

RESEARCH ARTICLE

Elemental composition and health risk assessment of PM₁₀, PM_{2.5}, at different microenvironments: Addis Ababa, Ethiopia

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OPEN ACCESS

Citation: Taye AE, Chandravanshi BS, Beshah FZ, Sahle-Demessie E (2024) Elemental composition and health risk assessment of PM₁₀, PM_{2.5}, at different microenvironments: Addis Ababa, Ethiopia. PLoS ONE 19(10): e0309995. <https://doi.org/10.1371/journal.pone.0309995>

Editor: Worradorn Phairuang, Chiang Mai University, THAILAND

Received: July 3, 2024

Accepted: August 21, 2024

Published: October 25, 2024

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Data Availability Statement: All relevant data are within the manuscript and its [Supporting Information](#) files.

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors declare that there are no conflicts of interest.

Abstract

This study was designed to evaluate the health risks faced by inhabitants living in the slum areas of Addis Ababa, Ethiopia. The levels of PM_{2.5} and PM₁₀ and elemental composition of the PM₁₀ were measured in indoors (in the kitchen and living room) and outdoors (at the roadside). A total of 75 sampling locations (45 indoor and 30 outdoor) were selected for the study. The levels of PM_{2.5} and PM₁₀ were determined using an AROCET531S instrument, while an universal air pump was used for the sampling of PM₁₀ for the determination of trace elements by inductively coupled plasma-optical emission spectroscopy (ICP–OES). The health impacts of PMs on the inhabitants of twelve microenvironments (MEs), where they spend much of their daily time, were estimated. The total amounts of PM_{2.5} and PM₁₀, and trace metals in PM₁₀ found in the nine or twelve MEs ranged from 10.6–119, 128–185, and 0.007–0.197 $\mu\text{g m}^{-3}$, respectively. According to the United States Environment Protection Agency (USEPA) guidelines, ten of the twelve MEs can cause significant health problems for inhabitants (HI > 1) due to PM_{2.5} and PM₁₀. Thus, special attention should be given by stakeholders/inhabitants to minimize the health impacts on long-term exposure. This study assessed the risk of levels of trace elements on the inhabitants who spend most of their daily lives. The study revealed that the lifetime cancer risk values for the individual and cumulative trace elements were within the tolerable range set by the USEPA guidelines.

Introduction

Air pollution is major concern in the world due to its impact on the longevity of humans and ecosystems [1]. Although the world's air quality has greatly improved, many regions, especially those in developing countries with dense populations, continue to experience poor air quality [2,3]. Indoor and outdoor air pollution in low- and middle-income countries accounts for 99% and 90%, respectively, of the total deaths worldwide [4]. Chronic and acute exposure to polluted air causes a variety of health complexities in humans, including premature death,

neurological disorders, gastrointestinal discomfort, hematological disorders, increased cardio-pulmonary morbidity and mortality, dermatitis, and cancer [1,2]. The World Health Organization (WHO) has recently released data showing that 17 people die from air pollution-related causes every minute. The data have also indicated that the life expectancy of populations exposed to high levels of $PM_{2.5}$ decreased the average global life expectancy at birth by approximately 1 year, with decreases of 1.2 to 1.9 years in polluted Asian and African countries [5,6]. Inhabitants of urban areas are much more affected than the rural areas by air pollution due to the expansion of industries, increasing use of biomass as domestic energy, high population density, absence of a good road network, and prevalence of old and poorly maintained vehicles [7–10].

Air pollution in sub-Saharan African (SSA) countries is relatively high due to the use of large amounts of biomass as a fuel source for cooking, limited access to affordable clean fuels, the use of low-efficiency stoves, and the enormous number of old vehicles. The SSA uses approximately 500,000 tons of firewood daily for its daily energy needs [3]. Compared to higher-income homes with effective ventilation systems and a greater likelihood of utilizing high-efficiency stoves, low-income housing is more affected by indoor air pollution [11]. According to a WHO report, the use of inefficient stoves causes the death of 600,000 Africans per year [8,12].

There are variations in the chemical composition of air pollution even within a single nation. This heterogeneity may be caused by varying sociodemographic traits, cultural customs and perceptions, source types and locations, and meteorological circumstances [2,13]. Hence, exposure assessment based on age, sex, activity level, and socioeconomic status is a promising method for remedial action at the individual level. Furthermore, in daily practice, people in the modern world have a much more mobile lifestyle than in recent decades that can be a cause for variation in the contaminant levels of exposure to the inhabitants in multiple locations for different durations. The personal exposure assessment for such people considering a fixed site monitoring method may not be adequately characterized [3,13]. At the same time, the daily activity patterns of individuals have a substantial effect on the total daily intake of pollutants. Thus, spatiotemporal variations in the concentration of contaminants require dynamic cross-pollution measurements of contaminants. Consequently, personal exposure assessments in different microenvironments are a better solution for the determination of pollutants with spatiotemporal variability and for providing more detailed information on individual short-term exposure to indoor and outdoor air pollution [2,3,13]. Therefore, in this study, the individual daily activity patterns in different microenvironments where people spend most of their time are considered in the exposure assessment of the population.

Several studies related to $PM_{2.5}$ and PM_{10} and trace metals bound in the particulate matter in developed and developing countries have been reported in the literature [14–20]. However, there are few studies on air pollution in Ethiopia, and that too without examining the synergistic effects of combined microenvironments on health impact [21–23]. Thus, the synergistic impact of combined MEs, as well as the information on the impacts of respirable air pollutants including $PM_{2.5}$, PM_{10} and heavy metals bound in PM_{10} on inhabitants living in metropolitan city such as Addis Ababa is mandatory. Hence, assessment of exposure to air pollutants using the microenvironmental (ME) modeling approach (average exposure is calculated using time spent and time-averaged concentrations at various places) still needs to be implemented [13]. Moreover, health risk assessments (estimates or predictions) for staying and operating in different combined MEs have yet to be reported in Ethiopia. Therefore, the objectives of this study are as follows: (1) to investigate the levels of $PM_{2.5}$ and PM_{10} and concentrations of trace elements in PM_{10} , in the kitchen (during cooking time), living room (feeding time), and roadside (commuting time), (2) to calculate the total dose intake of $PM_{2.5}$, PM_{10} , and trace

elements in PM_{10} at different combined MEs, and (3) to estimate the potential health risk to inhabitants due to $PM_{2.5}$ and PM_{10} , and trace elements in PM_{10} at combined MEs. The results of this study can inform policy options and mitigation strategies to reduce exposure to harmful pollutants effectively and efficiently.

Materials and methods

Study region

Addis Ababa, Ethiopia's capital city, is 2,800 meters above sea level and is situated at $9^{\circ}1'48''N$ and $38.74^{\circ}E$ latitude and longitude. Addis Ababa city covers 500 km^2 with $3,000\text{ km}$ of road network, 45.5% of which is asphalt, and 54.5% is a gravel road [22]. The city is the center of many diplomatic and international organizations (the African Union and the World Economic Commission). Human activities, including daily traffic flow, numerous urban constructions, and industrial activities, impact the overall air quality of the city [24,25].

Microenvironment information

The microenvironments under the study cover the living room (a place where inhabitants eat, study, watch television, discuss and play with their family members), kitchen (an area where inhabitants bake traditional staple food, *Injera*, using different traditional, improved, and clean stoves; cooking traditional sauce called 'Wot' using electricity, kerosene and charcoal of fuels) and roadside (a place where inhabitants are waking, waiting for a taxi and commuting to work during rush hours). These MEs were selected because inhabitants spend most of their daily lives in these places. The pollutant levels in kitchens and roadsides are also expected to be too high. Besides, although the pollutant level in the living room is expected to be low, inhabitants spend more time there than in the kitchen and roadside.

Furthermore, the type and location of the house selected for the study were mainly based on socioeconomic status, family size, altitude, population density, and the willingness of the owner to allow the researcher. Forty-five households from the three sub-cities (fifteen homes from each) were selected for kitchen and living room MEs. In contrast, thirty sampling locations near the city's major transportation corridors and roadside locations near the downtown roadside were selected for roadside MEs. A purposive sampling method was employed for selecting houses and sampling locations where the level of pollutants is expected to be high. The determination of levels of $PM_{2.5}$ and PM_{10} , and the levels of trace elements in PM_{10} were performed at each ME. Then, the integrated exposure assessment based on the total exposure concentration of the pollutants was calculated using Eq 1. Accordingly, the exposure time and amounts of pollutants are considered [26]. The time spent and level of pollutants could vary by location, affecting the total exposure level of people in these MEs. Consequently, the total levels of exposure are calculated as the product of the sum of time spent by a person in different MEs and the time-averaged air pollution concentrations occurring in those MEs divided by the total time spent in all MEs. The mathematical representation of the concept is given in Eq 1 [13,26]:

$$E_i = \frac{1}{T} \left(\sum_{j=1}^m C_{ij} t_{ij} \right) \quad (1)$$

where C_{ij} is the concentration of the pollutant measured in the j^{th} ME of the i^{th} individual; E_i is the exposure concentration of the i^{th} individual; T is the total time spent in all MEs; m is the number of different MEs; and t_{ij} is the time spent by the i^{th} individual in the j^{th} ME. Fig 1 displays the sampling region.

