Magnetic susceptibility and heavy-metal contamination in topsoils along the Izmit Gulf coastal area and IZAYTAS (Turkey)

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Abstract

The study on topsoil contamination due to heavy metals was carried out by using the Magnetic susceptibility (MS) measurements in Izmit industrial city, northern Turkey. We attempted to investigate correlations between the concentration of selected heavy metals and the MS from 41 sample sites around Izmit Gulf. These investigations let us quantify and standardize the MS method, which may have consequences for long term monitoring of anthropogenic pollution, especially in urban areas. The MS surfer contour map based on the topsoil measurements was compiled with a randomly ranged distance density. The soil samples collected throughout the industrial areas, the parks, road sides and residential areas were also analyzed by Atomic Absorption Spectrometer. Heavy metals Cu, Ni, Cr and Pb show strong correlations with MS, while Zn and Co show a weak correlation with MS. Moreover, the Tomlinson pollution load index (PLI) shows insignificant correlation with the MS.

The MS was examined vertically (0–30 cm) with respect to anthropogenic and/or lithogenic influences at the fourteen sample sites. The maximum values were mostly observed in depths of 2–5 cm and the MS values on the depth profiles vary between $10 \times 10^{-8}$ m$^3$ kg$^{-1}$ and $203 \times 10^{-8}$ m$^3$ kg$^{-1}$. The study revealed that MS is an inexpensive, fast and non-destructive method for the detection and mapping of contaminated soils.

Keywords: Magnetic susceptibility, Heavy metals, Soil contamination, Izmit, Turkey

1. Introduction

Taking magnetic measurements on soil sediments and identified pollution sources has become a widespread practice as a reliable, efficient and sensitive method for evaluating polluted samples. This method is promising as an alternative to conventional chemical analysis. Magnetic susceptibility (MS) values depend on the composition, grain size of magnetic minerals and their source, such as lithogenic, pedogenic and anthropogenic origins. In this paper, we demonstrate an application of MS measurements to evaluate the degree of pollution along the Izmit Gulf coastal area, Turkey.

MS operates as efficiently as chemical measurements on soil and sediment samples for monitoring anthropogenic pollutions. In this context, several studies revealed important insights about pollution in soil, air and water samples through heavy metal and industrial activities. Led by Le Borgne’s (1955, 1956) pioneering work, researchers identified important sources of contamination such as seasonal changes in climate (Tite and Linnington, 1975), lithological differences in sediments due to changes in their depositional environments (Mullins and Tite, 1973) and magnetic enhancement of topsoils due to natural processes (Mullins, 1977). MS was shown to be highly effective for investigating industrial pollutants, traffic and other atmospheric pollutants (Thompson and Oldfield, 1986; Thornton, 1991; Strzyszcz, 1993; Hay et al., 1997; Strzyszcz and Magiera, 1998; Durza, 1999; Hoffmann et al., 1999; Morris et al., 1995; Kapicka et al., 1999).

Many researchers reported that MS measurements are very useful in investigating industrial discharges and exhaust gases in urban regions. It appears that atmospheric deposition is one of the major sources of contamination in topsoil samples (Shu et al., 2000; Lecoanet et al., 2001; Goddu et al., 2004; Knab et al., 2001; Hanesch and Scholger, 2005; Lu et al., 2007). Hanesch and Scholger (2002) also used MS measurements to estimate anthropogenic sourced pollution levels of the soils and sediments in urban area. Further, several authors emphasized the value of MS studies in determining heavy-metal pollutions in Turkey (Aydin and Gelisli, 1996; Gelisli et al., 1996; Gelisli and Aydin, 1998; Okay et al., 2001). Tolun et al. (2001) and Ozkul (2003) studied the effects of industrialism on heavy-metal concentrations in Izmit and surrounding areas through laboratory testing of collected samples. According to this study, Izmit Gulf region shows high concentrations of Cu, Pb, Zn, Ni and Co.

