

# Chemical fractionation of heavy metals in fine particulate matter and their health risk assessment through inhalation exposure pathway

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Received: 8 March 2018 / Accepted: 20 November 2018 / Published online: 11 December 2018  
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**Abstract** Samples of PM<sub>2.5</sub> were collected from an urban area close to a national highway in Agra, India and sequentially extracted into four different fractions: water soluble (*F1*), reducible (*F2*), oxidizable (*F3*) and residual fraction (*F4*) for chemical fractionation of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni) and lead (Pb). The metals were analyzed by inductively coupled plasma optical emission spectroscopy in each fraction. The average mass concentration of PM<sub>2.5</sub> was  $93 \pm 24 \mu\text{g m}^{-3}$ . The total concentrations of Cr, Pb, Ni, Co, As and Cd in fine particle were  $192 \pm 54$ ,  $128 \pm 25$ ,  $108 \pm 34$ ,  $36 \pm 6$ ,  $35 \pm 5$  and  $8 \pm 2 \text{ ng m}^{-3}$ , respectively. Results indicated that Cd and Co had the most bioavailability indexes. Risk Assessment Code and contamination factors were calculated to assess the environmental risk. The present study evaluated the potential Pb hazard to young children using the Integrated Exposure Uptake Biokinetic Model. From the model, the probability density of PbB (blood lead level) revealed that at the prevailing atmospheric concentration, 0.302 children are expected to have PbB concentrations exceeding  $10 \mu\text{g dL}^{-1}$  and an estimated IQ (intelligence quotient) loss of 1.8 points. The predicted blood Pb levels belong to Group 3 ( $\text{PbB} < 5 \mu\text{g dL}^{-1}$ ). Based on the bioavailable

fractions, carcinogenic and non-carcinogenic risks via inhalation exposure were assessed for infants, toddlers, children, males and females. The hazard index for potential toxic metals was 2.50, which was higher than the safe limit (1). However, the combined carcinogenic risk for infants, toddlers, children, males and females was marginally higher than the precautionary criterion ( $10^{-6}$ ).

**Keywords** Fine particulate matter · Heavy metals · Sequential extraction procedure · Inhalation exposure pathway · IEUBK model · Sensitivity analysis · Health risk

## Introduction

Atmospheric fine particulate matter (PM) is of concern due to its adverse health effects (Ostro et al. 2014; Ram et al. 2016). PM<sub>2.5</sub>, having larger surface area, has greater potential to absorb air pollutants, especially high concentrations of toxic metals such as As, Cd, Cr, Cu, Mn, Ni, Pb, V and Zn (Hu et al. 2012; Li et al. 2013). Toxicological and epidemiological studies have revealed that toxicity of PM is mainly due to absorbed toxic metals (Zhai et al. 2014). According to the classification of the International Agency for Research on Cancer (IARC), metals such as As, Cd, Ni and Cr(VI) are Group 1 carcinogens, while Pb and Co are Group 2A carcinogens (IARC 2011). These toxic

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elements can be associated with particulate matter and enter the body through ingestion, inhalation and dermal contact (Zhang et al. 2015). For children, metals may pose a greater risk due to their absorption of heavy metals from the digestive system and their higher hemoglobin sensitivity compared to adults due to their lower body-weight at early ages (Kurt-Karakus 2012).

Use of arsenic in production of glass, pesticides, mining activities and smelting releases significant amounts of As to the atmosphere (de la Campa et al. 2011); arsenic released by these activities exceeds its natural emissions by a factor of 3 (WHO 2000). It is the most toxic element for human health (Smith et al. 2006). EPA has calculated an oral cancer slope factor of  $1.5 \text{ (mg kg}^{-1} \text{ day}^{-1})^{-1}$  for inorganic arsenic. On the basis of hyperpigmentation, keratosis and vascular complications in humans, the Reference Dose (RfD) for inorganic arsenic is  $3 \times 10^{-4} \text{ (mg kg}^{-1} \text{ day}^{-1})$  (US EPA 1998).

Chromium is found in the earth's crust in varying oxidation states ranging from Cr(II) to Cr(VI) (Gibb et al. 2015). Trivalent Cr(III) is the most stable state and exists in nature as ferrochromite ( $\text{FeCr}_2\text{O}_4$ ) ores, whereas hexavalent Cr(VI) is the second most stable state and exists as  $\text{PbCrO}_4$  or  $\text{ZnCrO}_4$ . The hexavalent Cr(VI) form is released to the atmosphere from ferrochrome metallurgy, power plants, incinerators, cement plants, dyes, pigments, tanneries and welding processes (Huang et al. 2014). Cadmium is released from both natural and anthropogenic sources into the air. Anthropogenic sources such as burning of fossil fuels, mining and smelting of ores, atmospheric deposition from metallurgical industries, incineration of plastics, batteries and sewage sludge, are the major contributors (Khan et al. 2017). Cd is a carcinogenic metal that can cause toxic reactions in low concentration (Tang et al. 2018). Cobalt occurs in the environment along with other metals such as Cu, Ni, Mn and As. It is used in super-alloys, alloys and pigment manufacture. High concentrations of Co can occur in the air near industrial areas. Nickel is widely found in the environment and released from natural sources such as volcanic emission, soil dust, forest fire, vegetation, and sea salt, while its anthropogenic sources include combustion of diesel, fuel oil and coal, metallurgical operations, electroplating, alloys, batteries, coins, spark plugs, industrial plumbing, machinery parts, stainless-steel, nickel-chrome

resistance wires, and catalysts (Cempel and Nikel 2006). The toxicity of Ni depends on its speciation, physical form, concentration levels and exposure pathway. Lead is also a naturally occurring metal present in trace amounts in the earth's crust. It enters into the environment due to fossil fuel burning, mining, lead-acid batteries, ammunition, devices to shield X-rays, metal products, industrial, agricultural and domestic applications. Pb has adverse health effects on humans and biota (ATSDR 2007; JECFA 2011). Inorganic Pb compounds are largely incorporated into the human body through inhalation and ingestion and very little through dermal contact ( $< 0.3\%$ ) (ATSDR 2007; Pizzol et al. 2010; JECFA 2011). Pb in dust and soil contributes to elevated blood lead levels in children and can be deposited in their teeth and bones (Lanphear et al. 2000; Jusko et al. 2008; JECFA 2011). Zheng et al. (2013) used an Integrated Exposure Uptake Biokinetic Model (IEUBK) (U.S. EPA 2010) to evaluate the health risk linked with Pb exposure for young children. In current years, the industrial use of Pb has notably diminished (Song et al. 2012).