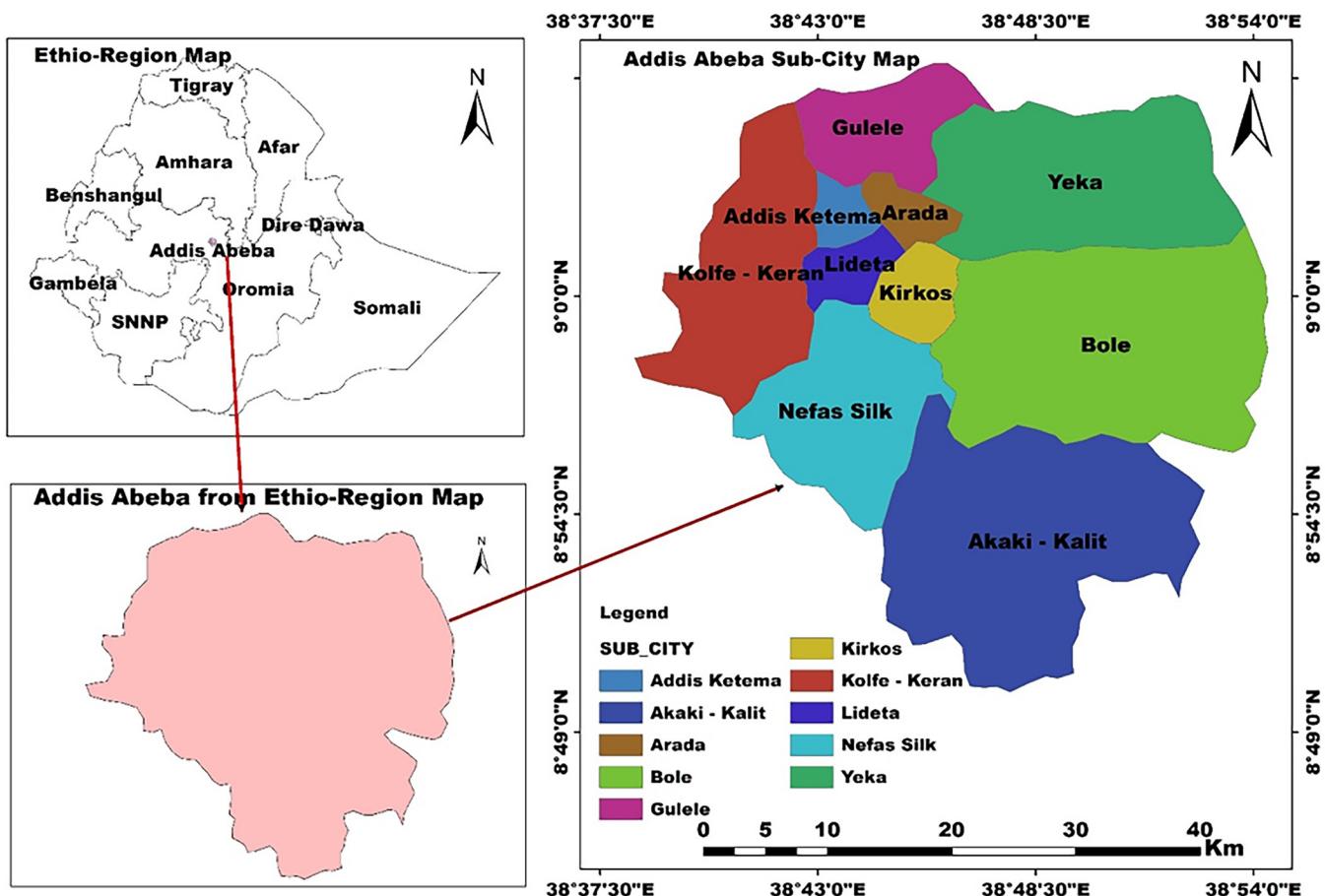


Fig 1. Map showing the sampling area of the ten sub-cities (source: The GADM database).

<https://doi.org/10.1371/journal.pone.0309995.g001>

Statistical analysis

The Shapiro–Wilk test was used to assess the normality of the concentrations of $PM_{2.5}$ and PM_{10} , and trace elements in PM_{10} . The Kruskal–Wallis test and analysis of variance (ANOVA) were used to test for significant differences in the concentrations of pollutants across each ME. All the statistical tests were reported by considering a p value of 0.05. $PM_{2.5}$ and PM_{10} were reported as the geometric mean (GOM) and geometric standard deviation (GSD), while the concentration of trace elements in PM_{10} was reported as the arithmetic mean and standard deviation. All the statistical data analyses were performed using SPSS (Statistical Package for Social Sciences), Microsoft Excel 2016, and Microcal TM Origin version 8.

Measurement of $PM_{2.5}$, PM_{10} and sampling of trace elements in PM_{10}

The levels of $PM_{2.5}$ and PM_{10} were determined using AROCET531S (Met One Instrument., OR 07526, USA) within 2 min intervals in each ME. Before entering the field, the instrument was calibrated based on the manufacturer's operating procedures. The equipment placement was different in each ME's depending on the inhabitants' breathing zone. It was 1.5 meters above the ground and 1 m away from the stove during baking of *Injera*, 1 m above the ground, and 1 m away from the stove/seat during cooking of the *Wot*. Similar arrangement was also made in the living room.

An universal air pump (SKC 224-PCTX4 Model, SKC Ltd, U.K.) integrated with a glass microfiber filter (Whatman®, GE Healthcare U.K. Limited, Amersham Place, U.K.) inside was used for sampling PM₁₀ for determination of trace elements by ICP-OES. The sampling device was positioned 1.5 meters above the ground for kitchen (when baking *Injera*) and roadside MEs, which is the average breathing zone for inhabitants. The kitchen (during cooking) and living room MEs were raised to a height of 1 m. The manufacturer's manual was used to calibrate the instrument's flow rate [27]. To eliminate the humidity and VOCs on the filters, the filter paper was dried in an oven at 150°C for two hours before sampling. The PM₁₀-loaded filters were folded and wrapped with aluminum foil after the sampling process was complete before being brought back to the laboratory. Finally, to extract the elemental makeup of PM₁₀, the wet digestion method developed by the US EPA [28] was used. The literature provides the specifics of the process [27].

Method validation

The precision and accuracy of the method ensure the data quality. Thus, the instruments were calibrated, standard deviations were evaluated, and recovery tests were performed. A series of working standard solutions, 0, 0.5, 1, 2, 3, 4, and 5 µg mL⁻¹ for Ni, Pb, Fe, Cr, Co Cu, Mn, As, Cd, and Sn and 0, 1, 2, 3, 6, 8, and 10 µg mL⁻¹ for B, were prepared from a stock solution of 100 mg L⁻¹. The linearity (r^2) of the calibration curves ranged from 0.990 to 0.999, which are acceptable. The method detection limit was calculated using the standard deviation of seven replicate measurements multiplied by three (3 s), which ranged from 0.0001 to 0.003 µg m⁻³. The percent recovery, determined using the spiking method, was in the range of 92 to 110%, which are within the acceptable range. The details of the calibration curve equations and correlation coefficients for each are shown in [S1 Table](#).

Inhabitants' health risk assessment of PM_{2.5} and PM₁₀

The health risk assessment of inhabitants due to PM_{2.5} and PM₁₀ was performed by considering a method established by the U.S. EPA using the microenvironment (ME) modeling method [29]. Thus, MEs were classified based on type, frequency, and time spent for each activity. The most common activities performed by a particular adult are cooking *Wot* (two times per day), baking *Injera* (two times per week), seating in the living room (every day) and commuting to work or another purpose (every day). Consequently, twelve MEs were evaluated (nine possible MEs by considering all activities and three MEs by excluding baking *Injera* from all) to estimate the health risk of exposed inhabitants. The details of each ME and the parameters used in the risk assessment are given in [Table 1](#). The hazard quotient (HQ) and hazard index (HI) values were used for estimating inhabitants' cancer and noncancer risk. The average daily intake (ADD) in µg kg⁻¹ day⁻¹ of PM (PM_{2.5} and PM₁₀) used for calculating HQ was calculated via Eqs 2 and 3. The HQ and HI values were obtained using Eqs 4 and 9, respectively.

$$ADD = \frac{C \times IR \times ED}{AT \times BW} \quad (2)$$

$$ED = \frac{EF \times TA \times EL \times 1 \text{ day}}{24 \text{ h}} \quad (3)$$

$$HQ = \frac{ADD}{RfD} \quad (4)$$

Table 1. The time required for all activity (TA), exposure frequency (EF), body weight (BW), exposure longevity (EL), average time (days), intake rate (IR) and exposure duration (ED).