To identify the type of industrial polluting sources, some researchers used magnetic parameters. In this context, MS mapping of soils and sediments has become one of the most important tools for estimating anthropogenic pollution (Oldfield et al., 1985; Heller et al., 1998; Petrovsky et al., 2001; Schibler et al., 2002; Kapicka et al., 2003;
Jordanova et al. 2004; Lu et al., 2005a,b). These studies illustrate the relationships between heavy-metal contents and the MS measurements in soil, road dust, airborne particle and sediment from sea, river and lake samples. The use of magnetic measurement as a heavy-metal pollution indicator is based on the fact that origin of heavy metals and magnetic particles is genetically related. By focusing on environmental and magnetic factors, such studies demonstrated the relationship between heavy-metal contents and magnetic properties, including lithological and pedological properties in soils (Jordanova et al., 2004; Schmidt et al., 2005). Several studies confirmed a direct correlation between the MS of contaminated soils and the presence of hydrocarbons and certain heavy metals such as Pb, Zn, Cr, etc. (Moreno et al., 2003; Desenfant et al., 2004; Lu and Bai, 2006).

In this paper, we would like to compare the results obtained from chemical analyses of heavy metals. Our main purposes are to (a) examine the relationship between the MS and heavy-metal contamination along the Izmit Gulf coastal area, (b) obtain robust information on the relative degree of industrial pollution, and (c) characterize the anthropogenic magnetic particles in road dust materials in the industrial section of the region.

## 2. Material and methods

### 2.1. Study area

Izmit is a coastal city located in the eastern Marmara Sea, near Istanbul (Fig. 1), and is one of the most populated and industrialized provinces of the Marmara Region (40°75′N, 29°91′E). It is one of the country’s most important gateways by rail, road, sea and air. Starting from the 1960s and during the 1980s, some of industrial facilities were initiated along the shores of the sheltered sea of the northern Marmara coast and Izmit Bay. Today these areas are the “hot spots” in relation to the environmental constraint of the industrial corporation. Its location and the rapid industrialization resulted in accelerated urban development. Izmit manufacturing industry shares 10% of investment goods, 2.8% of consumer product goods, and 27% chemicals within the manufacturing industry in Turkey. This region includes major industries, such as those that deal with iron production, and, refining, processing and transporting crude oils. Some of the industries and their sources of pollution are shown in Fig. 1. The city center has a population of 248,424 during the 2007 census. Neighboring Istanbul,
one of the world’s largest metropolitan centers, Izmit is one of the most densely populated cities of Turkey with 344 people per square kilometer, with a population growth of 20% per year (Tepecki and Anderson, 2006). It is located on the crossroad between Asia and Europe, as well as the Izmit Gulf, which is a natural harbour and a busy maritime line. Climatic conditions of the Izmit Gulf region are usually mild, whereas higher regions have more severe weather conditions. Izmit’s climate can be seen as a transition between Mediterranean and Black Sea climates. While summers are hot with scarce rainfalls, winters are rainy and occasionally cold. The average annual temperature is 15°C and average rainfall is 800 mm at Izmit.

One of the dominant landmarks in this area includes the Samanlı mountain, with 1,330 m in height starting from the west side of the Sakarya river, and reaching Pamukova and North of the Iznik Lake until Bozbunur. Izmit lies on one of Turkey’s active tectonic fault lines. As a result, this area has often been destructively affected by severe earthquakes. Izmit was heavily damaged by the Marmara Earthquake on August 17, 1999. More than 20,000 people died, over 70% of the buildings collapsed, and Turkey’s largest energy producing establishments were damaged (Tuysuz and Genc, 1999).

