JJEES

Volume 2, (Special Publication, Number 1), December. 2009
ISSN 1995-6681
Pages 38- 49

Jordan Journal of Earth and Environmental Sciences

Environmental Magnetism: Heavy Metal Concentrations in Soils as a Function of Magnetic Materials Content.

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Abstract

The magnetic materials contained in the urban soil or roadside soils have become increasingly important as they could serve as good adsorbent media for the heavy metals such as Co, Cr, Cd, Pb, Zn and Ni. Usually, Fe-Oxides or hydroxides such as the magnetite, hematite and goethite are contained in the soil originated through natural or anthropogenic processes.
The results obtained in this investigation indicate the positive correlation between magnetic materials content and the heavy metals concentrations; and show that magnetite (Fe_3O_4) is the main magnetic mineral phase, which might be attributed to various anthropogenic sources mainly the traffic related activities. Recently, this finding has an important implication in monitoring the urban and roadside soil heavy metal pollution, which is developed into new concept called the environmental magnetism.

Keywords: Magnetite, Urban soil, Heavy metals, Magnetic Proxies, Pollution, VSM.

1. Introduction

The first explicit description of environmental magnetism as a distinct field was reported by (Thompson & Oldfield, 1986). The environmental magnetism, a newly developing interdisciplinary trend, aimed to use the magnetic proxies as pollution indicator (Fassdinder et al. 1990; Morris et al. 1995; Versteeg et al. 1995; and Ptrovsky et al. 1999). The extent of this methodology was reviewed in details in (Oldfield et al. 1991; Versteeg et al. 1996; and Gautam et al. 2005).

Environmental magnetism has played an important role in understanding past climate change through studying of loess, lake and marine sediments magnetic properties (Waden, 2004). Furthermore, the environmental magnetism acts as a more rapid and non-destructive means of assessing pollution history of sediments (Brilhante et al. 1989, Foster et al., 1991, and Charlesworth & Lees, 2001). Moreover, Shilton et al., (2005) found positive relationship between magnetic contents and organic matter in dust samples.

Strzyszcz and Magiera, (1998) had investigated the correlation coefficient between magnetic susceptibility and heavy metal concentration in industrial areas. They showed that the magnetic susceptibility and the concentration of heavy metals in soil were in good correlation. Chalresworth and Lees (2001) reported a good correlation between heavy metal concentrations and magnetic proxies in Lake Core sediments. Good correlation was pointed out to exist between heavy metal and the magnetic mineral characteristics (Beckwith et al., 1986; Rose and Bianchi-Mosquera, 1993; Hunt et al., 1995). Kim et al. (2007), noticed a positive significant correlation between enrichment index of the magnetic susceptibility (**Ei** χ) and enrichment index of analyzed element (**Ei** metals), which confirmed the validity of use of magnetic proxies for heavy metal pollution.

Magnetic measurements were shown to be useful in investigating the atmospheric aerosols pollution, and source of pollution in many urban and industrial areas (Hoffman et al. 1999; Muxworthy et al. 2001; and Jordanov et al. 2003). Using the rapid and inexpensive environmental magnetism method, it is possible to obtain qualitative or semi-quantitative data on urban pollution, specially the magnetic susceptibility (Kim et al. 2007). Lu et al. (2005) showed that the magnetic properties and heavy metal content of automobile emission particulates resulted in significant positive correlations between the magnetic parameters and the contents of Pb, Cu and Fe. The magnetic measurements of various environmental materials, such as atmospheric particulates, roadside dust, soil, and vegetation, have successfully detected the source of pollution in many urban and industrial areas (Hoffman et al. 2003; and Jordanova et al. 2003).

Xia et al. (2001) suggested mixed contribution of magnetic materials from natural and anthropogenic sources; they confirmed the relationship between magnetic materials and pollution identification studies. Lu et al. (2005) showed that ferromagnetic materials were responsible for the magnetic properties of automobile emission particulates, and found that Cu, Pb, Cd and Fe are correlated with the magnetic particulates in automobile emissions.

The positive correlations between organic matter content of urban street dust and certain mineral magnetic

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properties were reported by (Shilton et al. 2005). In Jordan, the first attempt related to environmental magnetism implications was limited to motioning the roadside pollution using magnetic proxies (El-Hasan and Lataifeh, 2003; and El-Hasan, 2008). However, there are no previous studies in Jordan in using this implication to delineate the urban soil heavy metal pollution. The studied area was chosen as a known polluted area based on the results of (El-Hasan, 2002). The current work aimed to study the content and type of magnetic mineral phases in the urban soils of Sahab city, central Jordan, using two magnetic proxies, the initial magnetic susceptibility (χ_{in}) and the saturation magnetization (M_s). Moreover, this study aims to unravel the relationship between the heavy metals and magnetic parameters in soil samples and to determine the influences of the industrial activities in Sahab industrial city. Additionally, it aims to determine which magnetic proxies can be used as an effective environmental pollution probe, also to identify the magnetic mineral phases using the X-Ray Diffraction (XRD) technique. As well, to study the effect of grain size on the observed magnetic parameter, and to evaluate the environmental situation in accordance to the obtained results using the Index of Pollution (IP) and the categorization of samples based on their activities.

2. Study Area Settings

Sahab city is located in the central region of Jordan, 12 km to the east of the capital Amman (Fig. 1). It is of moderate topography with an altitude of around 700 m above sea level, and of moderate precipitation of around 250 mm/year. The soil of the study area is of Vertisol type, and the texture analysis shows that it has sandy clay; composed of sand 50%, clay 25% and silt 22% (El-Hasan, 2002)..