Code of ME	Inhabitants' activity	TA (h day ⁻¹)	EF (days year ⁻¹)	EL (years)	ED (days)	AT (days)	IR (m ³ day ⁻¹)	BW (kg)
'A'	Cooking <i>Wot</i> using electricity fuel, baking <i>Injera</i> using clean stove, seating in living room for family discussion, and commuting to work in roadside	10.1	104	50.0	2209	18250	20.0	60.7
'B'	Cooking <i>Wot</i> using kerosene fuel, baking <i>Injera</i> using clean stove, seating in living room for family discussion, and commuting to work in roadside,	10.3	104	50.0	2253	18250	20.0	60.7
'C'	Cooking <i>Wot</i> using charcoal fuel, baking <i>Injera</i> using clean stove, seating in living room for family discussion, and commuting to work in roadside	10.5	104	50.0	2297	18250	20.0	60.7
'D'	Cooking <i>Wot</i> using electricity fuel, baking <i>Injera</i> using improved stove, seating in living room for family discussion, and commuting to work in roadside	10.0	104	50.0	2188	18250	20.0	60.7
'E'	Cooking <i>Wot</i> using kerosene fuel, baking <i>Injera</i> using clean stove, seating in living room for family discussion, and commuting to work in roadside	10.3	104	50.0	2253	18250	20.0	60.7
'F'	Cooking <i>Wot</i> using charcoal fuel, baking <i>Injera</i> using improved, seating in living room for family discussion, and commuting to work in roadside,	10.5	104	50.0	2297	18250	20.0	60.7
'G'	Cooking <i>Wot</i> using electricity fuel, baking <i>Injera</i> using traditional stove, seating in living room for family discussion, and commuting to work in roadside,	10.0	104	50.0	2188	18250	20.0	60.7
'H'	Cooking <i>Wot</i> using kerosene fuel, baking <i>Injera</i> using traditional stove, seating in living room for family discussion, and commuting to work in roadside and	10.3	104	50.0	2253	18250	20.0	60.7
'T'	Cooking <i>Wot</i> using charcoal fuel, baking <i>Injera</i> using traditional stove, seating in living room for family discussion, and commuting to work in roadside.	10.5	104	50.0	2297	18250	20.0	60.7
'AA'	Cooking <i>Wot</i> using electricity fuel, seating in living room for family discussion, and commuting to work in roadside	8.85	365	50.0	6730	18250	20.0	60.7
'BB'	Cooking <i>Wot</i> using kerosene fuel, seating in living room for family discussion, and commuting to work in roadside	9.28	365	50.0	7056	18250	20.0	60.7
'CC'	Cooking <i>Wot</i> using charcoal fuel, seating in living room for family discussion, and commuting to work in roadside	9.07	365	50.0	6904	18250	20.0	60.7

Note: TA and EF for each ME were calculated based on the time required for each activity.

<https://doi.org/10.1371/journal.pone.0309995.t001>

where ADD is the average daily intake (μg kg⁻¹ day⁻¹); ED is the exposure duration (days); IR is the intake rate (m³ day⁻¹); C is the concentration of pollutant in the air (μg m⁻³); EF is the time spent in polluted ME (days year⁻¹); TA is the exposure time spent for all activities (hours day⁻¹); AT represents the averaging time (DE x 365 days year⁻¹); EL is the length of the exposure period (years); 1 day per 24 h is used as the conversion factor; BW is the body weight of inhabitants (60.7 kg, which is the average weight of an African adult); and RfD for PM_{2.5} and PM₁₀ are 10 μg m⁻³ and 20 μg m⁻³, respectively [12,28,30]. AT is the average time (67 years, which is Ethiopia's current average life expectancy) [31].

Assessment of the health risk of inhabitants due to trace elements in PM₁₀

PM₁₀ is a pollutant that significantly impacts human health, causing serious disease and premature death worldwide [32]. The air pollutants in general and the trace elements in PM₁₀ can enter the human body through three main exposure routes: inhalation, ingestion, and dermal absorption [33]. The levels of carcinogenic trace elements, including Cd, As, Pb, Cr, and Ni, and noncarcinogenic elements, including Cu, Fe, Zn, and Mn, bound to PM₁₀ were investigated in this study [34]. The U.S. EPA's integrated risk analysis framework, as expressed in Eqs 5–10, has been implemented to estimate the cancer and noncancer risk of inhabitants by elements in PM₁₀ via ingestion, inhalation, and dermal contact exposure routes [35].

$$D_{inh} = \frac{C \cdot InhR \cdot ED \cdot EF}{BW \cdot AT} \quad (5)$$

$$D_{ing} = \frac{C.IngR.ED.EF}{BW.AT} \times 10^6 \quad (6)$$

$$D_{der} = \frac{C.AF.SA.ABS.ED.EF}{BW.AT} \times 10^6 \quad (7)$$

$$HQ_{inh \text{ or } ing \text{ or } der} = \frac{D_{inh} \text{ or } D_{ing} \text{ or } D_{der}}{RfD} \quad (8)$$

$$HI = \sum HQ \quad (9)$$

$$LCRorCR = D_{inh}.IUR = D_{ing}.SF = D_{der} \cdot \left(\frac{SF}{G} \right) \quad (10)$$

where C refers to the concentration of elements in the air ($\mu\text{g m}^{-3}$ or mg kg^{-1}); D_{inh} refers to the daily dose by inhalation ($\text{mg kg}^{-1} \text{ day}^{-1}$); D_{ing} refers to the daily dose by ingestion ($\text{mg kg}^{-1} \text{ day}^{-1}$); D_{der} is the daily dose by dermal contact ($\text{mg kg}^{-1} \text{ day}^{-1}$); AT refers to the averaging time (years); inR refers to the ingestion rate (mg day^{-1} , 100 for adult); InhR refers to the inhalation rate for adult ($20 \text{ m}^3 \text{ day}^{-1}$); EF refers to the exposure frequency (day.year^{-1} , given in [Table 1](#) for each ME); ED refers to the exposure duration in years (18250 days, assumed starting at age of 17); BW refers to the body weight (kg, 60.5 which average body weight of adult African, LCR or CR refers to the lifetime cancer risk due to carcinogenic elements; IUR refers to the inhalation unit risk ($(\mu\text{g m}^{-3})^{-1}$); AF refers to the skin adherence factor ($\text{mg cm}^{-2} \text{ day}^{-1}$, 0.07 for adult adult), AT is the averaging time (ED x life expectancy (67 years, for non-cancer risk) and ED x 70, years for cancer risk); RfD is the reference dose of each intake path ($\text{mg kg}^{-1} \text{ day}^{-1}$, give in [Table 2](#) for each element); SF refers to the slope factor ($\text{mg kg}^{-1} \text{ d}^{-1}$, given in [Table 2](#)); ABS refers to the dermal absorption factor (unitless, 0.001 for Cd, 0.030 for As and 0.010 for other elements), SA refers to the surface area (cm^2 , 2011 for adult adult), and G refers to the gastrointestinal absorption factor, (unitless, give in [Table 2](#)). LCR or CR refers to the chance of an individual developing cancer [\[35\]](#)

Results and discussion

Average levels of PM_{2.5} and PM₁₀ at individual microenvironments

The levels of PM_{2.5} and PM₁₀ in different MEs while performing various activities during the study period are given in [Fig 2](#). The microenvironments included LR (living room), EF

Table 2. The RfD at different exposure routes and the IUR, SF and G values for different elements [\[35–37\]](#).