2.2. Geology

Fig. 1 shows the modified geological map of the region. Scholars who have studied this area (Ozdemir et al., 1982; Yılmaz et al., 1995; Gedik et al., 1999; Yigitbas et al., 1999; Ozalaybey et al., 2008) have found the following patterns: Triassic aged the Cakraz formation (c-T2); Recrystallized limestone and pebbles, red colored sandstone, siltstone, claystone, Campanian–Maestrichtian aged the Peksimet formation (c-T2); sandstone dominant conglomerate, limestone and...
marl, Campanian–Lutesiyen (Ludavian) aged the Akveren formation (c-T1); clayey limestone, marl and sandstone, Campanian–Lutesiyen (Ludavian) aged the Caycuma formation (c-T2); sandstone, claystone, marl, limestone and pebblestone, Holocene aged Alluvium (Q); gravels, sand, silt and clay (Sariaslan, 1999; Ozalaybey et al., 2008). Formation types of sample sites are provided in Table 1.

2.3. Sampling

In this study, the sampling stations were considered to pursue the project which covers the Izmit Gulf coastal area, and a small area around the Izmit Waste and Residue Treatment, Incineration and Recycling, Co., Inc. (IZAYDAS) (Fig. 1). Sampling stations were subdivided into two main groups: Stations 1 to 14 include both the topsoil and vertical profile MS measurements taken from an about 300 km² area in the Izmit Gulf coastal area, whereas stations 15 to 41 cover only topsoil samples around a factory of about 15 km² area. The vertical MS measurements were taken with 1-cm interval from 0 to 30 cm depth. The vertical MS measurements were stored in bags for use. Samples were dried and prepared following the protocol for acid digesting of sediments. Soils were digested in an oven using a mixture solution of the concentrated acids of HNO₃-HF-HClO₄. After digestion, the solution was cooled and diluted with 10–15 mL of distilled water, and filtered. The filtrate was then made up to 50 mL with distilled water and then analyzed for Cu, Pb, Zn, Ni, Cr, Cd and Co using atomic absorption spectrometer (Shimadzu model AA-6601F Shimatsu Ltd., Australia). Analytical variability was tested by repeated analysis on every ten samples. Experiments were performed in triplicate and the standard deviation was computed and indicated in the plots as error bars with a confidence limit of 95%. The optimum conditions of the instrument were wave length 283.3 nm, slit width 0.5 nm and lamp current 830 mA. The wave lengths and slit widths used were 213.9 nm and 0.7 nm for Zn, 232.0 nm and 0.2 nm for Ni, 357.9 nm and 0.7 nm for Cd, 228 nm and 0.7 nm for Cr, 228 nm and 0.7 nm for Cd and 240 nm and 0.7 nm for Co. The standard solutions of the elements were prepared in order to obtain the calibration curves.

2.5. Soil chemical analysis

Heavy-metal concentrations were determined only for topsoil samples (0–5 cm) by atomic absorption spectrometry. The samples were dried and prepared following the protocol for acid digesting of sediments. Soils were digested in an oven using a mixture solution of the concentrated acids of HNO₃-HF-HClO₄. After digestion, the solution was cooled and diluted with 10–15 mL of distilled water, and filtered. The filtrate was then made up to 50 mL with distilled water and then analyzed for Cu, Pb, Zn, Ni, Cr, Cd and Co using atomic absorption spectrometer (Shimadzu model AA-6601F Shimatsu Ltd., Australia). Analytical variability was tested by repeated analysis on every ten samples. Experiments were performed in triplicate and the standard deviation was computed and indicated in the plots as error bars with a confidence limit of 95%. The optimum conditions of the instrument were wave length 283.3 nm, slit width 0.5 nm and lamp current 830 mA. The wave lengths and slit widths used were 213.9 nm and 0.7 nm for Zn, 232.0 nm and 0.2 nm for Ni, 357.9 nm and 0.7 nm for Cd, 228 nm and 0.7 nm for Cr, 228 nm and 0.7 nm for Cd and 240 nm and 0.7 nm for Co. The standard solutions of the elements were prepared in order to obtain the calibration curves.