The study area is about 25 km^2 with 60,000 inhabitants. It compresses the Jordanian first and largest industrial estate King Abdullah the Second Industrial Estate (KAIE), which was established in 1980. It is located at the southeastern part of the study area (Fig. 1). It contains 365 firms with various types of industries such as engineering, chemical, pharmacological, food, plastic, rubber, and construction etc. Besides, an international highway and leading national roads crosses Sahab city.

The study area is dominated by Al-Hisa Phosphorite Unit (AHP) of Campanian-Mastrichitian age. It is 15 - 20 m thick, and consists of thin-bedded chert, white marl, chalky - marl, and phosphate (Fadda, 1991).

3. Sampling and Analytical Methods

A total of 56 samples were collected on a basis (500X500) grid across the whole city with a density of 9 samples per km^2, each soil sample was collected from upper soils (0-10 cm depth). The samples were collected during the period from January to April 2000. Each sample coordinate was delineated, using the GPS (Garmin GPS II Plus).

The samples extracted by taking 2g of soil sample (<2mm), then mixed with 25 ml of de-ionized water, vigorously shaken for 2 hours, and then centrifuged for an hour at 700 revolutions using Sorvall RC-5B Refrigerated Super Speed Centrifuge (model GFL-3032). The solution was then transferred into 50 ml polyethylene bottles (Water extract). Residual was treated with 25ml of 0.01M HNO_3 and again shacked and centrifuged as in the previous step; the extract was decanted into 50 ml-polyethylene bottles (Acid extract). The soil pH and the electrical conductivity (EC) were analyzed by mixing 1:5 ratios of soil and de-ionized water.

Heavy metals were determined using Perkin Elmer AAS Analyst 300, with graphite furnace HGA 800, and autosampler AS 72.The analytical accuracy was monitored by using (Fluka Chemika) reference standard solution. The error for all analyzed elements was within 5% of the certified references.

Samples were sieved into sand size (63-150μm), and silt size (<63 μm). The two different sizes samples were analyzed for their initial magnetic susceptibility χ_{in} and saturation magnetization M_s using Vibrating Sample Magnetometer (VSM). The VSM gives an indirect measure of the saturation magnetization (M_s) and the initial magnetic susceptibility χ_{in}. The parameters can be deduced from the initial magnetization curve with an applied magnetic field up to 10^4 Oe. The VSM was also used to determine the magnetic phase from the shape of the hysteresis loops (Xia et al. 2008).

The measurements were made at room temperature (RT) in an applied magnetic field (H) up to 1 Tesla (Oe). The saturation magnetization M_s was determined by plotting M versus 1/ H for each sample, and then extrapolating to 1/H equal zero. The intercept with the M - axis represents the M_s value, as shown Fig. (2a), and then the portion of M_s was recalculated to 1g samples. The initial magnetic susceptibility χ_{in} was calculated, using the following equations:

$$\chi_{in} = dM / dH \quad (1)$$

(Culity, 1972)

(χ_{in}) was deduced by calculating the slope of the line as H = zero and M = zero as shown in Fig. (2b). Then the portion of χ_{in} was recalculated to 1g sample.

The mineral constituents of the samples were determined using X-Ray Diffraction system (Philips-X` pert MpD) operating at 40 KV and 40 mA. Ten samples were pre-concentrated by separating the magnetic materials in each sample using ordinary magnet, then they were grinded till particle size became <63 μm, and after that they were analyzed using the XRD. The fine powder samples were randomly mounted on special slides and then scanned between 2° and 65°, using Ni-filtered Co K-α-radiation, divergent and scattering slits of 0.02° mm, a receiving slit of 0.15 mm, with stepping of 0.01° and scanning speed of 3°/min. For the M_s and χ_{in} heavy metals spatial distribution within the study area was graphically presented using computer program (Surfer, version 0.7).

4. Results and Discussion.

The total heavy metals (t-HM) were used as a measure for pollution, and represent the sum of the concentrations of (Fe, Mn, Cu, Co, Cr, Ni, Zn, Cd and Pb). The iron concentration, t-HM, magnetic susceptibility χ_{in} and saturation magnetization M_s in large and fine particles size