Parameter	Fe	Cu	Mn	B	Zn	Pb	Cr	Cd	As	Ni
RfD _{Inh}		0.040	0.00005		0.040	0.0035	0.0004	0.00001	0.000015	0.00005
RfD _{Ing}	0.070	0.040	0.140	0.200	0.300	0.0035	0.0003	0.001	0.015	0.050
RfD _{der}		1.00	1.00		1.00	1.00	0.025	0.025	1.00	0.040
IUR						0.00008	0.012	0.0018	0.043	0.0024
SF						0.280	0.50	0.640	1.50	0.084
G						1.00	0.025	0.025	1.00	0.040

Note: RfD_{Inh}, RfD_{Ing} and RfD_{der} are the reference doses for inhalation, ingestion and dermal contact exposure, respectively.

<https://doi.org/10.1371/journal.pone.0309995.t002>

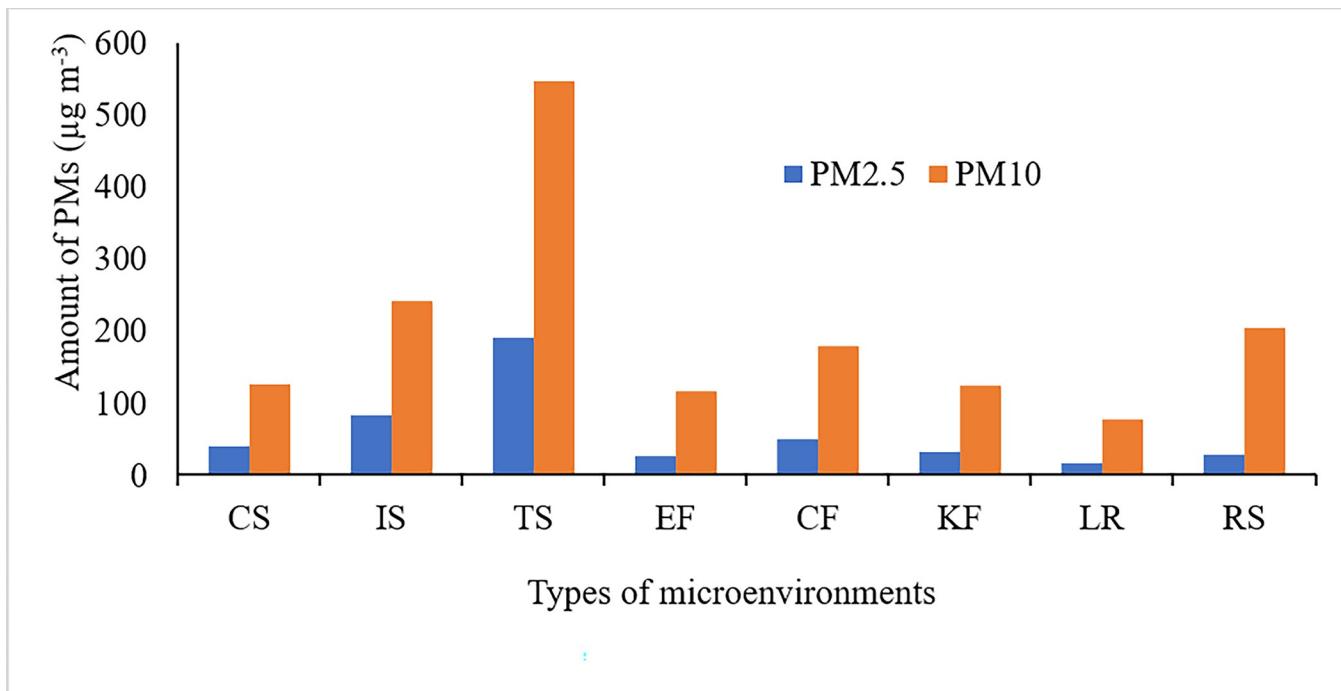


Fig 2. The level of PM_{2.5} and PM₁₀ at different microenvironments (CS, IS, TS, EF, CF, KF, LR and RS).

<https://doi.org/10.1371/journal.pone.0309995.g002>

(kitchen during cooking *Wot* using electricity fuel), KF (kitchen during cooking *Wot* using kerosene fuel), CS (kitchen during cooking *Wot* using charcoal fuel), RS (roadside during commuting), CF (baking *Injera* using a clean stove), IS (baking *Injera* using an improved stove) and TS (baking *Injera* using a traditional stove). The geometric mean of PM_{2.5} was found to range from 17.0 (LR) to 190 (TS) in the following order: LR < EF < RS < KF < CS < VF < IS < TS. The PM₁₀ concentration ranged from 77.6% (LR) to 547% (TS) in the following order: LR < EF < KF < CS < CF < RS < IS < TS. The highest amount was recorded at ME using the traditional stove for baking *Injera* due to the smoke coming from incomplete combustion of biomass [38]. Similar results were observed in previously studies that traditional stove has released more pollutants than improved and clean stove [39,40].

The ADD and total exposure level at combined microenvironments

The ADD, total exposure level and health risk estimation of the inhabitants were carried out based on two scenarios. (1) When an adult spends her daily time baking *Injera*, cooking *Wot*, seating a living room and commuting (A, B, C, D, E, F, G, H and I MEs) and (2) when an adult spends her/his time in the same activity as in scenario 1, excluding baking *Injera* (AA, BB and CC MEs). The daily average time spent by an adult in each MEs was calculated, and the obtained results showed that an adult spent 10.1, 10.3, 10.5, 10.0, 10.3, 10.5, 10.0, 10.3, and 10.5 h in A, B, C, D, E, F, G, H and I MEs, respectively. The results confirmed that 42.0 to 44.0% of adults' daily life was lost in these MEs. The total exposure levels of PM_{2.5} and PM₁₀ in the A, B, C, D, E, F, G, H and I MEs were calculated based on the inhabitants' exposure times, which ranged from 10.6 to 119 and 128 to 185 μg m⁻³, respectively. The highest value was observed in ME I, possibly due to the use of a large amount of biomass fuel for baking *Injera* and charcoal for cooking *Wot*. Similar result was reported in Kenya by [41], stating that traditional stoves have released large amounts of pollutant.

Table 3. The average daily dose (ADD) and total exposure level ([sum (C_{ij}xt_{ij})]/T) of PM_{2.5} and PM₁₀ at different MEs.

Types of MEs	ADD ($\mu\text{g kg}^{-1} \text{ day}^{-1}$)		Total exposure (mean \pm SD)	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
A	0.423	5.10	10.6 \pm 1.41	128 \pm 32.7
B	0.453	5.20	11.1 \pm 1.37	128 \pm 31.7
C	0.632	5.60	15.3 \pm 2.68	135 \pm 31.7
D	0.955	5.60	24.2 \pm 7.97	142 \pm 29.8
E	0.991	5.73	24.4 \pm 7.68	141 \pm 31.1
F	1.17	6.13	28.2 \pm 55.3	148 \pm 29.8
G	4.70	6.99	119 \pm 7.25	177 \pm 33.3
H	4.75	7.13	117 \pm 53.9	175 \pm 31.9
I	4.93	7.53	119 \pm 52.0	185 \pm 28.9
AA	0.86	15.6	7.08 \pm 1.12	129 \pm 42.6
BB	1.59	17.4	12.5 \pm 3.68	136 \pm 37.3
CC	1.42	19.4	17.6 \pm 1.28	156 \pm 40.8
RfD _{annual}	3.24	6.56	—	—

Note: RfD_{annual} is the annual average daily dose.

<https://doi.org/10.1371/journal.pone.0309995.t003>

On the other hand, the total time spent by an adult in the AA, BB and CC MEs was 8.85, 9.28 and 9.08 h, respectively. Thus, the total time spent in the AA, BB and CC MEs accounts for 36.9%, 38.7% and 37.8%, respectively, of the adult's daily time. The ADDs of PM_{2.5} and PM₁₀ ranged from 0.860 to 1.59 and 15.6 to 19.4 $\mu\text{g m}^{-3}$, respectively. The exposure levels of PM_{2.5} and PM₁₀ in the AA, BB and CC MEs ranged from 7.08 to 156, with the maximum and minimum values occurring in the CC and AA MEs, respectively, as presented in Table 3. The detailed values for the average daily doses and total exposure levels of PM_{2.5} and PM₁₀ at different MEs are given in Table 3.

Health risk assessment of PM_{2.5} and PM₁₀ at combined microenvironments

As inhabitants spend a larger proportion of their daily time in the studied MEs, they have high probability of getting non-cancer risk. Table 4 provides a summary of the HQ and HI calculations for the noncarcinogenic hazards of PM_{2.5} and PM₁₀ for an adult depending on the total exposure level at each ME. The HQ values is calculated by taking into account of each pollutant's separate effects. Thus, the HQs of PM_{2.5} and PM₁₀ across the MEs (A, B, C, D, E, F, G, H, and I) ranged from 0.130 to 1.52 and from 0.777 to 1.15, respectively. The HQ values of PM_{2.5} and PM₁₀ in the G', H', and I' MEs were higher than those in the other units, which indicates that inhabitants in these MEs had a significant noncancer risk. The I and A MEs had the maximum and lowest HQ values, respectively. The combined effects of PM_{2.5} and PM₁₀ were evaluated using HI, which was found to range between 0.907 (A) and 2.67 (I) MEs. An adult who spends more time in any of these MEs may be at risk for non-cancer health problems caused

Table 4. Hazard quotient (HQ) and hazard index (HI) results for PM_{2.5} and PM₁₀ at different MEs.

