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# Levels of trace elements in $PM_{10}$ collected at roadsides of Addis Ababa, Ethiopia, and exposure risk assessment

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**Abstract** Estimation of personal exposure to air pollution is needed to identify high-risk population and to develop mitigation strategies. In this study, an assessment of the potential effects of short-term exposure to $PM_{10}$ and the elements bound within $PM_{10}$ was conducted. Samples were obtained from the ten sub-cities of Addis Ababa (three sampling points from each) during the commuting time (traffic congestion and taxi queues). A particle counter consisting of a portable sampling unit with multi-fraction dust samplers was used for sample collection. The elemental composition was analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES). The mean concentrations of $PM_{10}$ ranged from 206 to 308 μg $m^{-3}$. The highest concentrations of pollutants were found in the major open-market part of the city, Addis Ketema. The lowest concentrations were found at the old-town, Arada sub-cities. The concentration of trace elements (Fe, Cd, As, Cr, Pb, B, Ni, Co, Sn, Cu, and Zn) bound in $PM_{10}$ ranged from below detectable limit to 0.981 μg $m^{-3}$. Regardless of the sampling sub-city, the overall patterns of the mean concentration of elements bound in $PM_{10}$ were found in the following increasing order of Cr < Cd < As < Co < Ni < Cu < Fe < Pb < Sn < B < Zn < Mn. The results showed that the primary source of Zn, Cr, and Cd may be emissions from on-road vehicles, tire and brake wear. Pb originates mainly from industries and suspended soil dust at the roadside, whereas As, Mn, and B are associated with dust resuspension and biomass and biofuel combustion, respectively. The carcinogenic and non-carcinogenic risks due to chronic exposure to trace elements bound in $PM_{10}$ at the roadside were assessed in accordance with the U.S. Environmental Protection Agency (US EPA) guidelines. It was determined that Mn, As, and Cd contributed substantially to the inducement of non-carcinogenic health problems to children and adults as a result of exposure while in close proximity to the roadsides.

**Keywords** Commuter exposure · Elemental composition · Health risk assessment · Vehicle sources · Addis Ababa · Ethiopia

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## Introduction

Cities and urban centers are essential to the commercial, cultural, social, and political life of most nations. Although cities are comprised of only 3% of the global land cover, more than 55% of the people are inhabiting them. The high population density combined with industrial and automobile emissions and energy use has resulted in increased localized pollution and environmental degradation. In many emerging economies, this problem is exasperated because of the continued use of biomass fuels as a source of domestic energy, rapid urbanization, and the aged transportation fleet (Petkova et al. 2013; Morakinyo et al. 2017).

Although it is known that transport facilities (e.g., cars, taxis, busses, and trains) and household energy use are significant contributors to air pollution, widespread urban sprawl and the slow change in traditional cooking methods are also contributors to the deterioration of urban air quality, particularly in a developing country (Petkova et al. 2013; Morakinyo et al. 2017). In Africa, the rate of urbanization is swift. In sub-Saharan Africa, the proportion of urban dwellers has increased from 10 to over 35% of the population in the past 60 years. It is projected that nearly 60% of the African population will live in cities by the year 2050, as compared with less than 40% in 2011. Additionally, the lack of a well-designed road network, an increase in vehicle ownership, and the prevalence of old, poorly maintained cars aggravate the level of air pollutants in most of the cities of developing countries, such as Ethiopia (Kume et al. 2010; Kinney et al. 2011; Ekpenyong et al. 2012; Tefera et al. 2016). Alok (2011) demonstrated that 53.5% of vehicles in Addis Ababa, Ethiopia's sprawling capital were more than 20 years old and 29.3% were more than 30 years old. Most of them lacked a pollution control device. Air pollution problems associated with commuter transport modes could worsen in the country unless the government and other stakeholders formulate regulations and policies to address them.

Health problems associated with urban air pollution are an increasing concern to public health officials and the population living in Africa's large metropolitan areas. A pilot study conducted by van Vliet and Kinney (2007) in Nairobi, Kenya, showed that roadway concentrations of $PM_{2.5}$ were approximately 20-fold higher than those obtained from the urban background site. Chen and Goldberg (2009) have estimated that 60% of chronic health problems are related to environmental factors such as exposure to urban air pollution. Notably, one of the worst health problems related to the exposure to particulate matter is caused by the emission from automobile exhausts (Cattaneo et al. 2010; Lee et al. 2012). In 2011, the United Nations Environment Program (UNEP) estimated that 90% of the urban air pollution in developing countries is attributed to gasoline and diesel motor vehicle emission (Kinney et al. 2011; Kelly and Fussell 2012). Despite this finding, there are very few studies related to urban air pollution in sub-Saharan cities, particularly in Ethiopia (Embiale et al. 2018).

People who either reside in or work near to congested, busy roads in urban areas suffer the impacts of poor air quality because elevated concentrations of pollutants tend to occur close to highways and streets. Urban building density and the configuration of the buildings on either side of the street can contribute to air stagnation and a low dispersion rate of pollutants. The congested traffic resuspends the dust in the atmosphere, thereby making it more breathable. This leads to an increase in the concentration of pollutants. People also carry out activities near primary sources of urban air pollution (e.g., heavily trafficked roads). Therefore, the health risks due to high concentrations of pollutants near the roads are expected to be high (Gulliver and Briggs 2004; Gulliver and Briggs 2007; de Nazelle et al. 2012; Aziz et al. 2015; Ramos et al. 2016; Shi and Ng 2017). Some studies have reported that the contribution to the total daily exposure while commuting accounts for up to 60% of black carbon and 12% of $PM_{2.5}$, although the time of exposure is short (1–1.5 h) (Karanasiou et al. 2014).

Most studies conducted on outdoor air pollution and its related health impacts are based on the measurement of the air pollutants at fixed monitoring sites, which is not sufficient to accurately predict or estimate the personal exposure. As a result, the exposure is significantly underestimated because the distribution of emission sources, from either a point or traffic source, is complex and varies at the low-level scale across space. The use of advanced wearable sensors to collect personal exposure data is a more accurate method of exposure assessment than the use of fixed monitoring data. For instance, studies conducted in the UK showed that the levels of exposure to $PM_{10}$ during commute and in-car were 67% and 13%, respectively, higher than exposure measured at fixed-point measurement (Levy et al. 2000; Gulliver and Briggs 2007; Devi et al. 2009; Cattaneo et al. 2010;

Rabinovitch et al. 2016; Shi and Ng 2017). The exposure measurement of outdoor air particulate matter conducted so far in Ethiopia is based on a 24-h analysis at the selected fixed monitoring site (Etyemezian et al. 2005; Gebre et al. 2010; Son and Bell 2013).

To understand the potential health implications of chronic exposure to road dust, a systematic study is needed to gain a better understanding. In particular, heavy metals bound to airborne particulate matter can interfere in the normal development and growth of the body tissues and their proper functioning. For instance, the presence of toxic trace elements in particulate matter aggravates carcinogenesis, teratogenesis, and mutagenesis (Mohanraj et al. 2004). Therefore, the chemical characterization of particulate matter is vital for understanding its effect on both people and the environment. Also, the determination of trace elements bound in particulate matter is useful for identifying the sources in addition to estimating the health impacts due to exposure (Salcedo et al. 2014). Fossil fuel combustion, vehicular traffic, electroplating, and metal alloy industries are some of the sources that can increase the introduction of trace metals in the body through polluted particulate matter suspendered in the air (Basha et al. 2006; Schwarze et al. 2006). The distribution of metals across the size of particulate matter varies considerably. Studies have shown that 70–90% of the heavy metals (e.g., Cu, Cd, Ni, Zn, and Pb) are found in the $PM_{10}$ fraction (Mohanraj et al. 2004). This study evaluated the comprehensive measurement of $PM_{10}$ at the roadside microenvironment during periods of high traffic congestion and at different commuting times (i.e., early morning and late afternoon). The elemental composition of $PM_{10}$ was determined, and the health risk due to lifelong exposure to $PM_{10}$ was assessed.

