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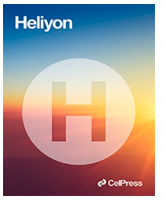

Research article

Levels and health risk assessments of particulate matter and inorganic gaseous pollutants in urban and industrial areas of Hawassa city, Ethiopia

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ABSTRACT

Air pollution is a global public health concern due to its harmful health effects. However, there is scarce data on concentrations and sources of inorganic gaseous pollutants (NO_2, CO, and SO_2) and particulate matter ($PM_{2.5}$ and PM_{10}) in Ethiopia, particularly Hawassa City. Thus, the goal of this research is to determine the indoor and outdoor concentrations of $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 in urban and industrial areas of Hawassa City, Ethiopia, and to evaluate potential health concerns. A portable gas monitor device (HoldPeak Laser PM meter, HP 5800D) was used to measure the levels of PM_{10} and $PM_{2.5}$. The Aeroqual Series 500 Portable Air Quality Monitor (Aeroqual Ltd., New Zealand) was used to measure the concentrations of NO_2, CO, and SO_2. The results of this study showed that the average concentrations of $PM_{2.5}$, PM_{10}, and NO_2 ranged from 8.8 to 310.7, 20.1–515.8, and 40.0–123.7 μg/m^3, respectively, during the dry season. In the wet season, the ranges for $PM_{2.5}$, PM_{10}, NO_2, and CO levels were 17.2–117.4, 24.3–167.2, 31.8–111.3, and 77–33312 μg/m^3, respectively. The wide range of variations in the concentrations of $PM_{2.5}$, PM_{10}, NO_2 and CO variations may be related to spatial and temporal factors such as sampling locations and seasonal changes. In both the wet and dry seasons, the hazard quotient (HQ) for $PM_{2.5}$ and PM_{10} was greater than one, suggesting a non-carcinogenic effect. The $PM_{2.5}$ excess lifetime cancer risk (ELCR) ranged from 0.1 to 0.7, which is greater than the recommended values by the WHO (ranging from 1×10^{-5} to 1×10^{-6}) and the USEPA (less than 1×10^{-6}). The HQ and ELCR values imply a considerable health risk for the general population.

1. Introduction

The harmful consequences of air pollution on health make it a serious global public health concern. Nitrogen dioxide, sulfur dioxide, carbon monoxide, and particulate matter are among the pollutants that pose a severe risk to public health [1–3]. Particulate matter ($PM_{2.5}$–PM_{10}) inhalation can trigger a variety of health difficulties in both humans and animals, including birth defects, low birth weight, premature delivery, lung cancer, respiratory diseases, and asthma [4,5]. Indoor particulate matter can be produced

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Table 1
Description of sampling sites.

	Sampling site	Description of the Sampling Locations	Coordinates
Urban areas (Outdoor)	S1	Roadside of Main highway road (There was a coffee ceremony using coal during sampling in the wet season.)	7°2′57.12"N, 38°29′43.21"E
	S2	Roadside of near bus station	7°2′52.30"N, 38°29′18.36"E
	S3	Roadside of Turufat road	7°2′30.26"N, 38°28′46.22"E
	S4	Roadside of Piasa Road	7°3′04.76"N, 38°28′23.14"E
	S5	Roadside of Areb sefer Road	7°3′23.85"N, 38°28′36.22"E
	S6	The old market	7°3′26.47"N, 38°28′30.02"E
	S7	Fikir Haike (recreational area, a public park)	7°3′11.17"N, 38°27′58.56"E
	S8	Amoragedel (recreational area, a public park)	7°2′41.01"N, 38°27′23.69"E
Urban areas (Indoor)	S9	Household near S1	7°2′58.69"N, 38°29′35.68"E
	S10	Household near S2 (Injera was baking using biomass wood at all sampling times.)	7°2′56.10"N, 38°29′34.61"E
	S11	Household near S3	7°2′30.27"N, 38°28′43.98"E
	S12	Household near S4	7°3′00.89"N, 38°28′20.40"E
	S13	Household near S5	7°3′22.55"N, 38°28′29.53"E
	S14	Household (Residential with a separate kitchen)	7°2′07.90"N, 38°29′14.72"E
	S15	Household (Residential with a kitchen inside, there was a coffee ceremony using stove during sampling in the wet season)	7°1′49.58"N, 38°29′50.80"E
	S16	Household near S15	7°1′53.96"N, 38°29′48.79"E
Industrial areas (Outdoor)	S17	Ambient of Industry 1 (BGI a large-scale brewery factory and beverage production company)	7°1′54.11"N, 38°30′32.41"E
	S18	Ambient of Industry 2 (Hawassa Industrial park)	7°4′22.02"N, 38°29′48.15"E
	S19	Ambient of Industry 3 (Tabor Ceramic Factory)	7°4′52.5"N, 38°29′29.16"E
Industrial areas (Indoor)	S20	Household near S17	7°1′53.96"N, 38°30′33.90"E
	S21	Household S18	7°4′21.01"N, 38°29′47.46"E
	S22	Household S19	7°4′54.05"N, 38°29′31.29"E

during cooking and combustion activities, including the uses of fireplaces, and kerosene heaters, as well as cigarette smoking [2,6,7]. Outdoor PM can originate from transportation, various industrial processes, volcanoes, dust storms, and forest fires [8]. Cooking fires, combustion of fossil fuel in industries, power generators, and vehicles are the primary producers of inorganic gaseous air pollutants, which include sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen dioxide (NO_2) [9,10]. The respiratory system of humans might experience irritation of the airways due to significant NO_2 exposure. Short-term exposures to SO_2 may damage the human respiratory system. Exposure to CO at low levels causes tiredness in healthy people and chest aches in people with heart disease, and it is lethal at very high levels [11–13].

Air pollution data is limited in most African countries, including Ethiopia. The existing studies in Ethiopia indicate high concentrations of air pollution that exceeded the WHO guidelines [14]. There is still a scarcity of data on the levels and sources of inorganic gaseous pollutants and particulate matter in most of the African countries, including Ethiopia. Therefore, the purpose of this study is to investigate the indoor and outdoor concentrations of $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 in the urban and industrial areas of Hawassa City, Ethiopia, in both dry and wet seasons and assess potential health risks. To the best of our knowledge, this study is the first to investigate $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 with broad sampling sites, i.e., the indoor and outdoor of industrial and urban areas, including roadsides, recreational areas, marketplaces, and households in Ethiopia in the dry and wet seasons. The outcomes of this study are vital in supporting the concerned government bodies in raising awareness and stepping up their initiatives to improve the air quality in urban and industrial areas. The results would also add to the scant data on $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 in developing countries and contribute to future global efforts to minimize air pollution.