ME	A	B	C	D	E	F	G	H	I	AA	BB	CC
HQ for PM _{2.5}	0.130	0.140	0.195	0.295	0.306	0.362	1.45	1.47	1.522	0.265	0.490	0.677
HQ for PM ₁₀	0.777	0.793	0.853	0.853	0.873	0.935	1.07	1.09	1.15	2.38	2.65	2.96
HI (Σ HQ)	0.907	0.933	1.05	1.15	1.18	1.30	2.52	2.56	2.67	2.65	3.14	3.64

<https://doi.org/10.1371/journal.pone.0309995.t004>

by $PM_{2.5}$ and PM_{10} , according to the results, which showed that all MEs, with the exception of MEs A and B, have an HI value greater than unit.

Furthermore, the noncancer health risk of an adult who did not bake *Injera* was estimated by considering the AA, BB, and CC MEs. The HQs of $PM_{2.5}$ and PM_{10} at the AA, BB, and CC MEs were 0.265–0.677 and 2.38–2.96, respectively. Thus, the HQs of PM_{10} at the AA, BB, and CC MEs were higher than one, and hence inhabitants at these MEs might have a significant health problem. Similarly, the cumulative effects of the $PM_{2.5}$ and PM_{10} concentrations on the AA, BB, and CC MEs ranged from 2.65–3.64, indicating that inhabitants in these MEs might have significant health effects. Therefore, minimize the staying in AA, BB and CC microenvironments is highly recommended to prevent the health impacts.

The level of trace elements across each microenvironment

The corresponding levels of Fe, Cu, Mn, B, Zn, Pb, Cr, Cd, Sn, As, Ni and Co were 0.013 (EF)–0.254 (IS); BDL (CS, TS and IS)–0.057 (RS); 0.001 (CF)–0.444 (RS); 0.01 (LR)–0.632 (IS); 0.01 (LR)–0.351 (IS); 0.001 (LR)–0.109 (RS); 0.02 (EF)–0.013 (RS); 0.0007 (EF)–0.027 (RS); 0.001 (EF)–0.120 (RS); 0.002 (CF)–0.036 (RS); 0.003 (LR)–0.044 (RS); and 0.001 (EF)–0.04 (RS).

The results revealed that the highest levels of most of the trace elements were found in the outdoor microenvironment at the roadside (RS), except for boron and zinc, which were highest in the kitchen microenvironment during baking of *Injera* using an improved stove. This might be due to high traffic congestion, which releases more trace metals through smoke [38]. Similarly, the highest level of B and Zn in improved stove might be due to their micronutrient nature for a plant growth, and that burning of such plant sources resulted for high amount of the metals in particulate matter [42,43]. The general patterns of the investigated elements in different microenvironments are depicted in Fig 3.

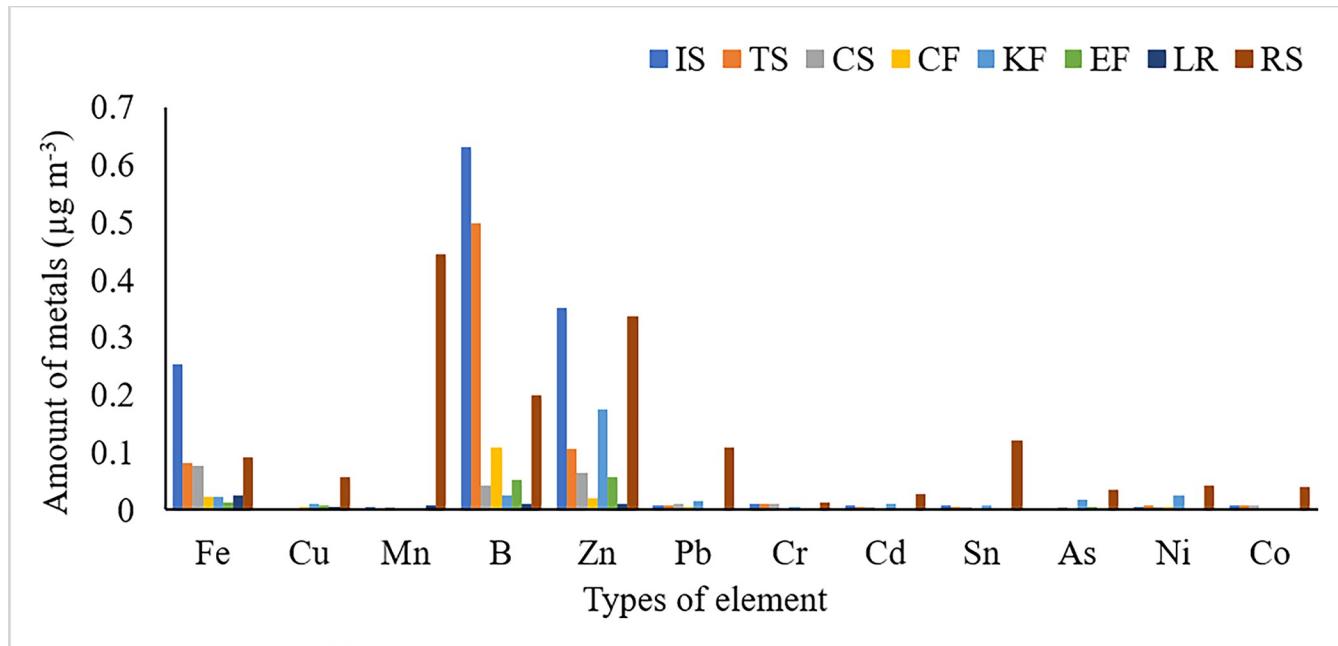


Fig 3. The level of trace elements at different microenvironments (CS, IS, TS, EF, CF, KF, LR and RS).

<https://doi.org/10.1371/journal.pone.0309995.g003>

Table 5. The exposure levels of trace elements in combined MEs (mean \pm SD $\mu\text{g m}^{-3}$ per microenvironment).