## Materials and methods

### Description of the study area

Ethiopia is the second most populous country in Africa (86.6 million, 2012, while the estimate for 2018 is 108.3 million). Addis Ababa has a population exceeding 3 million (ECSA 2012). The city has been growing at a rate of 2.1% from 1994 to 2010 (Do et al. 2013). It is situated at the central highland plateau of the country at an altitude varying between 2200 and 2800 m and between latitude 9.0300° N and longitude 38.7400° E. The average minimum and maximum annual temperatures range from 9.53 to 23.2 °C, and the average annual rainfall is 1170 mm (Sanbata et al. 2014).

Outdoor air pollution is mainly affected by geographical location, metrological factors (e.g., wind, temperature, and humidity), potential air pollution sources, and major socioeconomic activities. To obtain a representative sample, three sampling points from each of the ten different sub-cities (urban districts) (Addis Ketema, Akaki Kality, Arada, Bole, Gulele, Kerkos, Kolfe Keranio, Lideta, Nefas Silk-Lafto, and Yeka) were selected. Thus, a total of 30 sites in ten different sub-cities were selected. The geographical locations of sampling points are depicted in Fig. 1. The selected sites differ in their altitude, socioeconomic activities, and population density. The details of socioeconomic activities involved in the sampling points are given in Table 1.

The distance between each sampling point location and the main roads ranged from 2.5 to 7.6 m. The altitudes range from 2146 (at the Akaki Kality sub-city) to 2657 m (at the Gulele sub-city).

### Sampling and mass determination

The particulate matter samples for $PM_{10}$ analysis were collected using a portable sampling unit equipped with multi-fraction dust samplers (Institute of Occupational Medicine, Universal Air Pump, SKC 224-PCTX4 Model, SKC Ltd., UK). The unit had a vacuum pump, an internal flow regulator, a timer, and an airflow calibration unit. The airflow was adjusted in the laboratory to 2.2 L $min^{-1}$ with a high-precision rotameter before being taken into the field for sample collection. It was checked immediately upon return to the laboratory. The $PM_{10}$ sampling was carried out in daytime rush hours during the dry season (September 30, 2017, to November 15, 2017) and during the wet season (June 15, 2017, to August 30, 2017) from 6:00 a.m. to 10:00 a.m. and 2:00 p.m. to 6:00 p.m. at the roadsides. The vacuum pump was attached to a belt worn around the waist, and the inlet cyclone was placed near the collar as close as possible to the breathing zone. Glass microfiber filters with a diameter of 25 mm GF/A (Whatman®, GE Healthcare UK Limited, Amersham Place, UK) were used to collect $PM_{10}$, which was put inside the universal sampler. After the completion of sampling, the filter was placed in aluminum foil, returned to the laboratory, and placed in a desiccator. The mass of the particulate matter was measured gravimetrically. Each filter was oven

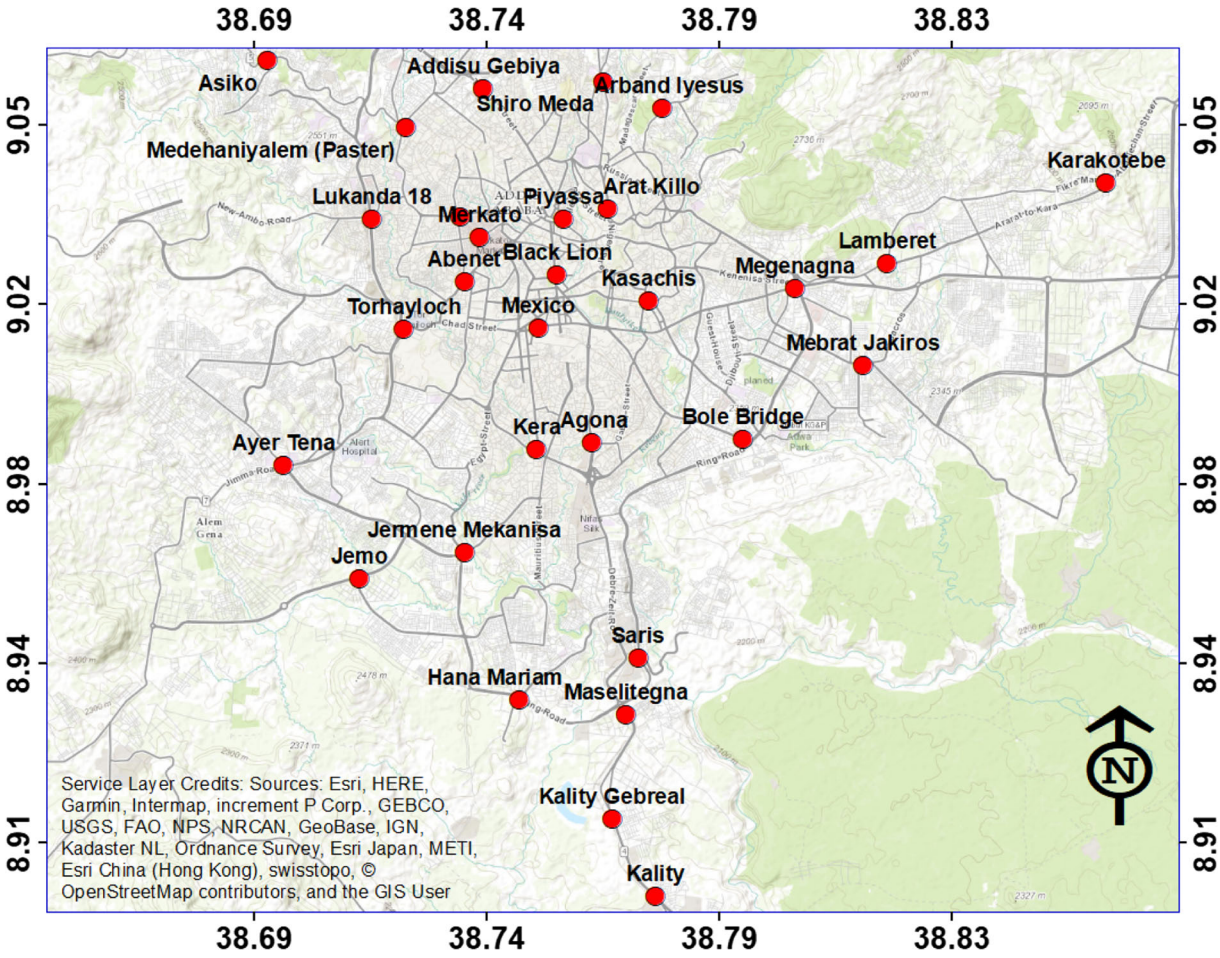



**Fig. 1** The GIS sampling point locations selected for $PM_{10}$ pollution measurement

dried at a temperature of 105 °C for 2 h before sampling to remove moisture. A total of 120 filters were used for collecting the $PM_{10}$ samples. The difference between the weight of the filter before and after sampling was considered the mass of particulate matter collected during a given period of time. The filter samples were weighed using an analytical balance with 0.001 mg sensitivity (AT 250, Mettler-Toledo, USA). The results were expressed as micrograms of $PM_{10}$ per cubic meter of air.

