Inhalation health risk assessment of ambient $PM_{2.5}$ and associated trace elements in Cape Town, South Africa

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Abstract

Few human health risk assessment studies of air pollution exist in Africa. This study used the US EPA health risk framework to investigate the human health risks due to inhalation exposure to ambient $PM_{2.5}$ and some of its trace element composition (Cl, Si, and Ti) in Cape Town, South Africa, for 12 months (April 2017 to April 2018). The safe average daily dose was determined using the yearly WHO guideline and South African ambient air quality standard for $PM_{2.5}$ and the US EPA regional screening levels for trace elements. The average yearly $PM_{2.5}$ concentration (13 $\mu g/m^3$) was above the yearly WHO guideline (5 $\mu g/m^3$), but below the yearly South African standard (20 $\mu g/m^3$). The average yearly $PM_{2.5}$ concentration posed a low risk to adults (Hazard Quotient = 0.66) compared to infants (HQ = 2.13) and children (HQ =1.96). Cl posed health risks to all age groups (HQ > 1). The study concludes that $PM_{2.5}$ and its trace element components pose adverse health effects to all population age groups. The toxicity of $PM_{2.5}$ depends on its composition; hence this study recommends a source apportionment study to quantify the source contributions and inform the right abatement strategies.

Keywords: Cape Town; human health risk assessment; inhalation exposure; $PM_{2.5}$; trace elements

Introduction

The World Health Organization (WHO) updated the recommended limits for ambient $PM_{2.5}$ in 2021 (WHO 2021). $PM_{2.5}$ refers to airborne particles with an aerodynamic diameter of 2.5 µm or smaller (WHO 2021). This pollutant was the main reason for an estimated 5 million premature deaths and 147 million disability-adjusted life years in 2017 (Cohen et al. 2017; Orellano et al. 2020; Ostro et al. 2018; WHO 2021). Inadequate reporting on $PM_{2.5}$ levels, its composition, or potential health effects exists in Africa (Agbo et al. 2021; Coker and Kizito 2018; deSouza 2020; Fayiga et al. 2018; Gaita et al. 2014; Kalisa et al. 2019; Maenhaut et al. 1996; Ostro et al. 2018; Petkova et al. 2013; Ritchie et al. 2016; Tshehla and Djolov 2018). South Africa lacks epidemiological studies on the effects of ambient air pollution on human health (Katoto et al. 2019; Olutola et al. 2019; Olutola and Wichmann 2021; Thabethe et al. 2021; Wichmann and Voyi 2012).

$PM_{2.5}$ is an indicator of air pollution globally for numerous reasons. $PM_{2.5}$ is hazardous to human health than larger fractions of PM, as its physical size enables it to penetrate and cause harm to the lower respiratory system (Mannucci and Franchini 2017). Their porosity absorbs toxic agents depending on the geographical, meteorological, and source profiles (Mannucci and Franchini 2017). $PM_{2.5}$ may contain volatile organic compounds such as benzene, polyaromatic hydrocarbons (Morakinyo et al. 2017), heavy metals (Morakinyo et al. 2021), and trace elements (Chalvatzaki et al. 2019; Edlund et al. 2021).

$PM_{2.5}$ exposure implicates developing or exacerbating human diseases in various age groups. Diseases reports, including cancers, pregnancy complications, cardiovascular and respiratory diseases, exist in different population age groups (adults, children, and infants) (Cakmak et al. 2016; Lavigne et al. 2016; WHO 2021). Nevertheless, most epidemiological studies came from developed countries (Williams et al. 2021).

Since 2005, South Africa has been enforcing the National Environmental Management: Air Quality Act (NEMAQA) (Act 39 of 2004) and monitoring the criteria air pollutants (Department Of Environmental Affairs 2005). On 29 June 2012, the NEMAQA started enforcing the monitoring of $PM_{2.5}$ (Department Of Environment Affairs 2012). In September 2017, Cape Town began to monitor $PM_{2.5}$; however, the data quality is poor due to missing data (Department of Environmental Affairs and Development Planning 2022). Poor air quality monitoring and lack of air pollution epidemiological studies in the country could lead to the underestimation of the disease burden of air pollution (Cohen et al. 2017; Coker and Kizito 2018; Ostro et al. 2018; WHO 2021). In 2018, the Western Cape Province conducted a health risk assessment that indicated the need to collect detailed and reliable air quality data (Department of Environmental Affairs and Development Planning 2022). Therefore, this paper reports the human health risks of $PM_{2.5}$ and associated trace elements in Cape Town over 12 months.

Materials and methods

Sampling site and procedures

Williams et al. (2021) reported the study location and $PM_{2.5}$ sampling methods in detail. $PM_{2.5}$ sampling was conducted in the Kraaifontein suburb from 18 April 2017 to 16 April 2018.

Weather variables

We obtained hourly data for temperature (°C), relative humidity (%), wind speed (m/s), and precipitation (mm) from the South African Weather Services. Daily averages were calculated for 24 hours from 9 a.m. to 9 a.m.for each sampling day. Daily averages were at least 18 hourly values; otherwise, they were set as missing.