Element	A	B	C	D	E	F
Fe	0.075 \pm 0.010	0.073 \pm 0.02	0.073 \pm 0.016	0.055 \pm 0.012	0.053 \pm 0.015	0.053 \pm 0.014
Cu	0.0242 \pm 0.01	0.0243 \pm 0.01	0.0243 \pm 0.01	0.024 \pm 0.011	0.024 \pm 0.086	0.024 \pm 0.084
Mn	0.179 \pm 0.087	0.176 \pm 0.070	0.172 \pm 0.080	0.179 \pm 0.090	0.175 \pm 0.086	0.172 \pm 0.084
B	0.170 \pm 0.039	0.160 \pm 0.040	0.153 \pm 0.040	0.155 \pm 0.040	0.144 \pm 0.04	0.137 \pm 0.040
Zn	0.180 \pm 0.062	0.182 \pm 0.070	0.197 \pm 0.060	0.151 \pm 0.061	0.154 \pm 0.060	0.170 \pm 0.058
Pb	0.046 \pm 0.021	0.044 \pm 0.020	0.045 \pm 0.020	0.046 \pm 0.021	0.044 \pm 0.021	0.045 \pm 0.020
Cr	0.007 \pm 0.002	0.007 \pm 0.002	0.008 \pm 0.002	0.007 \pm 0.002	0.007 \pm 0.002	0.008 \pm 0.002
Cd	0.013 \pm 0.005	0.012 \pm 0.005	0.014 \pm 0.005	0.013 \pm 0.005	0.012 \pm 0.005	0.014 \pm 0.005
Sn	0.050 \pm 0.023	0.049 \pm 0.023	0.049 \pm 0.020	0.050 \pm 0.024	0.049 \pm 0.023	0.049 \pm 0.023
As	0.016 \pm 0.007	0.016 \pm 0.007	0.018 \pm 0.007	0.016 \pm 0.007	0.016 \pm 0.007	0.017 \pm 0.006
Ni	0.019 \pm 0.008	0.019 \pm 0.008	0.023 \pm 0.008	0.020 \pm 0.008	0.019 \pm 0.008	0.022 \pm 0.008
Co	0.018 \pm 0.008	0.017 \pm 0.007	0.017 \pm 0.007	0.018 \pm 0.008	0.017 \pm 0.007	0.017 \pm 0.007
	G	H	I	AA	BB	CC
Fe	0.055 \pm 0.016	0.052 \pm 0.015	0.044 \pm 0.015	0.052 \pm 0.022	0.048 \pm 0.021	0.051 \pm 0.021
Cu	0.024 \pm 0.010	0.024 \pm 0.012	0.033 \pm 0.014	0.028 \pm 0.014	0.027 \pm 0.014	0.028 \pm 0.014
Mn	0.180 \pm 0.088	0.176 \pm 0.086	0.172 \pm 0.084	0.203 \pm 0.115	0.193 \pm 0.110	0.200 \pm 0.112
B	0.102 \pm 0.0400	0.092 \pm 0.040	0.083 \pm 0.040	0.110 \pm 0.050	0.096 \pm 0.040	0.094 \pm 0.050
Zn	0.147 \pm 0.0640	0.149 \pm 0.063	0.162 \pm 0.061	0.158 \pm 0.086	0.156 \pm 0.082	0.182 \pm 0.084
Pb	0.046 \pm 0.020	0.045 \pm 0.020	0.052 \pm 0.021	0.051 \pm 0.028	0.048 \pm 0.027	0.051 \pm 0.027
Cr	0.007 \pm 0.020	0.007 \pm 0.002	0.008 \pm 0.002	0.007 \pm 0.003	0.007 \pm 0.003	0.008 \pm 0.003
Cd	0.013 \pm 0.005	0.012 \pm 0.005	0.014 \pm 0.005	0.014 \pm 0.006	0.013 \pm 0.007	0.015 \pm 0.006
Sn	0.050 \pm 0.024	0.049 \pm 0.024	0.049 \pm 0.023	0.056 \pm 0.031	0.053 \pm 0.030	0.055 \pm 0.030
As	0.016 \pm 0.007	0.016 \pm 0.007	0.018 \pm 0.007	0.017 \pm 0.009	0.017 \pm 0.009	0.020 \pm 0.009
Ni	0.020 \pm 0.008	0.019 \pm 0.008	0.022 \pm 0.008	0.021 \pm 0.011	0.020 \pm 0.010	0.024 \pm 0.011
Co	0.017 \pm 0.008	0.017 \pm 0.008	0.017 \pm 0.007	0.019 \pm 0.010	0.018 \pm 0.010	0.018 \pm 0.010

Note: SD is standard deviation.

<https://doi.org/10.1371/journal.pone.0309995.t005>

Exposure level of trace elements in PM₁₀

The exposure levels of the analyzed elements at the A, B, C, D, E, F, G, H, and I MEs ranged from 0.007 (Cr) to 0.179 (Zn), 0.007 (Cr) to 0.018 (Zn), 0.008 (Cr) to 0.197 (Zn), 0.007 (Cr) to 0.179 (Mn), 0.007 (Cr) to 0.175 (Mn), 0.008 (Cr) to 0.172 (Mn), 0.007 (Cr) to 0.180 (Mn), 0.007 (Cr) to 0.176 (Mn) and 0.008 (Cr) to 0.172 (Mn) $\mu\text{g m}^{-3}$, respectively. The results revealed that the level of Cr was the lowest in all MEs, whereas the levels of Zn in A, B, and C and of Mn in E, F, G, H, and I were the highest. In addition, the total exposure level, regardless of the type of metal, ranged from 0.657 (H) to 0.796 (A) $\mu\text{g m}^{-3}$ in the order of H < I < G < E < F < D < B < C < A. On the other hand, the total exposure levels of the elements in the AA, BB and CC MEs were calculated, and their corresponding values ranged from 0.007 (Cr) to 0.203 (Mn), 0.007 (Cr) to 0.193 (Mn) and 0.007 (Cr) to 0.198 (Mn), respectively. The overall metal exposure levels, regardless of the presence of trace elements, were 0.734, 0.694 and 0.744 $\mu\text{g m}^{-3}$ for the AA, BB, and CC MEs, respectively. The exact values for the total exposure level of each element at each ME are summarized in Table 5.

Health risk assessment of trace elements

Although baking *Injera* is not a daily routine for inhabitants, it has contributed to the intake of a large amounts of pollutants during the time of baking. As a result, the health risk of the adult

was estimated by considering two scenarios: (1) when an adult was baking *Injera* A, B, C, D, E, F, G, H, and I MEs) and (2) when the adult was not baking *Injera* (AA, BB and CC MEs). Thus, inhabitants' adverse carcinogenic and noncarcinogenic health risks are estimated using three exposure routes (ingestion, inhalation, and dermal contact) at each ME under two scenarios. The study results for scenarios 1 and 2 are shown in Tables 6 and 7, respectively.

Risk assessment at the A, B, C, D, E, F, G, H, and I microenvironment

The cumulative and individual elemental risk of inhabitants in each ME were assessed based on the method established by the U.S. EPA (i.e., using HQ and HI) [44]. The cancer and non-cancer risks to inhabitants from exposure to trace elements were determined for each ME through ingestion, inhalation and dermal contact. The analysis was performed to determine the commutative and individual effects of trace elements using HQ, HI, and LCR values. The cumulative impact is calculated based on each route's total element intake through all exposure routes (sum of HI of each element) and the total element intake (sum of HI of all elements in a single route). The individual element risk is based on the intake of a single element through each exposure route (HQ_{inh}, HQ_{ing} and HQ_{der}) and the intake of a single element through the three exposure routes (sum of HQ_{inh}, HQ_{ing} and HQ_{der}). The obtained results indicated that the adult had a negligible noncarcinogenic risk because the individual element HQ values in both cases for all the elements in all the microenvironments were less than 1. However, the cumulative effect in both cases showed that the HI was greater than one, which indicates that the analyzed elements had a significant health impact on the exposed inhabitants due to their cumulative effect. Different exposure pathways have different contributions to the total exposure level. The dermal contact pathway has the lowest subsidy. Inhalation is the dominant route, followed by ingestion and dermal contact routes, for all MEs. Regarding the individual elements, Mn, Cd and As account for the majority of the commutative effect. The general trends of the HI values followed a decreasing order of I > H > F > C > E > B > G > D > A.

An adult's cancer risk due to carcinogenic elements was estimated as an individual and cumulative effect in a manner similar to that used for the noncancer risk assessment. LCR values for many individual elements at all MEs through inhalation and ingestion routes were within the tolerable range set by the U.S. EPA (1×10^{-6} to 1×10^{-4}). However, except for Cr in dermal contact, the LCR values of all the tested elements are below the limit value (1×10^{-6}). The ingestion route is the predominant exposure route, followed by inhalation and dermal contact. The cumulative LCR for all metals was within the tolerable range set by the USEPA. Thus, inhabitants have a low probability of developing cancer in their lifetime. Nevertheless, the LCR values for all the elements are tolerable and below the standard. Furthermore, Cr and Cd contribute more to the LCR. Hence, wearing masks might reduce the intake of PM₁₀, minimizing its effect [28].

Similarly, the cancer and noncancer risk of inhabitants who spent time in the AA, BB and CC MEs were also estimated for the A, B, C, D, E, F, G, H and I MEs. The results revealed that both individual elements (a single element in each route and a single element in all routes) and the cumulative effect of trace elements (all elements in a single route and all elements in all routes) in the AA, BB and CC MEs were less than unity, which indicates that a adult in these MEs has limited potential health impacts from noncarcinogenic risk. Mn, Cr, and Cd contributed the most to the total exposure. In addition, although an adult is less likely to have a non-cancer risk, inhabitants who spent more time in CC MEs were more likely to have a noncancer risk than inhabitants who spent more on BB or AA MEs. This might be due to charcoal fuel, which contributes to high levels of pollutants. Inhalation is the predominant route of exposure, in contrast to dermal and ingestion. At the same time, many individual elements and their

Table 6. Health risk assessment (for both carcinogenic and noncarcinogenic risks) of heavy metal exposure for inhabitants at different MEs.