2. Material and methods

2.1. Description of the study area

The research was conducted in Hawassa, Ethiopia, the capital of the Sidama Regional State, which is located 275 km south of Addis Ababa, the capital of Ethiopia.

Hawassa City's coordinates are 7°3′43.4″ N latitude and 38°28.581′ E longitude in terms of geology. The two seasons are from November to February for the dry season and from March to October for the wet season [15,16]. According to projections from the Ethiopian Statistical Service (ESS), the projected population of Hawassa city is 441536 [17]. Samples were collected from the urban and industrial environments of the city in the dry season between December 10, 2021, and January 19, 2022, and in the wet season between August 1, 2023, and September 10, 2023.

2.2. Sampling site

Representative sampling sites were selected purposively from urban (8 outdoor and 8 indoor) and industrial (3 outdoor and 3 indoor) areas of Hawassa city. Taking into consideration high-traffic roadsides, industries, recreational areas, marketplaces, and households near the selected roadsides and industries. In the city of Hawassa, there are various industries, such as textile manufacturing, ceramic factories, and the soft drink industry. From the various industries in the city, BGI a large-scale brewery factory and beverage production company, Hawassa Industrial Park (which hosts different factories that produce mainly textile and garment products), and Tabor Ceramic Factory were chosen in this study due to their large scale and use of chemicals, which could potentially be a significant cause of air pollution in the area. Samples were collected in the wet and dry seasons; the indoor samples were taken from the living rooms of the selected households near roadsides and industries. The outdoor samples were collected from the ambient air near selected industries, roadsides, recreation areas, and a market. The recreational areas are public parks, and during the measurement, the recreational areas were crowded with fish sellers, buyers, adults, and children who were there for entertainment. The total number of sampling locations was 22, and the total measurements in our study were 132 for each pollutant (3 days × 2 times/day × 22 sampling locations) in each season. The exact sampling site coordinates were obtained using the Global Positioning System (GPS), and the detailed information of sampling locations is described in Table 1.

2.3. Sampling design and measurement methods

The target pollutants for this study were particulate matter ($PM_{2.5}$ and PM_{10}) and inorganic gaseous pollutants (NO_2, CO, and SO_2). These pollutants were included in the study due to their harmful effects on human health and the environment, as well as their contribution to air pollution in urban areas like Hawassa. All the portable air monitor devices used in this study were new and factory calibrated. The measurements of the concentrations of $PM_{2.5}$ and PM_{10} were done using a portable gas monitor device called a laser particulate meter (HoldPeak Laser PM meter-HP 5800D, Zhuhai Jida Huapu Instrument Company Limited, China). The range of $PM_{2.5}$ and PM_{10} detection is 0–999.9 μg/m^3
and 0–1999.9 μg/m^3, respectively, with a resolution of 0.1 μg/m^3. The Aeroqual Series 500 Portable Air Quality Monitor (Aeroqual Ltd., New Zealand) was used to measure the concentrations of NO_2, CO, and SO_2. It is a real-time sampler with an electrochemical gas sensor head that is interchangeable. The sampling location coordinates were obtained with a hand-held automated Garmin GPS 72H Global Positioning System (GPS) navigator (Taiwan). The following parameters were measured from each sampling site: temperature, relative humidity, and the concentrations of NO_2, CO, SO_2, $PM_{2.5}$, and PM_{10} on three separate days (two weekdays and a weekend day) at two moments during the day: in the morning from 7:00 to 12:00 and in the afternoon from 13:30 to 18:30. Every sampling site underwent a continuous measurement for an hour during these moments (i.e. 1 h in the morning and 1 h in the afternoon), and the concentration shown on the device screen was recorded every 3 min. At the end of each measurement (1 h measurement at each moment), the mean of the 20 notes was given as the particulate matter and inorganic gaseous pollutant concentrations for each sample site for each moment (for each morning and afternoon). The indoor measurements were performed in the living room of each household, and the devices were positioned at a height of about 1.5 m above the ground and 1 m away from doors and windows. The instruments were placed approximately 2 m above the ground for the outdoor measurements.

2.4. Risk assessment

2.4.1. The cancer risk and non-carcinogenic risk of $PM_{2.5}$ and PM_{10}

The excess lifetime cancer risk and non-carcinogenic risk were estimated according to the risk assessment methodology used by the United States Environmental Protection Agency [18–21]. ELCR was computed using Equation (1) [19,22,23].

$$\mathrm{ELCR} = \mathrm{LADD} \times \mathrm{SF} \tag{1}$$

In this case, SF is the slope factor (kg day μg^{-1}), LADD is the lifetime average daily dose (μg kg^{-1} day^{-1}), and ELCR is the excess lifetime cancer risk.

LADD was computed by using Equation (2) [19,20].

Table 2
Risk parameters used for calculating HQ and ELCR for $PM_{2.5}$ and PM_{10} in indoor and ambient air.

Parameters	Adults	Reference:
Inhalation rate (m^3/day)	20	[50]
Body weight (kg)	60.7	[51]
Exposure duration (year)	50	[50]
Exposure frequency (day/year)	365	[50]
Averaging time (day) for		
- Non-carcinogens	18,250	
- Carcinogens	25550	
Unit risk (UR)	0.008 $(\mu g/m^3)^{-1}$ for $PM_{2.5}$	[24]
Inhalation reference concentration (RfC)	10 $\mu g/m^3$ for $PM_{2.5}$	[30]
	20 $\mu g/m^3$ for PM_{10}	

RfD = RfC (inhalation reference concentration $\mu g/m^3$) × Assumed inhalation rate (m^3/day) × 1/BW (kg);
Slope factor or carcinogenic potency slope (SF)](BW × UR)/IR; Averaging time (days) for carcinogens = 70 years × 365 days per year, for carcinogens = ED × 365 days per year;
BW for RfD and SF = 70 kg.

Table 3
The six levels of AQI, health concern, and break point concentrations of NO_2 and CO.