2.6. Data analysis

Statistical analyses of the magnetic measurements and chemical compositional data were carried out using Microsoft Excel 2002 SP3. Correlation coefficients were obtained in order to establish the relationship between heavy-metal concentrations and magnetic parameters in the topsoil samples. Mapping of the MS distribution was created with the Surfer 4.0 software.

The Tomlinson pollution load index (PLI) was calculated to examine its correlation with the MS. The linear correlation between the PLI and MS originally was predicted by Angulo (1996). Chan et al. (2001) used the PLI to show how much a sample exceeds the contents

![Table 1](image)

Fig. 2. Magnetic measurement results of the topsoil samples along the Izmit Gulf coastal area, Turkey. MC1, MCRS and MCRC samples were collected around the Izmit Gulf. MCI and MC1 around the factory.
of heavy-metal background of the natural environments. The PLI, which is a result of the contribution of several heavy metals, is defined as the root of the multiplication of the concentration factors (CFHMk).

$$PLI = \sqrt[n]{\prod_{k=1}^{n} CF_{HMk}}$$  \hspace{1cm} (1)

where $CF_{HMk}$ was the ratio of the concentrations of each heavy metal ($C_{HM}$) to the amv given in Table 1 which means the mean values.

$$CF_{HMk} = \frac{C_{HM}}{amv}$$  \hspace{1cm} (2)

A good correlation between PLI and $\chi_{LF}$ suggested that the combined heavy-metal pollution degree could be assessed by the intensity of MS.

3. Results

3.1. Topsoil samples

3.1.1. Characterization of magnetic properties

Table 1 shows the results of the chemical analysis and magnetic measurements (PLI, magnetic susceptibilities ($\chi_{LF}$ and $\chi_{HF}$) and frequency-dependent susceptibility ($\chi_{FD}$)) on the topsoil samples. The MS ($\chi_{LF}$) measurements show that they vary from $10 \times 10^{-8}$ m$^3$ kg$^{-1}$ to $203 \times 10^{-8}$ m$^3$ kg$^{-1}$ with an average of $86 \times 10^{-8}$ m$^3$ kg$^{-1}$. As illustrated in Fig. 2, the $\chi_{LF}$ values can be divided into four different areas; MCI, McI (mean $\chi_{LF}$: $143 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged 78–203 $\times 10^{-8}$ m$^3$ kg$^{-1}$), mean $\chi_{LF}$: $68 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged 53–86 $\times 10^{-8}$ m$^3$ kg$^{-1}$), MCRS (mean $\chi_{LF}$: $107 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged: 15–193 $\times 10^{-8}$ m$^3$ kg$^{-1}$), MCRC (mean $\chi_{LF}$: $65 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged 45–91 $\times 10^{-8}$ m$^3$ kg$^{-1}$) and MCP, McP (mean $\chi_{LF}$: $14 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged 10–21 $\times 10^{-8}$ m$^3$ kg$^{-1}$, mean $\chi_{LF}$: $15 \times 10^{-8}$ m$^3$ kg$^{-1}$, ranged 12–20 $\times 10^{-8}$ m$^3$ kg$^{-1}$).

Fig. 3. Surfer contour maps of the $\chi_{LF}$ values ($\times 10^{-8}$ m$^3$ kg$^{-1}$) and heavy-metal contaminations, created using Surfer 4.0, for the topsoils along the Izmit Gulf coastal area, Turkey (excluding IZAYTAS samples). The data used is given in Table 1.
The $\chi_{LF}$ values depend on geology of the area, sedimentation and anthropogenic dope additive materials (Dearing et al., 1996; Lu et al., 2007). Lu et al. (2007) showed that the $\chi_{LF}$ value of natural 'non-polluted' topsoil samples depends on five major soil-forming factors: parent material, climate, geomorphology, vegetation and time. The $\chi_{LF}$ of MCP non-polluted samples from the study area vary between $10 \times 10^{-8}$ m$^3$ kg$^{-1}$ and $21 \times 10^{-8}$ m$^3$ kg$^{-1}$, which is much lower than the $\chi_{LF}$ measured for the polluted topsoil samples. The high $\chi_{LF}$ values in industrial areas (MCI-XX; XX shows the number of sample) and especially near the pollution units around the IZAYDAS can be explained by the anthropogenic input of various origins although the samples have similar soil types and geology.