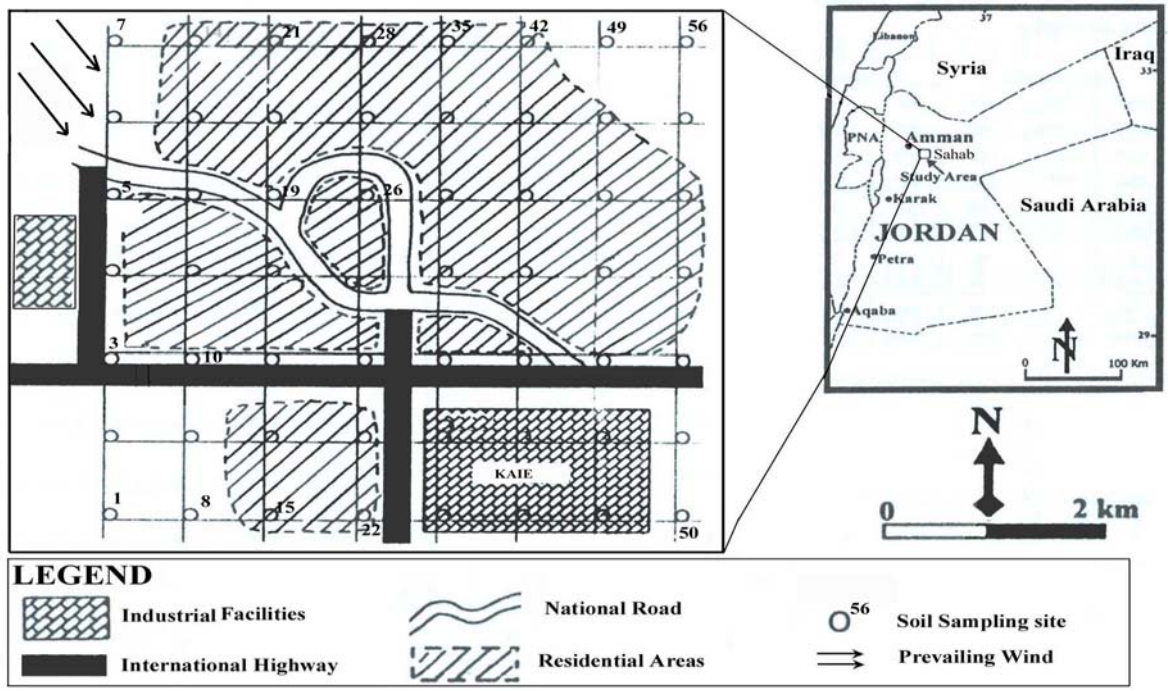


Fig. 1: Location map and sampling sites *(after El-Hasan, 2008)*.

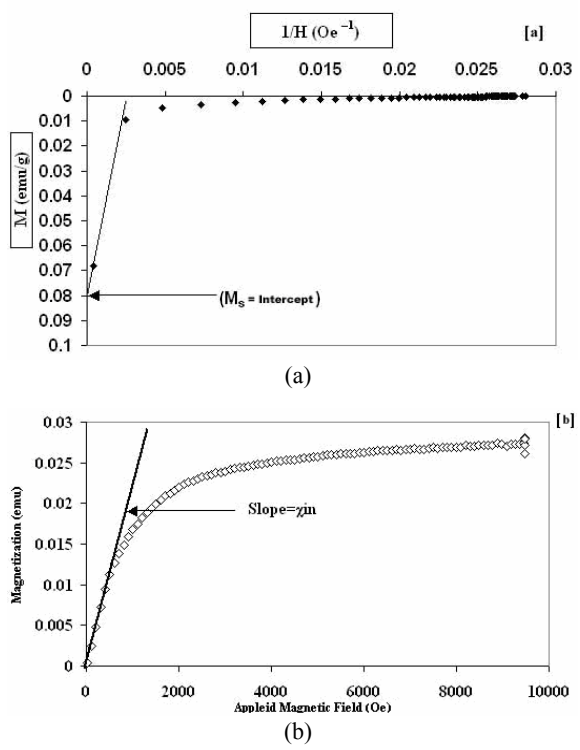


Fig. (2): a) M vs. 1/H plotting for a representative sample showing the determination of Ms values b) M vs. H plot for a representative sample showing how to calculate the initial magnetic susceptibility χin (slope of the bold line). (after El-Hasan and Lataifeh, 2003).

are presented in Table (1). Where the calculated results indicate the domination of the magnetic susceptibility over the saturation magnetization, which might be due to the fact that susceptibility represents the total contribution of ferromagnetic minerals (Dearing, 1999), while the saturation magnetization is only a measure of the magnitude of atomic magnetic moment.

4.1. Particle Size Effect

Many previous studies reported the dependence of the values of magnetic material concentrations on particle size (e.g. Heller et al., 1998; and Shi & Cioppa, 2006). Xia et al., (2001) has used the finest grain size (< 63 μm) in tracing street dust magnetic properties. Thomas (1987) pointed out that particles of size <2mm represent typical urban streams and soils, while (Forstner, 1983) indicated that those < 63 μm represent the lake basin sediments. The current study has divided the studied sample sizes into two categories < 63 μm and > 63 μm. Similar grain size categories were used by (Charlesworth & Lees, 2001).

By comparing the values of (χ_{in}) and ($\mathbf{M_s}$) in Table (1), we noticed an increase in magnetic proxies values of the large size particles more than that for the fine size particles Fig. (3). This might be attributed to the fact that large size particles of greater than 63 μm in diameter have low degree of pedogenesis process, which is the main factor that causes the degradation and disintegration of the particles. The low degree of pedogenesis is usually caused by the low precipitation and lower chemical weathering rate. The average annual precipitation in the studied area does not exceed 250 mm/year with high evaporation rates (Fadda, 1991; and Department of Meteorology 2004).

Table (1): Values of studied parameters (χ_{in}) and (M_s), Fe and t-HM contents in samples for the two investigated particle sizes.