Epidemiological studies have shown different associations between air pollution and respiratory health for females and males. Several studies report stronger effects among women and girls than among men and boys (Dong et al. 2011). Sex-linked traits such as hormonal status and body size influence the transport of environmentally derived chemicals in biological systems. Growth and size of the lung, deposition of fine particles, gas absorption, gas-blood barrier permeability, airway hyper-responsiveness, vascular response, and inflammation all differ by sex (Sood et al. 2008; Brauner et al. 2009). However it is not well understood whether observed modifications can be attributed to biological and exposure differences between men and women.

In order to assess the potential environmental and health effects of metals in particulate matter, it is crucial to know not only the total metal concentrations but also their labile, bioavailable, mobile and immobile fractions (Feng et al. 2009; Betha et al. 2014). The labile fraction is more easily accessible to environmental receptors and more harmful to animals than the resistant fraction (Feng et al. 2009), while the water-soluble fractions are easily mobilized on interaction with human body fluid. This fraction is therefore the most bio-accessible heavy metal fraction (Mukhtar

and Limbeck 2013). Generally, anthropogenic elements like Zn, As and Cd have relatively high proportions in the labile or mobile fraction, whereas geogenic metals such as Ti and Fe exist in high proportions in the residual fraction (Feng et al. 2009; Schleicher et al. 2011; Li et al. 2015). In India, several studies have focused on total metal concentrations, seasonal variations and identification of sources of atmospheric particles (Kulshrestha et al. 2014; Pipal et al. 2014; Das et al. 2015) and very few studies have focused on health risk due to exposure to particulate matter (Kumar et al. 2014; Khanna et al. 2015; Izhar et al. 2016). These studies also do not consider the chemical fractionation of the heavy metals and their mobility. In this study chemical fractionation of metals (As, Cd, Co, Cr, Ni and Pb) in fine particulate matter collected from an urban site was performed using the modified BCR sequential extraction method. The main objective of the adopting the fractionation procedure was to determine the mobility potential of these metals and to evaluate the health risk of these metals to infants, toddlers, children, males and females. Although this scheme is reported to provide conditions almost identical to the deposition and solubilisation in the human lung (Schleicher et al. 2011; Li et al. 2015), it does not simulate the gastrointestinal processes occurring in humans, for which several *in vitro* assays such as the IVG (In Vitro Gastrointestinal), PBET (Physiologically Based Extraction Test), SBRC (Solubility Bioaccessibility Research Consortium), UBM (United Barge Method) etc. (Ruby et al. 1996; Schroder et al. 2003; Marschner et al. 2006; Denys et al. 2012) and *in vivo* assays (swine feeding trials) have been developed and applied to measure the bioaccessibility of heavy metals in polluted soils, road dust, water, food and air (Ng et al. 2015). Even though the Tessier extraction scheme is associated with some uncertainties it was chosen as the indicator of bioavailability in this work and has been widely used to assess the bioavailable fraction of atmospheric aerosols (Feng et al. 2009; Sun et al. 2014; Varshney et al. 2016; Li et al. 2017; Jan et al. 2018) and soil (Schilderman et al. 1997; Schroder et al. 2003; Liang et al. 2016; Gope et al. 2017).

## Materials and methods

### Site description

Agra (27°10'N, 78°02'E) is a city located in the central part of northern India. It is situated on the banks of the river Yamuna in Uttar Pradesh, India. It is about 204 km of south of Delhi and surrounded by the Thar Desert of Rajasthan on its southeast, west and northwest peripheries. Agra is a well-known tourist site; it is the most populated city in Uttar Pradesh and the 24th most populated in India. It is a visitor destination due to the Taj Mahal, Agra Fort, Soamibagh Samadh Temple and Fatehpur Sikri. Agra has semiarid weather and a subtropical climate. The population of Agra was about 1.84 million in 2017 with a population density of 1084 persons km<sup>-2</sup> and female: male ratio of 0.87:1.0. The summer period is hot and dry with the temperature ranging from 32 to 48 °C with predominant wind direction being south–southeast and northeast. In winter the temperature ranges from 2 to 15 °C and wind direction changes to west–northwest and north–northwest (IMD 2009). Three main National Highways (NH-2, NH-3 and NH-11) pass through the city. The dominant industrial activities are metallurgical processes, foundries, nickel plating units, diesel engine manufacturing, tanneries, lime kilns, pulverization, engineering works and chemicals. Besides local sources, glass industries in Firozabad, Mathura refinery and brick factories are also located within 40 km of Agra.

Sampling of PM<sub>2.5</sub> was carried out on the roof of a building situated close to National Highway 2 from March to August, 2016. The sampling site is shown in Fig. 1. Aerosol samples were collected on quartz fiber filters (Pallflex, Tissuquartz) for 24 h by a fine particulate sampler (APM 550, Envirotech) at a flow rate of 16.6 L min<sup>-1</sup>. Collected samples were put in polyethylene bags and brought to the laboratory and stored in a refrigerator. Before and after the sampling the filters were weighed to determine the aerosol mass by the difference in two digits. Prior to weighing, all filters were conditioned in a desiccator at 25 °C and 40% relative humidity for 48 h.