Figs. 3 and 4 show the surfer contour maps of the $\chi_{LF}$ and heavy-metal content distributions for the topsoil samples. As illustrated, the $\chi_{LF}$ values differ significantly in different stations. It appears that the higher $\chi_{LF}$ values are concentrated mostly in the industrial plant areas (heavy machine manufacture, petrochemical works, traffic emissions etc.). In Fig. 3, the high $\chi_{LF}$ values are concentrated mostly in the eastern and western parts of the area where a lot of MCI are located. In the MCRC, the magnetic minerals may be derived from the traffic emissions. The topsoil samples (McI and McP) taken from near the IZAYTAS yield high $\chi_{LF}$ values and heavy-metal contents. As seen in Fig. 4, the low $\chi_{LF}$ values and heavy-metal contents are found mostly in the MCP compared to other areas. On the other hand, the high $\chi_{LF}$ values and heavy-metal concentrations are encountered in the topsoil samples taken from the anthropogenic polluted areas as seen in the surfer contour maps (Figs. 3 and 4).

The frequency-dependent susceptibility ($\chi_{FD\%}$) values are given in Table 1. Dearing (1999) showed the relation between $\chi_{FD\%}$ and the paramagnetic component. $\chi_{FD\%}$ of topsoil samples range from 3\% to 11\% with a mean value of 6\%. The mean values in the urban samples increase from the MCI (mean = 4.7\%) towards MCRC (mean = 5.9\%) and the MCRS (mean = 8.2\%) regions. Such a low value of $\chi_{FD\%}$ indicates that the magnetic properties of the samples are predominantly contributed by the coarse multidomain grains, rather than by the super paramagnetic particles (Lu et al., 2007). Dearing's $\chi_{FD\%}$ model (Dearing, 1999) predicted two types of magnetic clusters in the samples. A few of samples with a $\chi_{FD\%}$-2\% are dominated by coarse multi domain grains. Fifteen $\chi_{FD\%}$ values were placed between 2\% and 6\%, which belong to an intermediate group (Fig. 2). These values correspond to a mixture of multi domain and stable single domain. Most samples were evaluated to be dominated by the frequency-dependent grains ($\chi_{FD\%}$-6\%); hence the ferromagnetic grains (i.e. Fe) are present in high concentration (Table 1).
level changes. The topsoil samples contain high mean concentrations around the gulf: Cu (25 mg kg\(^{-1}\)), Pb (32 mg kg\(^{-1}\)), Zn (74 mg kg\(^{-1}\)), Cr (35 mg kg\(^{-1}\)), Ni (40 mg kg\(^{-1}\)), Cd (0.21 mg kg\(^{-1}\)), and Co (17 mg kg\(^{-1}\)) and around the IZAYTAS: Cu (62 mg kg\(^{-1}\)), Pb (77 mg kg\(^{-1}\)), Zn (61 mg kg\(^{-1}\)), Ni (5 mg kg\(^{-1}\)), Cd (0.06 mg kg\(^{-1}\)), and Co (20 mg kg\(^{-1}\)). Metal concentrations also show large standard deviations alluding a great heterogeneity of heavy-metal pollution. The measured high concentrations of the heavy metals and the MS values of the MCI and MCRS topsoil samples indicate the presence of a considerable amount of magnetic particles accompanying the heavy-metal emission. Cu, Pb and Zn concentrations in the MCI and MCRS are significantly higher than those in the MCP. These metal concentrations may be affected by the dust deposition which may be resulted from the various industrial activities. It has been well established that Cu is a common element in automobile thrust bearing, brake lining, and other parts of the engine (Lu et al., 2005a,b), therefore the corrosion of metal wear in the automobile engine may cause releasing of heavy metals particularly Cu and Pb to the environment and consequently accumulating on the topsoil. Pb has been used as an effective indicator of traffic-induced pollution caused by automobile exhausts (Lu et al., 2007).