Sample No.	Fine size (< 63 μm)		Large size (> 63 μm)		t-HM (ppm)	Fe (ppm)
	χ_{in} (emulg.Oe)10^{-5}	M_s (emulg)	χ_{in} (emulg.Oe) 10^{-5}	M_s (emulg)		
1	1.21	0.002	1.27	0.0025	8.8	6.3
2	0.90	0.002	1.46	0.0026	20.4	17.5
3	1.43	0.002	1.92	0.0027	32.8	28.6
4	1.83	0.002	1.65	0.0026	26.7	22.6
5	1.44	0.003	1.87	0.0028	76.5	71.5
6	1.25	0.002	1.28	0.0028	9.4	3.3
7	1.65	0.002	1.68	0.0023	15.8	13.8
8	1.56	0.004	1.31	0.0022	13.8	12
9	1.29	0.002	1.47	0.0028	9.8	7.3
10	1.73	0.002	2.37	0.0047	101	95
11	1.02	0.002	1.19	0.0021	8.0	3.4
12	1.42	0.003	1.49	0.0036	25.3	20.5
13	1.18	0.003	1.59	0.0025	9.9	7.6
14	1.38	0.002	1.87	0.0030	28.1	24.8
15	1.27	0.002	1.72	0.0026	22.1	18.8
16	1.40	0.002	1.24	0.0022	11.2	7.3
17	1.60	0.002	2.00	0.0030	53.2	46.4
18	1.36	0.003	1.44	0.0023	10.1	6.8
19	1.61	0.002	2.02	0.0030	48.2	42.6
20	1.52	0.002	1.72	0.0024	31.4	24.5
21	1.53	0.003	1.88	0.0030	37.0	32.4
22	1.35	0.002	1.34	0.0025	15.5	11.4
23	2.11	0.003	2.16	0.0041	89.2	82.9
24	1.07	0.002	1.57	0.0027	8.8	4.4
25	1.09	0.002	1.18	0.0023	8.7	4.4
26	1.27	0.004	1.59	0.0048	41.8	37.6
27	1.38	0.002	1.40	0.0019	18.4	13.5
28	1.31	0.002	1.38	0.0023	19.3	14.5
29	0.99	0.002	1.17	0.0018	24.6	21.1
30	1.56	0.003	1.60	0.0031	37.8	30.4
31	1.13	0.002	1.59	0.0026	15.3	8.6
32	1.35	0.003	1.41	0.0026	25.3	19.1
33	1.43	0.002	1.48	0.0024	20.8	14.6
34	1.32	0.003	1.35	0.0031	15.6	9.5
35	1.45	0.003	1.46	0.0029	39.0	34
36	0.88	0.002	1.23	0.0020	24.6	20.6
37	0.94	0.001	1.01	0.0015	6.5	4.5
38	1.10	0.002	1.29	0.0022	18.2	11.1
39	1.13	0.002	1.50	0.0027	21.8	17.6
40	0.91	0.001	1.14	0.0016	13.4	10.5
41	0.83	0.002	1.10	0.0025	20.9	16

Table 1 continues next page……

42	1.04	0.002	1.45	0.0025	18.1	12.4
43	0.96	0.002	1.33	0.0017	18.5	13.9
44	1.44	0.002	1.47	0.0020	16.9	12.9
45	1.40	0.002	1.43	0.0025	24.6	19.8
46	1.44	0.002	1.45	0.0027	26.2	17.9
47	1.02	0.002	1.29	0.0023	16.1	11.4
48	1.14	0.002	1.38	0.0026	18.7	13.9
49	0.94	0.002	1.62	0.0031	16.8	11.9
50	0.88	0.002	1.67	0.0029	14.4	10.3
51	1.18	0.002	1.13	0.0019	14.5	11.8
52	1.67	0.002	1.75	0.0026	43	38.1
53	1.62	0.002	1.60	0.0026	24.2	18.4
54	0.90	0.002	1.29	0.0024	13.4	8.5
55	0.96	0.002	1.66	0.0026	23.5	19.6
56	0.90	0.002	1.33	0.0025	22.9	17.8
Average	1.28	0.0022	1.50	0.0026		
Max	2.11	0.0041	2.37	0.0048		
Min	0.83	0.0014	1.01	0.0015		
ST. Dev.	0.28	0.0005	0.28	0.00062		
Threshold	1.21	0.002	2.05	0.00384		

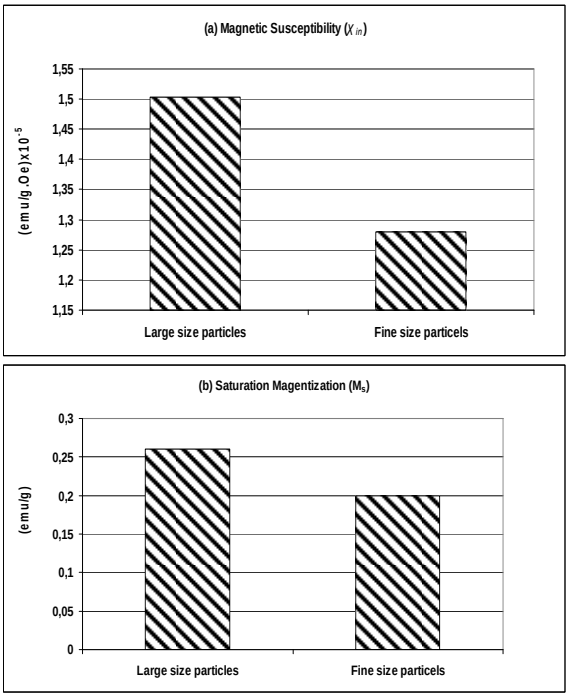


Fig. (3): Histogram showing the difference between the fine and large size particles in their contents of the (a) Magnetic susceptibility, and (b) Saturation magnetization.

Therefore, the climatic conditions would lower the pedogenesis as a result of lowering the chemical weathering rate. Similar results were reached by Kim et al., (2007) and El-Hasan, (2008). The effect of the post-depositional processes (diagenetic) or pedogenesis on the magnetic signal was recognized by (Hofmann et al. 1999).

The values of χ_{in} for large grain size particles range (1.01 - 2.37 x10^{-5} emu/g.Oe) with an average of (1.5 x10^{-5} emu/g.Oe). The value of M_s ranges from (0.0015 - 0.0048 emu/g) with an average of (0.0026 emu/g). The spatial distribution of χ_{in} and M_s are illustrated graphically in Figures (4 a & b).