## Determination of trace elements

An analysis of 11 elements (Mn, Cd, Co, B, As, Ni, Cr, Pb, Zn, Cu, and Fe) in the $PM_{10}$ was conducted using a standard procedure developed by the US EPA, which mainly uses aqua regia mixture for digestion. A mixture of 5 mL concentrated nitric acid (69–71% Sigma-Aldrich, Germany) and 15 mL concentrated hydrochloric acid (37%, Sigma-Aldrich, Germany) was used to prepare the sample extracts for elemental analysis. A round bottom flask (100 mL) fitted with a reflux condenser and Kjeldahl digestion block (Kjeldatherm, Gerhardt GmbH and Co. KG, Type KB 40 S, Bonn, Germany) was used for the digestion of all the $PM_{10}$-loaded filter papers. After cooling, the extracted solution was filtered through the cellulose filter (Whatman I) and adjusted to a final volume of 20 mL using deionized water. Finally, the sample solution was kept in a precleaned polyethylene bottle and refrigerated until analyzed. Triplicate filters and reagent blanks were also processed following a similar procedure for sample treatment (Leili et al. 2008). The concentrations of the elements were determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES; Model Arcos FH2, 22-09-2010, Spectro Analytical

**Table 1** The locations and the surrounding status (the specific socioeconomic activities) of $PM_{10}$ monitoring sites at Addis Ababa

| Sampling sites | Sampling points | Distance from road (m) | Description of sampling sites |
|---|---|---|---|
| Gulele sub-city | Addisu Gebiya | 3 | Retail shops, street food sellers, and various other businesses, relatively low vehicle and pedestrian traffic, bus stop and near a roadside, pickup point for passengers, serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of northern parts |
| | Shiromeda | 3.5 | Retail shops, street food sellers, and various other businesses, relatively low vehicle and pedestrian traffic, minibus stop and near a roadside, pickup point for passengers |
| | Arband Iyesus | 4 | Retail shops, shoeshine boys, and some restaurants, and relatively low vehicle and pedestrian traffic, minibus stop and near a roadside, pickup point for passengers |
| Kolfe Keranio sub-city | Ayertena | 4 | Street fast food, tea and coffee sellers, and minibus stop near a roadside and pickup point for passengers, and has high vehicle and pedestrian traffic at hours |
| | Asiko Bus Station | 3.5 | Retail shops, street vendors, and various other businesses, and has high vehicle, pedestrian traffic major, minibus stop, and near a congested, pickup point for passengers and rural bus station and one soap factory, it also serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of western parts |
| | Lukanda 18 | 3.5 | Commercial cooking smoke exhaust from roadside buildings, cafe and restaurants, street vendors, and various other businesses, heavy pedestrian and vehicle traffic at the commuting times, major minibus and bus stops and pickup point for passengers, and serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of northwestern parts |
| Akaki Kality sub-city | Kality | 6 | Retail shops, street vendors, and various other businesses, heavy pedestrian and vehicle traffic most of the day, major minibus stop and near a congested and pickup point for passengers, and serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of southern parts, dust blowing from graveled road |
| | Kality Gebrieal | 3 | Few cafes and restaurants, many industries, some retail shops, and various other businesses, and has high vehicle and pedestrian traffic at most of the days, the road at the sampling point is paved, and the road served for all types of vehicle (both heavy trucks and automobiles), serves as an important commuter route into and out of Addis Ababa and southern parts of Ethiopia, dust blowing from graveled road |
| | Maselitegna | 3 | Street vendors, very few cafes, and various other businesses, and has high vehicle and pedestrian traffic at most of the days, most of the road at the sampling point is paved, and presence of highway approximately 200 m far from the sampling point which allows heavy trucks, dust blowing from graveled road |
| Lideta sub-city | Torayloch | 5 | Street vendors, supermarkets, and various other businesses, heavy pedestrian and vehicle traffic most of the day, major minibus stop and pickup point for passengers, relatively low traffic congestions |
| | Mexico | 3.7 | Book shops, government institutions, cafe and restaurants, street vendors, and various other businesses, and heavy pedestrian and vehicle traffic at commuting time |
| | Abenet | 4 | |

**Table 1** (continued)

| Sampling sites | Sampling points | Distance from road (m) | Description of sampling sites |
|---|---|---|---|
| | | | Retail shops, cafe and restaurants, street vendors, and various other businesses, and has relatively low vehicle and pedestrian traffic, the availability of heavy truck is almost negligible during sampling |
| Bole sub-city | Jakrose Square | 3.3 | Retail shops, cafe and restaurants, street vendors, and various other businesses, and has high vehicle and pedestrian traffic, the availability of heavy truck is during sampling, congested pickup point for passengers |
| | Bole Bridge | 4 | Ethiopia international airport, hotels, supermarkets, street vendors, and various other businesses, and has high vehicle and pedestrian traffic, the availability of heavy truck is almost negligible during sampling, compacted buildings |
| | Saris Abo | 4 | Retail shops, cafe and restaurants, and various other businesses, and has highways which allow heavy truck and pedestrian traffic at commuter time, during sampling there was highly Wendy |
| Nefas Silk-Lafto sub-city | Hana Mariam | 2.5 | Retail shops, cafe and restaurants, and various other businesses, and has high vehicle and pedestrian traffic at most of the days, road side is paved, and presence of highway which allows heavy trucks, dust blowing from graveled road |
| | Jemo | 5 | Street vendors, heavy pedestrian, and vehicle traffic most of the day, major minibus and bus stop, nearly a congested pickup point for passengers and serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of southwest parts |
| | Jermene Square | 3.2 | Retail shops, cafe and restaurant, and various other businesses, relatively medium vehicle and pedestrian traffic, bus and minibus stops near a roadside, pickup point for passengers, presence of highway approximately 250 m far from the sampling point which allows heavy trucks |
| Yeka sub-city | Megenagna | 6 | Near a major minibus stop, nearly a congested pickup point for passengers, many street vendors, street food sellers, many retail shops and other business centers, availability of heavy tuck ways, has high vehicle and pedestrian traffic at most of the days |
| | Kara Kotebie | 2.5 | Retail shops, street vendors, and various other businesses, low pedestrian and vehicle traffic most of the day, major minibus stop and pickup point for passengers and serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of north east parts |
| | Lambert Bus Station | 3.4 | Retail shops, supermarkets, and various other businesses, and has high vehicle and pedestrian traffic |
| Addis Ketema sub-city | Medehaniyalem School | 5 | Retail shops, schools, hospitals, street vendors, and various other businesses, and has relatively low vehicle and pedestrian traffic, the availability of heavy truck is almost negligible during sampling |
| | Merkato | 4 | In general, it is the largest and compacted market center in the country where many people were available (general and retail shops, supermarkets, street venders, and various other businesses), and has a very high vehicle and worker traffic at most of the days, many buildings under construction, some of the roads are paved |
| | Merkato Bus Station | 5 | Retail shops, street vendors, and various other businesses, heavy pedestrian and vehicle traffic most of the day, major minibus and bus stops and near a congested pickup point for passengers and serves as an important transfer point for minibusses and busses linking urban, peri-urban, and rural destinations of northern parts |
| Kerkos sub-city | Kera | 2.7 | Many general and retail shops, cafe and restaurants, street vendors, and various other businesses, and has high vehicle and pedestrian |

**Table 1** (continued)

| Sampling sites | Sampling points | Distance from road (m) | Description of sampling sites |
|---|---|---|---|
| | | | traffic, some heavy trucks have been seen during sampling, street sweepers, slaughterhouse |
| | Agona | 4.5 | Retail shops, street food sellers, cafe and restaurant, and various other businesses, relatively medium vehicle and pedestrian traffic, bus and minibus stops near a roadside, pickup point for passengers |
| | Kasachis | 3.2 | Retail shops, hotels, street vendors, and various other businesses, and has relatively low vehicle and pedestrian traffic, the availability of heavy truck is almost negligible during sampling |
| Arada sub-city | Black Lion | 2.5 | Retail shops, supermarkets, some governmental origination where many people visit per day (Black Lion Hospital, immigration office, and others), and various other businesses, and relatively medium vehicle and pedestrian traffic, bus and minibus stops near a roadside, pickup point for passengers |
| | Arat Kilo | 7.6 | Cafe and restaurants, street vendors, supermarkets, both primary and secondary schools, Addis Ababa University, particularly College of Natural Science, and various other businesses, and has high vehicle and pedestrian traffic in most of the days (especially at commuter time) |
| | Piyassa (Minlik Square) | 4 | General and retail shops, hotels, street vendors, and various other businesses, and has relatively medium vehicle traffics, high pedestrian traffic, the availability of heavy truck is almost negligible during sampling (except public busses) |

Instrument GMDH, Baush Strass, 10.47533, Klev, Germany) in Horticulture Ethiopia PLC located at Debrezeyt. The calibration solutions were prepared by diluting a commercial 1000-mg/L standard solution of each element (UNI-CHEM, chemical reagents). A picture of a typical filter paper used for sampling is shown in Fig. 2. The standard solutions of each element were prepared by the appropriate dilution of 1000 mg $mL^{-1}$ stock solution in 2% $HNO_3$. The concentration of the element bound in the particulate matter was obtained using Eq. 1:

$$C\left(\mu g\ m^{-3}\right) = \frac{(C_1 - C_b)}{V_o} \times V \quad (1)$$

where $C_1$ is the element concentration in the solution of the sample ($\mu g\ m^{-3}$), $C_b$ is the element concentration in the solution of the blank filter ($\mu g\ m^{-3}$), $V$ is the sample solution volume (20 mL), and $V_o$ is the sampling air volume ($m^3$).

