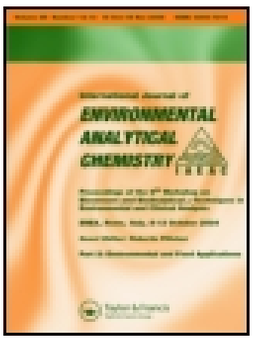

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ARTICLE

Health risk assessment of total volatile organic compounds, particulate matters and trace elements in PM_{10} in typical living rooms in Addis Ababa, Ethiopia

Asamene Embiale[a], Bhagwan Singh Chandravanshi[a], Feleke Zewge[a] and Endalkachew Sahle-Demessie[b]

[a]Department of Chemistry, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, Ethiopia; [b]Department of Chemistry, Missouri University of Science and Technology, Rolla, MO, USA

ABSTRACT

Nowadays, particulate matter and total volatile organic compounds in the air are the primary environmental concern of the world due to their health impact. Therefore, the present work was focused on the assessment of short-term exposure to particulate matter (PMs) in the air samples of different particle size (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}) and total suspended particles (TSP), total volatile organic compounds (TVOCs) and trace elements in PM_{10} in the living room (a place where inhabitants spent more of their indoor time). PMs and TVOCs were measured by simple and portable sensors, respectively. The elemental composition of PM_{10} was analysed by using inductively coupled plasma-optical emission spectroscopy (ICP-OES). The geometric mean (GOM) of PMs in the living room ranged from 5.68 to 99.0 μg m^{-3}, whereas the TVOCs were found to be 289 μg m^{-3}. The health risk due to exposure to $PM_{2.5}$, PM_{10}, and TSP was performed according to the United States Environmental Protection Agency prescription using hazard quotient calculation (HQ) and hazard index calculation (HI). The results showed that HI and HQ for $PM_{2.5}$, PM_{10} and TSP were less than one indicating that the non-carcinogenic effect is not significant. The levels of trace elements (Fe, Cd, As, Cr, Pb, B, Ni, Co, Sn, Cu, and Zn) in PM_{10} were found in the range: 0.001–0.026 μg m^{-3}. The carcinogenic and non-carcinogenic risks due to elements in PM_{10} exposure were also not significant.

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Living room; air quality; volatile organic compounds; particulate matters; elemental composition; health risk assessment

1. Introduction

Many people, especially children, spend 70 to 90% of their time in a variety of indoor environments [1–3]. At present, the indoor air we breathe is one of the biggest challenges faced by the world [2]. The human exposure to the indoor air pollutants (such as NO_2, SO_2, CO, particulate matters (PMs) and total volatile organic compounds (TVOCs)) could affect health, wellbeing, and productivity of building occupants [2]. Outdoor (such as industrials discharges, garage exhaust, and transport vehicle emissions) and indoor activities, including cooking fuel combustion, degradation of furnishing material and wall paints, incense

CONTACT Bhagwan Singh Chandravanshi bscv2006@yahoo.com

burning, and smoking are the principal factors responsible to indoor air contaminants [4,5].

Many epidemiological studies have shown a strong association between exposure to particulate matters with different aerodynamic diameters and adverse health effects such as lung cancer, heart failure, asthma, and mortality [6]. As reported in the global burden of disease around 3.2 million annual premature deaths and over 110 million disability-adjusted life years were attributable to indoor air pollution, whereas 3.1 million deaths from outdoor air pollution are attributable to indoor air pollution (16% of the value attributed by indoor) [6–9].

Particulate matters in the indoor air are composed of inert carbonaceous cores with multiple layers of various adsorbed particles. These particles are metals, acid salts, sulphates, nitrates, hydrogen ions, ammonium, elemental carbon, silica, alumina, organic compounds, particle-bound water, and biological elements (such as endotoxins, allergens and pollen fragments) [10,11]. The indoor air also contains a broad range of volatile organic compounds (VOCs), including paraffinic, olefinic and aromatic hydrocarbons, and various oxygen-, nitrogen-, sulphur-, and halogen-containing molecules [12,13]. The sum of all the VOCs is grouped as the total volatile compounds (TVOCs). Human exposure to TVOCs can also cause for conjunctive irritation, nose and throat discomfort, headache and sleeplessness, allergic skin reaction, nausea, fatigue, dizziness, loss of coordination, leukaemia, anaemia, cancer, and damage to the liver, kidney and central nervous system [12,14].

The significant factors for the severity of diseases caused by particulate matters (PMs) are their amount, chemical composition, size, and exposure time [15–17]. It has been reported that an increase in PM_{10} by a concentration change of 10 μg m^{-3} can yield a 1% increase in overall mortality and a 3–6% increase in deaths associated with respiratory disease [18]. An increase of 10 μg m^{-3} in annual mean levels of $PM_{2.5}$ was also associated with an 8–28% increase in the risk of cardiopulmonary mortality, 15–21% increase in mortality due to lung cancer, 12–14% increase in overall cardiovascular mortality [19,20]. Normal development and growth of body tissues and their proper functioning are associated with the particulate matter contaminated by heavy metals, which can pose different health problems. For example, carcinogenesis, teratogenesis, and mutagenesis are caused by the presence of toxic trace elements in particulate matters [21]. Therefore, it is necessary to assess the short-term exposure to particulate matters and their chemical composition analysis at a specific environment for the policy interventions to reduce adverse health effects.

The indoor air pollutants are usually higher than outdoor due to a low air exchange rate, the small spatial volume of households, and the use of low fuel-efficient stoves. Furthermore, many people spent most of their time in households, which also increased the probability of breathing high amounts of pollutants [22–24]. Therefore, assessments of indoor air pollutants are necessary for an accurate estimation of individual air pollution exposure and remedial action.

Several studies have been conducted on health risk assessment of TVOCs and trace elements in particulate matter in different parts of the world. Valavanidis, Fiotakis and Vlachogianni [16] have studied the toxicological assessment of airborne particulate matter and the importance of the size and composition of particles. Kushwaha et al. [25] studied human exposure to particulate matter and their risk assessment. Kena,

Abebe and Alem [26] have reported the effects of indoor air pollution by biomass fuels on the respiratory functions of women. Pope et al. [9] assessed the exposure to household air pollution from wood burning and association with respiratory symptoms and lung function in non-smoking women. Jones [27] reported indoor air quality and health risk factors associated with respiratory conditions [12]. Long-term exposures to volatile organic compounds (VOCs) have been associated with adverse health effects from allergies to the more complex set of symptoms called the Sick Building Syndrome (SBS) [28]. Other researchers who conducted a comprehensive review of the literature concluded that non-industrial building indoor air pollution, including VOCs, is a cause of many health effects.