A										Total in 3 routes		B										Total in 3 routes			
	Inhalation exposure		Dermal contact		Ingestion exposure		LCR	HI	Inhalation exposure		Dermal contact		Ingestion exposure		LCR*	HI**									
Elements	LCR	HQ	LCR	HQ	LCR	HQ			LCR	HQ	LCR	HQ	LCR	HQ											
Fe						9.8E-05		9.8E-05											9.8E-05				9.8E-05		
Cu		0.0001		3.1E-07		0.0006		0.0007		0.0001		3.2E-07			0.0006				0.0007				0.0007		
Mn		0.6515		2.3E-06		0.0012		0.6527		0.6625		2.3E-06			0.0012				0.664						
B						0.0008		0.0008											0.0008				0.0008		
Zn		0.0001		2.3E-06		0.0005		0.0007		0.0001		2.4E-06			0.0006				0.0007						
Pb	5.1E-07	0.0024	1.3E-07	5.7E-07	8.3E-06	0.0119	8.9E-06	0.0143	5.2E-07	0.0024	1.3E-07	5.9E-07	8.4E-06	0.012	9.0E-06	0.0144									
Cr	1.3E-05	0.0136	1.5E-06	9.6E-07	2.4E-06	0.0023	1.6E-05	0.0159	1.3E-05	0.0137	1.5E-06	9.7E-07	2.4E-06	0.0023	1.7E-05	0.016									
Cd	3.2E-06	0.2345	3.3E-07	6.6E-07	5.4E-06	0.0117	8.9E-06	0.2462	3.2E-06	0.2332	3.2E-07	6.6E-07	5.3E-06	0.0117	8.9E-06	0.245									
As	9.4E-06	0.1899	6.9E-07	6.0E-07	1.5E-05	0.0475	2.5E-05	0.2374	9.8E-06	0.1976	7.2E-07	6.3E-07	1.6E-05	0.0494	2.6E-05	0.2471									
Ni	6.5E-07	0.0708	4.0E-07	6.2E-06	1.1E-06	0.0004	2.1E-06	0.0711	6.6E-07	0.0713	4.1E-07	6.3E-06	1.1E-06	0.0004	2.1E-06	0.0717									
HI*	2.6E-05	1.1629	3.0E-06	1.4E-05	3.5E-05	0.0769	6.2E-05 ^a	1.2398 ^b	2.7E-05	1.1809	3.0E-06	1.4E-05	3.3E-05	0.0789	6.3E-05 ^a	1.2598 ^b									
C										D															
Fe						9.8E-05		9.8E-05											7.2E-05	0	7.2E-05				
Cu		0.0001		3.2E-07		0.0006		0.0005721		0.0001		3.1E-07			0.0006	0	0.0007								
Mn		0.6497		2.3E-06		0.0012		0.0011601		0.6575		2.3E-06			0.0012	0	0.6587								
B						0.0007		0.0007208										0.0007	0	0.0008					
Zn		0.0001		2.6E-06		0.0006		0.0006196		9.2E-05		2.1E-06			0.0005	0	0.0006								
Pb	5.3E-07	0.0024	1.3E-07	6.0E-07	8.6E-06	0.0122	9.2E-06	0.0122529	5.2E-07	0.0024	1.2E-07	5.9E-07	8.4E-06	0.012	9.0E-06	0.0144									
Cr	1.3E-05	0.0145	1.6E-06	1.0E-06	2.6E-06	0.0024	1.8E-05	0.0024377	1.3E-05	0.0136	1.5E-06	9.6E-07	2.4E-06	0.0023	1.6E-05	0.0158									
Cd	3.7E-06	0.2657	3.7E-07	7.5E-07	6.1E-06	0.0133	1.0E-05	0.013295	3.2E-06	0.2294	3.2E-07	6.4E-07	5.2E-06	0.0115	8.7E-06	0.2408									
As	1.1E-05	0.2213	8.1E-07	7.0E-07	1.8E-05	0.0553	2.9E-05	0.0553473	9.4E-06	0.1898	6.9E-07	6.0E-07	1.5E-05	0.0474	2.5E-05	0.2372									
Ni	7.5E-07	0.0818	4.7E-07	7.2E-06	1.2E-06	0.0004	2.4E-06	0.0004116	6.7E-07	0.0726	4.1E-07	6.4E-06	1.1E-06	0.0004	2.2E-06	0.073									
HI*	2.9E-05	1.2366	3.3E-06	1.6E-05	3.6E-05	0.0868	6.9E-05 ^a	0.0869 ^b	2.6E-05	1.1654	3.0E-06	1.4E-05	3.2E-05	0.0765017	6.2E-05 ^a	1.2419 ^b									
E										F														Total in 3 routes	
	Inhalation exposure		Dermal contact		Ingestion exposure		LCR	HI	Inhalation exposure		Dermal contact		Ingestion exposure		LCR*	HI**								Total in 3 routes	
Elements	LCR	HQ	LCR	HQ	LCR	HQ			LCR	HQ	LCR	HQ	LCR	HQ											
Fe						7.1E-05		7.1E-05											7.2E-05					7.2E-05	
Cu		0.0001		3.2E-07		0.0006		0.0007		0.0001		3.2E-07			0.0006	0	0.0007								
Mn		0.6652		2.3E-06		0.0012		0.6663		0.6533		2.3E-06			0.0012		0.6545								

(Continued)

Table 6. (Continued)

B					0.0007		0.0007					0.0007		0.0007		
Zn		9.7E-05		2.0E-06	0.0005		0.0006		0.0001		2.2E-06		0.0005		0.0006	
Pb	5.2E-07	0.0024	1.3E-07	5.9E-07	8.4E-06	0.0120	9.0E-06	0.0144	5.3E-07	0.0024	1.3E-07	6.1E-07	8.6E-06	0.0123	9.3E-06	
Cr	1.2E-05	0.0136	1.5E-06	9.6E-07	2.4E-06	0.0023	1.6E-05	0.0159	1.3E-05	0.0144	1.6E-06	1.0E-06	2.6E-06	0.0024	1.8E-05	
Cd	3.1E-06	0.2268	3.1E-07	6.4E-07	5.2E-06	0.0113	8.6E-06	0.2381	3.6E-06	0.260	3.6E-07	7.3E-07	5.9E-06	0.0130	9.9E-06	
As	9.8E-06	0.1966	7.1E-07	6.2E-07	1.6E-05	0.0491	2.6E-05	0.2457	1.1E-05	0.2206	8.1E-07	7.1E-07	1.8E-05	0.0552	3.0E-05	
Ni	6.7E-07	0.0728	4.1E-07	6.4E-06	1.1E-06	0.0004	2.2E-06	0.0734	7.7E-07	0.0835	4.7E-07	7.3E-06	1.2E-06	0.0004	2.5E-06	
HI*	2.7E-05	1.1774	3.0E-06	1.4E-05	3.3E-05	0.0781	6.3E-05 ^a	1.2556 ^b	2.9E-05	1.2346	3.3E-06	1.5E-05	3.6E-05	0.0863	6.9E-05 ^a	1.321 ^b

G

Fe					7.1E-05		7.1E-05					7.1E-05		7.1E-05		
Cu		0.0001		3.1E-07		0.0006		0.0007		0.0001		3.2E-07		0.0006		0.0007
Mn		0.6587		2.3E-06		0.001		0.6599		0.6663		2.3E-06		0.001		0.6675
B					0.0005		0.0005							0.0004		0.0004
Zn		8.9E-05		1.9E-06		0.0004		0.0005		9.4E-05		2.0E-06		0.0005		0.0006
Pb	5.2E-07	0.0024	1.3E-07	5.9E-07	8.5E-06	0.0121	9.1E-06	0.0145	5.2E-07	0.0024	1.3E-07	6.0E-07	8.5E-06	0.0121	9.1E-06	0.0145
Cr	1.3E-05	0.0136	1.5E-06	9.6E-07	2.4E-06	0.0023	1.6E-05	0.0158	1.2E-05	0.0136	1.5E-06	9.6E-07	2.4E-06	0.0023	1.6E-05	0.0159
Cd	3.2E-06	0.2334	3.2E-07	6.6E-07	5.3E-06	0.0117	8.9E-06	0.2451	3.2E-06	0.2381	3.2E-07	6.5E-07	5.3E-06	0.0115	8.8E-06	0.2424
As	9.7E-06	0.1958	7.2E-07	6.2E-07	1.6E-05	0.0490	2.6E-05	0.2448	1.0E-05	0.2027	7.4E-07	6.4E-07	1.6E-05	0.0507	2.7E-05	0.253
Ni	6.6E-07	0.0717	4.0E-07	6.3E-06	1.1E-06	0.0004	2.1E-06	0.0720	6.6E-07	0.0718461	4.0E-07	6.3E-06	1.1E-06	0.0004	2.2E-06	0.0722
HI*	2.7E-05	1.1757	3.0E-06	1.3E-05	3.3E-05	0.0780	6.3E-05 _a	1.2538 ^b	2.7E-05	1.1878706	3.1E-06	1.3E-05	3.4E-05	0.0797	6.4E-05 _a	1.2675 _b