The calibration curves showed linearity ($r^2 > 0.9897$) of the detector response for the quantified elements found in the samples. The limit of detection, based on three times the standard deviation ($3\sigma$) of the blank, was determined for each element. The calibration curves and the limit of detection (LOD) for detected elements are summarized in Table 2. The performance of the method was verified by a recovery test through standard addition. The results were within the acceptable range of 92–110%. The spiking measurement was performed in triplicate. The average percent recovery and standard deviation of each element were as follows: Fe (101 ± 1.2), Cu (102 ± 4.6), Mn (98.4 ± 6.0), B (105 ± 1.5), Zn (92 ± 4.2), Pb (109 ± 1.8), Cr (110 ± 1.2), Cd (102 ± 4.3), Sn (99.6 ± 6.2), As (106 ± 4.3), Ni (108 ± 3.5), and Co (109 ± 3.9).




**Fig. 2** The photo of the filter paper before and after sampling at Akaki Kality sub-city (Maselitegna sub-site) on October 25, 2017

**Table 2** The calibration equation for the quantification of elements in $PM_{10}$ using ICP-OES

| Type of element | Calibration equations | Correlation coefficient ($r^2$) | LOD in μg $mL^{-1}$ |
|---|---|---|---|
| Fe | $y = 0.36x + 1027$ | 0.9997 | 0.054 |
| Cu | $y = 0.92x + 4470$ | 0.9989 | 0.028 |
| Mn | $y = 1.71x + 782$ | 0.9999 | 0.007 |
| B | $y = 0.08x + 892$ | 0.9976 | 0.195 |
| Zn | $y = 0.21x + 1034$ | 0.9919 | 0.027 |
| Pb | $y = 0.05x + 633$ | 0.9897 | 0.857 |
| Cr | $y = 0.46x + 998$ | 0.9912 | 0.089 |
| Cd | $y = 1.47x + 626$ | 0.9973 | 0.070 |
| Sn | $y = 0.07x + 198$ | 0.9975 | 1.368 |
| As | $y = 0.08x + 144$ | 0.9975 | 0.647 |
| Ni | $y = 0.24x + 1445$ | 0.9952 | 0.520 |
| Co | $y = 0.11x + 1085$ | 0.9975 | 0.044 |

## Statistical package used in data analysis

IBM SPSS version 20.0, Microcal™ Origin version 16.0 (Micrical software, Inc., USA), and Microsoft Excel 2013 were used for the data analysis. Analysis of variance (ANOVA) was used to evaluate the significance of the differences in concentration of $PM_{10}$ and elements bound in $PM_{10}$ across and within sub-cities. A principal component analysis (PCA) that is based on the correlation matrix was conducted for the data to estimate the sources of elements and to classify the correlated elements (Shah et al. 2012; Tahri et al. 2013; Rao et al. 2015). An hierarchical cluster analysis (HCA) was used for the identification of the possible sources of $PM_{10}$. Generally, the significant difference for all the tests was set to $p = 0.05$.

## Risk analysis

According to a 2010 report by the International Agency for Research on Cancer (IARC), 223,000 people died due to lung cancer caused by air pollution. Health risk associated with an elemental species varies because of differences in their toxicity, concentrations, and mobility behavior. Therefore, the determination of their associated cancer and non-cancer risk is vital to the prioritization of an individual elemental species related to the total risk contributions and to take a remediation and emission control at the individual element (Izhar et al. 2016).

Long-term exposure to air pollutants like heavy metals bound to particulate matter increases cancer and non-cancer health risks (Liu et al. 2017, 2018a, b; Benson et al. 2017). The lifetime cancer risk is a method of estimating the probability of a person developing cancer over their lifetime as a result of exposure to the identified carcinogens, whereas non-carcinogenic effects mean the likelihood of a person developing health problems other than cancer during their exposure time to the contaminants (Benson et al. 2017). Exposure to trace elements found in the particulate matter can occur through inhalation, ingestion, and dermal routes (Sidhu et al. 2017). The elements under consideration in this study can be classified as carcinogenic and non-carcinogenic metals. According to Integrated Risk Information System (IRIS), Cu, Fe, Zn, and Mn are classified as non-carcinogenic and Cd, As, Pb, Cr, and Ni are classified as carcinogenic metals (Kushwaha et al. 2012; Liu et al. 2017, 2018a, b).

Carcinogenic and non-carcinogenic risks of chronic exposure to roadside dust due to elements in $PM_{10}$ for both children and adults via direct inhalation, ingestion, and dermal absorption were assessed at different locations. The assessment enhances the understanding of the severity of the health risks and helps to identify appropriate remedial actions. To facilitate this effort, the health risk attributed to the exposure of elements bound within the particulate matter was calculated using US EPA's methodology as expressed in Eqs. 2–7 (Liu et al. 2018a, b). The daily doses were estimated using Eqs. 2–4:

$$D_{\text{inh}} = \frac{C \times \text{InhR} \times \text{ED} \times \text{EF}}{\text{BW} \times \text{AT}} \tag{2}$$

$$D_{\text{ing}} = \frac{C \times \text{IngR} \times \text{ED} \times \text{EF}}{\text{BW} \times \text{AT}} \times 10^{6} \tag{3}$$

$$D_{\text{der}} = \frac{C \times \text{AF} \times \text{SA} \times \text{ABS} \times \text{ED} \times \text{EF}}{\text{BW} \times \text{AT}} \times 10^{6} \tag{4}$$

Hazard quotient (HQ) can be expressed as the ratio of a potential exposure level or dose to a reference dose:

$$\text{HQ} = \frac{D}{RfD} \tag{5}$$

$$\text{HI} = \sum \text{HQ} \tag{6}$$

$$\text{LCR or CR} = D_{\text{inh}} \times \text{IUR} = D_{\text{ing}} \times \text{SF} = D_{\text{der}} \times \left(\frac{\text{SF}}{G}\right) \tag{7}$$

