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Health Risks of Atmospheric Fine Particulate Matter ($PM_{2.5}$) and Its Trace Elements in Mabopane, South Africa

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ABSTRACT

Atmospheric fine particulate matter ($PM_{2.5}$) contributes to approximately 4 million premature deaths globally each year. This study aimed to investigate the health risks of atmospheric $PM_{2.5}$ and its trace elements in Mabopane, South Africa. $PM_{2.5}$ samples were collected every sixth day from June 15, 2022 to February 28, 2023 using a GilAir-5 sampler at 4.0 L/min on the Mabopane Fire Station rooftop. Health risks were evaluated using US EPA guidelines, WHO air quality limits, South African National Ambient Air Quality Standards (SANAAQS), and US EPA trace element reference levels. The mean $PM_{2.5}$ level was 10 $\mu g/m^3$ (range: 1.1–29 $\mu g/m^3$), exceeding the WHO annual air quality limit (5 $\mu g/m^3$) but below SANAAQS (20 $\mu g/m^3$). $PM_{2.5}$ posed health risks (hazard quotient > 1) across all age groups. Among 18 trace elements, Ca, Fe, K, S, and Si showed the highest levels (110–240 ng/m^3). The excess cancer risk from Ni was 1.2×10^{-6}. These findings underscore the need for targeted air quality controls to reduce $PM_{2.5}$ and trace elements from dust and anthropogenic sources, to protect public health in Mabopane and similar areas.

1 | Introduction

Air pollution has become recognized as the leading environmental threat to human health, owing to its significant contribution to the global disease burden (World Health Organization 2021). Globally, air pollution is responsible for an estimated 8 million premature deaths annually, making it the 2nd leading risk factor for deaths (Health Effects Institute 2024). Nearly 100% of the global population is exposed to air pollution levels that exceed the WHO air quality limits (World Health Organization 2021). Specifically, $PM_{2.5}$ accounts for 4 million premature deaths annually (Health Effects Institute 2024). $PM_{2.5}$ refers to particles with an aerodynamic diameter of less than 2.5 μm. $PM_{2.5}$ can penetrate deeply into the lungs, irritate the alveolar walls, and impair lung function (Xing et al. 2016). In South Africa, premature deaths due to $PM_{2.5}$ exposure range from 25,035 to 34,898 annually (Marais et al. 2019; Simelane and Langerman 2023). The country is ranked 4th in Africa for the highest number of deaths due to $PM_{2.5}$ (Clean Air Fund 2023). Predictions suggest that premature deaths related to $PM_{2.5}$ exposure in South Africa may continue to rise by 2030 (Marais et al. 2019). This will hinder the country's progress toward achieving Sustainable Development Goal (SDG) 3.9, which aims to reduce health complications and mortality rates associated with air, water, and soil pollution by 2030 (Sustainable Development Goals 2015).

The health effects associated with air pollution include cardiovascular diseases, chronic obstructive pulmonary disease (COPD), asthma, respiratory diseases, and lung cancer (World Health Organization 2021). While most epidemiology studies only investigated $PM_{2.5}$ mass, the composition of $PM_{2.5}$ is quite diverse. $PM_{2.5}$ composition includes black carbon, organic carbon, soot, and also trace metals such as S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Br, Sr, Pb, and Co (Ma et al. 2022). Evidence from epidemiology and toxicology studies is starting to show that some of the components of $PM_{2.5}$ may be more dangerous to human health than simply $PM_{2.5}$ mass (Boman et al. 2023; Howlett-Downing et al. 2023). However, there is a paucity of epidemiological studies focusing on the health risks of air pollution and its chemical composition in low-middle-income countries (Lim et al. 2022).

In order to mitigate $PM_{2.5}$ air pollution exposure it is necessary to know its sources. Potential anthropogenic sources of $PM_{2.5}$ include tail-pipe and non-tail-pipe vehicular emissions, industrial emissions, brick kilns, coal combustion, biomass burning, and construction activities (Jawaa et al. 2024). In South Africa, major sources of $PM_{2.5}$ include industries, residential solid fuel burning, vehicles, dust, biomass burning, and mining operations (Adeyemi et al. 2021; Djolov and Tshehla 2018; Muyemeki et al. 2021; Van der Westhuizen et al. 2024). Power generation accounts for approximately 23% of $PM_{2.5}$ emissions (Health Effects Institute 2022). Trace elements originate from traffic (Ni, Cu, Zn, Pb), biomass and industrial emissions (S, Cr, K, Pb), coal combustion (Cl, K, Sb), and soil dust (Ca, Ti, Si, Fe) (Jawaa et al. 2024; Liu et al. 2020; Morantes et al. 2021; Muyemeki et al. 2021; Van der Westhuizen et al. 2024).