3.1.3. Relationship between MS and heavy-metal content

Chan et al. (1997) showed that certain heavy metals, such as Pb, Zn and Cu are preferentially adsorbed onto the exterior surface of the fly

![Graphs showing the relationship between MS and heavy-metal content](image)

**Fig. 5.** The contents of Pb, Cu, Zn, Cr, Co, and Ni and the \(\chi\)LF for topsoil samples. Equations and correlation coefficients \((R^2)\) between the \(\chi\)LF and heavy-metal contents were given on the graphs.
ash and aerosols from the industrial emissions, which often contain significant amounts of Fe oxides. A strong and positive correlation between heavy-metal content with \( \chi LF \) is therefore expected. Gelisli and Aydin (1998) claimed that the presence of common heavy metals in the traffic emissions also accounts for the strong correlations between MS and heavy metals in the urban topsoil side of the heavy traffic roads in Trabzon, Turkey. They emphasized that anthropogenic pollution was the dominant factor influencing topsoil susceptibility. Thus, they suggested that the high correlation coefficients between \( \chi LF \) measurements and heavy-metal content can be used as an indicator of pollution.

The scatter plots of MS versus Cu, Pb, Cr, Co, Ni and Zn contents are given in Fig. 5 where the correlation coefficients between the heavy-metal contents and MS are also given. In general, all heavy metals except Co and Zn show good associations with \( \chi LF \). The highest coefficient between the MS and the heavy metal Ni is \( R^2 = 0.82 \). Correlations between the MS and the concentration of other heavy metals are as follows: Pb \( (R^2 = 0.61) \), Cr \( (R^2 = 0.59) \), Cu \( (R^2 = 0.60) \), Co \( (R^2 = 0.06) \) and Zn \( (R^2 = 0.0) \).

The correlations between \( \chi LF \) with heavy-metal contents were also studied for the topsoil samples. As shown in Table 1 and Fig. 5, a positive correlation \( (R^2 > 0) \) exists between the MS and the Pb, Ni, Cu contents and Cr (negative correlation) but not Co or Zn. The relations between \( \chi LF \) and \( \chi FD\% \), and \( \chi LF \) and PLI were also shown for the same samples (Fig. 6). As can be seen from Fig. 6, relatively very low correlation coefficient is found between PLI and \( \chi LF \) \( (R^2 = 0.20) \). Also, very low negative correlation between \( \chi FD\% \) and \( \chi LF \) is found.

It is necessary to show the background value of MS in the study area to define the anthropogenic input or natural enhancement of magnetic minerals. Hanesch and Scholger (2002) showed that geochemical techniques could be used to distinguish existing natural background from anthropogenic anomalies. These results were used in order to reveal the sources of pollution. The value of the layer (10–30 cm) was used as an approximation for the soil background level, because the soiling process acts within this layer but anthropogenic pollution influences are to the upper horizons. Based on randomly placed profiles around the industrial region and rural areas (Fig. 7), the present study revealed the vertical variation of \( \chi LF \). In Fig. 8, the mean \( \chi LF \) values get high levels of \( 85 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \) at 5 cm; then the values drop off abruptly to a nearly constant level \( 40 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \) at 10–30 cm. As a result, we were able to use the \( \chi LF \) value at the depth of 10–30 cm as the background value.