**Table 3** The constant values used in risk calculation (Benson et al. 2017; Kushwaha et al. 2012; Liu et al. 2018a, b)

| Parameter | | Fe | Cu | Mn | B | Zn | Pb | Cr | Cd | As | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RfD | Inhalation | | 0.04 | 0.00005 | | 0.04 | 0.0035 | 0.0004 | 0.00001 | 0.000015 | 0.00005 |
| | Ingestion | 07 | 0.04 | 0.14 | 0.2 | 0.3 | 0.0035 | 0.0003 | 0.001 | 0.015 | 0.05 |
| | Dermal | | 1 | 1 | | 1 | 1 | 0.025 | 0.025 | 1 | 0.04 |
| | IUR | | | | | | 0.00008 | 0.012 | 0.0018 | 0.043 | 0.0024 |
| | SF | | | | | | 0.28 | 0.5 | 0.64 | 1.5 | 0.084 |
| | *G* | | | | | | 1 | 0.025 | 0.025 | 1 | 0.04 |

where $C$ is the concentration of the element (μg $m^{-3}$ or mg $kg^{-1}$); $D_{inh}$, $D_{ing}$, and $D_{der}$ are the daily doses through inhalation (mg $kg^{-1}$ $day^{-1}$), through ingestion (mg $kg^{-1}$ $day^{-1}$), and through dermal absorption (mg $kg^{-1}$ $day^{-1}$), respectively; InhR is the inhalation rate ($m^3$ $day^{-1}$); ED is the exposure duration (years); EF is the exposure frequency (day $year^{-1}$); BW is the body weight (kg); AT is the average time (years); LCR is the lifetime cancer risk; IUR is the inhalation unit risk ((μg $m^{-3}$)$^{-1}$); D refers to daily dose; RfD refers to the reference dose of each intake path (mg $kg^{-1}$ $day^{-1}$); SF is the slope factor (mg $kg^{-1}$ $d^{-1}$); AF is the skin adherence factor (mg $cm^{-2}$ $day^{-1}$); ABS is the dermal absorption factor (unitless); SA is the surface area ($cm^2$); and $G$ is the gastrointestinal absorption factor.

The parameters considered for health risk assessments due to trace element concentration at all the sample locations are given in Tables 3 and 4. The carcinogenic risk was found to exceed the unconditionally acceptable risk of $10^{-6}$ in the case of heavy metal elements for all the inhabitant populations (https://www/epa.gov/IRIS/basic-information-about-integratedrisk-inforamtiuon-sysem). However, the US EPA threshold for acceptable risk is between $1 \times 10^{-4}$ and $1 \times 10^{-6}$ (i.e., the probability of 1 in 10,000 to 1 in 1,000,000 that an individual may develop cancer from lifetime exposure to a carcinogen) as a commonly referenced benchmark for the protection of public health (Benson et al. 2017; Izhar et al. 2016; Liu et al. 2018a, b). Therefore, these values were used as threshold values for this study.

## Results and discussion

### $PM_{10}$ concentration

The mean concentration of $PM_{10}$ ranged from 206 to 308 μg $m^{-3}$ (with an overall mean of 255 μg $m^{-3}$). The highest and the lowest values were in the samples from Addis Ketema and Arada sub-cities, respectively. The

**Table 4** The exposure parameters for health risk assessments (Benson et al. 2017; Liu et al. 2018a, b; Walpole et al. 2012)

| Parameters | Values | |
|---|---|---|
| | Children | Adults |
| InhR ($m^3$ $day^{-1}$) | 7.6 | 20 |
| ED (year) | 6 | 30 |
| EF (days $year^{-1}$) | 122 | 122 |
| AT (days) | | |
| For non-carcinogenic | ED × 365 | ED × 365 |
| For carcinogenic | 70 × 365 | 70 × 365 |
| IngR (mg $day^{-1}$) | 200 | 100 |
| SA ($cm^2$) | 1077.5 | 2011.25 |
| AF (mg $cm^{-2}$ $day^{-1}$) | 0.02 | 0.07 |
| ABS | As (0.03), Cd (0.001), and others (0.01) | As (0.03), Cd (0.001), and others (0.01) |
| BW (kg) | 15 | 60.7 |

highest particulate matter concentrations were detected at the center of the business district, Addis Ketema sub-city, possibly because of the high population density and traffic congestion throughout the day. Additional study is required to determine the exact cause. The results of $PM_{10}$ for all the sub-cities are summarized in Tables 5 and 6. A one-way ANOVA, based on the *F*-test, was used to detect significant differences among the sub-cities included in the study. The results indicate that there was no significant difference in $PM_{10}$ pollution levels among the sub-cities.

## Elemental concentration

The total concentration of the elements in $PM_{10}$ samples collected from the ten sub-cities was determined using ICP-OES. The results (mean ± standard deviation (SD)) are given in Tables 5 and 6.

The concentrations of Fe, Cu, Mn, B, Zn, Pb, Cr, Cd, Sn, As, Ni, and Co were in the range 0.02–0.197, below the detection limit (BDL)–0.219, 0.008–0.981, 0.057–0.284, 0.074–0.557, 0.023–0.173, 0.001–0.023, 0.003–0.064, 0.004–0.231, 0.002–0.059, 0.002–0.096, and 0.001–0.100 μg $m^{-3}$, respectively. The maximum concentrations of Fe, Cu, Mn, B, Zn, Pb, Cr, Cd, Sn, As, Ni, and Co were measured at Lideta, Addis Ketema, Nefas Silk-Lafto, Kerkos, Arada, Kerkos, Akaki Kality, Kerkos, Gulele, Addis Ketema, Yeka, and Kolfe Keranio, respectively. Except for Cu, the minimum concentrations were measured at Arada, Lideta, Gulele, Yeka, Addis Ketema, Addis Ketema, Kolfe Keranio, Yeka, Arada, and Bole, respectively. The minimum value of Cu was measured as BDL at Arada, Kolfe Keranio, Nefas Silk-Lafto, and Gulele. The ANOVA test was applied to the data to determine whether or not there is a concentration variation across the studied sub-cities. The results indicated that all the elemental concentrations have a significant difference across sub-cities ($p < 0.05$), except B which did not show a significant difference ($p = 0.19$). The concentrations of the $PM_{10}$ bound trace elements from this study were compared with the literature-reported values for other cities of the world (Table 7). The results show the levels of the trace elements found in this study are lower than the reported results. The variation might be due to the unique characteristics of the cities such as topography, weather conditions, sources of pollution, traffic volumes, and composition of the fleet including gasoline and diesel vehicles (Ragettli et al. 2013; Ramos et al. 2016).

On the contrary, the patterns for the mean concentration of elements bound in $PM_{10}$, regardless of the sampling sub-cities, were found in the following increasing order: Cr < Cd < As < Co < Ni < Cu < Fe < Pb < Sn <B < Zn < Mn. A similar trend was reported with a minor change in a previous study (Gebre et al. 2010).

## Source identification of elements

The principal component analysis (PCA) and the hierarchical cluster analysis (HCA) were used to identify the possible sources of the elements bound in $PM_{10}$. The PC

**Table 5** The mean concentration of elements (in μg $m^{-3}$) in a blank filter and sample filter before deduction of blank

| Sample code | Bole | Akaki | Arada | Kolfe Keranio | Addis Ketema | Lideta | Kerkose | Nefas Silk Lafto | Gulele | Yeka | Blank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 7.381 | 7.371 | 7.333 | 7.432 | 7.411 | 7.408 | 7.416 | 7.43 | 7.51 | 7.367 | 7.313 |
| Cu | 0.975 | 1.001 | BDL | BDL | 1.189 | 1.086 | 1.111 | BDL | BDL | 1.025 | 0.969 |
| Mn | 0.66 | 0.767 | 1.268 | 1.246 | 1.621 | 1.204 | 1.226 | 1.05 | 0.648 | 1.146 | 0.639 |
| B | 13.67 | 13.77 | 13.64 | 13.77 | 13.57 | 13.73 | 13.76 | 13.65 | 13.55 | 13.77 | 13.49 |
| Zn | 21.02 | 21.08 | 21.25 | 20.99 | 21.06 | 20.76 | 21.15 | 20.9 | 20.93 | 21.12 | 20.69 |
| Pb | 11.59 | 11.59 | 11.61 | 11.65 | 11.57 | 11.64 | 11.52 | 11.56 | 11.63 | 11.67 | 11.49 |
| Cr | 2.877 | 2.885 | 2.884 | 2.869 | 2.88 | 2.875 | 2.869 | 2.865 | 2.872 | 2.879 | 2.859 |
| Cd | 2.962 | 2.946 | 2.997 | 2.975 | 2.991 | 2.961 | 2.955 | 2.944 | 2.951 | 3.006 | 2.941 |
| Sn | 4.606 | 4.607 | 4.582 | 4.497 | 4.656 | 4.724 | 4.635 | 4.623 | 4.615 | 4.586 | 4.492 |
| As | 5.388 | 5.392 | 5.405 | 5.412 | 5.418 | 5.403 | 5.367 | 5.424 | 5.393 | 5.403 | 5.364 |
| Ni | 3.302 | 3.302 | 3.273 | 3.273 | 3.337 | 3.304 | 3.357 | 3.298 | 3.294 | 3.312 | 3.262 |
| Co | 3.285 | 3.374 | 3.304 | 3.38 | 3.294 | 3.291 | 3.297 | 3.368 | 3.34 | 3.303 | 3.284 |