According to data illustrated in Table (1) the values of initial magnetic susceptibility χ_{in} and the saturation magnetization M_s are higher in the following samples (3, 5, 10 and, 19), particularly the sample (19) is located at the center of the city and influenced by the highest density of traffic jam. Samples (3 & 5) are located at the international highway and the main entrance of Sahab city respectively, where both have a high traffic density. The sample (36) is located in the middle of King Abdullah II Industrial Estate (KAIE) that is affected by the industrial activity alone. However, it bears low values of both χ_{in} and M_s in large particle size (0.002 emu/g and 1.23 x10^{-5} emu/g.Oe), respectively. This would indicate the influence of traffic as the prime source of magnetic pollution. Although, Kim et al. (2007) has found that industrial areas bear the higher magnetic concentrations, with intermediate concentrations in traffic area, the lowest concentrations were found in park areas.

4.2. Relationship between magnetic proxies and heavy metal distribution

The correlation coefficient was used in order to clarify the relationship between the magnetic proxies and heavy metal contents. The high correlation coefficient between the heavy metals concentration with the initial magnetic susceptibility (χ_{in}) and saturation magnetization (M_s) was obvious (Table 2). This table shows that the correlation coefficient between the t-HM and the initial magnetic susceptibility (χ_{in}) values are (0.77 - 0.59) for large and

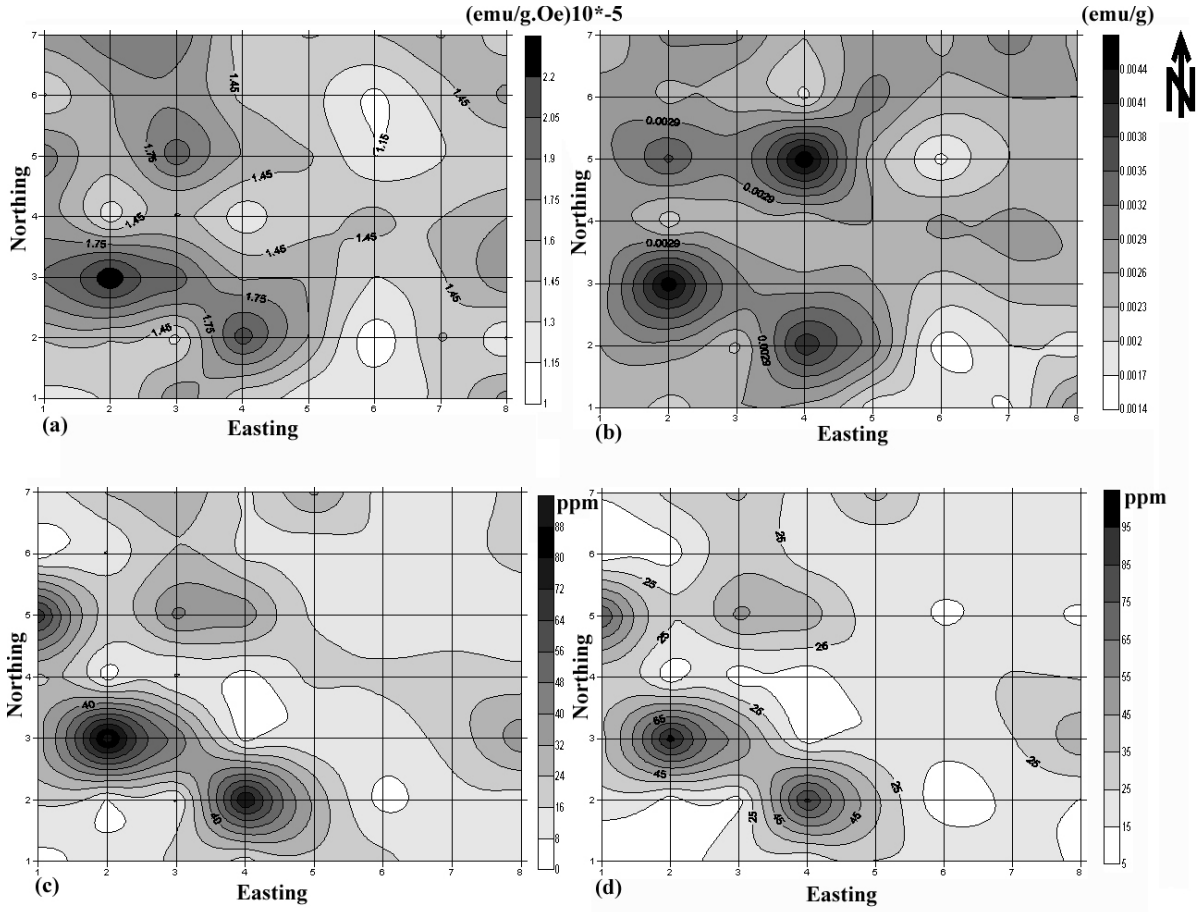


Fig. (4): Contour maps showing the distribution of studied parameters (a) Magnetic Susceptibility, (b) Saturation magnetization, (c) Fe, (d) Total heavy metal (t-HM).

Table 2. Correlation coefficient matrix for χ_{in}, M_s, t-HM and Fe in both fine and large particle size.