### Sequential extraction of metals

The sequential extraction procedure (SEP) developed by Espinosa et al. (2002) was used for fractionation of



**Fig. 1** Location of study area in Agra

metals into four fractions: water-soluble ( $F1$ ), reducible ( $F2$ ), oxidizable ( $F3$ ), and residual fraction ( $F4$ ). For extraction, three-fourths of each quartz fiber filter was cut into small pieces with Teflon coated scissors and was put into a conical flask. For the  $F1$  fraction, 20 mL of de-ionized water (pH = 7) was added to the flask and ultra-sonicated for 30 min followed by centrifugation. Then the extract was filtered by Sartorius filter paper (Sartorius Stedim Biotech, 393) using a funnel and stored in a polyethylene bottle at 4 °C until analysis. The residue was dried on a water bath. For the  $F2$  fraction, to the residue obtained from the first step, 20 mL  $\text{NH}_2\text{OH}\cdot\text{HCl}$  (0.25 M at pH = 2.0) solution was added. The mixture was shaken for 2 h at room temperature (25 °C). The supernatant was decanted into a polyethylene bottle and the residue was heated on a hot plate to reduce the volume to 1–2 mL. De-ionized water was added to achieve a final volume of 20 mL. The residue was dried on a water bath. For the  $F3$  fraction, to the residue obtained from the second extraction step, 7.5 mL  $\text{H}_2\text{O}_2$  solution was added drop wise till dryness, followed by another addition of 15 mL of 30%  $\text{H}_2\text{O}_2$  at 95 °C and evaporation to near dryness. Then 15 mL  $\text{CH}_3\cdot\text{COONH}_4$  (2.5 M at pH = 3.0) was added and the contents shaken for 90 min at room temperature. The

contents were concentrated to 1–2 mL on a hot plate and final volume was made up to 20 mL with de-ionized water. For the  $F4$  fraction, the residue obtained from  $F3$  fraction was digested with 10 mL ( $\text{HNO}_3\text{:HCl:HF}$ ) (ratio = 2:6:2) by heating at 95 °C for 5 h and evaporated to near dryness. After cooling, the dried mass was dissolved in de-ionized water and made up to 20 mL. All the four fractions were preserved in a refrigerator at 4 °C until analysis.

#### Sample analysis

Metal concentrations were analyzed in each fraction by an inductively coupled plasma-optical emission spectrometer (ICP-OES; Thermo Fisher, ICAP 6300 Duo). The instrument was equipped with a multiplier collector and a radio frequency power of 750–1500 W was applied to the plasma. The instrument was operated with coolant Ar gas at a flow rate of 12 L  $\text{min}^{-1}$ , an auxiliary Ar gas flow rate of 1.5 L  $\text{min}^{-1}$ , and a nebulizer Ar flow rate of 1 L  $\text{min}^{-1}$ . The sample flow rate was 1 mL  $\text{min}^{-1}$ . A calibration curve was plotted from the known standard solutions (0, 0.05, 0.1, 0.5, 1, 10 and 20 mg  $\text{mL}^{-1}$  standards), prepared by step dilution of a multi-element standard solution (Fluka, 54704; 1000 mg  $\text{L}^{-1}$ ) ( $R^2 > 0.999$ ). Dilute

HNO<sub>3</sub> was used as blank and for the dilution of standards. Metal analysis in all the four fractions was done in triplicate, and the concentration was reported as the average of the triplicates. For all the metals, limits of detection (LOD) were determined. LOD has been defined as the concentration of analyte giving signal equal to the blank signal ( $\gamma_b$ ) plus three standard deviations of the blank, ( $S_b$ ),  $\{LOD = \gamma_b + 3S_b\}$ , here  $\gamma_b$  and  $S_b$  were determined from the regression equation of the calibration curves of each metal (Miller and Miller 2010; Verma et al. 2017). The value of the intercept of the regression line was used as an estimate of  $\gamma_b$ , and  $S_b$  values were calculated from the standard deviation of the slope of the regression line as,  $[S_b = (S_{y/x}) / \{\sum_i (x_i - x_m)^2\}^{1/2}]$ , where,  $S_{y/x} = [ \{ \sum_i (y_i - \hat{y})^2 / n - 2 \}^{1/2}]$ , here  $(y_i - \hat{y})$  are the y- residuals and  $n - 2$  is the degree of freedom for the data points of the regression line.  $(x_i - x_m)$  are the deviations from mean values of  $x$  ( $x$  represents the concentration values in the calibration curve for each metal) (Miller and Miller 2010; Verma et al. 2017). The method detection limit (MDL) for Cr, Pb, Ni, Co, As and Cd was 1.86, 3.16, 2.57, 2.28, 1.27 and 2.18 ng m<sup>-3</sup>, respectively.

Quality control in monitoring

Before weighing the samples, the weighing balance (Mettler Toledo, ME 204) was calibrated each time. The sampler was also cleaned periodically to make it free from dust particles. The filter in the wins impactor was changed twice in a week after sampling and immersed in 3–4 drops of silicon oil. Collected filter paper was wrapped in aluminium foil promptly after sampling and kept in polyethylene zip-lock bags, then stored in airtight containers in a refrigerator at 4 °C until analysis. Filters were handled only with clean Teflon coated forceps to avoid the possibility of contamination and then forceps were cleaned with ethanol and de-ionized water. For metal analysis, glassware was soaked in 2% HNO<sub>3</sub> overnight and then washed with de-ionized water several times, and dried at 180 °C in an oven for 30 min.

Internal check recovery of elements

The total metal concentrations in the PM<sub>2.5</sub> samples were also separately determined by digestion of the filters with a mixture of HClO<sub>4</sub>, HNO<sub>3</sub> and HF. An

internal check of the recovery of each metal by SEP was performed, which was calculated as follows:

$$\text{Recovery (\%)} = (F1 + F2 + F3 + F4) / TC \times 100,$$

where  $F1, F2, F3$  and  $F4$  refer to the concentration extracted in each fraction, respectively, and  $TC$  is the total concentration of heavy metals. Generally, the recovery ranges were from 84 to 118% for the analyzed metals, which indicates that the sum of the metal concentrations in the four fractions are in good agreement with the total concentrations and this SEP is reliable and repeatable. In addition, a few unexposed filter papers were spiked with a known amount of metal to ascertain the efficiency of the extraction procedure. The analytical procedure for the recovery test was the same as that for field samples. The recovery test results for the metals were 96.7% for Cr, 95.9% for Pb, 103.1% for Ni, 96.3% for Cd, 109.3% for As and 94.4% for Co.