Izhar et al. [29] studied annual trends in occurrence of submicron particles in ambient air and health risk posed by particle bound metals. Morakinyo et al. [30] assessed health risk of inhalation exposure to sub-10 μm particulate matter and gaseous pollutants. Liu, Shang and Wan [31] reported sources and health risks of heavy metals in $PM_{2.5}$. Chalvatzaki et al. [32] have reported the characterisation of human health risks from particulate air pollution. Embiale et al. [33] have determined the levels of trace elements in PM_{10} collected at roadsides of Addis Ababa, Ethiopia, and estimated their risk assessment. Embiale et al. [34,35] have studied short-term exposure to PMs and TVOCs in indoor air and their health risk assessment during cooking of Ethiopian sauces and investigated trace elements in PM_{10} from the baking of injera and health risk assessment. Health risk assessment from exposure to trace elements, TVOC and PM_{10} emitted during the cooking of Ethiopian traditional dish sauces and cook-stoves during *Injera* baking in Ethiopia has been well studied [36,37].

In Ethiopia, a very few studies were conducted in assessments of CO, NO_2, PM_{10}, $PM_{2.5}$, and TSP in both the indoor and outdoor air under different scenarios [26,35–44]. The findings of these studies give a clue that inhabitants are living in polluted areas. Despite this, these studies have limited information in the identification and determination of the potentially toxic metals bound in PM_{10}, TVOCs, and PMs (PM_1, $PM_{2.5}$ and PM_4, PM_7, PM_{10}, TSP) at the living-room. Consequently, in this work living room has been selected to estimate PMs and TVOCs short-term exposure to determine the elemental composition of PM_{10} and to assess the health risk of exposed persons. Many of the family members spend most of their indoor time in the living-room [44]. Hence, the living-room was selected as a sampling site in this study.

2. Experimental

2.1. Description of study area

The study area is the city of Addis Ababa. Its geographical locations and climatic conditions have been described in our earlier study [33]. Since many of the family members spent most of their time in the living room, when they stayed at home, the living room microenvironment (ME) was selected for exposure assessment in this study. A total of 45 households were selected from the three sub-cities (15 households from each sub-city) based on altitude differences, socio-economic activities, and population density. The details characteristics of each sub-city were stated in our previous work [34].

2.2. Sampling protocol for TVOCs and PMs

The levels of TVOCs were measured using a simple and portable sensor called AEROQUAL series 500 (Aeroqual Limited, Auckland, New Zealand) using photo ioniser detector. The zero calibration was done before each measurement using zero grade air cylinder according to the manufacturer protocol. The flow rate was adjusted to 0.5 L min^{-1}, and then switched on and warmed up for 3 min. The samplers were put side by side 1 m above the ground at the centre of the living room, since many family members are at the sitting position in the living room. The measurements were carried out within 2 min interval for 4 hours [34]. The measurement was carried out between 30 January 2017, and 30 September 2017.

The level of PMs was measured by a portable sensor called AROCET531S (Met One Instrument., Inc. Grants Pass, OR 07526, USA). It uses a laser-diode-base optical sensor, in which it uses light scatter technology to distinguish, measure, and count particles. The scattered light by an individual particle is converted to an electric pulse which is proportional to the particle size. This detected information or electric pulse can be altered into particle mass using the mass-density conversion factor, or displayed as particles per size range, depending on how the AROCET531S is configured. The sensor has data logger cable which is used to log the data collected to the computer. The measurement was carried out within 2 min interval for 4 hours. The calibration was done by using flow metre by fitting it to the inlet fitting on the unit, which is 2.83 L min^{-1}. In addition, the zero-count calibration test was performed after each measurement by following the manufacturer's standard operating procedure. Thus, the zero-count filter was attached to the inlet nozzle until smallest particle size should have a count less than or equal to one. The PMs sampler was put side by side to the TVOCs sampling instrument, it was put 1 m above the ground. This is the appropriate breathing zone of the family members. The instrument contains an ambient air inlet nozzle which is used to reduce the turbulence in the air sample, and it has also a temperature and humidity sensor which were used for measuring the ambient temperature and relative humidity of the room [34].

2.3. Sampling protocol for trace elemental analysis

Universal air pump (SKC 224-PCTX4 Model, SKC Ltd, UK) was used for the sampling of PM_{10} used for trace element analysis. The PM_{10} was loaded on glass microfiber filters, which were present inside it. It has a vacuum pump, an internal flow regulator, a timer, and an airflow calibration unit. The airflow was adjusted to 2.2 L min^{-1} with a high-precision rotameter in the lab before taking to the field and checked immediately on return. 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. The filter was oven-dried at 150°C for 2 h before sampling to remove the humidity and VOCs on the filter. The sampler was put 1 m above the ground, at the centre from the seat. This is the appropriate breathing zone of the family members. Once the sampling was over, the filter was placed in aluminium foil, returned to the laboratory and kept in a desiccator [33,34,37]. The sampling time and duration were selected when the family members were doing their routine activities (eating, watching television, reading, and others). The sampling was carried out between 30 August 2017 to

30 September 2017 from 6:00 AM to 10:00 AM and 6:00 PM to 9:00 PM in the living room. The sampling was done in two rounds (morning and evening) and mixed for the analysis to get detectable/measurable concentration of trace elements.

2.4. Sample preparation for trace element analysis

The sample preparation method used for the digestion of PM_{10} loaded filter papers was the standard procedure developed by US EPA, which mainly uses aqua-regia mixture for digestion. Accordingly, 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 for the extraction of elements. 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) were used for digestion of all the PM_{10} loaded filter papers. After cooling, the extracted solution was filtered on the cellulose filter (Whatman I) adjusted to a final volume of 20 mL using de-ionised water. Finally, it was put in a pre-cleaned polyethylene bottle and refrigerated until analysed. Triplicate reagent blank filters were also processed following a similar procedure for the sample treatment [33,43].