		Fine			
		χ_{in}	M_s	t-HM	Fe
Large	χ_{in}		0.50	0.59	0.59
	M_s	0.68		0.23	0.24
	t-HM	0.77	0.66		0.99
	Fe	0.77	0.66	0.99	

fine size particles, respectively. Whereas the correlation coefficient between the t-HM and the saturation magnetization (M_s) have the values (0.66 - 0.23) for large and fine size particles, respectively. Moreover, the correlation coefficient showed large difference between the two magnetic proxies; where the correlation between M_s and heavy metals is lower than the correlation between χ_{in} and heavy metals. This might be attributed to the fact that χ_{in} is the measure of the value of a respective quantity at the origin of the initial magnetization curve.

The distribution of all studied parameters (Fe, total heavy metals (t-HM), χ_{in} and M_s) are shown as contour maps using the Surfer 7.0 as illustrated in Fig. (4). There is an obvious correlation between the χ_{in} and M_s together with total heavy metals (t-HM) and iron (Fe). This is in agreement with the results obtained from correlation coefficient in Table (2). There are many previous studies that reached similar conclusions (e.g. Bityukova et al., 1999); they found the Ni, Cr, Zn, Cu, Pb and Mo are the heavy metals that influenced the low field susceptibility (χ_i). In addition, the laboratory studies reveal that Fe-oxides particles in soil are highly adsorbing of heavy metals (Rose and Bianchi-Mosquera, 1993).

4.3. Magnetic mineral phases characterization

The magnetic materials contained in the samples of high magnetic susceptibility were pre-concentrated with ordinary magnet. A similar way of treatment was done by (Kim et al., 2007). The pre-concentrated samples were investigated using the X-ray diffractometer; the results showed that the magnetite is the main magnetic mineral phase (Fig. 5). The X-ray chart in figure (5) is for the sample (No. 23), which is located at a mixed area; where residential and traffic activities are usually intervening. This conclusion indicates the effect of anthropogenic origin of the magnetic pollutant materials, like the manufactured iron structures such as the vehicle structures

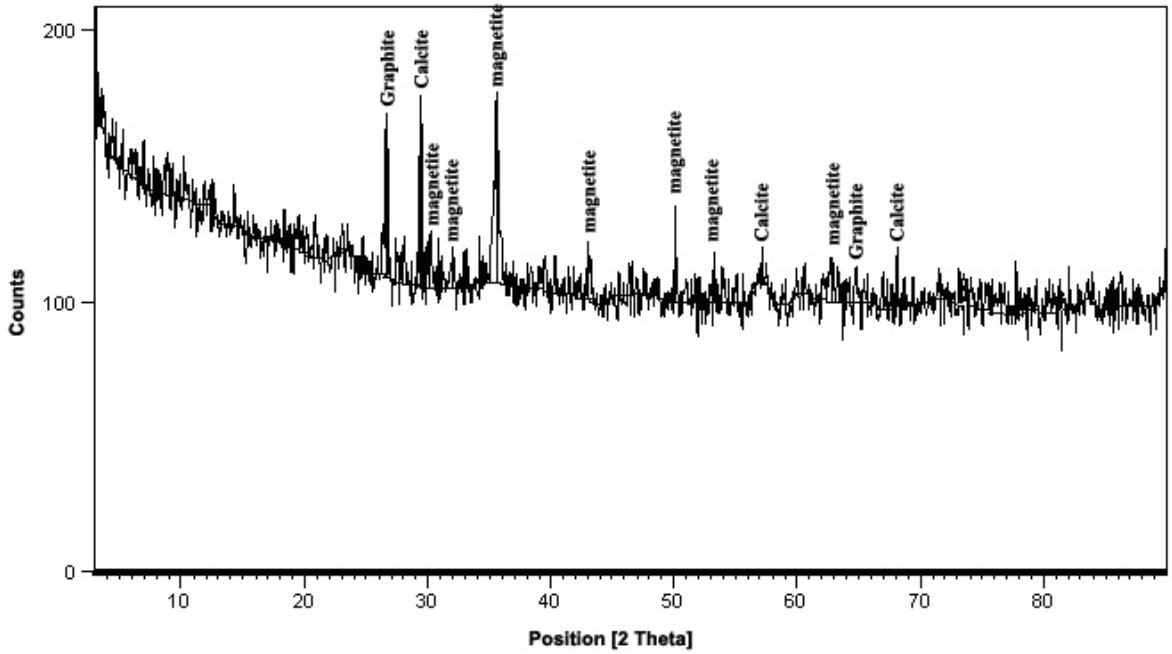


Fig. (5): X-Ray diffraction chart for selected soil sample, showing that magnetite is the main magnetic mineral phase.

which are mainly composed of magnetite-like materials (Kapicka et al. 2003). Shi & Cioppa, (2006) attributed small grain magnetic source to the construction debris or eroded river sediments whereas the larger magnetic particles are associated with industrial and traffic areas. Moreover, this result was reached by (Thomson and Oldfield, 1986). Hofmann et al., (1999) found the magnetite-like phase is the responsible for enhancement of magnetic signal in roadside soil whereas the natural magnetic materials are often composed of hematite and goethite (Xia et al. 2008). Gautam et al., (2004) reported that manufactured bricks and kilns used stable hematite and magnetite; similar results were also reported in (Hofmann et al., 1999; and Guatam et al. 2005). Furthermore, the hysteresis loop for the same sample (No. 23) shows a typical ferrimagnatic material with low coercive force (i.e. steep and narrow loops) as shown in Fig. (6), which confirms the presence of magnetite as the main magnetic mineral, such an observation was reported also by (Xia et al. 2008).