Health risk assessment model

Human health risk assessment was performed based on the bioavailable ( $F1 + F2$ ) metal concentrations. The carcinogenic and non-carcinogenic risks posed by airborne metals via inhalation of PM<sub>2.5</sub> were calculated using US Environmental Protection Agency (US EPA) human health risk assessment models (US EPA 2009), which mainly involve exposure assessment and risk characterization. The sensitive residents were divided into infants (0–1 year), toddlers (0.5–5 years), children (5–19 years) and adults (males and females). It is well known that the health risk associated with metals in PM arises from the inhalation of particles followed by their deposition in the respiratory tract. Thus, the deposition fraction of particles by size was considered. According to Volckens and Leith (2003), the fraction of particles deposited in the lungs can be calculated as

$$E_i = -0.081 + 0.23 \times \ln(d_p)^2 + 0.23 \times \sqrt{d_p}$$

where  $d_p$  is the particle diameter;  $d_p = 2.5 \mu\text{m}$  is thus used for PM<sub>2.5</sub> in this study.

The inhalation exposure concentration (EC), hazard quotient (HQ) for non-cancer risk, and carcinogenic risk (CR) posed by a toxic metal in PM<sub>2.5</sub> were calculated as



$$EC = (C \times E_i \times ET \times EF \times ED) / ATn$$

$$HQ = EC / (RfC \times 1000 \mu\text{g mg}^{-1})$$

$$CR = IUR \times EC$$

where  $C$  is the metal concentration in  $PM_{2.5}$  ( $\mu\text{g m}^{-3}$ ),  $ET$  is the exposure time ( $24 \text{ h day}^{-1}$ ),  $EF$  is the exposure frequency ( $180 \text{ days year}^{-1}$ ),  $ED$  is the exposure duration (1 year for infants, 4.5 years for toddlers, 17 years for children, 24 years for males and females) (US EPA 2009),  $ATn$  is the averaging time ( $ATn = ED \times 365 \text{ days} \times 24 \text{ h day}^{-1}$  for non-carcinogens, and  $ATn = 70 \text{ years} \times 365 \text{ days year}^{-1} \times 24 \text{ h}$  for carcinogens),  $RfC$  is the inhalation reference concentration ( $\text{mg m}^{-3}$ ), and  $IUR$  is the inhalation unit risk ( $(\mu\text{g m}^{-3})^{-1}$ ). The values of  $RfC$  for As, Cd, Co, Cr(VI) and Ni are  $1.50 \times 10^{-5}$ ,  $1.00 \times 10^{-5}$ ,  $6.00 \times 10^{-6}$ ,  $1.00 \times 10^{-4}$  and  $1.40 \times 10^{-5} \text{ mg m}^{-3}$ , respectively (US EPA 2011). The values of  $IUR$  for As, Cd, Co, Cr(VI), Ni and Pb are  $4.30 \times 10^{-3}$ ,  $1.80 \times 10^{-3}$ ,  $9.00 \times 10^{-3}$ ,  $8.40 \times 10^{-2}$ ,  $2.40 \times 10^{-4}$  and  $8.00 \times 10^{-5} (\mu\text{g m}^{-3})^{-1}$ , respectively (US EPA 2013).  $C$  is the exposure-point concentration. As mentioned above, metals in the bioavailable fraction ( $F1 + F2$ ) are considered to be highly bio-accessible and present the greatest risks to biota (Schleicher et al. 2011; Mukhtar and Limbeck 2013; Betha et al. 2014). Thus, for the calculation of  $EC$ , the bioavailable fraction was used instead of the total metal concentrations. According to US EPA (2013), Cr(VI) and Cr(III) are classified as Group A (human carcinogens) and Group D (not classifiable for human carcinogenicity), respectively. Cr(VI) and Cr(III) exist in a ratio of 1:6 in the atmosphere (Taner et al. 2013; Li et al. 2016). Since in this study the total concentration of Cr was determined, for the estimation of  $EC$  the concentration of Cr(VI) was assumed to be 1/7th of the total Cr concentration. Carcinogenic risk is the probability of developing cancer due to lifetime exposure to a specific carcinogen. For carcinogens, the acceptable or tolerable risk range is between  $1 \times 10^{-6}$  (1 in 1,000,000) and  $1 \times 10^{-4}$  (1 in 10,000) (US EPA 2011). Hazard quotient (HQ) is the ratio of the probable exposure to a contaminant and the level at which no negative effects are observed. The hazard index (HI) is the sum of HQ and is used to evaluate the overall potential for non-carcinogenic health effects.

HQ and/or HI less than 1 indicate that there are no non-carcinogenic effects. Conversely, values greater than 1 indicate probability of non-carcinogenic effects (US EPA 2011).

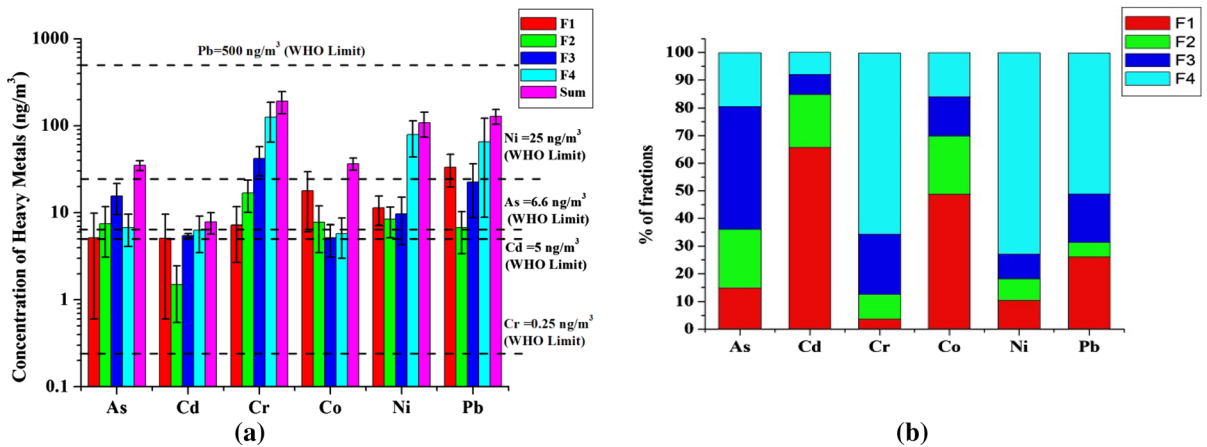
## Results and discussion

### $PM_{2.5}$ mass concentrations

The average  $PM_{2.5}$  concentration was  $93.2 \mu\text{g m}^{-3}$  (range  $37.8\text{--}133 \mu\text{g m}^{-3}$ ) and the daily  $PM_{2.5}$  concentrations during the sampling period exceeded the 24-h limit proposed by WHO ( $25 \mu\text{g m}^{-3}$ ). The weights of the filter paper ranged from 124 to 147 mg, the weight of  $PM_{2.5}$  collected ranged from 126 to 149 mg, the weight difference ranged from 0.9 to 3.1 mg and the mass of  $PM_{2.5}$  of subsamples for each of the assays (after cutting 3/4th part) ranged from 0.6 to 2.3 mg.

