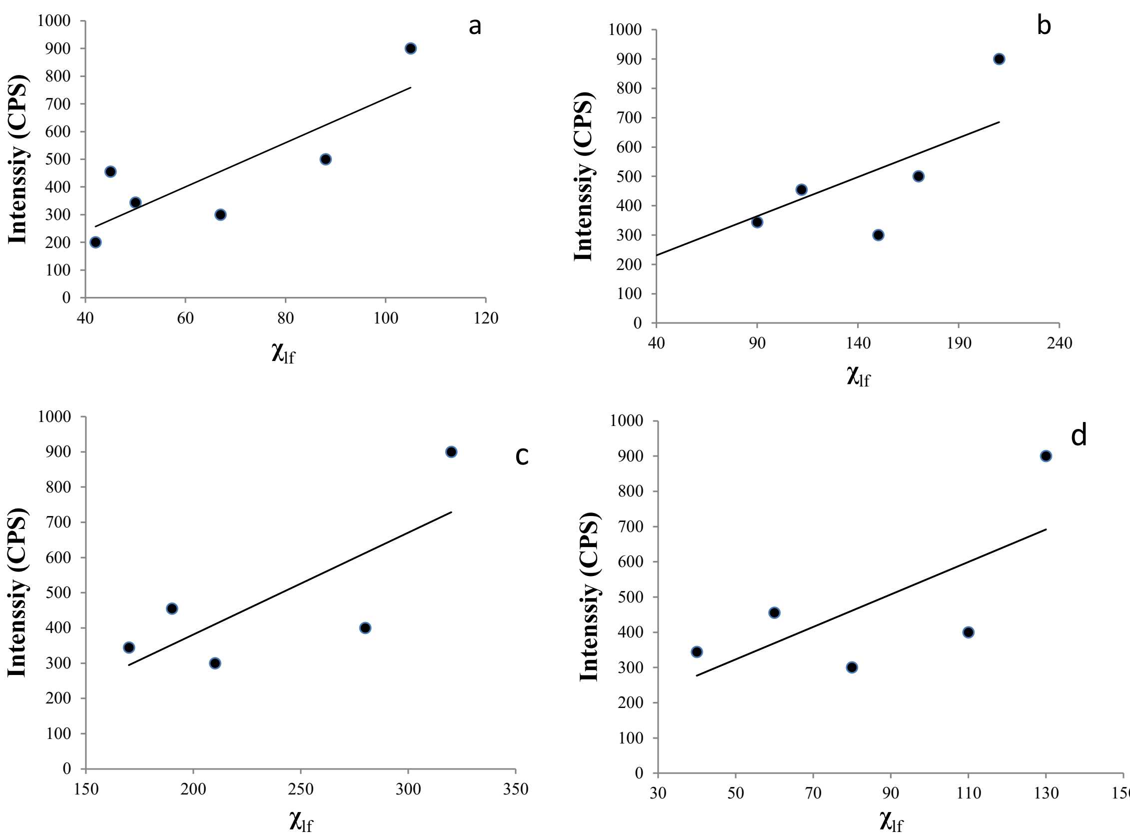

Fig. 7 Relationships between χ_{lf} values and X-ray peak intensities for magnetite/maghemite in the various soils developed on sedimentary rocks and deposits. (**a**) Limestone, (**b**) marl, (**c**) shale, (**d**) Qom formation

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suggest that χ_{lf} measurements can be used to quantify ferrimagnetic minerals in the soils of semiarid regions where low concentrations of magnetic minerals could be found. The quantification of magnetic minerals using magnetic susceptibility suggests that this relationship might be unreliable in soils with large quantities of diamagnetic minerals such as $CaCO_3$, organic matter, halite, and gypsum. Therefore, removing the diamagnetic components from the soils might be necessary to identify or quantify effectively ferrimagnetic minerals using magnetic susceptibility

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Compliance with ethical standards

Conflict of Interest

The authors declare that they have no conflict of interest.

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