Air Quality Index (AQI) Values	Levels of Health Concern	NO_2 ($\mu g/m^3$)	CO (ppm)	Colors	Air pollution level
0 to 50	Good	0–53	0–4.4	Green	Level 1
51 to 100	Moderate	54–100	4.5–9.4	Yellow	Level 2
101 to 150	Unhealthy for Sensitive Groups	101–360	9.5–12.4	Orange	Level 3
151 to 200	Unhealthy	361–649	12.5–15.4	Red	Level 4
201 to 300	Very Unhealthy	650–1249	15.5–30.4	Purple	Level 5
301 to 500	Hazardous	1250–2049	30.5–50.4	Maroon	Level 6

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

In this case, BW is body weight (kg), AT is average exposure time (days), ED is exposure duration (years), EF is exposure frequency (days/year), IR is inhalation rate (m^3/day), and C is the pollutant concentration ($\mu g/m^3$).

The SF value of every contaminant is available through the USEPA's IRIS (Integrated Risk Information System). However, if the exact value of SF is not present, Equation (3) is used as described in Ref. [24].

$$SF = \frac{UR \times BW}{IR} \quad (3)$$

Where, UR stands for unit risk $(\mu g/m^3)^{-1}$, IR is for inhalation rate (m^3/day), and SF (kg day μg^{-1}) is the slope factor.

Equation (4) was used to estimate the risk assessment for the non-carcinogenic risk using the hazard quotient (HQ), which is the ratio of LADD to the reference dose (RfD) [19,20,23].

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

Where RfD is the reference dose ($\mu g\ kg^{-1}\ day^{-1}$) and RfD = RfC (inhalation reference concentration $\mu g/m^3$) × Assumed inhalation rate (m^3/day) × 1/BW (kg). The HQ stands for hazard quotient. LADD is the lifetime average daily dose ($\mu g\ kg^{-1}\ day^{-1}$) (Equation (2)).

A 1.0 HQ is considered the standard for safety. A HQ of less than 1.0 denotes a small or nonexistent danger. Modest concerns exist when the HQ values fall between 1.1 and 10. There are significant hazards present when the HQ values are higher than 10 [19,20,22,25]. Table 2 lists the parameters that were applied to this study's health risk estimation.

2.4.2. Air quality index (AQI) of NO_2 and CO

The air quality index (AQI) is an indicator of the quality of the ambient air. Air pollution levels and associated health risks increase with increasing AQI values [26]. The AQI for NO_2 and CO at the outdoor sampling sites was calculated. The AQI for each pollutant were derived using Equation (5), as described in ([27–29]. The WHO standard (1 h averaging time) used for this calculation was for NO_2 (200 $\mu g/m^3$) and for CO (35000 $\mu g/m^3$) [30].

$$AQI_{Pollutant} = \frac{Pollutnat\ Concentration}{WHO\ Standard} \times 100 \quad (5)$$

The six levels of AQI and health concern are presented in Table 3, and they were taken from the USEPA [31] and described as follows:

Level 1 air pollution is considered to have satisfactory air quality as it poses minimal risk to human health. Level 2 pollution is

Table 4
Arithmetic mean concentration (μg/m^3) values of $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, temperature (T), and relative humidity (RH) in all sampling locations during the dry and wet seasons.

Sampling site	Dry season							Wet season						
	$PM_{2.5}$	PM_{10}	NO_2	CO	SO_2	T (°C)	RH (%)	$PM_{2.5}$	PM_{10}	NO_2	CO	SO_2	T (°C)	RH (%)
S1	25.3	57.5	93.0	ND	ND	30.0	31.1	87.2	115.4	88.0	2695	ND	20.8	69.3
S2	43.5	85.3	104.0	ND	ND	29.2	34.3	44.1	85.5	31.8	77	ND	21.5	64.7
S3	25.3	40.0	94.7	ND	ND	30.3	30.7	49.1	74.7	111.3	7948	ND	21.3	64.3
S4	14.3	35.2	101.2	ND	ND	29.7	28.4	26.6	35.7	83.0	1632	ND	23.5	60.3
S5	17.4	33.5	99.0	ND	ND	29.8	30.6	28.3	59.7	81.7	475	ND	21.5	64.5
S6	20.7	60.2	92.3	ND	ND	29.4	30.8	40.4	75.0	95.2	1637	ND	20.7	65.8
S7	8.8	20.1	51.8	ND	ND	30.2	29.4	25.3	37.2	68.2	ND	ND	21.5	64.2
S8	10.0	33.4	65.0	ND	ND	30.2	30.3	17.2	24.3	82.5	1350	ND	22.3	60.0
S9	32.6	79.4	62.8	ND	ND	28.5	35.2	117.1	159.1	79.7	271	ND	20.5	69.0
S10	310.7	515.8	64.3	ND	ND	28.9	38.0	113.3	131.8	75.2	138	ND	21.0	67.2
S11	17.5	36.4	92.0	ND	ND	28.5	36.3	64.9	92.5	86.7	8920	ND	20.7	66.5
S12	21.0	70.5	71.0	ND	ND	29.0	34.4	98.8	167.5	71.7	299	ND	22.5	64.3
S13	44.9	108.4	59.7	ND	ND	27.4	34.9	91.8	135.3	59.3	888	ND	22.5	61.8
S14	21.7	40.8	40.0	ND	ND	27.5	36.0	112.0	151.4	62.3	370	ND	21.8	55.2
S15	60.2	132.4	54.0	ND	ND	28.8	34.4	117.4	189.7	50.0	1495	ND	21.0	66.7
S16	34.8	75.7	76.5	ND	ND	28.5	34.9	100.5	167.2	57.8	493	ND	22.5	62.8
S17	142.5	270.0	80.3	ND	9.0	26.9	31.8	22.6	37.0	66.2	33312	16.7	20.3	68.3
S18	23.7	89.6	123.7	ND	ND	29.0	30.8	30.8	42.5	41.2	11974	ND	20.8	70.0
S19	22.7	105.7	99.6	ND	ND	30.2	24.3	27.4	93.6	35.3	16143	ND	21.3	67.0
S20	78.3	129.6	68.2	ND	ND	28.4	31.3	107.2	128.8	62.3	11336	ND	21.0	68.7
S21	32.8	148.9	92.3	ND	ND	30.0	30.0	63.3	90.7	45.5	11728	ND	21.0	69.8
S22	19.8	55.0	64.8	ND	ND	28.1	32.0	47.1	138.0	51.2	1489	ND	21.5	67.7

deemed acceptable, but small number of individuals may perceive it as a moderate health concern. Level 3 is labeled as unhealthy for sensitive groups, with the general population less likely to be affected, but individuals from sensitive groups may experience health issues. Level 4 is classified as unhealthy, with potential health consequences for anyone and more severe effects on vulnerable groups. Level 5 is extremely harmful, triggering a health alert and leading to more severe health impacts for everyone. Level 6 poses a public health risk, resulting in emergency situations and health alerts, with a higher likelihood of serious health repercussions for the entire population.