The City of Tshwane Metropolitan Municipality, where Mabopane is located, has a legislative responsibility to manage air quality and air pollution sources, including enforcing air quality bylaws and developing effective air quality management strategies, such as air quality management plans and air quality monitoring networks for Tshwane, including Mabopane (Department of Environmental Affairs 2004). The current air quality management plan has not been updated to align with air quality management legislation (City of Tshwane Metropolitan Municipality 2006). The City of Tshwane Metropolitan Municipality operates seven permanent ambient air monitoring networks: Bodibeng, Booysens, Ekandustria, Mamelodi, Olievenhoutbosch, Pretoria West, and Rosslyn.

“*Bodibeng, located approximately 4 km from the sampling site, is prone to poor data recovery due to inadequate maintenance and power outages, which might hinder the use of the data for health risk studies and policy adjustments.*”

Bodibeng, located approximately 4 km from the sampling site, is prone to poor data recovery due to inadequate maintenance and power outages, which might hinder the use of the data for health risk studies and policy adjustments. The government plans to designate Tshwane as an air pollution priority area due to its poor air quality levels (Burger 2024). Of all the possible compositions of $PM_{2.5}$, a national air quality standard exists only for lead (Pb), however, nearly none of the air quality monitoring stations in the country report on Pb (Department of Environmental Affairs 2009). This health risk assessment study is the first to report on the human health risks due to $PM_{2.5}$ and its trace element composition in the semi-urban area of Mabopane. Recent studies have primarily focused on industrial, rural, and urban environments in South Africa (Alfeus et al. 2022; Edlund et al. 2021; Howlett-Downing et al. 2023; Morakinyo et al. 2021). The study aimed to investigate the health risks of atmospheric $PM_{2.5}$ and its trace elements in Mabopane, South Africa.

2 | Materials and Methods

2.1 | Sampling Site

The study was conducted at the Mabopane Fire Station (25.4928°S, 28.0872°E) in Northern Gauteng, South Africa (**Exhibit 1**). Mabopane, a semi-urban township about 40 km from Pretoria and 80 km from Rustenburg, experiences average temperatures of 19°C in winter and 29°C in summer. With a population of 110,972 (Statistics South Africa 2011), it is predominantly Black and shaped by its apartheid legacy, characterized by poor infrastructure and limited basic services (Donaldson 2014; Pernegger and Godehart 2007). The sampling site is bordered by a busy road, residential areas (West and North), and a shopping center with a train station (South). Major air pollution sources include mineral dust, vehicle emissions, diesel-powered generator, biomass, and coal burning from vendors and residents, and frequent waste burning due to poor collection services.

2.2 | Sampling Procedure

$PM_{2.5}$ samples were collected every sixth day from June 15, 2022 to February 28, 2023, on the rooftop of the Mabopane Fire Station, 6 m above ground. Using a GilAir-5 personal air sampler (Sensidyne, Germany) at 4 L/min, 37-mm PTFE membrane filters (2 µm pore size; Zefon International, USA) were used. Each 24-hour sample ran from 9 a.m. to 9 a.m., consistent with similar studies in Gauteng (Adeyemi et al. 2022; Howlett-Downing et al. 2022). A total of 40 samples were collected. Meteorological data were sourced from the Wonderboom weather station, located approximately 25 km southeast of the sampling site.

2.3 | Gravimetric Analysis

The study followed a similar protocol to other studies (Adeyemi et al. 2022; Becker et al. 2024). Briefly, sampling filters and blanks were conditioned for 24 h (temperature: 20.1°C–22°C; RH: 43%–54%) at the School of Health Systems and Public Health air quality lab, University of Pretoria, before weighing. Post-exposure filters were stored at 4°C. A Mettler-Toledo XP6 ultra-microbalance (±1 µg sensitivity) was used to measure mass before and after sampling.

2.4 | Trace Elements Analysis

“*The analysis of the sampling filters for trace elements was conducted at the Atmospheric Science Section, University of Gothenburg, using the XEPOS 5 energy-dispersive X-ray fluorescence (EDXRF) spectrometer (Spectro Analytical Instruments GmbH, Germany).*”