2.5. Determination of trace element

The concentrations of 11 elements (Mn, Cd, Co, B, As, Ni, Cr, Pb, Zn, Cu, and Fe) in the PM_{10} were determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES; Model Arcos FH2, 22–09-2010, Spectro Analytical Instrument GMDH, Baush Strass, 10.47533, Klev, Germany). The calibration solutions were prepared by diluting a commercial 1000 mg L^{-1} standard solution of each element (UNI-CHEM, chemical reagents). Hence, a series of working standard solution of elements 0, 0.5, 1, 2, 3, 4 and 5 µg mL^{-1} for Cu, Mn, Cd, Sn, As, Ni, Pb, Fe, Cr, Co and 0, 1, 2, 3, 6, 8 and 10 µg mL^{-1} for B were prepared by appropriate dilution with 10% HNO_3 of 1000 mg mL^{-1} elements stock solution [33,37]. The calibration curve showed good linearity ($r^2 > 0.9897$) of the detector response for quantified elements.

2.6. Health risk assessment for $PM_{2.5}$, PM_{10} and TSP

To estimate the nature and probability of adverse health effects of air pollutants, US Environmental Protection Agency (US EPA) protocols were used for health risk assessment. Accordingly, HQ (hazard quotient) and HI (hazard index) were used to evaluate the non-carcinogenic risks. An HQ < 1 indicates no significant risk, and HQ > 1 suggests that the non-carcinogenic effect is likely to appear whilst a high chronic risk is denoted for HQ > 10 [30,32,34,37]. Consequently, the present study has estimated health risk due to $PM_{2.5}$, PM_{10}, and TSP exposure. ADD (average daily intake, also called chronic daily intake) (µg kg^{-1} day^{-1}) was calculated using equations (1 and 2). Annual threshold values set by World Health Organisation (WHO) and US Environmental Protection Agency (US EPA) were used as reference dose (RfD) while dealing with a dose–response assessment [25,30,44]. The average current life expectancy for an Ethiopian is around 67 years, exposure frequency of 350 days/year, and exposure duration of 50 years was taken for HQ and ADD calculations. The air intake rate for an adult is 20 m^3 per day, and body

weight for an adult Ethiopian is assumed to be an African adult weight, which is 60.7 kg. South African infant and child body weight were used in the risk assessment due to the non-availability of Ethiopian [45,46]. An adult Ethiopian body is assumed to be the weight of an African adult, which is 60.7 kg. The air intake rate of an adult person is 20 m^3 per day. The exposure duration is classified as acute (exposure duration is below two weeks), the sub-chronic exposure duration is above two weeks and below 7 years), and the chronic (exposure duration is above 7 years) types of exposure [45]. The exposure duration used in this study is above two weeks and below 7 years. Thus, it falls under the sub-chronic type of exposure. The annual average of $PM_{2.5}$ (10 μg m^{-3}), PM_{10} (20 μg m^{-3}), and TSP (150 μg m^{-3}) values set by WHO and US EPA were used to calculate HQ and RfD for the sub-chronic type of exposure of this study [47]. The parameters used for the health risk assessment in the living room are given in Table 1.

The following equations are used for calculating of average daily intake (ADD) and HQ to characterise the health risk due to $PM_{2.5}$, PM_{10} and TSP

$$ADD = \frac{\text{CAxIRxED}}{\text{ATxBW}} \tag{1}$$

$$ED = \frac{EFxDExETx1day}{24h} \tag{2}$$

where ADD is the average daily intake (μg kg^{-1} day^{-1}); CA is the contaminant's concentration in air (μg m^{-3}); ET is the exposure time spent (hours day^{-1}); EF is the exposure frequency (days $year^{-1}$); IR is the intake rate (m^3 day^{-1}); ED is the exposure duration (days), DE is the duration of exposure (years); AT is the averaging time (DE x 365 days $year^{-1}$); 1 day 24^{-1} h^{-1} is the conversion factor from hours to days.

$$HQ = \frac{ADD}{RfD} \tag{3}$$

where HQ is the hazard quotient; RfD reference dose (this will convert to the same unit as ADD) (μg kg^{-1} day^{-1}), that RfD expressed in μg kg^{-1} day^{-1} would be equal to the RfD in μg m^{-3} multiplied by 20 m^3 air inhaled per person per day divided by 70 kg per person. It should be noted that the average weight of an African woman is assumed to be 60.7 kg. However, there is no conversion factor using the weight 60.7 kg for calculating RfD; hence, 70 kg per person, the weight used by US EPA was also in this study.

Table 1. Exposure frequency, exposure time, intake rate, body weight, exposure duration and averaging time for different exposed groups.

Exposed group	Exposure time (h day^{-1})	Exposure frequency (days $year^{-1}$)	Duration of exposure (years)	Exposure duration (days)	AT (days)	IR (m^3 day^{-1})	BW (kg)
Infant (birth to 1 yr)	2.05	350	1	30.0	365	6.80	11.3
Child (2–5 yrs)	2.05	350	5	150	1825	10.0	22.3
Child (6–14 yrs)	2.05	350	12	359	4380	13.5	45.3
Adult (15–65 yrs)	2.05	350	50	1495	18,250	20.0	60.7

Note: AT = averaging time, IR = intake rate and BW = body weight.

2.7. Health risk assessment due to elements in PM_{10}

The elemental species have different toxicity, concentrations, and mobility behaviour, and their health risk also varies. Hence, the determination of their cancer and non-cancer risk has a vital role in prioritising individual metal species to the total risk contributions and taking remediation and emission control at the individual level [29]. Cancer and noncancer risk will develop due to the exposure to elements bound to PM_{10} [31,48,49]. Cancer risk, also called lifetime cancer risk, estimates the probability of a person developing cancer over his/her lifetime as a result of exposure to the identified carcinogens. In contrast, noncarcinogenic effects mean the likelihood of a person developing health problems other than cancer effects during his exposure time to contaminants [49]. Exposure of trace elements found in the particulate matters can occur through inhalation, ingestion, and dermal absorption routes [50]. The aspects under consideration in this study can be classified as carcinogenic and noncarcinogenic metals. According to integrated risk information system (IRIS), Cu, Fe, Zn and Mn are classified as noncarcinogenic; meanwhile, Cd, As, Pb, Cr and Ni are carcinogenic metals [25,31,48].