I

Total in 3 routes

	Inhalation exposure		Dermal contact		Ingestion exposure		LCR*	HI**
Elements	LCR	HQ	LCR	HQ	LCR	HQ		
Fe							5.97E-05	
Cu		0.000156		4.39E-07		0.000779		0.0009356
Mn		0.65154		2.29E-06		0.001163		0.6527054
B						0.000391		0.000391
Zn		0.000102		2.17E-06		0.000513		0.0006175
Pb	6.0E-07	0.002775	1.5E-07	6.88E-07	9.8E-06	0.013953	1.05E-05	0.016728
Cr	1.4E-05	0.0146	1.6E-06	1.0E-06	2.6E-06	0.002433	1.8E-05	0.0170303
Cd	3.7E-06	0.2699	3.7E-07	7.6E-07	6.2E-06	0.013496	1.0E-05	0.2834123
As	1.1E-05	0.2282	8.3E-07	7.2E-07	1.8E-05	0.057039	3.0E-05	0.2851934
Ni	7.6E-07	0.0821	4.7E-07	7.2E-06	1.2E-06	0.00041	2.5E-06	0.0824858
HI*	3.0E-05	1.2493	3.4E-06	1.5E-05	3.8E-05	0.090237	7.1E-05 ^a	1.340 ^b

Note: HI^* is the sum of all hazard quotients of all elements in each exposure route; HI^{**} is the sum of all hazard quotients of each element in all exposure routes; LCR^* is the sum of the lifetime cancer risk values of each element in all exposure routes; the values in bold and italics indicate the sum of all LCR values of all cancer risk elements in each exposure route; a is the total LCR of all elements by all routes; and b is the sum of all trace elements in all routes.

<https://doi.org/10.1371/journal.pone.0309995.t006>

Table 7. 1Health risk assessment (both carcinogenic and non-carcinogenic risks) form heavy metal exposure of woman via inhalation, ingestion, and dermal exposure pathways at 'AA', 'BB' and 'CC' MES.

Elements	'AA' ME						Total in 3 routes		'BB' ME						Total in 3 routes	
	Inhalation route		Dermal route		Ingestion route				Inhalation route		Dermal contact route		Ingestion route			
	LCR	HQ	LCR	HQ	LCR	HQ	LCR*	HI**	LCR	HQ	LCR	HQ	LCR	HQ	LCR*	HI**
Fe						4.5E-05		4.5E-05							4.4E-05	4.4E-05
Cu		8.4E-05		2.4E-07		0.0004		0.0005		8.6E-05		2.4E-07		0.0004		0.0005
Mn		0.4935		1.7E-06		0.0009		0.4944		0.4943		1.7E-06		0.0009		0.4952
B						0.0003		0.0003							0.0003	0.0003
Zn		6.4E-05		1.4E-06		0.0003		0.0004		6.7E-05		1.4E-06		0.0003		0.0004
Pb	3.8E-07	0.0018	9.4E-08	4.4E-07	6.2E-06	0.0088	6.7E-06	0.0106	3.8E-07	0.002	9.3E-08	4.3E-07	6.1E-06	0.0088	6.6E-06	0.0105
Cr	7.9E-06	0.0086	9.3E-07	6.1E-07	1.5E-06	0.0014	1.0E-05	0.010	7.9E-06	0.0085	9.2E-07	6.0E-07	1.5E-06	0.0014	1.0E-05	0.0099
Cd	2.3E-06	0.1641	2.3E-07	4.6E-07	3.8E-06	0.0082	6.3E-06	0.1723	2.2E-06	0.1605	2.2E-07	4.5E-07	3.7E-06	0.0080	6.1E-06	0.1685
As	7.0E-06	0.1411	5.2E-07	4.5E-07	1.1E-05	0.0353	1.9E-05	0.1763	7.2E-06	0.1447	5.3E-07	4.6E-07	1.2E-05	0.0362	1.9E-05	0.1809
Ni	4.8E-07	0.0517	2.9E-07	4.5E-06	7.8E-07	0.0003	1.5E-06	0.0519	4.7E-07	0.0513	2.9E-07	4.5E-06	7.7E-07	0.0003	1.5E-06	0.0515
HI*	1.8E-05	0.861	2.1E-06	9.8E-06	2.4E-05	0.0560	4.4E-05 ^a	^b	1.8E-05	0.8612	2.1E-06	9.8E-06	2.4E-05	0.0566	4.4E-05 ^a	0.9179 ^b
'CC' ME																
Fe						4.5E-05		4.5E-05								
Cu		8.7E-05		2.5E-07		0.0004		0.0005								
Mn		0.4934		1.7E-06		0.0009		0.494								
B						0.0003		0.0003								
Zn		7.5E-05		1.6E-06		0.0004		0.0005								
Pb	3.9E-07	0.0018	9.7E-08	4.5E-07	6.4E-06	0.0091	6.8E-06	0.0109								
Cr	8.6E-06	0.0093	1.0E-06	6.6E-07	1.7E-06	0.0016	1.1E-05	0.0109								
Cd	2.6E-06	0.1884	2.6E-07	5.3E-07	4.3E-06	0.0094	7.2E-06	0.1978								
As	8.2E-06	0.1654	6.0E-07	5.2E-07	1.3E-05	0.0413	2.2E-05	0.2067								
Ni	5.6E-07	0.0603	3.4E-07	5.3E-06	9.0E-07	0.0003	1.8E-06	0.061								
HI*	2.0E-05	0.9186	2.3E-06	1.1E-05	2.7E-05	0.0638	4.9E-05 ^a	0.982424 ^b								

Note: HI* designates the sum of all hazard quotient of all elements in each exposure routes, HI** designates the sum of all hazard quotient of each element in all exposure routes, LCR* designates the sum of lifetime cancer risk value of each element in all exposure routes, the values which bold and italic indicates the sum of all LCR values of all cancer risk elements in each exposure routes

^a indicates total LCR of all elements by all routes and

^b indicates the sum of all trace elements in all routes.

<https://doi.org/10.1371/journal.pone.0309995.t007>

cumulative values of LCR in all routes, except dermal contact, were found to be in the tolerable range (1×10^{-6} to 1×10^{-4}) [28]. Cr and As are the two dominant elements for the total exposure routes.

Conclusion

The total exposure levels of PM_{2.5} and PM₁₀ and the elemental composition of PM₁₀ at different combined MEs A, B, C, D, E, F, G, H, and I, AA, BB and CC were assessed. The highest exposure levels were observed in I ME (cooking *Wot* using charcoal fuel, baking *Injera* using traditional stove, seating in living room for family discussion, and commuting to work in roadside), that the time spent in this ME should be minimized to reduce the health impacts. The HQs of PM_{2.5} for G, H, and I MEs, and PM₁₀ for G, H, I, AA, BB and CC MEs are > 1 , indicating that inhabitants at these MEs might have significant non-cancer health problems. The HI values of PM_{2.5} and PM₁₀ for all MEs except 'A' and B, were > 1 , revealed that inhabitants at all the MEs, except at the A and B MEs, could have significant health problems due to the synergistic effect of the pollutants. Similarly, the individual metal non-cancer risk assessment showed no significant impact (HQ < 1), while the cumulative impact of trace elements showed a significant impact (HI > 1) in all MEs. The lifetime cancer risk assessment for carcinogenic elements in all MEs were found within the tolerable range set by U.S. EPA threshold values, which means 1 adult from a million inhabitants can be at risk of developing cancer in her lifetime. Moreover, among the activities, baking *Injera* using traditional stove is the highest pollutant contributor that an immediate alternative solution should be implemented.

Overall, awareness of the public and stakeholders on the health impacts of PM_{2.5} and PM₁₀ and elements in PM₁₀ at these MEs is highly recommended. The study also suggested that stakeholders look for alternative solutions to reduce air pollution, including promoting the use of clean fuels through minimizing costs, improving of the efficiency of existed stoves, promoting public bus transportation, and reducing taxation of electric cars. Inhabitants also recommended using more efficient and clean stoves, as well as well-ventilated kitchens. Moreover, minimizing the frequency and time spent at MEs with high levels of pollutants (such as G, H, I, AA, BB and CC) is another mechanism for mitigating health problems. Additional studies on the assessment of the toxic organic pollutants in the both indoor and outdoor air and the chemical composition of plant biomass, which is most commonly used as fuel for most Ethiopia, is highly recommended.

Supporting information

S1 Table. The calibration curve equation for the eleven elements in PM₁₀.
(DOCX)

Acknowledgments

The authors would like to express their sincere acknowledgement to all the participants.

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