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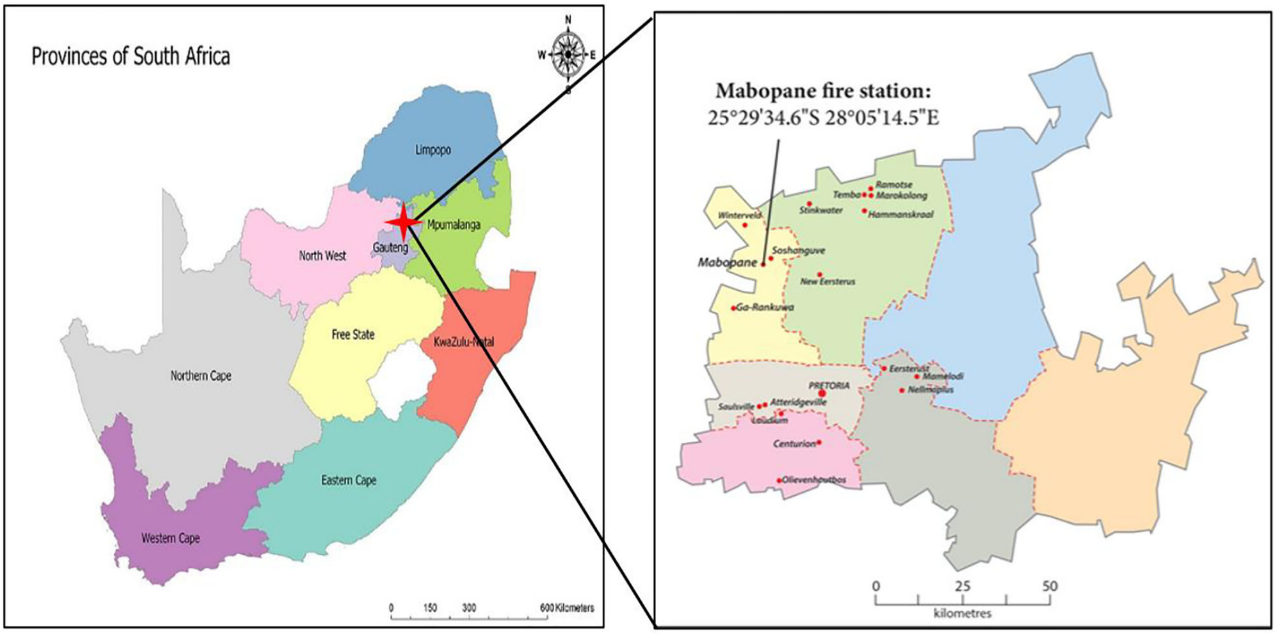

EXHIBIT 1 | Sampling site (red star indicates Mabopane township). [Color figures can be viewed at wileyonlinelibrary.com.]

EXHIBIT 2 | Variables and assumptions used for the health risk assessment.[a]

Variable	Population	Value	Source
Body weight	Adults (South Africa)	71.9 kg	US AID (2016)
	Children (South Africa)	13.8 Kg	
	Infants (South Africa)	7.6 kg	
	Reference	73.7 kg	Ogden et al. (2004)
Inhalation rate	Adults and reference	14.9 m^3/day	US EPA (2011)
	Children	9.0 m^3/day	
	Infants	5.4 m^3/day	

[a] Alfeus et al. (2022).

GmbH, Germany). The Spectro XRF Analyser Pro software was employed to process and quantify the EDXRF spectra from $PM_{2.5}$ filter samples, analyzing them for 2200 s across four analytical ranges to optimize the analysis. Eighteen trace elements were identified: Ag, Ba, Br, Ca, Cl, Cu, Fe, K, Mn, Ni, S, Sb, Si, Sr, Ti, U, V, and Zn (**Exhibit 2**).

2.5 | Health Risk Assessment

The human health risk assessment (HHRA) followed the United States Environmental Protection Agency (US EPA) model (U.S. Environmental Protection Agency 2011), assuming inhalation as the primary exposure route for atmospheric $PM_{2.5}$ and associated trace elements (Alfeus et al. 2022). The concentrations of Ba, Cl, Ni, S, Si, and Ti exceeded reference concentration (RfC) values, which represent safe daily exposure thresholds. These elements were included in hazard quotient (HQ) analyses for infants, children, and adults.

The field average daily dose (FADD) was calculated using Equation (1) (Alfeus et al. 2022):

$$\mathrm{FADD} = (\mathrm{C} \times \mathrm{IR}) / \mathrm{BW} \tag{1}$$

where C is the average $PM_{2.5}$ or elemental concentration (μg/m^3 or ng/m^3), IR is the inhalation rate (m^3/day), and BW is body weight (kg). Age-specific BW values for South African populations were used, while *IR* values were adopted from US EPA guidelines (Exhibit 2).

The safe average daily dose (SADD) was calculated using Equation (2):

$$\mathrm{SADD} = (\mathrm{C} \times \mathrm{IR}) / \mathrm{BW} \tag{2}$$

where *C* represents the WHO (5 μg/m^3) and South African National Ambient Air Quality Standard (SANAAQS) (20 μg/m^3) annual $PM_{2.5}$ limits, or the US EPA RfC values for trace elements (Exhibit 2).