The health risk assessment due to the PM_{10} bound elements exposure was calculated using US EPA's methodology as expressed in equation 4–9 [48].

$$D_{inh} = \frac{CxInhRxEDxEF}{BWxAT} \tag{4}$$

$$D_{ing} = \frac{CxIngRxEDxEF}{BWxAT} x10^{6} \tag{5}$$

$$D_{der} = \frac{CxAFxSAxABSxEDxEF}{BWxAT} x10^{6} \tag{6}$$

$$HQ = \frac{D}{RfD} \tag{7}$$

$$HI = \sum^{H} Q \tag{8}$$

$$LCRorCR = D_{inh}xIUR = D_{ing}xSF = D_{der}x\left(\frac{SF}{G}\right) \tag{9}$$

where C is concentration of elements (μg m^{-3} or mg kg^{-1}), D_{inh}, D_{inge} and D_{der} is daily dose through inhalation (mg kg^{-1} day^{-1}), through ingestion (mg kg^{-1} day^{-1}) and through dermal contact (mg kg^{-1} day^{-1}), respectively; InhR is inhalation rate (m^3 day^{-1}), ED is exposure duration (years), EF is exposure frequency (day $year^{-1}$), BW is body weight (kg), AT is averaging time (years), LCR is lifetime cancer; IUR is inhalation unit risk ((μg m^{-3})$^{-1}$); 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 skin adherence factor (mg cm^{-2} day^{-1}); ABS is dermal absorption factor (unitless), SA is surface area (cm^2) and G is the gastrointestinal absorption factor. The parameter considered for health risk assessments due to trace element in this study is given in Tables 2 and 3.

Table 2. The constant values used in risk calculation [25,48,49].

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

Table 3. The exposure parameters for health risk assessments at living room microenvironment [46,48,49].

	Values	
Parameters	Children	Adults
InhR (m^3 day^{-1})	7.6	20
ED (year)	6	30
EF (days $year^{-1}$)	32	32
AT (days): (for non-carcinogenic)	ED x 365	ED x 365
:(for carcinogenic)	70 x 365	70 x365
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

According to US EPA, total cancer risks associated with exposure to contaminants over a lifetime are higher than 1×10^{-4} are generally considered unacceptable. However, the US EPA's threshold range indicated for tolerable risk is between 1×10^{-4} and 1×10^{-6} (i.e., the probability of 1 in 10,000 to 1 in 1000,000 that an individual may develop cancer from lifetime exposure to a carcinogen) as a commonly referenced benchmark for the protection of public health [29,48,49]. Therefore, these values were used as threshold values throughout this study.

2.8. Statistical package used in data analysis

Sampling for PMs data from the measuring instruments was uploaded to a computer using the cable and software provided by the manufacturer. Data filtering and summarising were done using different software. TVOCs were recorded on the notebook at a 2-min interval and feed to the computer manually. The data were logged to the computer manually for the determination of elemental concentration. The statistical data analysis was carried out using IBM SPSS version 20.0, Microcal™ Origin version 6.0 (Micrical software, Inc. USA) and Microsoft Excel 2013. The Kruskal-Wallis test was applied to determine the significant differences in concentration of PMs, TVOCs, and values of AT, RH, and L-volume across the sampling sites. Kruskal–Wallis test and analysis of variance (ANOVA) were used to evaluate the significance of the differences in concentration of PMs, TVOCs, and elements bound in PM_{10}, respectively. The Wilcoxon signed-rank test was applied to assess the significant difference in concentration of PMs and TVOCs across seasons. Also, a Shapiro-Wilks statistical test was used to determine whether the data fit a standard or log-normal distribution function. The concentration data were better

described using the log-normal distribution function than the normal distribution where the GOM and GSD were used to report the data. The significant difference for all the tests was set to 0.05.

3. Results

All the measured data were tested by a Shapiro–Wilks test [51] which indicated that the PMs and TVOCs data are not normally distributed. Consequently, the data are better described as log-normally distributed and reported as GOM and GSD. However, the level of trace elements bounded in PM_{10} showed a normal distribution, and hence the data are reported as the arithmetic mean and standard deviation.

3.1. Characteristics of living room

The location of the living room with respect to the bedroom showed that 29 houses had separate living room from bedroom and that of 16 houses were found within the bedroom. The main ventilations in the selected households showed that 16 houses had only a single door, 2 houses had a single window and 27 houses had both a window and door ventilation. The household family size ranged from 2 to 7 people and the living room volumes were varied from 5.46 to 51.6 m^3, respectively. The living room characteristics (such as ventilation type, the volume of the living room, family size) of the selected households are given in Table 4.

3.2. The levels of PMs and TVOCs

The indoor levels of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP, and TVOCs pollutants at the studied living rooms are given in Table 5. The ranges of levels of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP and TVOCs were 4.12–7.87, 12.9–27.3, 43.5–86.0, 57.7–108, 74.0–131 and 261–402 μg m^{-3}, respectively. The highest values of PMs and TVOCs were found at Gulelle sub-city, whereas the lowest values of PM_1, $PM_{2.5}$ and PM_4, PM_7, PM_{10}, TSP, TVOCs were found at Arada and Akaki Kality sub-cities, respectively. The variations in the levels of pollutants might be due to variations in the fuels used for cooking activities and due to variations in the population density and traffic intensity.

The Kruskal-Wallis test was applied to determine the significant differences in concentration of PMs, TVOCs and values of AT, RH and L-volume across the sampling sites. The results showed that the data for Arada sub-city vs Gulelle sub-city and Gulelle sub-city vs Akaki Kality sub-city showed a significant difference ($p < 0.05$). Besides, Arada sub-city vs Akaki Kality sub-city also showed a significant difference ($p < 0.05$), except PM_4 ($p = 0.07$) and AT ($p = 0.05$).