As illustrated in Figs. 3 and 4, the surfer contour maps showed high correlations of the heavy metals and \( \chi LF \). As given in Fig. 3, there is a general increase in the \( \chi LF \) values near the probable pollution units of MCI-XX and MCRS-XX. This is consistent with the distribution of heavy metals. The high \( \chi LF \) values and heavy-metal contents are recorded at the same points. Fig. 4 shows the distribution of the pattern of the surfer contour \( \chi LF \) values and heavy-metal contents around the IZAYTAS. The pattern shows a general increase in the \( \chi LF \) values and heavy-metal contents near the IZAYTAS. Both surfer contour \( \chi LF \) maps in Figs. 3 and 4 are used based on their capability to visualize spatial relationships. In Fig. 3, higher values are concentrated in the southeastern part where there are a lot of industrial plants, for the other parts of the city given the MS anomalies viewing by MCRC-XX where the magnetic minerals may be derived from the traffic emissions. The values of \( \chi LF \) are relatively smaller in MCP-XX compared to MCI-XX around the city and IZAYTAS, as shown in Figs. 3 and 4. The magnetic enhancement of topsoil is mainly ascribed to anthropogenic inputs of magnetic minerals, compared to the background \( \chi LF \) value. These results confirm the enhanced values of \( \chi LF \) measurements in the topsoil, which are weakly affected by lithology. These results also gave us information about the main magnetic carriers in these layers using the \( \chi FD \) and background \( \chi LF \) values for pedogenic or anthropogenic origins.

The relationship between the \( \chi LF \) and heavy-metal content for all the topsoil samples is grouped in defined clumps. Clumps MCI and MCRS show higher Pb, Zn, Ni, Cu and Cr concentrations than their corresponding clump of MCP and MCRC.

3.2. Characterization of the vertical MS profiles

The vertical profile variations of the \( \chi LF \) measurements belonging to the four different areas are shown in Fig. 7. The \( \chi LF \) values for each profile are given in Table 2. The \( \chi LF \) vertical variation values of the soils from the MCI-XX, ranged from 0 to \( 320 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1} \) throughout the profiles (Fig. 7). These profiles are divided into four groups. The graphs of all soil profiles out of two profiles were taken roadside coded MCRS-XX from study area. The \( \chi LF \) values gradually increase from 0 cm to 3–4 cm in its surface horizons (0–5 cm), and steeply decreased from 5 cm to 10 cm horizon. After this depth the \( \chi LF \) values continue to decline. In addition, values reach their maximum levels, except the profile of MCRS-XX where the maximum value is at 10 cm. These behaviors explain clearly the contribution of ferrimagnetic minerals of anthropogenic origin. MCP-XX profiles show bimodal \( \chi LF \) distributions within the 0–5 cm interval where the \( \chi LF \) values were changing between 0 and \( 20 \times 10^{-6} \text{ SI} \). The soil profiles of MCP-XX show low contributions of ferrimagnetic minerals of anthropogenic origin after 5 cm. In particular, the upper 0–5 cm and further depths of soil profile from industrial area (MCI-XX) exhibit ten to fifteen times larger enhancement of \( \chi LF \), compared to those from the background area. This indicates that urban sediments accumulated higher amounts of anthropogenic materials.

Fig. 6. Relationship between \( \chi HF \), \( \chi FD\% \), PLI and \( \chi LF \) for the topsoil samples. Equations and correlation coefficients \( (R^2) \) between \( \chi LF \) and heavy-metal contents were given on the graphs.
Soil profile from the MCRS-XX exhibits the largest enhancement of $\chi_{\text{LF}}$ as its values are fifteen to twenty times higher than those from the background area. This indicates that these sediments most likely accumulated with a higher amount of anthropogenic materials particularly sourced from the heavy traffic. In the MCRC-XX, MS values contain lower input of anthropogenic magnetic materials due to close association to MCI-XX and MCRS-XX. These soil profiles exhibit lower magnetic enhancement on top horizon but upper magnetic enhancement due to MCP-XX. The mean $\chi_{\text{LF}}$ values of all the vertical profiles of the each area are redrawn as shown in Fig. 8 which supports the above mentioned interpretations. The two profiles (MCP13 and MCP14) for the Lower-middle Eocene aged are made up of the sandstone, claystone and conglomerate unit and at top the Quaternary aged alluvium (i.e. gravel, sand, silt and clay). These sample sites are located far from anthropogenic pollution sources, and placed in a very low $\chi_{\text{LF}}$ soil medium such as limestone. Therefore the $\chi_{\text{LF}}$ values change at low levels ($0-20 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$).