Shilton et al., (2005) found higher magnetite more than hematite in dust magnetic minerals. Moreover, Gautam et al. (2004) have found that magnetite is the dominant magnetic phase for typical road dust samples. Moreover, the magnetite presence in soil was attributed to be as a result of the pedogenesis (Banerjee, 2006).

4.4. Environmental aspects

The environmental implication of the obtained results shows that magnetic proxies can be used as environmental monitoring tools, for both natural and anthropogenic sources of pollution. The discrimination between lithological and anthropogenic influence on topsoil, using the magnetic susceptibility was successfully done by (Magiera et al., 2005). Therefore, the data were further treated using the index of pollution (IP).

The early-developed method of calculating the index of pollution (IP) of (Chester et al., 1985) was used. This method was successfully used in evaluating the urban pollution in Karak city, central Jordan (El-Hasan and Jiries, 2000).

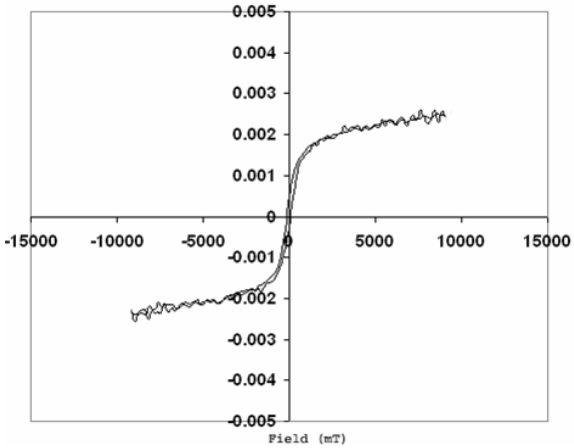


Fig. (6): Magnetic hysteresis loop of the topsoils from the study area of Sahab city.

This technique is based on assigning the ABS (Artificial Background Samples) in the sampling sites. The site numbers (9, 14, 24, 15 and 37) were chosen as the ABS due to their lowest concentration of heavy metals, and site numbers (37, 40, 41, 43 and 51) were chosen as the ABS due to their lowest concentration of magnetic proxies. Then the threshold for each element based on the ABS was calculated. The Index of pollution (IP) was then calculated by dividing the concentration of each element by the new threshold of the ABS of that element as follows:

$$Threshold = (X_{(ABS)} + 2\,\sigma_{(ABS)}) \quad (2)$$

Chester et al., (1985).

$$IP = Conc.\ E/Threshold \quad (3)$$

Chester et al., (1985).

Where, $X_{(ABS)}$ is the average of elements in the ABS samples, and $\sigma_{(ABS)}$ is the standard deviation of each element of the ABS samples as shown in Table (3).

According to the data presented in Table (3), we notice the existence of a positive relationship between the IP for heavy elements and both the IP for the initial magnetic susceptibility χ_{in}, and the saturation magnetization M_s. Moreover, there was a clear positive significance correlation coefficient between the IP of both χ_{in} and M_s with the IP for total heavy metals (IP t-HM) and the IP for iron (IP Fe). The correlation significance was also higher in the large size particles (0.66, 0.77) between M_s and χ_{in}, respectively, rather than for fine size particles (0.24 and 0.59) between M_s and χ_{in} respectively as shown in Table 4.

The samples were categorized into four groups based on the dominating activities at each site. These groups are traffic (17 samples), industrial (11 samples), residential (20 samples) and the rest were considered as background (8 samples), which are the empty spaces. The averages of the χ_{in}, M_s, t-HM and Fe in both particle sizes are illustrated in Table 5.

Traffic samples bear the highest magnetic materials for both sizes, where the χ_{in} and M_s are (1.66 10^{-5} (emu/g.Oe), 0.0029 emu/g) and (1.41 10^{-5} (emu/g.Oe), 0.0022 emu/g) for large and fine particle, respectively. However, residential sites came in the second place followed by industrial, and finally the background sample (Fig. 7).

The traffic pollution was pointed out as the main source for magnetic pollution (Hoffmann et al., 1999; Lu, 2003 and Lu et al. 2005; and Guatam et al. 2005). Moreover, (Shilton et al. 2005) had reported the traffic related emissions enhancing strong magnetic signature.

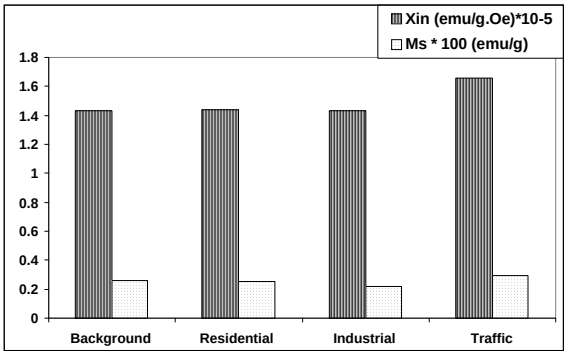
Using the magnetic susceptibility χ_{in} the enrichment series was as follows: Traffic> Residential> Industrial> Background, in both fine and large particle sizes. However, for the saturation magnetization M_s in large size particles it was: Traffic> Background>Residential> Industrial, whereas in fine particles there was no significant variation between the four categories (Table 5).

This would confirm that χ_{in} as well the large size particles exhibit more clearly magnetic signature than M_s and fine particles. And it indicates that the traffic areas have usually higher magnetic susceptibility. Although the background samples have the lowest magnetic concentrations, their concentrations have little difference from other categories (Table 5). This might be attributed to the fact that these samples are mainly composed of red soils which normally have high Fe content. The analytical measurement of χ_{in} and M_s for these samples, using the VSM, usually measures not only the adsorbed magnetic materials (anthropogenic) but also the magnetic materials of natural origin inside the soil itself. This caused high magnetic signature in the background samples.