The ADD of PMs and TVOCs and hazard quotients (HQ) of $PM_{2.5}$, PM_{10} and TSP are given in Table 6. According to US EPA, if the HQ calculated is less than 1, the contaminates could not induce any health impact on the exposed organism (human), whereas its value is greater than 1 that contaminates induce/cause some health impact on the exposed human [45]. The data in Table 6 clearly indicate that HQ for all age groups is below 1 which indicates that any person who stays at living room for 2.05 h per day will not have any health problems due to $PM_{2.5}$, PM_{10} and TSP exposure separately. HI for individuals at

Table 4. Some characteristic of living room for selected households.

Site code	Ventilation type/area of ventilation (m^2)/position	Family size	Position of bed room and living room	Volume of living room (m^3)
arA	Door, 1.62, open	5	Separated	5.46
arB	Door, 1.43, open	5	Separated	28.0
arC	Door, 1.44, open	2	Separated	5.46
arD	Door, 1.52, open	5	Separated	26.1
arE	Door, 1.62, open	4	Not separated	17.2
arA	Door, 1.2, open	3	Not separated	19.8
arB	Door,1.28, open	5	Not separated	25.8
arC	Door, 1.71, open	5	Not separated	30.0
arD	Door,1.71, open	4	Not separated	38.7
arE	Door, 1.48, open	4	Not separated	34.8
arA	Door, 1.4, open	2	Not separated	51.6
arB	Door, 1.57, open	1	Not separated	34.8
arC	Door, 1.67, open	1	Separated	11.5
arD	Door, 1.67, open	1	Separated	12.0
arE	Door, 1.2, open	3	Separated	18.0
guA	Door, 1.6, partially open	5	Separated	24.0
guB	Door, 1.81, closed	2	Not separated	12.0
guC	Door, 1.85, open	6	Not separated	8.0
guD	Door, 1.66, open	1	Not separated	6.0
guE	Door, 1.2, open	3	Not separated	12.0
guA	Door, 1.81, open	6	Not separated	15.0
guB	Door, 1.86, open	4	Not separated	18.8
guC	Door, 1.00, open	4	Not separated	13.0
guD	Door, 1.95, open	4	Not separated	15.0
guE	Door, 1.57, open	3	Not separated	22.5
guA	Door, 1.71, open	3	Not separated	22.5
guB	Door, 1.76, open	4	Not separated	18.8
guC	Door, 1.31, partially open	5	Not separated	15.6
guD	Door, 1.71, open	2	Not separated	21.0
guE	Door, 1.57, partially open and window, 0.26, open	5	Not separated	23.4
akA	Door, 1.2, open	3	Not separated	8.26
akB	Door, 1.94, open	2	Separated	16.2
akC	Door, 1.76, open	5	Not separated	24.0
akD	Door, 1.95, open	4	Separated	13.7
akE	Door, 1.67, partially open and window, 0.3, open	2	Not separated	24.2
akA	Door, 1.76, open	2	Separated	13.7
akB	Door,1.11, open	6	Not separated	24.0
akC	Door, 1.85, open	3	Separated	26.0
akD	Door, 1.95, open	5	Not separated	53.2
akE	Door, 2.4, open	4	Not separated	9.00
akA	Door, 1.76, open	3	Separated	30.6
akB	Door, 1.67, open	4	Separated	8.00
akC	Door, 1.71, open	6	Not separated	63.0
akD	Door, 1.71, open	4	Separated	8.28
akE	Door, 1.62, open	2	Separated	40.6

Site code: ar = Arada sub-city; gu = Gulelle sub-city; ak = Akaki Kality sub-city; A, B, C, D and E represent different households in each sub-city.

the different age were calculated, and the results for infants (age between birth–1 year), child (age between 2 and 5 years), child (age between 6 and 14 years) and adults (15–65 years) were found to be: 0.91, 0.66, 0.47 and 0.51, respectively. Hence, HI is below 1 which confirmed that cumulative exposure of $PM_{2.5}$, PM_{10} and TSP may not induce non-carcinogenic health problems to all age group at the living room who spent 2.05 h per day. However, this does not mean that their contribution to the total chronic

Table 5. The level of PMs, TSP and TVOCs, room temperature, relative humidity and living room volume at Arada, Gulelle and Akaki Kality sub-cites.

Sampling code	PM_1 (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_4 (μg m^{-3})	PM_7 (μg m^{-3})	PM_{10} (μg m^{-3})	TSP (μg m^{-3})	TVOCs (μg m^{-3})	AT (^oC)	RH (%)	Time (min)	LR-vol (m^3)
A	4.18 ± 1.8	12.9 ± 2.0	29.7 ± 2.0	54.2 ± 2.0	74.9 ± 2.1	99.7 ± 2.2	233 ± 2.1	22.6 ± 1.1	40.6 ± 1.3	128 ± 1.1	20.1 ± 1.9
B	7.87 ± 1.7	27.3 ± 1.7	55.2 ± 1.0	86.0 ± 1.6	108 ± 1.7	131 ± 1.7	402 ± 1.7	20.4 ± 1.1	58.2 ± 1.2	122 ± 1.1	15.4 ± 1.5
C	5.69 ± 1.5	14.1 ± 1.6	26.4 ± 1.7	43.5 ± 1.7	57.7 ± 1.8	74.0 ± 1.9	261 ± 1.9	22.7 ± 1.1	46.7 ± 1.3	119 ± 1.1	19.9 ± 2.0

PMs = particulate matters, TSP = total suspended particles, TVOCs = total volatile organic compounds, AT = atmospheric living room temperature, RH = relative humidity, LR-vol = living room volume, A = Arada sub-city, B = Gulelle sub-city, C = Akaki Kality sub-city.

Table 6. ADD for PMs and TVOCs and for HQ for $PM_{2.5}$ PM_{10} and TSP at the living room.