**Table 6** The level of $PM_{10}$ and its elements concentrations (mean ± SD, in μg $m^{-3}$) after deduction of blank at Addis Ababa

| Analyte type | Bole | Akaki | Arada | Kolfe Keranio | Addis Ketema | Lideta | Kerkos | Nefas Silk Lafto | Gulele | Yeka |
|---|---|---|---|---|---|---|---|---|---|---|
| $PM_{10}$ | 259 ± 90 | 279 ± 103 | 205 ± 35.6 | 253 ± 52.8 | 308 ± 53.7 | 292 ± 18.4 | 253 ± 66.2 | 227 ± 77.0 | 238 ± 27.9 | 231 ± 57.1 |
| Fe | 0.068 ± 0.002 | 0.058 ± 0.020 | 0.020 ± 0.001 | 0.119 ± 0.007 | 0.117 ± 0.007 | 0.197 ± 0.037 | 0.054 ± 0.008 | 0.098 ± 0.040 | 0.095 + 0.013 | 0.103 ± 0.018 |
| Cu | 0.005 ± 0.002 | 0.032 ± 0.002 | BDL | BDL | 0.219 ± 0.004 | 0.116 ± 0.003 | 0.055 ± 0.004 | BDL | BDL | 0.142 ± 0.006 |
| Mn | 0.020 ± 0.003 | 0.127 ± 0.002 | 0.628 ± 0.005 | 0.606 ± 0.001 | 0.411 ± 0.033 | 0.008 ± 0.008 | 0.507 ± 0.014 | 0.981 ± 0.002 | 0.565 + 0.002 | 0.587 ± 0.001 |
| B | 0.176 ± 0.150 | 0.282 ± 0.222 | 0.154 ± 0.140 | 0.279 ± 0.094 | 0.159 ± 0.138 | 0.057 ± 0.075 | 0.284 ± 0.062 | 0.078 ± 0.041 | 0.244 ± 0.110 | 0.274 ± 0.009 |
| Zn | 0.331 ± 0.320 | 0.386 ± 0.045 | 0.557 ± 0.110 | 0.304 ± 0.780 | 0.208 ± 0.192 | 0.239 ± 0.068 | 0.431 ± 0.008 | 0.369 ± 0.124 | 0.074 ± 0.039 | 0.463 ± 0.118 |
| Pb | 0.099 ± 0.004 | 0.097 ± 0.001 | 0.114 ± 0.100 | 0.160 ± 0.002 | 0.062 ± 0.870 | 0.140 ± 0.059 | 0.173 ± 0.040 | 0.073 ± 0.010 | 0.152 ± 0.002 | 0.023 ± 0.003 |
| Cr | 0.015 ± 0.001 | 0.023 ± 0.001 | 0.022 ± 0.007 | 0.007 ± 0.006 | 0.003 ± 0.003 | 0.001 ± 0.002 | 0.017 ± 0.005 | 0.017 ± 0.004 | 0.013 ± 0.002 | 0.007 ± 0.004 |
| Cd | 0.021 ± 0.003 | 0.005 ± 0.003 | 0.055 ± 0.003 | 0.033 ± 0.002 | 0.003 ± 0.001 | 0.009 ± 0.009 | 0.064 ± 0.003 | 0.049 ± 0.002 | 0.019 ± 0.001 | 0.013 ± 0.003 |
| Sn | 0.113 ± 0.003 | 0.114 ± 0.001 | 0.089 ± 0.007 | 0.004 ± 0.001 | 0.130 ± 0.033 | 0.122 ± 0.020 | 0.093 ± 0.039 | 0.163 ± 0.0003 | 0.231 ± 0.0003 | 0.142 ± 0.003 |
| As | 0.023 ± 0.001 | 0.027 ± 0.002 | 0.040 ± 0.110 | 0.053 ± 0.001 | 0.059 ± 0.009 | 0.027 ± 0.021 | 0.038 ± 0.002 | 0.052 ± 0.018 | 0.038 ± 0.011 | 0.002 ± 0.001 |
| Ni | 0.040 ± 0.002 | 0.041 ± 0.002 | 0.011 ± 0.04 | 0.012 ± 0.001 | 0.036 ± 0.026 | 0.032 ± 0.008 | 0.050 ± 0.018 | 0.075 ± 0.003 | 0.042 ± 0.002 | 0.096 ± 0.002 |
| Co | 0.001 ± 0.0001 | 0.090 ± 0.002 | 0.020 ± 0.002 | 0.100 ± 0.001 | 0.084 ± 0.005 | 0.057 ± 0.005 | 0.019 ± 0.005 | 0.010 ± 0.002 | 0.007 ± 0.004 | 0.013 ± 0.002 |

*BDL* below detection limit

**Table 7** The comparison of the mean concentration of trace elements (ng $m^{-3}$) of the present study to other studies conducted in the world

| Name of city and country | $PM_{10}$ (mg $m^{-3}$) | Fe | Cu | Mn | B | Zn | Pb | Cr | Cd | Sn | As | Ni | Co | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Addis Ababa, Ethiopia[a] | 254 | 0.093 | 0.057 | 0.444 | 0.199 | 0.336 | 0.109 | 0.013 | 0.027 | 0.120 | 0.036 | 0.0436 | 0.040 | Present study |
| Zaragoza (Spain)[b] | 42.9 | 666 | 22.8 | 24.7 | – | 212 | 18.7 | 7.7 | – | – | – | 0.833 | 0.128 | (Lopez et al. 2005) |
| Federal Road Police (FRP), Brazil[c] | – | 394 | 19 | 9 | – | 78 | – | – | – | – | – | – | – | (dos Anjos Paulino et al. 2014) |
| Adelina de Castro State School (AC), Brazil[c] | | 775 | 34 | 16 | – | 135 | – | – | – | – | – | – | – | |
| Hanggang monitor station (HG), China[C] | – | 5543 | 154 | 180 | – | 1019 | 195 | 19.2 | 4.1 | – | 21.2 | 10.7 | 2.4 | (Dai et al. 2015) |
| Zhiwuyuan (ZWY), China[C] | | 1993 | 117 | 68.9 | – | 795 | 159 | 7.5 | 3.8 | – | 16.3 | 6.2 | 1.1 | |
| HermanosSerdán(HS), Mexico[d] | 89.5 | 971 | 33.9 | 24.1 | – | – | 32.7 | 31.9 | 4.4 | – | 22.2 | 9.8 | 0.95 | (Morales-Garcia et al. 2014) |
| Ninfas (NIN), Mexico[b] | 49.7 | 934 | 26.7 | 23.3 | – | – | 17.7 | 16.3 | 2.0 | – | 21.8 | 6.0 | 0.68 | |
| Tecnológico (TEC), Mexico[b] | 55.9 | 1203 | 86.6 | 33.5 | – | – | 48.9 | 41.9 | 5.5 | – | 42.4 | 18.6 | 1.88 | |
| Jharkhand, India[e] | 258 | 8900 | 1440 | 470 | – | 680 | 150 | 320 | 60 | – | – | 10 | – | (Dubey et al. 2012) |
| Jharkhand, India[f] | 134 | 8044 | 1426 | 240 | – | 532 | 269 | 42 | 42 | – | – | 10 | – | |

[a] Roadside area

[b] Highly industrialized chemical/petrochemical area

[c] Steel-related sites

[d] Residential and school area

[e] Coal mining area

[f] Non-mining area

loadings and corresponding variances for each element are given in Table 8. The results demonstrate that the first five elements explain 88.6% of the data variance. As shown in Table 8, 27.5% of the total variance of the data can be explained by PC1, which has a positive loading of Zn (0.433), Cr (0.409), and Cd (0.477). The primary source of these elements may be emission from on-road vehicles, tire and brake wear (Jandačka and Ďurčanská 2014). The second component, PC2, is dominated by Pb (0.437) which reportedly originated primarily from industries and suspended soil dust at the roadside (Zereini et al. 2005; Crilley 2014; Fortoul et al. 2015). PC3 is dominated by As (0.483) and Mn (0.496) which are mainly linked to dust resuspension, industries, car body component abrasion, and burning of municipal waste (Crilley 2014; Jandačka and Ďurčanská 2014). PC4 is dominated by Mn (0.446), the source of which is associated with industries and roadside soil resuspension. PC5 is highly loaded with B (0.770) which primarily comes from the combustion of biomass and resuspension of dust (Crilley 2014; Jandačka and Ďurčanská 2014).