Non-cancer risks were assessed using the HQ (Equation 3):

$$\mathrm{HQ} = \mathrm{FADD}/\mathrm{SADD} \tag{3}$$

$\mathrm{HQ} \leq 1$ indicates negligible to low risk, whereas $\mathrm{HQ} > 1$ suggests potential non-carcinogenic risk (Agency for Toxic Substances and Disease Registry 2025).

Ni was the only carcinogenic element identified, classified by the International Agency for Research on Cancer (IARC), and assigned an inhalation unit risk (IUR) by the US EPA (U.S. Environmental Protection Agency 2011). The cancer risk (CR) was estimated using Equation (4):

$$\mathrm{CR} = \mathrm{C} \times \mathrm{IRU} \tag{4}$$

where *CR* is the estimated excess cancer risk. The *IUR* for Ni refinery dust, 2.4×10^{-4} $(\mu g/m^3)^{-1}$, was used as a proxy for $PM_{2.5}$ bound Ni (Howlett-Downing et al. 2023). *CR* values $\geq 1 \times 10^{-4}$ indicate significant risk, while values $< 1 \times 10^{-6}$ are considered negligible (Agency for Toxic Substances and Disease Registry 2025).

2.6 | Statistical Analyses

> “*Statistical analyses were conducted using STATA Version 18, with HQs calculated in Excel.*”

Statistical analyses were conducted using STATA Version 18, with HQs calculated in Excel. As Shapiro–Wilk tests indicated non-normality in $PM_{2.5}$ and trace elements, non-parametric methods were used. Spearman's correlation assessed relationships between variables. Kruskal–Wallis tested seasonal differences (dry/cold: June–October vs. wet/humid: November–February) (Edlund et al. 2021) and Wilcoxon rank-sum tested differences between weekdays and weekends.

3 | Results and Discussion

3.1 | $PM_{2.5}$ and Meteorological Levels

The mean $PM_{2.5}$ level was 10 $\mu g/m^3$ (range: 1.1–29 $\mu g/m^3$), which was twice the WHO annual limit (5 $\mu g/m^3$) but below the SANAAQS limit (20 $\mu g/m^3$) (**Exhibit 3**) and was comparable to levels reported in Limpopo (11 $\mu g/m^3$) (Novela et al. 2020). Elevated levels were likely due to local sources such as vehicle emissions, mineral dust, and fossil fuel use by nearby food vendors, along with regional transport from coal-fired power plants (Adeyemi et al. 2021; Djolov and Tshehla 2018; Sepadi and Nkosi 2022). Comparable studies reported higher $PM_{2.5}$ levels in South Africa (88 $\mu g/m^3$) (Muyemeki et al. 2021), China (49 $\mu g/m^3$) (Boman et al. 2023), and Botswana (14 $\mu g/m^3$) (Lassman et al. 2020), while lower levels were observed in urban Kimberley (6 $\mu g/m^3$) (Becker et al. 2024). The semi-urban context of Mabopane, characterized by poor infrastructure and solid fuel use, likely contributes to air pollution. A 5 $\mu g/m^3$ increase in $PM_{2.5}$ is associated with a 13% rise in premature mortality (Strak et al. 2021), implying a similar risk in Mabopane. Achieving WHO air quality limits could prevent an estimated 1650 premature deaths in Pretoria (Altieri and Keen 2019). $PM_{2.5}$ level peaked during the dry/cold season (11 $\mu g/m^3$), consistent with increased biomass and coal use, as well as dust resuspension (**Exhibit 4**) (Muyemeki et al. 2021; Onyango et al. 2024). Weekday levels (12 $\mu g/m^3$) were significantly higher than weekend levels (7 $\mu g/m^3$; $p = 0.03$), likely due to increased traffic, a trend also observed in Uganda (Onyango et al. 2024). Meteorological conditions (temperature: 8.4°C–25°C; RH: 31%–94%; wind speed: 0.8–5.5 m/s) influenced $PM_{2.5}$ levels, particularly during the dry/cold season when temperature inversion, dust, and heating-related emissions are more prominent (Chen et al. 2020; Emekwuru and Ejohwomu 2023). These findings underscore the need for seasonally targeted air quality interventions in semi-urban settings.