2.5. Statistical analysis

Both Microsoft Excel and IBM SPSS (Version 25) were used for the statistical data analysis. The required pre-conditions of one-way ANOVA were not all satisfied, therefore, Kruskale-Wallis rank test was used i.e. using the Shapiro-Wilks test, and the data's normality was tested. The data for all pollutants in the dry and wet seasons were not normally distributed except for the data on NO_2 in the wet season. Therefore, the concentration data of NO_2 was tested for homogeneity using Levene's test, and the result showed a lack of homogeneity. Consequently, a post-hoc test was conducted after the independent sample Kruskal-Wallis test to assess statistical differences in the measured concentration levels. The correlation coefficients between temperature, relative humidity, NO_2, CO, $PM_{2.5}$, PM_{10}, and NO_2 were determine using Spearman's rho correlation.

3. Results and discussion

3.1. Concentrations of $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2

In this study, temperature and relative humidity, as well as the concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, were measured in urban and industrial areas during the dry and wet seasons. The arithmetic mean concentrations of $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, and values of temperature and relative humidity in all sampling sites during dry and wet seasons are given in Table 4. The percentiles P25, P50, and P75 of $PM_{2.5}$, PM_{10}, NO_2, CO, temperature, and relative humidity are indicated in Supplementary Table S1. $PM_{2.5}$, PM_{10}, and NO_2 were detected during both seasons and at all sampling sites. Carbon monoxide was detected during the wet season but not detected at all during the dry season at any of the sites. SO_2 was detected only at site S17 during both studied seasons. A wide range of variations in the concentrations of $PM_{2.5}$, PM_{10}, and NO_2 were observed across the sampling locations in dry and wet seasons. These variations may be due to spatial and temporal factors such as sampling locations and seasonal changes. The levels of $PM_{2.5}$, PM_{10}, and NO_2 in the dry season in all sampling sites ranged from 8.8 to 310.7, 20.1–515.8, and 40.0–123.7 μg/m^3, respectively. The concentration of $PM_{2.5}$ in the dry season in the outdoor urban ranged from 8.8 to 43.5 μg/m^3, which is analogous with the concentrations of $PM_{2.5}$ (20.1–41.2 μg/m^3) at roadsides in Addis Ababa [32] and 28.3–35.1 μg/m^3 in the Megenagna area in Addis Ababa [33]. However, it was lower than the daily $PM_{2.5}$ concentration (19.1–127.0 μg/m^3) in the city center of Addis Ababa [34] and the $PM_{2.5}$ concentration (39.6–85.3 μg/m^3) at roadside in Addis Ababa, Ethiopia [35]. The concentration of PM_{10} in the dry season in the outdoor urban range of 20.1–85.3 μg/m^3 was comparable with the mean of PM_{10} (54.4–65.8 μg/m^3) in the Megenagna area of Addis Ababa [33]. However,

it was lower than the GM of PM_{10} (148–300 μg/m^3) at roadsides in Addis Ababa [32] and PM_{10} concentration (54.2–247.4 μg/m^3) at the roadside vehicles in Addis Ababa, Ethiopia [35]. The concentration of NO_2 in the dry season in the outdoor urban ranged from 51.8 to 104.0 μg/m^3.

The levels of $PM_{2.5}$, PM_{10}, and NO_2 in the dry season in indoor urban areas ranged from 21.0 to 310.7, 36.4–515.8, and 40.0–92.0 μg/m^3 respectively. The findings of this investigation have shown that the highest concentrations of $PM_{2.5}$ (310.7 μg/m^3) and PM_{10} (515.8 μg/m^3) in S10, a residential house, pose a major risk to health. During all the sampling times, Injera, a staple food in Ethiopia, was prepared using biomass (firewood) in a separate kitchen close to the living room (S10). The reason for the higher concentrations of $PM_{2.5}$ and PM_{10} in S10 may be due to the baking of Injera using biomass wood, as indicated in Ref. [36]. Embaile et al. reported $PM_{2.5}$ concentrations of 174 ± 2.9 μg/m^3 and PM_{10} of 594 ± 2.5 μg/m^3 in the dry season during baking Injera using a traditional stove [36]. The lowest levels of $PM_{2.5}$ (8.8 μg/m^3) and PM_{10} (20.1 μg/m^3) were measured at S7, a recreation area.

The concentration of $PM_{2.5}$, PM_{10}, and NO_2 in the dry season in the outdoor industrial ranged from 22.7 to 142.5, 89.6–270.0, and 80.3–123.7 μg/m^3. The concentration range of $PM_{2.5}$ (22.7–142.5 μg/m3) in the dry season at outdoor industrial area reported in this study was consistent with the ambient $PM_{2.5}$ concentration (27.8–75.9 μg/m^3) reported within the range of 400–800 m of at Mugher Cement Factory in Ethiopia [37]. Furthermore, it was also comparable with 50.1–96.8 μg/m^3 of $PM_{2.5}$ in industries and main transportation stations in the city of Addis Ababa, Ethiopia [38].

The levels of $PM_{2.5}$, PM_{10}, and NO_2 in the dry season in the indoor industrial ranged from 19.8 to 78.3, 55.0–148.9, and 64.8–92.3 μg/m^3, respectively. The World Health Organization (WHO) 24-h and annual mean guidelines for $PM_{2.5}$ and PM_{10} are 25 and 10 μg/m^3 and 50 and 20 μg/m^3, respectively [39]. The outcomes of this study have indicated that the concentrations of $PM_{2.5}$ in the dry season in 50 % of the sampling sites were above the WHO 24-h mean guidelines for $PM_{2.5}$ (25 μg/m^3). The concentrations of PM_{10} were above WHO 24-h mean guidelines for PM_{10} (50 μg/m^3) in 68.2 % of sampling sites, this might pose a major risk to the local community in the study area.