5. Conclusions

The magnetic proxies show a good correlation with heavy metals, and thus can be used as indicator for pollution; this correlation was evident from the IP results too. The magnetic susceptibility was better than saturation magnetization as pollution proxy indicator. The large grain size bears higher magnetic materials than smaller size, which can be attributed to the lack or low rate of pedogenesis. Traffic areas show higher magnetic pollution than other industrial and residential areas.

(a)



(b)

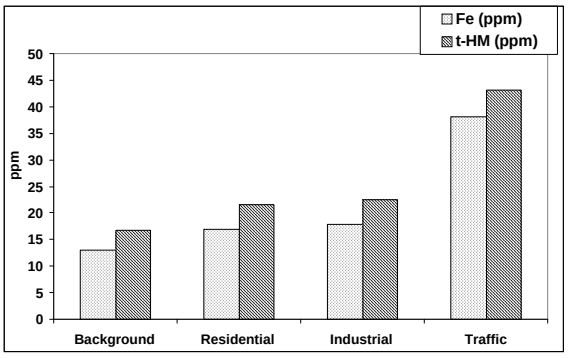


Fig. (7. a,b): Histogram showing the average values for all categories in a) Magnetic proxies, and b) Fe and t-HM.

Table 3. Index of pollution values for (χ_{in}) and (M_s), t-HM and Fe in the large size and fine size particles.

Sample	Fine particles		Large particles		IP t-HM	IP Fe
	IP- χ_{in}	IP-M_s	IP- χ_{in}	IP-M_s		
1	0.93	1.00	*0.94*	1.00	0.79	0.64
2	0.69	0.67	1.08	1.04	1.82	1.79
3	1.10	0.83	1.42	1.08	2.93	2.93
4	1.40	0.96	1.22	1.04	2.38	2.31
5	1.10	1.04	1.38	1.12	6.83	7.32
6	0.95	0.75	0.95	1.12	0.84	0.34
7	1.26	0.88	1.24	0.92	1.41	1.41
8	1.19	1.50	0.97	0.88	1.24	1.23
9	0.99	0.92	1.08	1.12	0.87	0.75
10	1.33	0.83	1.75	1.87	9.02	9.72
11	0.78	0.75	0.88	0.84	0.71	0.35
12	1.09	1.17	1.10	1.43	2.25	2.10
13	0.91	1.25	1.18	1.00	0.88	0.78
14	1.06	0.88	1.39	1.20	2.51	2.54
15	0.98	0.88	1.27	1.04	1.97	1.92
16	1.07	0.96	0.92	0.88	1.00	0.75
17	1.22	0.83	1.48	1.20	4.75	4.75
18	1.04	1.13	1.06	0.92	0.90	0.70
19	1.23	0.92	1.49	1.20	4.30	4.36
20	1.16	0.79	1.27	0.96	2.80	2.51
21	1.17	1.08	1.39	1.20	3.31	3.32
22	1.03	0.88	0.99	1.00	1.39	1.17
23	1.61	1.08	1.60	1.63	7.97	8.49
24	0.81	0.83	1.16	1.08	0.78	0.45
25	0.84	0.71	0.87	0.92	0.78	0.45
26	0.97	1.67	1.18	1.91	3.73	3.85
27	1.05	0.79	1.04	0.76	1.64	1.38
28	1.00	0.83	1.01	0.92	1.72	1.48
29	0.76	0.63	0.86	0.72	2.20	2.16
30	1.19	1.17	1.18	1.24	3.37	3.11
31	0.87	0.75	1.17	1.04	1.36	0.88
32	1.04	1.08	1.04	1.04	2.26	1.96
33	1.09	0.96	1.09	0.96	1.85	1.49
34	1.01	1.09	1.00	1.24	1.39	0.97
35	1.11	1.05	1.08	1.16	3.49	3.48
36	0.68	0.67	0.91	0.80	2.20	1.83
37	0.72	0.60	0.75	0.60	0.58	0.46
38	0.84	0.67	0.96	0.86	1.63	1.14
39	0.86	0.88	1.11	1.08	1.95	1.80
40	0.70	0.59	0.85	0.64	1.20	1.07
41	0.64	0.73	0.81	1.00	1.87	1.64
42	0.80	0.88	1.07	1.00	1.62	1.27
43	0.74	0.69	0.98	0.66	1.65	1.42
44	1.10	0.65	1.09	0.80	1.51	1.32
45	1.07	0.96	1.06	1.00	2.20	2.03
46	1.10	0.83	1.07	1.08	2.34	2.11
47	0.78	0.79	0.95	0.92	1.43	1.17
48	0.87	0.75	1.02	1.04	1.67	1.42
49	0.72	0.71	1.20	1.24	1.50	1.22
50	0.67	0.67	1.23	1.16	1.29	1.05
51	0.90	0.83	0.84	0.74	1.29	1.21
52	1.29	0.92	1.30	1.02	3.84	3.90
53	1.24	0.92	1.18	1.02	2.16	1.88
54	0.69	0.75	0.96	0.96	1.20	0.87
55	0.74	0.77	1.23	1.04	2.10	2.01
56	0.69	0.71	0.98	1.00	2.05	1.82

Acknowledgment

The authors are deeply thankful for Al-albayt University (Earth Science Institute) for their help in X-Ray Diffraction.

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