To demonstrate the correlation between trace elements and the sampling sub-cities, a biplot graph was constructed using PC1 and PC2. The results (Fig. 3) illustrate that the PCs associated with Mn, Zn, Cr, and Co were linked to Kerkos and Arada sub-cities, whereas Sn and Ni are associated with Yeka sub-city and As and Pb are associated with Kolfe Keranio sub-cites, respectively. Similarly, Fe is associated with Lideta and Addis Ketema sub-cities, while B is linked with Akaki Kality sub-city.

The HCA was also carried out to detect the multivariate similarity in elements. The cluster analysis was carried out for the 11 trace element pollutants as variables and the ten sampling sites. The corresponding cluster analysis–derived dendrogram is shown in Fig. 4. Four clusters were identified as follows: cluster 1 (Fe, Pb, As, and Co), cluster 2 (Mn, Cd, Zn, and Cr), cluster 3 (B), and cluster 4 (Sn and Ni) at 1 cm. From the cluster analysis, it can be concluded that there is a strong correlation between As-Co, Mn-Cd, Zn-Cr, and Sn-Ni which suggests that the sources of origin might be similar. The strong correlation in cluster 1 indicates that the sources are similar and they may be associated with a mixture of suspended roadside dust and industrial- and traffic-related activities. Fe is a ubiquitous element and it was detected in all samples, whereas Pb, As, and Co are associated with industries and combustions of gasoline and diesel fuels. There is a good correlation in cluster 2 which indicates that their sources are primarily the result of traffic-related sources including tire wear, brake calipers, and pad abrasions. The good correlation between Sn and Ni at cluster 4 suggests that their sources are from industries and oil combustions, since Ni is a tracer found in oil combustion (Hao et al. 2018; Qing et al.

**Table 8** Principal component analysis (PCA) results of elements in $PM_{10}$ at the roadside

| | PC1 | PC2 | PC3 | PC4 | PC5 |
|---|---|---|---|---|---|
| Fe | – | – | – | – | – |
| Mn | – | – | *0.483* | *0.446* | – |
| B | – | – | – | – | *0.770* |
| Zn | *0.433* | – | – | – | – |
| Pb | – | *0.437* | – | – | – |
| Cr | *0.409* | – | – | – | – |
| Cd | *0.477* | – | – | – | – |
| Sn | – | – | – | – | – |
| As | – | 0.389 | *0.496* | – | – |
| Ni | – | – | – | – | – |
| Co | – | 0.371 | – | 0.322 | – |
| Eigenvalue | 3.030 | 2.649 | 1.715 | 1.310 | 1.038 |
| Percentage of variance | 27.5% | 24.1% | 15.6% | 11.9% | 9.44% |
| Cumulative | 27.5% | 51.6% | 67.2% | 79.1% | 88.6% |

Only loads larger than 0.3 (absolute values) were reported; loads larger than 0.4 (absolute values) are in italics which are the main contribution elements to the component

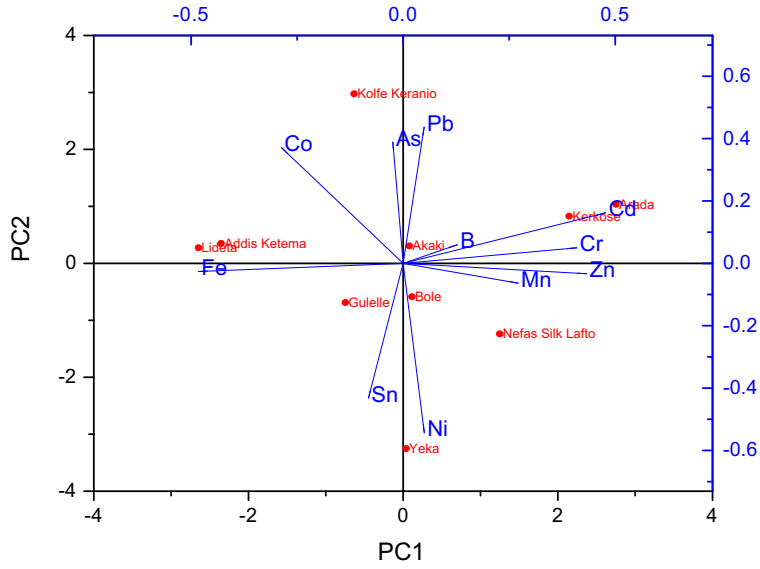



**Fig. 3** Biplot of scores and loading matrices for the first two PCs of $PM_{10}$ sampled at the roadside

2015; Varshney et al. 2016; Celo and Dabek-Zlotorzynska 2010).

## Exposure to roadside pollutants and health risk analysis

Exposure to polluted air with high levels of particulate matter (PM) affects human health and has been linked to various illnesses such as respiratory, cardiovascular, and neurological diseases. Exposure routes for adults, due to air-borne $PM_{10}$ and attached trace elements, occur by inhalation and direct ingestion pathways, followed by dermal contact (Table 9). Direct ingestion is also the primary pathway for children, followed by inhalation pathways and dermal contact. For the levels of air pollution measured in this study, the carcinogenic risks due to long-term exposure are found in a tolerable range and below given by US EPA (Benson et al. 2017). The carcinogenic risk posed by exposure to Pb through ingestion was higher than the risk posed to children by inhalation and dermal contact. The risk profile is similar for adults who are exposed to As.

The non-carcinogenic risks posed by individual elements were determined by using hazard quotient (HQ) of each element. The results indicate that Mn via inhalation is high for both the children and adults. The Mn metal is the only element which poses the non-

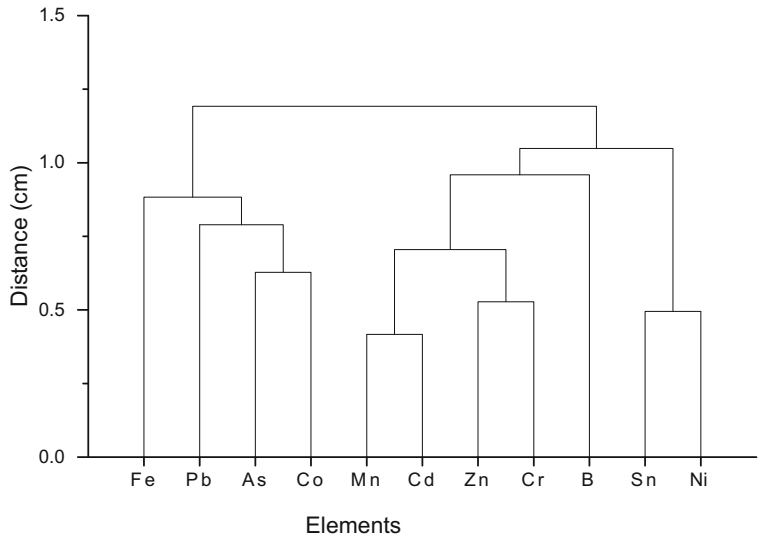



**Fig. 4** Dendrogram from the cluster analysis of 11 elements in ten sampling sites at Addis Ababa

**Table 9** Carcinogenic and non-carcinogenic risks due to each element for children and adults via inhalation, ingestion, and dermal exposure at the roadside microenvironment