### Fractionation of metals in $PM_{2.5}$

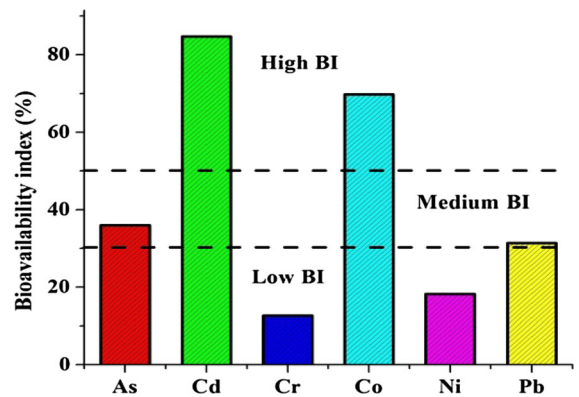
In this study, four sequentially extracted fractions were investigated: (i) soluble ( $F1$ ) (ii) reducible ( $F2$ ) (iii) oxidizable ( $F3$ ), and (iv) residual ( $F4$ ). Average concentration of heavy metals in each fraction is illustrated in Fig. 2a and their percentage distribution in the different fractions is shown in Fig. 2b. From Fig. 2b it is evident that Ni (72.8%), Cr (65.5%) and Pb (50.9%) were present mainly in the residual fraction. Cd (65.7%) and Co (48.8%) were mainly found in the soluble fraction, 44.5% of As existed in the oxidizable fraction while the smallest percentage of all metals existed in the reducible fraction. Among the four fractions investigated in this study, the soluble fraction has the highest potential to cause adverse health effects, as it can easily be dissolved and enter the blood stream from lung fluids (Espinosa et al. 2002). In a study conducted in Guangzhou, Feng et al. (2009) reported that more than 40% of Zn, Cd and As and more than 30% of Ni and Mn were distributed in the  $F1$  fraction, whereas more than 70% of Pb, more than 40% of Cd, Zn, and Cu and more than 30% of Mn and As were distributed in the  $F2$  fraction; meanwhile, more than 40% of Ni and more than 30% of Co, Mo, Cr and Cu were associated with  $F3$  and Cr (> 50%) was the dominant metal in the residual fraction in the  $PM_{2.5}$ . Canepari et al. (2010) found As and Cd had the



**Fig. 2** a Concentration of metals in four fractions in PM<sub>2.5</sub>. b Percentage of particle-bound metal fractions extracted using BCR sequential extraction procedure F1: soluble fraction; F2: reducible fraction; F3: oxidizable fraction; F4: residual fraction

highest extraction yield (about 60%), Cu, Pb and Zn (~ 40%) and Co and Ni (~ 25%), and Cr had the lowest extraction yield (~ 10%) in PM<sub>10</sub> samples. In the present study, the highest concentration was found for Pb (33.4 ng m<sup>-3</sup>) within the soluble fraction of PM<sub>2.5</sub>. It can be seen from Fig. 2a that the concentration of metals such as Pb, As and Ni in the soluble fraction was below the World Health Organization (WHO 2000) limit values of 500, 6.6 and 25 ng m<sup>-3</sup>, respectively while that of Cr and Cd exceeded the WHO limit values of 0.25 and 5 ng m<sup>-3</sup>, respectively. Since these are highly carcinogenic, they can cause serious health effects. The reducible, oxidizable and residual fractions are strongly associated with the crystalline structure of the minerals, hence are immobile and therefore are of no threat to human health. However, the reducible fraction of metals can pose a threat to human health when they become bioavailable under very low pH conditions (Fuentes et al. 2008). Metal adsorbed on the particle surface was extracted by the sequential extraction procedure in the soluble fraction (F1). This fraction of the metals can be easily released into aqueous solutions (Feng et al. 2009). Similarly, metals in the reducible fraction (F2), are susceptible to pH changes and redox conditions, they are thermodynamically unstable and could become available under anoxic conditions (Fuentes et al. 2008). Therefore, fractions F1 and F2 are considered bio-accessible fractions, as they can interact with human body fluids on inhalation and/or ingestion. The percentage of F1 and F2 relative to the total metal concentration is used as a bioavailability index (BI) to

evaluate the bioavailability and mobility of the metal (Feng et al. 2009; Sun et al. 2014). On the basis of BI values, metals may be categorized as having low bioavailability when BI < 30%, medium bioavailability when 30% < BI < 50%, and high bioavailability when BI > 50%. The metals with higher BIs are considered to be physiologically active and may cause more risks to humans than the metals with lower BIs. The calculated bioavailability indices for the 6 toxic metals are shown in Fig. 3. Cd and Co exhibited the highest bioavailability index, Pb and As had medium bioavailability index whereas Ni and Cr had low bioavailability index. Feng et al. (2009) found that Cd had the highest bioavailability index (~ 90%), followed by Pb (~ 85%) and As (~ 70%). Co and Ni