	ADD for PMs and TVOCs (μg kg^{-1} day^{-1})						
	PM_1	$PM_{2.5}$	PM_4	PM_7	PM_{10}	TSP	TVOCs
ADD_1	0.27	0.81	1.67	2.80	3.70	4.72	13.8
$ADD_{1\text{-}5}$	0.21	0.63	1.29	2.16	2.86	3.65	10.7
$ADD_{6\text{-}14}$	0.14	0.42	0.86	1.43	1.90	2.42	7.06
$ADD_{15\text{-}65}$	0.15	0.46	0.95	1.58	2.09	2.67	7.80
RfDannual	-	3.24	-	-	6.56	49.4	-
HQ for $PM_{2.5}$, PM_{10} and TSP							
HQ_1	-	0.25	-	-	0.56	0.10	-
$HQ_{1\text{-}5}$	-	0.19	-	-	0.44	0.07	-
$HQ_{6\text{-}14}$	-	0.13	-	-	0.29	0.05	-
$HQ_{15\text{-}65}$	-	0.14	-	-	0.32	0.05	-

ADD = average daily intake, PMs = particulate matters, TVOCs = total volatile organic compounds, HQ = hazard quotient, TSP = total suspended particles, ADD_1 = ADD for the infant below 1 year; $ADD_{1\text{-}5}$ = ADD for the child between1-5 years; $ADD_{6\text{-}14}$ = ADD for the child between 6–14 years; $ADD_{15\text{-}65}$ = ADD for the adults between 15–65 years; HQ_1 = HQ for the infant below 1 year; $HQ_{1\text{-}5}$ = HQ for the child between 1–5 years; $HQ_{6\text{-}14}$ = HQ for the child between 6–14 years; $HQ_{15\text{-}65}$ = HQ for the adults between 15–65 years.

exposure is small. Thus, sitting in the living room for 2.05 h per day can cover the total chronic intake of $PM_{2.5}$, PM_{10} and TSP in the range of 13–25, 29–59 and 5–10%, respectively, across all age groups.

3.3. Trace elements concentration

The concentrations of 11 elements (Mn, Cd, Co, B, As, Ni, Cr, Pb, Zn, Cu and Fe) were determined by ICP-OES. The calibration curves showed linearity ($r^2 > 0.9897$) of the detector response for all the quantified elements at all microenvironments. Limit of detection (LOD) of each element was determined based on 3 times the standard deviation (3σ) of the blank. The calibrations curve equations, correlation coefficients and LODs of detected elements are summarised in Table 7. The performance of the method was tested by recovery tests through standard addition, and the percent recoveries were found in the

Table 7. The calibration equation for the quantification of elements in PM_{10} using ICP-OES.

Element	Calibration equations	Correlation coefficient (r^2)	LOD in μg m^{-3}
Fe	y = 0.36x + 1027	0.9997	0.0001
Cu	y = 0.92x + 4470	0.9989	0.00007
Mn	y = 1.71x + 782	0.9999	0.00002
B	y = 0.08x + 892	0.9976	0.0005
Zn	y = 0.21x + 1034	0.9919	0.00007
Pb	y = 0.05x + 633	0.9897	0.001
Cr	y = 0.46x + 998	0.9912	0.0002
Cd	y = 1.47x + 626	0.9973	0.0002
Sn	y = 0.07x + 198	0.9975	0.003
As	y = 0.08x + 144	0.9975	0.002
Ni	y = 0.24x + 1445	0.9952	0.001
Co	y = 0.11x + 1085	0.9975	0.0001

PM_{10} = particulate matter-10, ICP-OES = inductively coupled plasma-optical emission spectroscopy, LOD = limit of detection. The data are taken from the article 'Health risk assessment of trace elements through exposure of particulate matter-10 during the cooking of Ethiopian traditional dish sauces' by Asamene Embiale, Bhagwan Singh Chandravanshi, Feleke Zewge & Endalkachew Sahle-Demessie published in Toxicological & Environmental Chemistry, 2020, 102:1–4, 151–169, DOI: 10.1080/02772248.2020.1770257, Published online: 9 June 2020. Reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

range of 93–109% which is between acceptable ranges. The spiking experiments were done in triplicate. The average % recoveries with their standard deviation of each element were: Fe (100 ± 1.21), Cu (103 ± 4.61), Mn (97.4 ± 5.0), B (104 ± 1.52), Zn (93 ± 4.12), Pb (108 ± 1.18), Cr (109 ± 1.22), Cd (104 ± 4.23), Sn (98.6 ± 4.12), As (104 ± 4.32), Ni (106 ± 1.85), and Co (107 ± 3.39).

The concentration of elements was found in the range from 0.001 (Pb) and as much as 0.026 μg m^{-3} (Fe). The pattern of the element in PM_{10} sampled at living room was: Pb < Co < Ni < Sn < As < Cr < Cd < Cu < Mn < B < Fe, respectively. The details of the result are given in Table 8.

3.4. Comparisons of TVOCs, PMs and trace elements in PM_{10} with other studies

The levels of TVOCs found in this study are higher as compared to the level found in Ghent, Belgium and Hanoi, Vietnam. According to [52], different levels of health index and amount of TVOCs found in this work is classified under multi-factor exposure range.

The result of the present study is compared with literature values (Table 9). The level of TSP and PM_{10} found in this work is higher than a similar study conducted in the city of Košice, Slovakia and Vienna measuring at different indoor microenvironments [53]. However, PM_1, $PM_{2.5}$ PM_{10} and TSP levels found in this study are lower as compared to

Table 8. PM_{10} bound elemental composition (mean ± SD, in μg m^{-3}) at the living room.

Element	Fe	Cu	Mn	B	Zn	Pb
Concentration	0.026 ± 0.012	0.005 ± 0.002	0.008 ± 0.004	0.010 ± 0.007	0.010 ± 0.009	0.001 ± 0.001
Element	Cr	Cd	Sn	As	Ni	Co
Concentration	0.003 ± 0.001	0.004 ± 0.001	0.003 ± 0.002	0.003 ± 0.002	0.003 ± 0.002	0.002 ± 0.001

PM_{10} = particulate matter-10, SD = standard deviation.

Table 9. The summary of indoor air pollutants at different measuring site in different countries.