4. Discussion

The lateral and vertical changing of magnetic particles and heavy metals were observed in the sampling area along the Izmit Gulf coastal area. Our results showed that the magnetic particles of samples in urban and residential areas formed multi domain grains originated from anthropogenic sources. The sources of anthropogenic particles were reported to increase the $\chi_{\text{LF}}$ of the urban topsoils. They were identified as emissions from fossil–fuel combustion processes, other particles from vehicles, building and road surfaces, and incorporated into disturbed soil surfaces (Lu et al., 2007). It was concluded that $\chi_{\text{LF}}$ had been successfully used to detect fly ash and ash particles by automobile emissions in the study area. On the other hand, only limited information was available about the value of the MS of metallurgical dusts. However, Lu et al. (2007) reported that Pb, Zn, Cd and Cu also account for the strong correlation between $\chi_{\text{LF}}$ and these two metals in the soils, we find high correlations between MS and Pb.
Cu, Ni and Cr. For Zn and Cd, correlations were low. Lu et al. (2007) reported that the correlation between magnetic concentrations and heavy-metal contents reveals a causal relation between the ferrimagnetic oxide and the heavy metals in urban topsoils.

Pb, Cu, Zn and Cd are preferably adsorbed on the exterior surface of fly ashes and aerosols from industrial emissions. Our results from four different areas supported Lu’s results. These metals give a strong correlation with $\chi_L F$ (Lu et al., 2005a,b), and so we took the same

Fig. 8. Mean $\chi_L F$ variations along the vertical profiles of soil samples from the MCI, MCRS, MCP and MCRC polluted areas.
results near highways. In metallurgical dusts and fly ash in the studied area, these researchers showed a strong correlation between $\chi$LF and Fe, Mn, Zn, Pb and Ni. In this study, we observed very strong correlations between $\chi$LF and four heavy elements in both sampling areas.

### 5. Conclusions

In this study, we tested the potential use of the $\chi$LF measurements for lateral and vertical distributions of heavy-metal pollution monitoring in urban soil samples. The $\chi$LF measurements for topsoil samples everywhere in the study area were higher than the background level, which was deeper than 10 cm. The $\chi$LF values show a significant correlation with the concentration of heavy metals except for Zn and Co. In contrast to chemical analysis techniques, the $\chi$LF measurements provide us cheaper and less time-consuming methods for identification of probable soil pollution. Also, we showed that $\chi$LF measurement could be used as a proxy measure for the degree of heavy-metal contamination, revealing the distribution of pollution parts in such industrial areas. The following conclusions are drawn:

1. Evaluated values of $\chi$LF ($>20 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) with higher heavy-metal concentrations of the soil samples proved to be strong indicators of anthropogenic contribution in the soil samples.
2. $\chi$LF measurements could yield useful information on the degree of pollution. This study shows that $\chi$LF shows strong correlations with heavy metals such as Pb, Cu, Cr and Ni; and weak correlations with Zn and Co.
3. $\chi$LF measurements show that the main magnetic components in urban soil samples are multidomain grains of ferrimagnetic minerals, which are introduced by industrial activities, automobile exhaust, and deposition of atmospheric particulates.

4. The enrichment of magnetic particles and heavy metals in the topsoil is considerably clear in industrial and roadside areas.

5. The Tomlinson pollution load index (PLI) shows no correlation with the MS. Since analytical measurements of heavy-metal contamination are expensive and laborious, a straight linear correlation between $\chi$LF and the mineral concentration of Cu, Cd and Pb confirms the use of magnetic technique as a simple, rapid, and non-destructive tool for assessment of heavy-metal contamination in the investigated region.

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