The normality of the $PM_{2.5}$, PM_{10}, and NO_2 concentration data during the dry season was tested using the Shapiro-Wilks test. For every pollutant during the dry season, the data were not normally distributed. Consequently, the Kruskal-Wallis sample test was applied to the $PM_{2.5}$, PM_{10}, and NO_2 data in all the sampling sites during the dry season. The results revealed that there are significant differences in the levels of $PM_{2.5}$, PM_{10}, and NO_2 across all sampling sites ($p < 0.000$). It doesn't, however, specify the location of this difference. Therefore, a pair comparison between the sampling sites was made using a post hoc test, and significance values have been adjusted by the Bonferroni correction. The results for $PM_{2.5}$ data from the post hoc test revealed that there are significant differences ($P \leq 0.038$) in 12 pairwise comparisons (i.e., S7 vs. S20; S7 vs. S21; S7 vs. S17; S7 vs. S10; S8 vs. S20; S8 vs. 21; S8 vs. S17; S8 vs. S10; S4 vs. S17; S4 vs. S10; S15 vs. S10; S5 vs. S10). Likewise, the results for PM_{10} data from the post hoc test revealed that there are significant differences ($P \leq 0.028$) in 15 pairwise comparisons (i.e., S7 vs. S17; S7 vs. S10; S7 vs. S20; S7 vs. S19; S11 vs. S10; S7 vs. S21; S5 vs. S17; S5 vs. S10; S4 vs. S17; S4 vs. S10; S8 vs. S10; S8 vs. S17; S11 vs. S17; S16 vs. S10; S3 vs. S10). Furthermore, the results for NO_2 data from the post hoc test showed that there are significant differences ($P \leq 0.000$) in seven pairwise comparisons (i.e., S16 vs. S11; S16 vs. S5; S16 vs. S19; S16 vs. S2; S16 vs. S18; S7 vs. S18; S12 vs. S18).

The levels of $PM_{2.5}$, PM_{10}, NO_2, and CO in the wet season ranged from 17.2 to 117.4, 24.3–167.2, 31.8–111.3, and 77–33312 μg/m^3, respectively (Table 4). The levels of $PM_{2.5}$, PM_{10}, NO_2, and CO in the wet season in the outdoor urban area ranged from 17.2 to 87.2, 24.3–115.4, 31.8–111.3, and 77–7948 μg/m^3, respectively. The concentrations of $PM_{2.5}$ and PM_{10} found in this study were comparable with the concentrations of $PM_{2.5}$, which varied from 15.30 to 70.20 μg/m^3, and PM_{10}, which varied from 16.3 to 77.5 μg/m^3 in Abuja Municipal Area, Nigeria [29]. The concentrations of $PM_{2.5}$, PM_{10}, NO_2, and CO in the wet season in the indoor urban ranged from 64.9 to 117.4, 92.5–189.7, 50.0–86.7, and 138–8920 μg/m^3, respectively. The results of the present study have shown a higher concentration of $PM_{2.5}$ (117.4 μg/m^3) and PM_{10} (189.7 μg/m^3) in S15, a residential house with an indoor kitchen, which may pose a major risk to health. A coffee ceremony was taking place during the measurement at S15; it may have contributed to the elevated PM_{10} levels, as also reported in Addis Ababa homes during coffee ceremonies [2]. The lower concentrations of $PM_{2.5}$ (17.2 μg/m^3) and PM_{10} (24.3 μg/m^3) were measured at S8, a recreation area. Likewise, the levels of $PM_{2.5}$, PM_{10}, NO_2, and CO in the wet season in the outdoor industrial area ranged from 22.6 to 30.8, 37.0–93.6, 35.3–66.2, and 11974–33312 μg/m^3. The level of $PM_{2.5}$ in the wet season in the indoor industrial area ranged from 47.1 to 107.2 μg/m^3, which is greater than the concentration of $PM_{2.5}$ (12.9–27.3 μg/m^3) in living rooms in Addis Ababa [40]. The level of PM_{10} in the wet season in the indoor industrial area ranged from 90.7 to 138.0 μg/m^3, which was comparable with concentrations of PM_{10} ranging from 57.7 to 108 μg/m^3 in living rooms in Addis Ababa [40]. The findings of the current study revealed that in 90.9 % of the sampling sites, the concentrations of $PM_{2.5}$ during the wet season exceeded the WHO 24-h mean guidelines for $PM_{2.5}$ (25 μg/m^3). In 77.3 % of sampling sites, the PM_{10} concentrations were above the WHO 24-h mean guidelines for PM_{10} (50 μg/m^3), suggesting a potentially significant risk to the surrounding population.

The normality of the $PM_{2.5}$, PM_{10}, CO, and NO_2 concentration data throughout the rainy season was examined using the Shapiro-Wilks test. The result from the Shapiro-Wilks test indicated that the concentration data for NO_2 is normally distributed; however, the data were not normally distributed for $PM_{2.5}$, PM_{10}, and CO. Therefore, the concentration data of NO_2 was tested for homogeneity using Levene's test, and the result showed a lack of homogeneity. Therefore, the Kruskal-Wallis sample test was applied to the $PM_{2.5}$, PM_{10}, NO_2, and CO data in all the sampling sites during the wet season, and the results revealed that there was no significant difference in the concentration of CO across all sampling sites ($p \leq 0.832$). However, there are significant differences in the concentrations of $PM_{2.5}$, PM_{10}, and NO_2 across all sampling sites ($p < 0.000$). However, it does not indicate where this difference is. Therefore, a pair comparison between the sampling sites was carried out using a post hoc test, and significance values have been adjusted by the Bonferroni correction. The results for $PM_{2.5}$ data from the post hoc test indicated that there are significant differences ($P \leq 0.036$) in 10 pairwise comparisons (i.e., S8 vs. S12; S8 vs. S1; S8 vs. S20; S8 vs. S15; S8 vs. S9; S8 vs. 14; S8 vs. S10; S17 vs. S9; S17 vs. S14; S17 vs. S10). The post hoc test results for PM_{10} data also revealed significant differences ($P \leq 0.038$) in nine pairwise comparisons (i.e., S8 vs.

Table 5
Overall arithmetic mean (μg/m^3) of $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, temperature (T), and relative humidity (RH).

	Dry season					Wet season					
	$PM_{2.5}$	PM_{10}	NO_2	T (°C)	RH (%)	$PM_{2.5}$	PM_{10}	NO_2	CO	T (°C)	RH (%)
Urban outdoor	20.7	45.7	87.6	29.8	30.7	39.8	63.4	80.2	1976.8	21.6	64.1
Urban indoor	67.9	132.4	65.0	28.4	35.5	102.0	149.3	67.8	1609.4	21.6	64.2
Industrial outdoor	63.0	155.1	101.2	28.7	29.0	26.9	57.7	47.6	20476.4	20.8	68.4
Industrial indoor	43.6	111.2	75.1	28.8	31.1	72.5	119.1	53.0	8184.1	21.2	68.7

Table 6
The I/O ratio of the arithmetic mean concentration (μg/m^3) of $PM_{2.5}$, PM_{10}, NO_2, and CO in dry and wet seasons at urban and industrial sampling sites.