**Fig. 3** The bioavailability index for particle bound heavy metals [percentage of the first two fractions (F1 and F2) to all fractions (F1, F2, F3 and residual fractions)] of toxic elements in PM<sub>2.5</sub>

had slightly lower BI values of about 40%. Cr had the lowest BI values of less than 20%. Yadav and Satsangi (2013) observed that Cd (80% in  $PM_{10}$  and 55% in  $PM_{2.5}$ ) had the highest bioavailability index. Pb in  $PM_{10}$  had intermediate BI in the range of  $\sim 50$ –40%, while Pb had BI in the range of  $\sim 40$ –30% in  $PM_{2.5}$ . Ni, Co and Cr in both fractions had the lowest BI values ( $< 20\%$ ). Sun et al. (2014) reported that As, Cd, Pb and Zn had the highest bioavailability index (about 70–80%), followed by Cu and Mn (about 50–60%). Cr and Ni showed about 40% bioavailability index while Co showed lower bioavailability index value of  $\sim 30\%$ . Varshney et al. (2016) found that Pb showed high percentage of bioavailability of 28%. Cd had lower percentage of bioavailability of  $\sim 17\%$ . Pb is considered to be carcinogenic and interacts with different enzymes. Several biological effects of Pb have been shown experimentally, including effects on heme biosynthesis, the nervous system, the kidneys, the reproductive organs, the cardiovascular system, the immune system, the liver, the endocrine system and the gastrointestinal tract. A greater BI value indicates that the metal may be fully available after interacting with human body fluids, posing higher risk to human health (ATSDR 2007; JECFA 2011). Children may be more unsafe than adults because of greater intake of Pb per unit body weight; their increased intake may be due to hand to mouth activities, higher physiological uptake rates and their rapidly developing systems. Epidemiological studies have revealed decreased neurobehavioral performance in children due to Pb exposure (Lanphear et al. 2000; Jusko et al. 2008; Bierkens et al. 2011; JECFA 2011). Studies indicate that for each  $10 \mu\text{g dL}^{-1}$  of blood lead, IQ (Intelligence Quotient) is reduced by 1–3 points (Chen et al. 2005). In order to evaluate the health risk due to Pb exposure for young children, the Integrated Exposure Uptake Biokinetic Model (IEUBK) (U.S. EPA 2010) was utilized in this study. The IEUBK model is a tool for site-specific risk assessment for young children exposed to Pb from different media and through different pathways in their environment. It helps to explore the relationship between environmental Pb and blood lead level (PbB) in children and to calculate the risk associated with elevated PbB. The mean concentration of Pb in  $PM_{2.5}$  was  $128 \text{ ng m}^{-3}$ . This mean Pb concentration was used in the IEUBK model win v1.1 (U.S. EPA 2010). The probability density of PbB is shown in Fig. 4,

which reveals that at the prevailing atmospheric concentration 0.302 children are expected to have PbB concentrations exceeding  $10 \mu\text{g dL}^{-1}$  and an estimated IQ loss of 1.8 points in children. Further from the model the predicted blood Pb levels belong to Group 3 (PbB  $< 5 \mu\text{g dL}^{-1}$ ) and would range between 1.9 and  $3.5 \mu\text{g dL}^{-1}$ . Although we have not measured PbB levels in children in this study, the predicted PbB levels compared to those measured at Pune (Pratinidhi et al. 2014), Lucknow (Ahamed et al. 2010), Mumbai (Jain and Hu 2006), Delhi (Kalra et al. 2003) and Chennai (Roy et al. 2009) where PbB levels are 50, 55.7, 5–20, 7.8 and  $11.4 \mu\text{g dL}^{-1}$ , respectively. Thus our estimates are lower than these values.

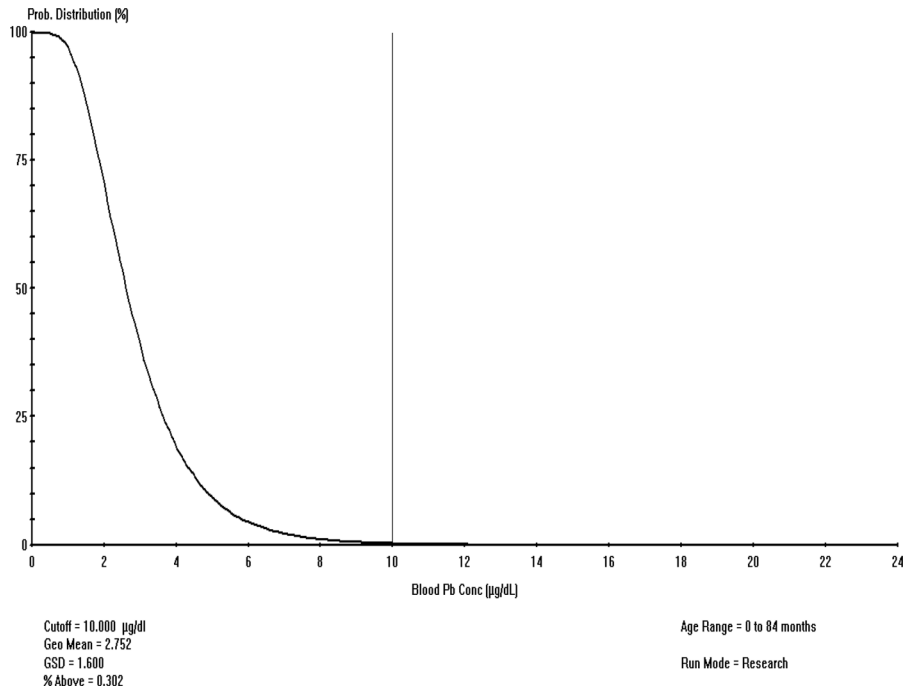
#### Contamination factor (CF)

Contamination factor (CF) is the ratio of metal concentration in the mobile phase ( $F1 + F2 + F3$ ) to the concentration in the residual phase (Jamali et al. 2007). It is used to estimate the relative retention time of metals.  $CF < 1$  implies low contamination,  $1 \leq CF \leq 3$  indicates moderate contamination,  $3 \leq CF \leq 6$  shows considerable contamination, and  $CF > 6$  presents very high contamination, low retention time and higher environmental mobility. The calculated results show that Cr, Ni and Pb had low contamination levels. Co and As had considerable contamination. The contamination factor of Cd exceeded 6, showing its lower retention time and greater mobility potential (Fig. 5).