3.2 | Trace Elements Concentration

Eighteen trace elements were measured, with the highest mean levels observed for Ca (110 ng/m^3), Fe (240 ng/m^3), K (84 ng/m^3), S (160 ng/m^3), and Si (220 ng/m^3) (Exhibit 3). A mean Fe/Ca ratio >1 (2.2) suggests significant dust contributions (Chatoutsidou and Lazaridis 2022; Morantes et al. 2021). Compared to an industrial site in Bloemfontein, Ca (100 ng/m^3) was similar, while Fe (130 ng/m^3), K (160 ng/m^3), S (540 ng/m^3), and Si (440 ng/m^3) were higher, likely due to biomass combustion (49%) and industrial activity (22%) (Van der Westhuizen et al. 2024). Edlund et al. (2021) reported comparable levels in rural Limpopo Ca (65 ng/m^3), Fe (110 ng/m^3), K (100 ng/m^3), S (350 ng/m^3), and Si (160 ng/m^3), largely attributed to crustal material (24%) and industrial activities (21%). These findings suggest that both dust and anthropogenic activities contributed to air pollution in Mabopane. In contrast, extremely high levels of Ca, Fe, and K were reported in coal-reliant villages in China (Wang et al. 2023).

Each of these elements is linked to specific sources: Ca and Si are crustal tracers (Adeyemi et al. 2021); Fe is associated with road dust and vehicular emissions (Jawaa et al. 2024); K is a marker for biomass combustion and brake wear (Alfeus et al. 2024; Jawaa et al. 2024); and S is indicative of coal and oil combustion or secondary aerosol formation (SO_4^{2-}, NO_3^-, and NH_4^+) (Hopke et al. 2020; Muyemeki et al. 2021)

Exposure to Ca, Fe, K, and Si at the observed levels has been associated with increased respiratory hospital admissions (Howlett-Downing et al. 2024). Seasonal analysis showed elevated Ca (130 ng/m^3), Fe (260 ng/m^3), K (110 ng/m^3), and Si (270 ng/m^3) during the dry/cold season (Exhibit 4), likely due to increased combustion for heating and resuspension of crustal dust (Novela et al. 2020; Van der Westhuizen et al. 2024). Similar trends were observed in Limpopo a rural region (Djolov and Tshehla 2018; Edlund et al. 2021). Interestingly, S levels peaked at 260 ng/m^3 during the wet/humid period in late November, probably due to increased fossil fuel use, photochemical SO_4^{2-} formation, and emissions from a diesel generator (diesel contains approximately 500 ppm S) used during power outages at sampling site (Hopke et al. 2020; Jawaa et al. 2024; SA Oil Directing Energy 2019; Sepadi and Nkosi 2022).

A similar pattern was noted in Greece during summer dust episodes (Chatoutsidou and Lazaridis 2022). Weekday S

EXHIBIT 3 | Descriptive statistics of $PM_{2.5}$ (μg/m^3), trace element concentrations (ng/m^3), and meterological conditions at Mabopane, South Africa, from June 15, 2022 to February 28, 2023. *N*: Number of samples with concentration above Limit of Detection (LoD).

Species	*N*	Mean	Median	Range
$PM_{2.5}$	40	10 ± 6.7	8.0	1.1–29
Ag	37	6.3 ± 4.7	5.8	LoD - 15
Ba	40	12 ± 11	8.1	0.7–38
Br	27	4.9 ± 2.7	4.5	LoD - 10
Ca	40	110 ± 86	75	2.4–360
Cl	40	5.6 ± 11	3.2	0.01–65
Cu	21	2.3 ± 1.4	2.3	LoD - 5.2
Fe	40	240 ± 110	200	130–670
K	40	84 ± 98	50	1.8–420
Mn	20	6.4 ± 4.1	5.9	LoD - 17
Ni	40	5.0 ± 3.7	4.4	0.5–18
S	40	160 ± 350	53	9.1–2100
Sb	24	18 ± 11	17	LoD - 55
Si	40	220 ± 320	74	7.8–1400
Sr	40	1.4 ± 1.0	1.1	0.1–3.7
Ti	40	13 ± 15	8.1	0.4–69
U	40	2.7 ± 1.9	2.2	0.1–6.0
V	8	34 ± 24	32	LoD - 77
Zn	30	4.4 ± 3.9	3.1	LoD - 14
Temperature (°C)	37	17 ± 5.1	18	8.4–25
Relative humidity (%)	37	59 ± 16	59	31–94
Windspeed (m/s)	37	3.1 ± 1.2	3.1	0.8–5.5

(190 ng/m^3) and Fe (260 ng/m^3) concentrations were significantly higher than weekend levels ($p < 0.05$), likely reflecting elevated traffic and coal use by food vendors (Sepadi and Nkosi 2022; Van der Westhuizen et al. 2024). These findings underscore the influence of both anthropogenic and natural sources on trace element levels in $PM_{2.5}$ and highlight the need for seasonal air quality interventions.

3.3 | Correlation of $PM_{2.5,}$ Trace Elements, and Meteorological Data

Exhibits 5 and 6 present the correlations between $PM_{2.5}$, trace elements, and meteorological parameters. $PM_{2.5}$ exhibited strong and statistically significant correlations ($p < 0.05$) with Br (0.7), Fe (0.7), K (0.6), Ti (0.5), and Ca (0.5), indicating common sources such as biomass combustion and mineral or road dust(Adeyemi et al. 2021; Muyemeki et al. 2021; Van der Westhuizen et al. 2024). Similar patterns were reported in Limpopo, where Br, Fe, K, and Ti also showed strong correlations with $PM_{2.5}$ (Edlund et al. 2021).