Sampling site		I/O ratio in dry season			I/O ratio in wet season			
		$PM_{2.5}$	PM_{10}	NO_2	$PM_{2.5}$	PM_{10}	NO_2	CO
Urban	**S9/S1**	1.3	1.4	0.7	1.3	1.4	0.9	0.1
	S10/S2	7.1	6.0	0.6	2.6	1.5	2.4	1.8
	S11/S3	0.7	0.9	1.0	1.3	1.2	0.8	1.1
	S12/S4	1.5	2.0	0.7	3.7	4.7	0.9	0.2
	S13/S5	2.6	3.2	0.6	3.2	2.3	0.7	1.9
Industrial	**S20/S17**	0.5	0.5	0.8	4.7	3.5	0.9	0.3
	S21/S18	1.4	1.7	0.7	2.1	2.1	1.1	1.0
	S22/19	0.9	0.5	0.7	1.7	1.5	1.4	0.1

S20; S8 vs. S22; S8 vs. S10; S8 vs. S9; S8 vs. S16; S8 vs. S15; S8 vs. S14; S4 vs. S15; S4 vs. S14). The post hoc test results for NO_2 data also revealed significant differences ($P \leq 0.001$) in nine pairwise comparisons (i.e., S2 vs. S6; S2 vs. S3; S19 vs. S6; S19 vs. S3; S18 vs. S6; S18 vs. S3; S21 vs. S3; S15 vs. S3; S22 vs. S3).

As presented in Table 4, the concentration of $PM_{2.5}$ level at 90.9 % of the sampling sites was found to be higher in the wet season. A similar trend of concentration of $PM_{2.5}$ was reported in the city center of Addis Ababa [34]. The concentration of PM_{10} level at 77.3 % of the sampling sites was found to be higher in the wet season. The concentration of NO_2 was higher in the dry season for most of the sampling sites (63.6 %). Table 5 depicts that the overall arithmetic mean of $PM_{2.5}$, $PM_{10,}$ and NO_2 in indoor urban areas in the dry season was 67.9, 132.4, and 65.0 μg/m^3, and in outdoor urban areas it was 20.7, 45.7, and 87.6 μg/m^3, respectively. Similarly, the overall mean of $PM_{2.5}$, PM_{10}, and NO_2 in indoor industrial areas in the dry season was 43.6, 111.2, and 75.1 μg/m^3, and in outdoor industrial areas it was 63.0, 155.1, and 101.2 μg/m^3. The findings of the present study (Table 5) for $PM_{2.5}$ in the dry season in indoor urban (67.9 μg/m^3) and industrial (43.6 μg/m^3) areas were comparable with the concentration of $PM_{2.5}$ (57.2 ± 1.89) in Addis Ababa using charcoal in the dry season [41]. However, it was greater than the concentration of $PM_{2.5}$ (18.1 μg/m^3) in living rooms in Addis Ababa, Ethiopia [40] and the concentration of $PM_{2.5}$ 39.2 ± 2.48 and 26.4 ± 2.02 μg/m^3 in households using kerosene and electricity, respectively, in the dry season in indoor Addis Ababa, Ethiopia [41].

The concentration of PM_{10} in the dry season in indoor urban (132.4 μg/m^3) and industrial (111.2 μg/m^3) was greater than the concentration of PM_{10} (80.2 μg/m^3) in living rooms in Addis Ababa, Ethiopia [40], however lower than the concentrations of the PM_{10} 144 ± 1.87, 152 ± 1.87, and 222 ± 1.62 μg/m^3 in households using electricity, kerosene, and charcoal, respectively, in the dry season in indoor Addis Ababa, Ethiopia [41]. The findings of the present study for $PM_{2.5}$ and PM_{10} in the dry season in outdoor urban areas (20.7 μg/m^3 and 45.7 μg/m^3), respectively, were analogous with the concentrations of $PM_{2.5}$ (30.3 ± 2.2 μg/m^3) and PM_{10} (58.6 ± 3.1 μg/m^3) in the Megenagna area in Addis Ababa [33]. The average concentrations of $PM_{2.5}$ and PM_{10} in the present study in the dry season in the outdoor industrial area were 63.0 μg/m^3 and 155.1 μg/m^3, respectively. The concentrations of $PM_{2.5}$ (63.0 μg/m^3) were comparable with the average concentrations of $PM_{2.5}$, 51.5 and 23.6 μg/m^3 in the cities of Beijing and Addis Ababa, respectively, but lower than 107.1 μg/m^3 in New Delhi [42]. The overall arithmetic mean of $PM_{2.5}$, PM_{10}, NO_2, and CO in indoor and outdoor in urban and industrial areas in the wet season is presented in Table 5. The concentrations of $PM_{2.5}$ in indoor urban areas in the wet season was 102 μg/m^3, which was greater than the concentrations of $PM_{2.5}$, 25.8 ± 2.18, 25.4 ± 1.70, and 45.1 ± 2.25 μg/m^3 in households using electricity, kerosene, and charcoal, respectively, in the wet season in indoor Addis Ababa, Ethiopia [41]. The concentrations of $PM_{2.5}$ (102.0 μg/m^3) and PM_{10} (149.3 μg/m^3) in indoor urban areas in this study were comparable with the $PM_{2.5}$ (83.31 μg/m^3) and PM_{10} (103.71 μg/m^3) in the living room in Abuja, Nigeria [43]. However, the $PM_{2.5}$ and PM_{10} concentrations in the current study were lower than the mean concentrations of $PM_{2.5}$ (344.03 ± 21.7 μg/m^3) and PM_{10} (752.8 ± 52.3 μg/m^3) for households using biomass fuel in Jimma, Ethiopia [44]. The PM_{10} (149.3 μg/m^3) in indoor urban areas in the wet season in this study was comparable with the concentrations of the PM_{10}, 91.8 ± 2.21, 102 ± 1.64, and 151 ± 2.17, in households using electricity, kerosene, and charcoal, respectively, in the wet season in indoor Addis Ababa, Ethiopia [41]. The $PM_{2.5}$ and PM_{10} in outdoor urban areas in the wet season were 39.8 and 63.4 μg/m^3, respectively. The concentration of $PM_{2.5}$ (39.8 μg/m^3) in the outdoor urban area of the present study was lower than the mean daily concentration of $PM_{2.5}$ (53.8 ± 25.0 μg/m^3) in the city center of Addis Ababa [34]. The overall mean of $PM_{2.5}$ and PM_{10} in indoor industrial areas in the wet season was 72.5 and 119.1 μg/m^3, and in outdoor industrial areas it was 26.9 and 57.7 μg/m^3, respectively. The concentrations of NO_2 (80.2 μg/m^3) and CO (1976.8 μg/m^3) in the outdoor urban area of the current study were less

Table 7
Overall Arithmetic mean of $PM_{2.5}$, PM_{10}, LADD (μg kg^{-1} day^{-1}) and HQ of $PM_{2.5}$ and PM_{10} and ELCR $PM_{2.5}$ in indoor and outdoor urban and industrial areas in the dry and wet season.