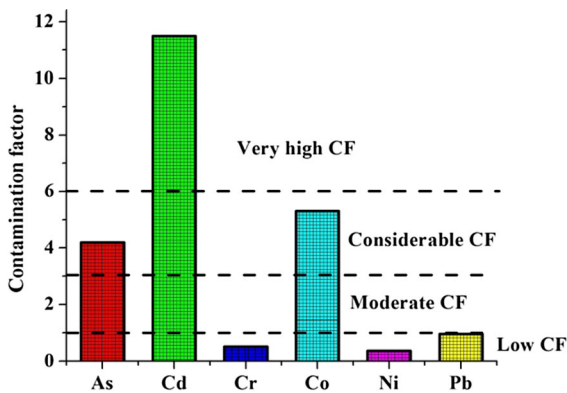
#### Risk assessment code (RAC)

Risk assessment code refers to the fraction of water soluble and exchangeable fraction ( $F1\%$ ) from the sequential extraction procedure. It is used to assess the environmental risk of heavy metal pollution (Li et al. 2013). The risk is negligible when the proportion of the  $F1$  fraction is  $< 1\%$ , low when the  $F1$  fraction is 1–10%, moderate when it is 11–30%, high when it is between 31 and 50%, and very high if  $> 50\%$ . As shown in Fig. 6, the RAC values show that Cd presents a very high environmental risk, Co presents a high risk, Pb and As present moderate risk and Cr and Ni show low risk. Li et al. (2015) showed that RAC values of metals in  $PM_{2.5}$  decreased in the following order:  $\text{Cd} > \text{As} > \text{Ni} > \text{Cr} > \text{Pb}$  in Xianlin, China: As, Cd and Ni presented a high risk (RAC, 31–50%)





**Fig. 4** Probability density of blood lead using IEUBK model

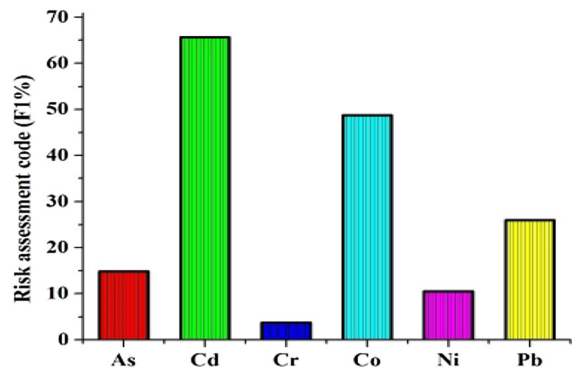


**Fig. 5** Contamination factor of heavy metals in PM<sub>2.5</sub>

and Pb and Cr with RAC value of 11–30% presented a medium risk.

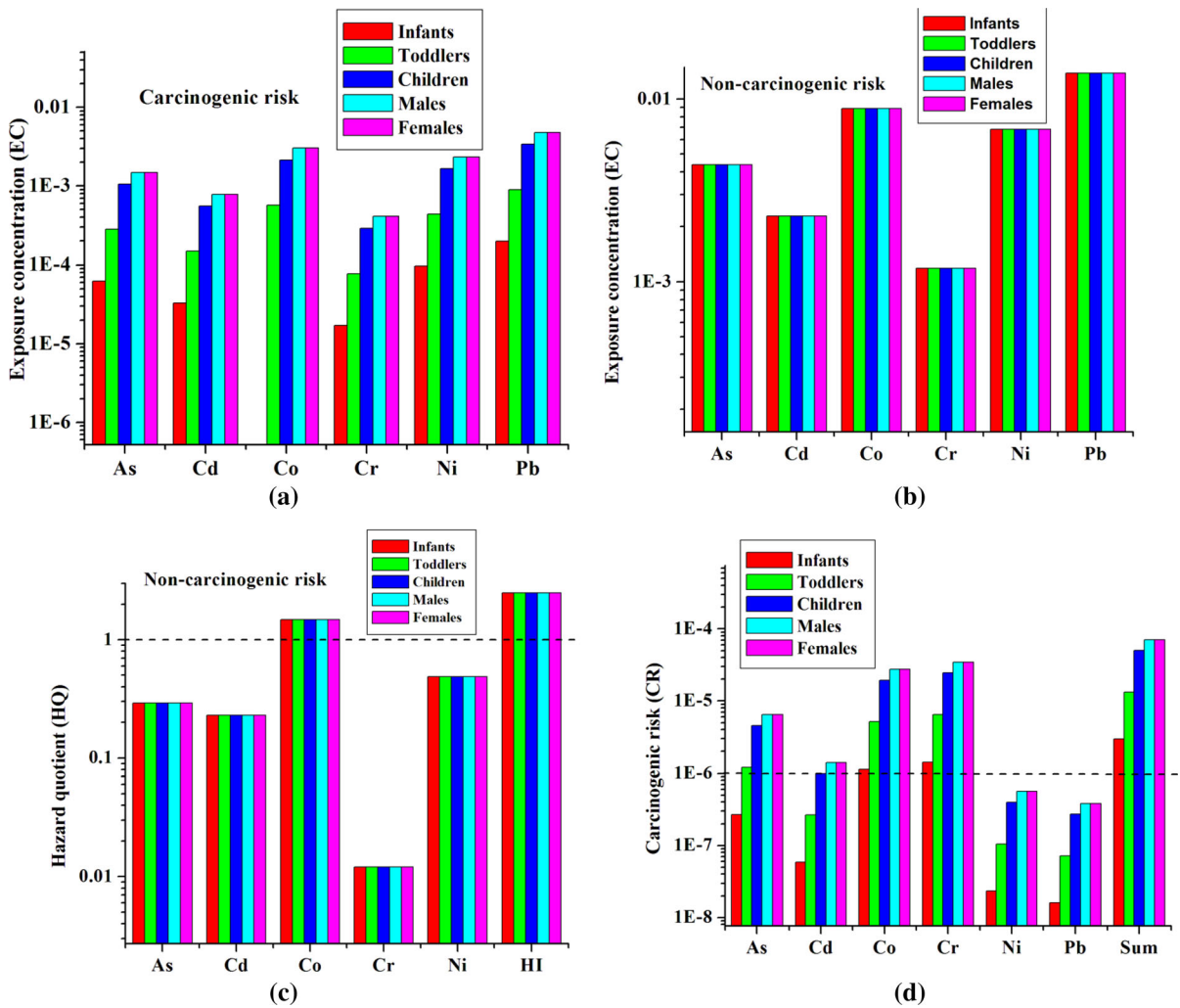
**Health risk posed by toxic metals in PM<sub>2.5</sub>**

The health risk caused by inhalation was analyzed to evaluate the potential adverse effects of exposure to airborne heavy metals on public health. Pb and Co had the highest EC values in the carcinogenic and non-carcinogenic risk assessments, respectively (Fig. 7a, b). As shown in Fig. 7c, the HQ values for inhalation



**Fig. 6** Risk assessment code for heavy metals

of As, Cd, Cr, Ni, and Pb were below the safe level (= 1) for all age groups. Co had the highest HQ value of 1.48 for all age groups. The hazard index (HI) for these metals was 2.50, which was higher than the safe level (= 1), indicating that accumulative non-carcinogenic risks are posed to all age groups via inhalation. Li et al. (2016) reported no threat (HI = 0.5) for children and adults due to exposure to the toxic metals As, Cd, Co, Cr(VI) and Ni in bioavailable fraction (F<sub>1</sub> + F<sub>2</sub>) through the inhalation pathway by exposure to PM<sub>2.5</sub> at an industrial site in China. Sun et al.