Average amount of pollutant (μg m^{-3})									
PM_1	$PM_{2.5}$	PM_4	PM_7	PM_{10}	TSP	TVOCs	Measuring site	Country	References
5.91	18.1	37.1	61.2	80.2	102	299	LR	Addis Ababa, Ethiopia	This study
7.5	16.7	-	-	68.0	125	-	CR	Beijing, China	[54]
15.5	28.1	-	-	63.0	105	-	Office		
29.4	62.2	-	-	199	329	-	SD		
21.4	44.1			133	227	-	SCR		
56.9	137	-	-	374	547	-	RS		
1.9	5.6	-	-	33.8	72.1	-	Libraries		
5.69	19.6	-	-	88.8	162	-	Supermarket		
111	161	-	-	211	247	-	Indoor road side	North-Central India, India	[55]
99	109	-	-	145	181	-	Urban site		
-	-	-	-	48.6	571	-	Kitchen	Košice, Slovakia	[53]
-	-	-	-	55.6	352	-	LR		
-	-	-	-	31.9	276	-	Working room		
-	44.0	-	-	53.0	45.5	-	RES	Vienna, Austria	[61]
-	48.5	-	-	54.5	56.0	-	CEN		
-	43.5	-	-	45.0	45.5	-	IND		
-	16.6	-	-	-	-	-	Class room	Taranto, south of Italy	[56]
-	-	-	-	-	-	60	House	Ghent, Belgium	[12]
-	-	-	-	-	-	102	House	Hanoi, Vietnam	

Note: PMs = particulate matters, TSP = total suspended particles, TVOCs = total volatile organic compounds, LR = living room; CR = computer room; SD = students' dormitories; SCR = students' classrooms; RS = restaurant; RES = residential place; IND = industrial area; CEN = centre for construction.

similar studies conducted in China and India [54,55]. Similarly, the level of $PM_{2.5}$ found in primary school placed in the district of Taranto (south of Italy) was comparable to this study [56].

Furthermore, the concentration of trace elements found in this study is compared with the literature values studied in different cities in the world (Table 10). The level of trace elements found in this study is relatively lower than a similar study conducted in China, Turkey and Thailand [57–60]. The level of Pb (0.010 μg m^{-3}) found in this study is lower as compared to similar study conducted at Vienna (which is 0.0276 μg m^{-3}), whereas the Cd level (0.003 μg m^{-3}) was found to be higher as compared to the same study (which is 0.0005 μg m^{-3}) [61]. The variation might be due to the difference in microenvironment, human activity, ventilation technique, level of outdoor pollutants, and rate exchange.

3.5. Carcinogenic and non-carcinogenic risk assessment at the living room ME

The carcinogenic and non-carcinogenic risks were calculated for inhabitants who spent 4 hours per day in the living room. The results are given in Table 11. The data clearly indicated that carcinogenic risk is predominantly caused by ingestion exposure pathway followed by inhalation and dermal contact pathways for children, whereas inhalation is followed by ingestion and dermal contact pathway for adults. The data further indicate that the metals (Pb, Cd, As, Cr and Ni) exposure through inhalation, ingestion and dermal contact for both children and adults showed a cancer risk value below the tolerable range.

The non-carcinogenic risk caused by the inhalation exposure pathway is the predominant path followed by ingestion and dermal contact paths for both children and adults. Besides, both HQ and HI values of the measured elements (Fe, Cu, B, Pb, Mn, Zn, Cr, Cd, As and Ni) were found below 1 for both children and adults through inhalation, ingestion and dermal contact which indicates that the individual elements and sum of all elements exposure will not induce non-carcinogenic health problems to the exposed person.

The total non-carcinogenic health risk due to elemental exposure through the three pathways was calculated by using the HQ sum of each element obtained at each pathway. The result (total HI = 0.06) confirmed that children could not have a likelihood to be

Table 10. Trace elements in indoor settings in different city around the world compared with this study (μg m^{-3}).

Pollutant type	Addis Ababa, Ethiopia[a]	Guangzhou, China[b]	Phitsanulok, Thailand[c]	Kocaeli City, Turkey[d]	Hong Kong, China[e]
Fe	0.026	0.024–0.071	0.80–2.70	0.156–0.197	0.115–0.719
Cu	0.005	0.041–0.080	1.00–1.10	0.061–0.067	0.002–0.124
Mn	0.008	0.033–0.084	-	0.055–0.056	0.008–0.268
B	0.010	-	-	-	-
Zn	0.010	0.475–1.572	1.30–1.60	0.093–0.136	0.048–0.435
Pb	0.010	0.218–0.382	0.60–1.70	0.09–0.092	0.002–0.038
Cr	0.001	0.038–0.066	0.90–1.50	0.010–0.012	-
Cd	0.003	0.006–0.013	0.200	-	
Sn	0.004	0.015–0.023	-	-	-
As	0.003	0.042–0.071	-	0.002	-
Ni	0.003	0.024–0.047	0.300	0.002–0.005	
Co	0.002	-	-	-	-
Reference	This study	[58]	[59]	[60]	[57]

Note: [a] the sampling area is living room, [b] the sampling area is different hospital, [c] the sampling site roadside household, [d] the smokers home and non-smokers home and [e] the smokers home and non-smokers home.

Table 11. Carcinogenic and non-carcinogenic risks of each element for children and adults via inhalation, ingestion, and dermal exposure at the living room microenvironment.