Temperature positively correlated with most pollutants, with a significant correlation observed between temperature and Fe ($r = 0.3$; $p < 0.05$). In contrast, Cu (−0.2) and Sb (−0.1) showed weak negative correlations, consistent with their attribution to non-exhaust vehicular emissions and waste combustion (Mardoñez et al. 2023). A comparable positive correlation between $PM_{2.5}$ and temperature ($r = 0.3$; $p = 0.005$) was reported in Malaysia (Amil et al. 2016)

Relative humidity was significantly and negatively correlated ($p < 0.05$) with $PM_{2.5}$ (−0.4), Ca (−0.6), Fe (−0.6), Si (−0.4), Ti (−0.6), and Zn (−0.6), suggesting enhanced dry deposition of particulates at higher humidity levels (>70%) in Mabopane (Chen et al. 2020; Wang and Ogawa 2015). This may partly explain the lower pollutant concentrations compared to other townships.

Wind speed showed negative correlations with most pollutants, including $PM_{2.5}$ (−0.2). Significant correlations were observed for Ba (−0.4), Br (0.4), Mn (−0.5), and Si (−0.4), indicating that lower wind speeds (2.9 m/s) limited air pollutant dispersion, while higher speeds (3.1 m/s) facilitated air pollutant dilution and resuspension (Wang and Ogawa 2015). These findings underscore the influence of meteorological conditions on ambient air quality in semi-urban settings.

3.4 | Non-Carcinogenic Risk Assessment

Exhibit 7 presents the AQ limits or standards, hazard quotients, and cancer risk for $PM_{2.5}$ and trace elements. Using the SANAAQS as a reference, the HQ for $PM_{2.5}$ was 0.52 for adults, children, and infants, indicating low risk. However, when the WHO guideline

EXHIBIT 4 | Descriptive statistics of $PM_{2.5}$ (μg/m^3), trace elements (ng/m^3), and meteorological levels at Mabopane, South Africa, from June 15, 2022 to February 28, 2023: Dry and cold/wet and humid season and weekdays/weekends. *N*: Number of concentrations above LoD.

Species	Dry and cold Mean (*N*)	Wet and humid Mean (*N*)	Weekdays Mean (*N*)	Weekends Mean (*N*)
$PM_{2.5}$	11 (25)	10 (15)	12 (29)	7 (11)
Ag	7.2 (23)	4.8 (14)	6.6 (27)	5.5 (10)
Ba	14 (25)	11 (15)	13 (29)	10 (11)
Br	4.7 (20)	5.3 (7)	5.8 (20)	2.2 (7)
Ca	130(25)	69 (15)	120 (29)	69 (11)
Cl	7.7 (25)	2.3 (15)	6.9 (29)	2.3 (11)
Cu	2.7 (14)	1.5 (7)	2.5 (18)	0.9 (3)
Fe	260 (25)	220 (15)	260 (29)	190 (11)
K	110 (25)	48 (15)	96 (29)	54 (11)
Mn	5.2 (9)	7.4 (11)	6.8 (13)	5.7 (7)
Ni	4.7 (25)	5.6 (15)	4.6 (29)	6.3 (11)
S	97 (25)	260 (15)	190 (29)	75 (11)
Sb	19 (18)	14 (6)	15 (17)	24 (7)
Si	270(25)	140 (15)	260 (29)	110 (11)
Sr	1.3 (25)	1.6 (15)	1.6 (29)	1.0 (11)
Ti	16(25)	8.1 (15)	16 (29)	7.5 (11)
U	2.6 (25)	2.8 (15)	2.7 (29)	2.6 (11)
V	43 (5)	20 (3)	30 (2)	47 (2)
Zn	4.2 (21)	4.9 (9)	5.3 (10)	2.6 (10)
Temperature (°C)	15 (25)	21 (12)	18 (27)	16 (10)
Relative humidity (%)	54 (25)	71 (12)	59 (27)	62 (10)
Windspeed (m/s)	3.1 (25)	2.9 (12)	1.0 (27)	4.1(10)

limit was applied, HQ values increased to 2.12 (adults), 2.25 (children), and 2.48 (infants), all exceeding the safe threshold of 1. The elevated HQs indicate that $PM_{2.5}$ exposure in Mabopane may pose non-carcinogenic health risks.