		$PM_{2.5}$	PM_{10}	LADDPM2.5	LADDPM10	HQPM2.5	HQPM10	ELCRPM2.5
Dry Season	**Urban outdoor**	20.7	45.7	6.8	15.0	2.4	2.6	0.1
	Urban indoor	67.9	132.4	22.4	43.6	7.8	7.6	0.4
	Industrial outdoor	63.0	155.1	20.7	51.1	7.3	9.0	0.4
	Industrial indoor	43.6	111.2	14.4	36.6	5.0	6.4	0.3
Wet Season	**Urban outdoor**	39.8	63.4	13.1	20.9	4.6	3.7	0.3
	Urban indoor	102.0	149.3	33.6	49.2	11.7	8.6	0.7
	Industrial outdoor	26.9	57.7	8.9	19.0	3.1	3.3	0.2
	Industrial indoor	72.5	119.1	23.9	39.3	8.4	6.9	0.5

than the concentrations of NO_2 (120 μg/m^3) and CO (4820 μg/m^3) in the ambient of Addis Ababa city [45] and the concentrations of CO (3350 μg/m^3) and NO_2 (130 μg/m^3) in Dire Dawa, Ethiopia [27]. The indoor-to-outdoor (I/O) ratio of the concentrations of $PM_{2.5}$, PM_{10}, NO_2, and CO in dry and wet seasons is indicated in Table 6. The I/O concentration ratio was calculated by dividing the concentrations of $PM_{2.5}$, PM_{10}, NO_2, and CO in each house near the roadside by concentrations in each roadside and concentrations in each house near the industries by concentrations in the ambient of each industry. The I/O concentration ratio of $PM_{2.5}$ and PM_{10} in S10 (a residential house near Roadside 2) was 7.1 and 6.0, respectively. This revealed that there were possible indoor sources and other outdoor sources (a kitchen) of $PM_{2.5}$ and PM_{10} in addition to traffic roadside sources. The results of the I/O ratio of $PM_{2.5}$ and PM_{10} in dry (62 %) and wet (100 %) seasons were greater than one, suggesting the presence of indoor sources. All the values of the I/O ratio of NO_2 in the dry season were less than or equal to one, 62 % of the results in the wet season were less than one, and 50 % of the I/O ratio of CO was less than one. This indicates that NO_2 and CO originated from outdoor sources.

3.2. Correlation of air pollutants with meteorological data

The correlation between $PM_{2.5}$, PM_{10}, and NO_2 concentration, temperature, and relative humidity in the dry season was assessed (Supplementary Table S2). According to Spearman's rho correlation results, the correlation between $PM_{2.5}$ and PM_{10} concentrations was found to be a positive statistically significant correlation ($r = 0.784$, p-value $= 0.01$). Similar results were reported in Akure, a metro capital city in the Niger Delta region of Nigeria, and in Lanzhou, the capital of Gansu province, China, and in 253 towns in Nigeria [46–48]. There was no statistically significant correlation between $PM_{2.5}$ and temperature and relative humidity or between PM_{10} and temperature and relative humidity. Furthermore, there was no statistically significant correlation between NO_2 and $PM_{2.5}$ or between NO_2 and PM_{10}. There was positive correlation between NO_2 and temperature ($r = 0.189$, p-value $= 0.05$) and negative correlation between NO_2 and relative humidity ($r = -0.175$, p-value $= 0.05$). Temperature was negatively correlated with relative humidity ($r = -0.718$, p-value $= 0.01$). The correlation between $PM_{2.5}$, PM_{10}, NO_2, and CO concentration, temperature, and relative humidity in the wet season is indicated in Supplementary Table S3. The results of Spearman's rho correlation in the wet season show that the correlation between $PM_{2.5}$ and PM_{10} concentrations was found to be a positive statistically significant correlation ($r = 0.898$, p-value $= 0.01$). There was no statistically significant correlation between $PM_{2.5}$ and temperature or relative humidity. However, there is a significant correlation between PM_{10} and relative humidity ($r = 0.184$, p-value $= 0.05$). Temperature was negatively correlated with relative humidity ($r = -0.888$, p-value $= 0.01$). There was no significant correlation between the concentrations of CO and NO_2 with the other variables.

3.3. Potential human health risk of detected pollutants

3.3.1. The cancer and non-carcinogenic risks of exposure to $PM_{2.5}$ and PM_{10}

By calculating the excess lifetime cancer risk as well as the non-carcinogenic risk, this study evaluated the health concerns related to $PM_{2.5}$ and PM_{10} exposure. The excess lifetime cancer risk (ELCR) was computed using Equation (1), the lifetime average daily dose (LADD) (μg kg^{-1} day^{-1}) using Equation (2), and the hazard quotient (HQ) using Equation (4). The USEPA advises against using ELCR values lower than 1×10^{-6}, while the World Health Organization (WHO) considered values between 1×10^{-5} and 1×10^{-6} to be tolerable for humans [20,21,49]. The HQ for $PM_{2.5}$ and PM_{10} indoors and outdoors in urban and industrial areas in the dry and wet seasons were greater than one (Table 7), which implies the likelihood of the non-carcinogenic impact occurring. An analogous outcome was reported when utilizing charcoal fuel alone; given that the HQ value of PM_{10} was greater than one, it seems probable that the individual cooking would suffer from detrimental health effects [41]. Similar results have been reported at roadsides at Addis Ababa HQ for $PM_{2.5}$ and PM_{10}, which showed a value larger than one, suggesting that exposure to $PM_{2.5}$ and PM_{10} could cause health issues [32]. Furthermore, ELCR $PM_{2.5}$ in indoor and outdoor urban and industrial areas ranged from 0.1 to 0.4 in the dry season and from 0.2 to 0.7 in the wet season (Table 7), which is greater than the recommended values by the WHO (ranging from 1×10^{-5} to 1×10^{-6}) and the USEPA (less than 1×10^{-6}). This ELCR value of $PM_{2.5}$ implies a significant risk for the general population.