Element	LCR	HQ	LCR	HQ
	Adult		Children	
Inhalation exposure				
Cu		$3.61x10^{-06}$		$5.55x10^{-06}$
Mn		0.004		0.007
Zn		$9.60x10^{-07}$		$1.47x10^{-06}$
Pb	$1.78x10^{-09}$	$8.21x10^{-06}$	$3.28x10^{-10}$	$1.26x10^{-05}$
Cr	$7.99x10^{-07}$	$8.67x10^{-04}$	$1.48x10^{-07}$	0.001
Cd	$1.60x10^{-07}$	0.012	$2.95x10^{-08}$	0.018
As	$2.87x10^{-07}$	0.006	$5.29x10^{-08}$	0.009
Ni	$1.60x10^{-08}$	0.002	$2.95x10^{-09}$	0.003
Sum (HI)	$1.26x10^{-06}$	0.025	$2.33x10^{-07}$	0.038
Ingestion exposure				
Fe		$5.36x10^{-06}$		$4.34x10^{-05}$
Cu		$1.81x10^{-05}$		$1.46x10^{-04}$
Mn		$8.25x10^{-06}$		$6.68x10^{-05}$
B		$7.22x10^{-06}$		$5.84x10^{-05}$
Zn		$4.81x10^{-06}$		$3.90x10^{-05}$
Pb	$2.89x10^{-08}$	$4.13x10^{-05}$	$2.81x10^{-08}$	$3.34x10^{-04}$
Cr	$1.55x10^{-07}$	$1.44x10^{-04}$	$1.50x10^{-07}$	$1.16x10^{-04}$
Cd	$2.64x10^{-07}$	5.7710^{-04}	$2.57x10^{-07}$	0.005
As	$4.64x10^{-07}$	0.001	$4.51x10^{-07}$	0.012
Ni	$2.60x10^{-08}$	$8.67x10^{-06}$	$2.52x10^{-08}$	$7.01x10^{-05}$
Sum (HI)	$9.38x10^{-07}$	0.002	$9.11x10^{-07}$	0.018
Dermal contact exposure				
Cu		$1.01x10^{-08}$		$6.30x10^{-09}$
Mn		$1.63x10^{-08}$		$1.01x10^{-08}$
Zn		$2.03x10^{-08}$		$1.26x10^{-08}$
Pb	$4.38x10^{-10}$	$2.03x10^{-09}$	$3.26x10^{-11}$	$1.26x10^{-09}$
Cr	$9.39x10^{-08}$	$6.10x10^{-08}$	$6.98x10^{-09}$	$3.78x10^{-08}$
Cd	$1.60x10^{-08}$	$3.25x10^{-08}$	$1.19x10^{-09}$	$2.02x10^{-08}$
As	$2.11x10^{-08}$	$1.83x10^{-08}$	$1.57x10^{-09}$	$1.13x10^{-08}$
Ni	$9.85x10^{-09}$	$1.52x10^{-07}$	$7.32x10^{-10}$	$9.45x10^{-08}$
Sum (HI)	$1.41x10^{-07}$	$3.13x10^{-07}$	$1.05x10^{-08}$	$1.94x10^{-07}$

LCR = life time cancer risk, HQ = hazard quotient.

affected by non-carcinogenic health problems. The percent contribution of inhalation, ingestion and dermal contact exposure pathways for children accounts to 67.8, 32.1 and 0.1%, respectively. The total HI for adults (total HI = 0.03) also confirmed that no likelihood of having non-carcinogenic health problems. The percent contribution of inhalation, ingestion, and dermal contact exposure pathways to the total HI was found in the order of 92.3, 7.6 and 0.11%, respectively.

4. Discussion

In this study, we measured the indoor levels of PMs and TVOCs pollutants and trace elements in the PM_{10}. We did not measure outdoor levels since the focus was to measure the pollutants in the indoor air (specifically in the living room). Exposure assessment for different microenvironments is needed for estimating the health impact of the exposed person and to determine appropriate remedial interventions. Hence, this study is the first attempt to look at the indoor air pollution in the typical living room in 45 different houses

in three different sub-cities at different geographical locations. There is a variation in the living room volume, family size, ventilation system and position of the living room with respect to bedroom and kitchens. All these factors affect the levels of the pollutants. However, it is not possible to estimate the contributions of individual factor to the total level of the pollutants.

This study is the first attempt to determine the indoor air pollution level of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP and TVOCs in a typical living room at Addis Ababa, Ethiopia. The sources of these pollutants are mostly from the cooking activities. In Ethiopia, biomass wood, charcoal, kerosene and electricity are the major fuels used for different cooking activities. Among the cooking activities, baking of *Injera* is the major source of indoor air pollution due to the high consumption of fuel. Other common cooking activities are preparation of different sauces and roasting and brewing of coffee in traditional manner. The PMs, TVOCs and trace elements contamination of indoor air also depends on outdoor penetration of pollutants and indoor emission from different sources such as movement of occupants, cooking activities, furnishing and ventilation system of the house [53,62]. The trace elements bound in the particulate matter at indoor microenvironment might be originated from biomass combustion, infiltration from outdoor through natural and mechanical ventilation, decomposition of trace elements containing paints, pottery glazes, batteries and from resuspended soil dust in indoor [4]. The concentration of PMs (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP) in the studied three sub-cities decreased in the order of Gulelle > Akaki-Kality > Arada sub-city. The variation in pollutant levels might be due to the difference in the volume of living room, movement of occupants, age of the house, the furnishing material and air exchange rate variation.

The health risk assessment result showed HQ and HI is below 1 which confirmed that both the individual and cumulative exposure of $PM_{2.5}$, PM_{10} and TSP may not induce non-carcinogenic health problems to all age group at this microenvironment. However, this does not mean that their contribution to the total chronic exposure is small. Hence, sitting in the living room can increase the total chronic intake of $PM_{2.5}$, PM_{10} and TSP in the range of 13–25, 29–59, and 5–10%, respectively, across all age groups.

5. Conclusion

The present study has assessed the levels of PMs and TVOCs in the living room. The level of PMs varied from 4.18 μg m^{-3} (for PM_1 in Arada sub-city) to 131 μg m^{-3} (for TSP at Gulelle sub-city) whereas, the amount of TVOCs varied from 233 μg m^{-3} (at Arada sub-city) to 402 μg m^{-3} (at Gulelle sub-city). The levels of trace elements bound in PM_{10} were found in the range of 0.001 (Pb) – 0.026 (Fe). The HQ for infant (below 1 year), the child between 1 and 5 years, the child between 6 and 14 years and the adults between 15 and 65 years were found in the range of 0.10 (TSP) – 0.56 (PM_{10}), 0.07 (TSP) – 0.44 (PM_{10}), 0.05 (TSP) – 0.29 (PM_{10}) and 0.05 (TSP) – 0.32 (PM_{10}), respectively. The estimated hazard quotient value is not higher than one for all types of pollutants, both the children and adults in the living room have a low risk of exposure to carcinogenic and non-carcinogenic health problems. The calculated HI was found in the range of 0.47 (for the child between 6 and 14 years) to 0.91 (for an infant below 1 year). Thus, it can be concluded that infants below 1 year are more affected than other age groups. Hence, improving indoor air quality through

changes in fuel use and improving the ventilation system of the house is crucial to prevent the disease caused by polluted air.

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Data availability Statement

All the data are included in the manuscript. There are no additional data with the authors.

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