This pattern is consistent with findings from other regions in South Africa (Alfeus et al. 2024; Edlund et al. 2021). For example, Edlund et al. (2021) reported HQs of 0.54 (adults), 1.52 (children), and 1.65 (infants) in Limpopo, while Howlett-Downing et al. (2023) found higher values in Pretoria of 1.17, 3.47, and 3.78 for adults, children, and infants, respectively. Similarly, Alfeus et al. (2022) observed HQs of 0.66, 3.47, and 3.78 in Cape Town. These findings underscore that populations across South Africa, whether in rural, urban, or semi-urban settings, may be at risk of health effects due to $PM_{2.5}$ exposure.

Seasonal variation further influenced HQ values. During the dry and cold season, HQs for $PM_{2.5}$ were 2.21 (adults), 2.34 (children), and 2.58 (infants), while slightly lower values were observed in the wet and humid season (1.98, 2.10, and 2.32, respectively). Nonetheless, all values exceeded 1, indicating persistent health risks across seasons. Children and infants are especially vulnerable due to their developing respiratory systems, immature immune responses, and higher inhalation rates (UNICEF 2019).

Among trace elements, Ni posed particular concern due to a HQ exceeding 1 for infants (1.03), except during the wet season (0.48). Ni from oil combustion, primarily in soluble forms (i.e., nickel sulfate), is highly bioavailable and toxic (Agency for Toxic Substances and Disease Registry 2024; Begum et al. 2022), while insoluble forms are less bioavailable and classified as Group 1 and 2B carcinogens (Agency for Toxic Substances and Disease Registry 2024). Mineral-bound Ni in soil dust exhibits low bioavailability and minimal toxicity (Hale et al. 2017). Exposure occurs via inhalation, ingestion, and dermal contact (Agency for Toxic Substances and Disease Registry 2024). The Ni/V ratio of 0.15 suggests oil combustion as a potential source (Amil et al. 2016; Peltier et al. 2009), though further source apportionment is needed. Notably, Ni exposure has been associated with atopic dermatitis in children (Tuchman et al. 2015), potentially relevant to the dermatitis prevalence observed in Mabopane (Bhuda et al. 2024).

3.5 | Carcinogenic Risk Assessment

The excess cancer risk (CR; Equation 4) from Ni over the study period was 1.2×10^{-6} (Exhibit 7). A similar value was reported by Howlett-Downing et al. (2023) for Pretoria during 2018–2019. Given the proximity of Mabopane to Pretoria (approximately

EXHIBIT 5 | Correlation between PM$_{2.5}$ and trace element levels at Mabopane, South Africa from June 15, 2022 to February 28, 2023.

	PM$_{2.5}$	**Ag**	**Ba**	**Br**	**Ca**	**Cl**	**Cu**	**Fe**	**K**	**Mn**	**Ni**	**S**	**Sb**	**Si**	**Sr**	**Ti**	**U**	**V**	**Zn**
Ag	0.2	1.0																	
Ba	0.0	−0.2	1.0																
Br	0.7*	0.2	0.3	1.0															
Ca	0.5*	−0.1	0.1	0.4*	1.0														
Cl	0.3*	0.2	0.3	0.3	0.4*	1.0													
Cu	0.2	−0.1	0.1	0.4	0.4	0.1	1.0												
Fe	0.7*	0.0	−0.1	0.5*	0.7*	0.3	0.1	1.0											
K	0.6*	0.2	−0.4*	0.4	0.6*	0.1	0.2	0.6*	1.0										
Mn	−0.1	−0.2	0.1	−0.1	−0.2	−0.2	0.2	−0.2	0.1	1.0									
Ni	−0.4*	−0.2	−0.0	0.1	−0.1	−0.0	−0.3	−0.2	−0.2	−0.1	1.0								
S	0.4*	0.0	−0.4*	0.4	0.4*	−0.2	0.0	0.4*	0.7*	0.1	−0.0	1.0							
Sb	−0.1	−0.0	−0.0	0.2	−0.1	0.0	0.3	−0.2	−0.1	0.4	0.2	0.6	1.0						
Si	0.4*	0.2	−0.4*	0.2	0.1*	0.2	0.2	0.6*	0.7*	0.3	−0.1	0.4*	−0.0	1.0					
Sr	0.7	−0.2	0.1	0.1	0.1	0.1	−0.1	0.2	0.1	0.1	−0.0	−0.4	−0.1	0.1	1.0				
Ti	0.5*	−0.1	0.0	0.5*	0.6*	0.4*	0.5*	0.7*	0.5*	0.3	−0.2	0.1	0.4	0.6*	−0.3	1.0			
U	0.0	0.2	−0.1	0.0	−0.0	−0.0	−0.2	0.2	0.0	0.1	0.1	0.0	−0.3	0.3	0.2	0.1	1.0		
V	0.1	−0.3	0.2	−0.0	0.6	0.1	−0.2	0.1	0.3	0.1	−0.1	0.3	1.0	−0.2	−0.2	0.1	0.1	1.0	
Zn	0.3	0.2	−0.3	0.2	0.4	0.2	0.0	0.4*	0.5*	−0.0	−0.0	0.2	0.2	0.4*	0.3*	0.4	0.4*	0.2	1.0

Note: Units: PM$_{2.5}$ (μg/m^3) and trace elements (ng/m^3).
*Significant: ($p < 0.05$).