| Type of metal | LCR Adults | HQ | LCR Children | HQ |
|---|---|---|---|---|
| Inhalation exposure | | | | |
| Cu | | $1.5 \times 10^{-4}$ | | $2.41 \times 10^{-4}$ |
| Mn | | 0.978 | | *1.504* |
| Zn | | $1.22 \times 10^{-4}$ | | $1.89 \times 10^{-4}$ |
| Pb | $4.43 \times 10^{-7}$ | 0.0034 | $1.36 \times 10^{-7}$ | 0.0052 |
| Cr | $7.93 \times 10^{-6}$ | 0.0143 | $2.44 \times 10^{-6}$ | 0.022 |
| Cd | $2.47 \times 10^{-6}$ | 0.297 | $7.60 \times 10^{-7}$ | 0.457 |
| As | $7.87 \times 10^{-6}$ | 0.264 | $2.42 \times 10^{-6}$ | 0.406 |
| Ni | $5.37 \times 10^{-7}$ | 0.097 | $1.65 \times 10^{-7}$ | 0.149 |
| Sum (HI) | $1.92 \times 10^{-5}$ | *1.650* | $5.78 \times 10^{-6}$ | *2.544* |
| Ingestion exposure | | | | |
| Fe | | $7.32 \times 10^{-5}$ | | $5.92 \times 10^{-4}$ |
| Cu | | $7.85 \times 10^{-4}$ | | 0.006 |
| Mn | | 0.0017 | | 0.014 |
| B | | $5.48 \times 10^{-4}$ | | 0.004 |
| Zn | | $6.17 \times 10^{-4}$ | | 0.005 |
| Pb | $7.20 \times 10^{-6}$ | 0.017 | $1.17 \times 10^{-5}$ | 0.139 |
| Cr | $1.53 \times 10^{-6}$ | 0.002 | $2.48 \times 10^{-6}$ | 0.019 |
| Cd | $4.08 \times 10^{-6}$ | 0.015 | $6.60 \times 10^{-6}$ | 0.120 |
| As | $1.27 \times 10^{-5}$ | 0.066 | $2.06 \times 10^{-5}$ | 0.534 |
| Ni | $8.72 \times 10^{-7}$ | $4.84 \times 10^{-4}$ | $1.41 \times 10^{-6}$ | 0.004 |
| Sum (HI) | $2.64 \times 10^{-5}$ | 0.105 | $4.28 \times 10^{-5}$ | 0.847 |
| Dermal exposure | | | | |
| Cu | | $4.42 \times 10^{-7}$ | | $7.85 \times 10^{-7}$ |
| Mn | | $3.44 \times 10^{-6}$ | | $6.12 \times 10^{-6}$ |
| Zn | | $2.60 \times 10^{-6}$ | | $4.63 \times 10^{-6}$ |
| Pb | $1.09 \times 10^{-7}$ | $8.45 \times 10^{-7}$ | $7.89 \times 10^{-7}$ | $1.50 \times 10^{-6}$ |
| Cr | $9.30 \times 10^{-7}$ | $4.03 \times 10^{-6}$ | $6.72 \times 10^{-6}$ | $7.16 \times 10^{-6}$ |
| Cd | $2.47 \times 10^{-7}$ | $8.37 \times 10^{-7}$ | $1.79 \times 10^{-6}$ | $1.49 \times 10^{-6}$ |
| As | $5.80 \times 10^{-7}$ | $8.37 \times 10^{-7}$ | $4.19 \times 10^{-6}$ | $1.49 \times 10^{-6}$ |
| Ni | $3.31 \times 10^{-7}$ | $8.53 \times 10^{-6}$ | $2.39 \times 10^{-6}$ | $1.51 \times 10^{-5}$ |
| Sum (HI) | $2.20 \times 10^{-6}$ | $2.16 \times 10^{-5}$ | $1.59 \times 10^{-5}$ | $3.83 \times 10^{-5}$ |

Italics indicate higher from threshold values

carcinogenic risk for both the children and adults through the inhalation pathway. Also, none of the elements posed a non-carcinogenic health risk through dermal contacts. However, the total non-carcinogenic risk due to exposure to all the elements at each exposure pathway showed hazard index (HI) > 1 for both the children and adults though through inhalation only. The total non-carcinogenic health risk due to elemental exposure through the three pathways was calculated by summing the HQ of each element obtained at each pathway. The result (total HI = 3.39) confirms that children could be affected by non-carcinogenic health problems. The calculated percent contribution of each exposure pathway for the total risk values (total HI) indicates that inhalation, ingestion, and dermal contact exposure pathways for children account for 75.00, 24.99, and 0.01%, respectively. Similarly, the total HI for adults (total HI = 1.76) confirms that they are also likely to

have non-carcinogenic health problems. The percent contribution of inhalation, ingestion, and dermal contact exposure pathways to the total HI was 94.04, 5.955, and 0.005%, respectively.

## Conclusion

In Addis Ababa, as in many emerging economies that are experiencing significant population growth, rapid industrialization and increased motorized traffic are outpacing the ability to provide the necessary infrastructure and services resulting in serious air pollution problems. The composition of trace elements bound to particulate matter in the air samples suggests traffic-related abrasion particles such as tire wear, brake calipers, pad abrasion, and car body are significant sources of environmental pollution with potential health implications. The pollution concentrations of $PM_{10}$ in the sub-cities of Addis Ketema, Lideta, and Akaki Kality were higher relative to the other sub-cities. The elements bound in $PM_{10}$ were also analyzed, and the overall patterns of elements bound in $PM_{10}$ regardless of the sampling sub-cities were found in the increasing order of Cr < Cd < As < Co < Ni < Cu < Fe < Pb < Sn < B < Zn < Mn. The health risk assessment for adults and children was evaluated using the trace elements bound in $PM_{10}$ regardless of sampling sites. The HQ values for all the elements are less than one, except for Mn, for children. Exposure to $PM_{10}$ containing Mn is likely to induce any non-carcinogenic health problems for children. However, the HI value is higher than one, which implies that both children and adults exposed to 8 h per day at the roadside are likely to have the non-carcinogenic health problems due to $PM_{10}$. Therefore, there is a need to increase awareness among the public and stakeholders about the health impacts due to exposure to $PM_{10}$ while commuting. This information can then be used as a basis for planning and developing methods to reduce exposure to roadside air pollution.

## Recommendations

Improvement in the outdoor air quality can be achieved by improving public transportation and formulating regulations to discourage car usage and urban planning aimed at reducing commute times and increasing green space. Although measuring the pollutant levels and examining different health issues would provide a more realistic estimation of the health impacts for the exposed person, this study was limited on the estimation of the health impacts based on measuring the concentration of trace elements bound in $PM_{10}$. The heavy metals and other elements present in $PM_{10}$ are not the only hazardous air pollutants; there are toxic organic substances, including polycyclic aromatic hydrocarbons that may also be present, depending on the sources. However, analysis of other toxic pollutants was beyond the scope of this study. This study will foster an understanding of the sources of pollution and inform the policymakers who may formulate strategies to address the environmental problems. The goal is to build energy-efficient and sustainable cities that are attractive to live and work. This study focused on the assessment of the health consequences of a single air pollutant, particulate matter, and related trace elements. However, air masses may contain other contaminants and humans are simultaneously exposed to a complex mixture of these pollutants. The present study should be expanded to a multi-pollutant approach to air quality so that air quality management including health risk assessment and setting regulator standard should take multiple pollutants.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflicts of interest.

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