3.3.2. Air quality index of NO_2 and CO

The WHO standards for CO (35000 μg/m^3) and NO_2 (200 μg/m^3), as well as the mean concentration in Table 3, were used to calculate the AQI pollutant value. Equation (5) was used to construct the air quality index (AQI) of CO and NO_2. The results and

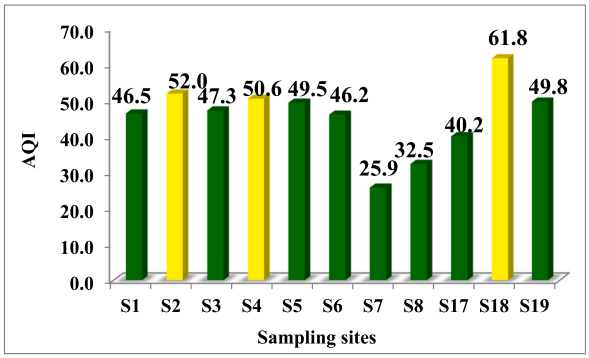

Fig. 1. Air quality index (AQI) for NO_2 in 11 outdoor sampling sites and corresponding AQI color code in the dry season.

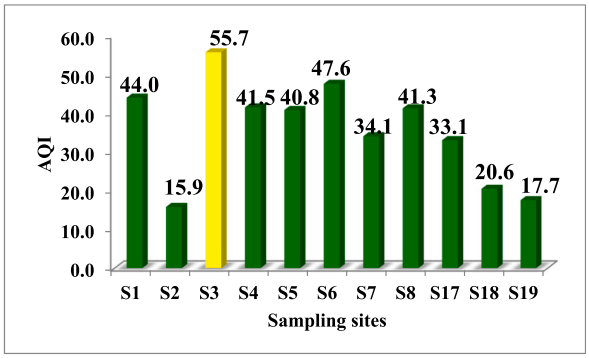

Fig. 2. Air quality index (AQI) for NO_2 in 11 outdoor sampling sites and corresponding AQI color code in the wet season.

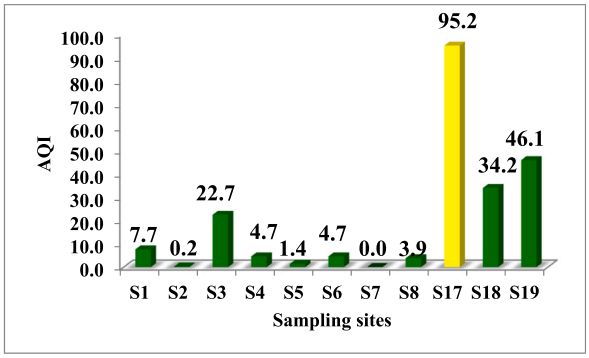

Fig. 3. Air quality index (AQI) for CO in 11 outdoor sampling sites and corresponding AQI color code in the wet season.

findings of the present study revealed that in 72.7 % of the outdoor sampling locations (8 out of 11 sites are with green color code in Fig. 1) in the dry season had good level of air pollution. The air quality is considered acceptable, and there is minimal to no risk to human health from NO_2 exposure. On the other hand, the air quality at 27.3 % of the outdoor sampling sites (3 out of 11 have a yellow color code in Fig. 1) were acceptable; but, it may cause a sensible health distress for a small number of persons. In similar way, wet season results (Fig. 2) and results of the present study revealed that the level of air pollution is good, the air quality is satisfactory, and there is little or no health risk due to NO_2 exposure in 90.9 % of the outdoor sampling locations in the wet season. In addition, the air quality at 9.1 % of the outdoor sampling sites was acceptable; however, it may pose a moderate health concern for a very small number of individuals. The AQI of CO in the outdoor sampling locations in the wet season are indicated in Fig. 3. The findings of this study shown that there is minimal to no risk to health from CO exposure, and the air quality is adequate in 90.9 % of the outdoor sampling locations in the wet season. While 9.1 % of the outdoor sampling sites had acceptable air quality, a very tiny percentage of people may have moderate health concerns.

4. Conclusions

This was the first study of its type to look at the indoor and outdoor air quality in dry and wet seasons in urban and industrial areas of Hawassa, Ethiopia. In most of the sampling sites, the general trend for $PM_{2.5}$ and PM_{10} concentrations was higher in the wet than in the dry season. The results of this study revealed that the levels of $PM_{2.5}$ and PM_{10} at 50 % and 68.2 % of the sampling locations, respectively, during the dry season and 90.9 % and 77.3 % of the sampling locations, respectively, during the wet season were above the WHO guidelines. Suggesting a significant potential significant risk to the to the urban and industrial population. All the values of the I/O ratio of NO_2 in the dry season were less than or equal to one, 62 % of the results in the wet season were less than one, and 50 % of the I/O ratio of CO was less than one. This indicates that NO_2 and CO originated from outdoor sources. The air quality index (AQI) of NO_2 and CO computed in the wet season revealed that the air quality is satisfactory (90.9 %) and acceptable, however, may cause a moderate health worry for small number of persons (9.1 %). The HQ for $PM_{2.5}$ and PM_{10} in urban and industrial areas in the dry and wet seasons was greater than one, which suggests that the non-carcinogenic effect is likely to appear. The ELCR of $PM_{2.5}$ in urban and industrial areas exceeded WHO and USEPA recommendations, posing a significant risk to the general population during both wet and dry seasons. Governments and academic experts can use the vital data set provided by this study to intensify their efforts to improve the city's air quality. The results would also add to the scant data on $PM_{2.5}$ and PM_{10} in developing countries and contribute to future global efforts to minimize air pollution. Based on our study, a policy recommendation to improve air pollution quality could be to implement stricter regulations on emissions from vehicles and industries. Additionally, investing in green infrastructure and promoting public awareness about the importance of reducing air pollution could also be effective measures to improve the air quality of the city.

Data availability statement

The data associated with this study has not been deposited in a publicly available repository. The data associated with this study will be made available on request.

CRediT authorship contribution statement

Abebech Nuguse Amare: Writing – original draft, Visualization, Data curation, Conceptualization. **Solomon Sorsa:** Writing – review & editing, Supervision. **Zinabu Gebremariam:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33286.

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