EXHIBIT 6 | Correlation between air pollution and meteorological data at Mabopane, South Africa, from June 15, 2022 to February 28, 2023.

Variable	$PM_{2.5}$	Ag	Ba	Br	Ca	Cl	Cu	Fe	K	Mn	Ni	S	Sb	Si	Sr	Ti	U	V	Zn
Temperature	0.2	0.0	0.0	0.3	0.2	0.1	−0.2	0.3*	0.2	0.3	0.1	0.3	−0.1	0.2	0.1	0.3	0.3	0.1	0.1
Relative humidity	−0.4*	−0.1	0.2	−0.3	−0.6*	−0.2	−0.2	−0.6*	−0.6*	0.4	0.2	−0.2	0.0	−0.4*	−0.1	−0.6*	−0.2	−0.6	−0.6*
Windspeed	−0.2	0.0	−0.4*	−0.4*	−0.1	−0.2	−0.4	−0.1	0.1	−0.5*	0.2	0.0	0.1	−0.4*	0.1	−0.2	0.0	0.1	0.2

Note: Units: $PM_{2.5}$ (μg/m^3), trace elements (ng/m^3), temperature (°C), relative humidity (%), and windspeed (m/s).
*Significant: ($p < 0.05$).

EXHIBIT 7 | AQ limits or standards, hazard quotients (HQ), and cancer risk for $PM_{2.5}$ and trace elements.

		Adult HQ			Children HQ			Infant HQ		
Species	AQ limits or standards (μg/m^3)	Full study	Dry/cold	Wet/humid	Full study	Dry/cold	Wet/humid	Full study	Dry/cold	Wet/humid
$PM_{2.5}$	20*	0.52	0.54	0.48	0.52	0.54	0.48	0.52	0.54	0.48
$PM_{2.5}$	5**	**2.12**	**2.21**	**1.98**	**2.25**	**2.34**	**2.10**	**2.48**	**2.58**	**2.32**
Ba	0.5***	0.02	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03
Cl	0.15***	0.04	0.05	0.02	0.04	0.05	0.02	0.04	0.04	0.02
Ni	0.014***	0.88	0.34	0.41	0.93	0.34	0.40	**1.03**	**1.03**	0.48
S	1.0***	0.16	0.10	0.27	0.17	0.10	0.26	0.19	0.19	0.31
Si	3.0***	0.08	0.09	0.05	0.08	0.09	0.05	0.09	0.09	0.06
Ti	0.10***	0.13	0.16	0.08	0.14	0.16	0.08	0.16	0.16	0.10

Note: HQs ≥ 1, indicated in bold.
*Annual SANAAQS (Department of Environmental Affairs 2012).
**Annual WHO air quality limits (World Health Organization 2021).
***U.S. Environmental Protection Agency (U.S. Environmental Protection Agency: EPA 2011).

40 km), the consistent CR over time indicates a stable, low but measurable cancer risk from Ni exposure in the region. In contrast, Edlund et al. (2021) reported a higher Ni-related CR (3.4 $\times 10^{-6}$) in rural Limpopo, approximately 300 km from Mabopane. Ni exposure has been associated with lung and nasal cancers (Seilkop and Oller 2003); notably, concentrations exceeding 1 $\times 10^{-6}$ ng/m^3 were linked to 74 cancer-related deaths among refinery workers in Wales, underscoring the potential health risks for populations across urban and rural South Africa.

4 | Conclusions

$PM_{2.5}$ levels in Mabopane exceeded annual WHO air quality limits, posing non-carcinogenic health risks, particularly to children and infants, despite being within annual SANAAQS. Trace elements, especially Ni, contributed to elevated health risks, including measurable cancer risk. These findings underscore the need for stronger air quality controls and targeted measures to reduce $PM_{2.5}$ and its trace elements from mineral dust and anthropogenic sources, to protect public health, particularly among vulnerable populations in Mabopane and similar regions. A source apportionment study is recommended to support evidence-based strategies in semi-urban areas like Mabopane.

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Conflicts of Interest

The authors declare no competing interests.

Data Availability Statement

We did not receive ethics approval to share raw field data publicly. The data belongs to the University of Pretoria (UP). The raw data analyzed in the current study are available from UP on reasonable request.

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