**Fig. 7** **a** Exposure concentration (EC) of carcinogenic risk **b** exposure concentration (EC) of non-carcinogenic risk **c** hazard quotient (HQ) of non-carcinogenic risk **d** carcinogenic risk (CR) of inhalation exposure to PM<sub>2.5</sub>

(2014) found HI values of 1.86 for As, Cd, Co, Cr, Ni and Mn exceeded the safe level of 1 at Nanjing, China.

As shown in Fig. 7d, the carcinogenic risks of inhaling airborne Ni and Pb for all age groups, Cd for both infants and toddlers, and As for infants were less than the acceptable limit ( $10^{-6}$ ). The carcinogenic risks of Cr and Co for all age groups; As for toddlers, children, males and females (adults); and Cd for males and females exceeded the acceptable limit ( $10^{-6}$ ), indicating that the carcinogenic risks of these elements from PM<sub>2.5</sub> exposure are not negligible. The combined carcinogenic risk from these metals was  $2.9 \times 10^{-6}$ ,  $1.3 \times 10^{-5}$ ,  $5.0 \times 10^{-5}$  and  $7.0 \times 10^{-5}$  for infants, toddlers, children, and adults (males and females),

respectively, which were higher than the acceptable limit, indicating some probability that people of all age groups living in the vicinity may develop cancer from exposure to particulate-bound toxic metals through inhalation during their lifetime. The decreasing order of carcinogenic risk for the carcinogenic metals follows a similar trend for all age groups: Cr(VI) > Co > As > Cd > Ni > Pb. Among the different age groups of residents at the sampling site, the carcinogenic risk increased in the order (from low to high): adults > children > toddlers > infants. Feng et al. (2009) reported low cancer risks from bioavailable fractions ( $F_1 + F_2$ ). The estimated risks were  $31.4 \times 10^{-6}$ ,  $6.5 \times 10^{-6}$ ,  $3.6 \times 10^{-6}$  and

$2.8 \times 10^{-7}$  for As, Cr, Cd and Ni, respectively. Yadav and Satsangi (2013) found the cancer risks of Cr, Cd, Ni, and Pb were  $5.5 \times 10^{-5}$ ,  $4.1 \times 10^{-5}$ ,  $1.2 \times 10^{-6}$ , and  $2.5 \times 10^{-7}$ , respectively for PM<sub>2.5</sub> in bioavailable fraction in Pune, India.

A number of assumptions have been considered in health risk assessment which might introduce uncertainties into the results; e.g., reference toxic data, default exposure parameters and population characteristic parameters and uncertainties in the assessment model. Other exposure routes such as ingestion and dermal contact, exposure from indoor particulate matter and presence of other toxic constituents including mercury, elemental carbon, and polycyclic aromatic hydrocarbons in fine particulate matter were not considered in this study.

## Conclusions

Samples of PM<sub>2.5</sub> were collected during March to August 2016 at an urban location in Agra, India. Average mass concentration of PM<sub>2.5</sub> during study period was observed to be  $93 \pm 24 \mu\text{g m}^{-3}$ , which is far in excess of WHO limits. The mean metal concentrations decreased in the following order: Cr > Pb > Ni > Co > As > Cd. In the PM<sub>2.5</sub> samples, the concentrations of As were above the NAAQS and WHO limits, whereas those for Pb were below the NAAQS and WHO limits. The concentrations of Cd and Ni exceeded these limits. A four-step SEP was applied to analyze the chemical fractionation of heavy metals in PM<sub>2.5</sub>. The concentrations of Pb, As and Ni in the soluble fraction were below the WHO limits, while those of Cr and Cd exceeded the WHO limits. The bioavailability index values calculated for all metals were in the order of Cd > Co > As > Pb > Ni > Cr. Among these metals, Cd and Co showed high bioavailability indexes. The contamination factor results showed a wide range of contamination levels for different metals. Cr, Ni and Pb exhibited low contamination, Co and As exhibited considerable contamination and Cd exhibited very high contamination, showing their lower retention time and high mobility potential. The present study investigated the potential lead exposure to young children using the IEUBK Model. The results showed that the probability density of PbB (blood lead level) reveals that at the prevailing atmospheric concentration, 0.302 children

are expected to have PbB concentrations exceeding  $10 \mu\text{g dL}^{-1}$  and an estimated IQ decrement of 1.8 points. The predicted blood lead levels would range between 1.9 and  $3.5 \mu\text{g dL}^{-1}$ , which belong to Group 3 (PbB <  $5 \mu\text{g dL}^{-1}$ ). Human exposure to airborne As, Cd, Co, Cr, Ni and Pb was assessed for infants, toddlers, children, males and females via inhalation. The HI for the inhalation of As, Cd, Co, Cr, and Ni was 2.50 and above the safe limit of 1. The combined carcinogenic risk of As, Cr, Cd, Co, Ni, and Pb via inhalation for all age groups was higher than the precautionary criterion ( $10^{-6}$ ). The results provided by the present study may contribute to a better understanding of the potential risks associated with human exposure to metals in aerosol form at urban locations, constituting useful information to be considered by air quality managers. Further, in view of the uncertainties associated with the BCR extraction scheme, a comparison and its validation with in vitro and in vivo assays is necessary.

**Acknowledgements** This work was supported by UGC-BSR (No. ETP/UGC Res. Fellowship/3089) and Department of Science and Technology (Project No. SB/S4/AS-150/2014). We are grateful to Dr. Tarun Gupta and Mr. Amit Kumar Singh, IIT Kanpur for their help in analyzing samples by ICP-OES. We are thankful to Director and Head, Department of Chemistry, Dayalbagh Educational Institute, Agra, for providing us the necessary facilities.

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