XRF analysis of $PM_{2.5}$ samples

The trace element composition of the $PM_{2.5}$ filter samples was analyzed using a XEPOS 5 energy-dispersive x-ray fluorescence (EDXRF) spectrometer (Spectro analytical instruments GmbH, Germany) at the Atmospheric Science Division, University of Gothenburg, as done in other studies (Adeyemi et al. 2021; Edlund et al. 2021; Howlett-Downing et al. 2022). The Spectro XRF Analyzer Pro software processed and quantified the EDXRF spectra for each filter using a total time of 3000 seconds, automatically divided between four analytical setup conditions. The concentrations of the following 19 elements were analyzed: As, Ba, Br, Ca, Cl, Cu, Fe, K, Ni, Pb, S, Sb, Se, Si, Sr, Ti, U, V, and Zn.

EDXRF detected eight trace elements (Ca, Cl, Fe, K, S, Si, Ti, and Zn) with high signal (i.e., concentration detected) to noise (also known as uncertainty) ratios, namely S/N ratios were larger than one (Table 1S). The other 11 trace elements had many values below the limit of detection and, therefore, low S/N ratios (Table 2S).

The uncertainty is determined if the concentration detected exceeds the limit of detection (LoD). Equation (1) measured the uncertainty of the EDXRF analysis method (Norris et al. 2014; Reff et al. 2007). Other local studies followed the same approach to exclude elements with low S/N ratios (Adeyemi et al. 2022; Howlett-Downing et al. 2022).

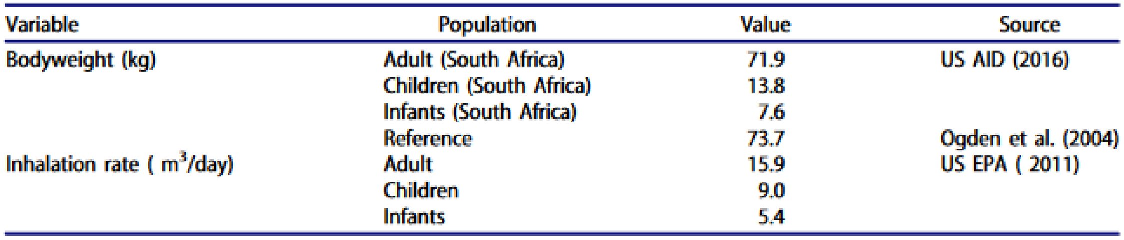
$$\text{Uncertainty} = 5/6 * \text{LoD} \quad (1)$$

If trace elements above the LoD had missing values, then the median concentration substitutes missing values. The uncertainty was calculated as four times the median level (Reff et al. 2007).

Statistical analysis

SAS version 9.3 performed the statistical analyses. According to the Shapiro–Wilk's test, most exposure variables did not have normal Gaussian distributions, and non-parametric tests were applied. This study applied the spearman rank-ordered correlation analysis to investigate the correlation between exposure variables. Kruskal–Wallis tests determined whether the median exposure variables differed significantly between seasons and months. Seasons were: Autumn (March to May), winter (June to August), spring (September to November) and summer (December to February); as done in other local studies (Adeyemi et al. 2022; Howlett-Downing et al. 2022). Wilcoxon's rank-sum tests investigated whether median exposure variables differed significantly between weekdays and weekends.

Table 1. Variables and assumptions used for the health risk assessment*.



Variable	Population	Value	Source
Bodyweight (kg)	Adult (South Africa)	71.9	US AID (2016)
	Children (South Africa)	13.8	
	Infants (South Africa)	7.6	
	Reference	73.7	Ogden et al. (2004)
Inhalation rate (m^3/day)	Adult	15.9	US EPA (2011)
	Children	9.0	
	Infants	5.4	

*Edlund et al. (2021)

Health risk assessment of $PM_{2.5}$ and trace elements

This study applied the same method to a study conducted in Thohoyandou, South Africa. The study followed the standardized US EPA human health risk assessment (HRA) framework (Edlund et al. 2021; USEPA 2018). This study used Equation (2) to calculate field average daily doses (FADD) from ambient air concentrations of $PM_{2.5}$, Cl, Si, and Ti. Inhalation is assumed to be the predominant and continuous route of exposure. The other five trace elements (Ca, Fe, K, S, and Zn) do not have reference concentrations (RfCs) and were not investigated.

$$\text{FADD} = (C * \text{IR})/\text{BW} \tag{2}$$

where C indicates the average concentration over the 121 days during the 1-year sampling period (in $\mu g/m^3$ for $PM_{2.5}$ and ng/m^3 for the trace elements), IR is the inhalation rate (m^3/day), and BW is the body weight (kg). The BW values of the local adult, children, and infant populations were applied. Since no local data were available for inhalation rates, the US EPA recommended values were applied (Table 1).

Equation (3) estimated the safe average daily doses (SADD).

$$\text{SADD} = (C * \text{IR})/\text{BW} \tag{3}$$

where C indicates the yearly $PM_{2.5}$ WHO guideline ($5\ \mu g/m^3$), yearly $PM_{2.5}$ South African national ambient air quality standard (NAAQS) ($20\ \mu g/m^3$), or US EPA non-cancer RfCs of Cl, Si and Ti (Department Of Environment Affairs 2012; USEPA 2019; WHO 2021).

Equation (3) used the adult BW value of the USA when the yearly WHO guideline or the US EPA reference concentrations (RfC) were applied as the safe level, i.e., to be in line with the studies on which these safe levels are based (USEPA. 2011). The adult BW value of the local population was applied when the yearly South African NAAQS were used as the safe level. We then calculated the non-cancer health risks for each exposure variable using Equation (4). Unitless hazard quotients (HQ) expressed the non-cancer health risks:

$$\text{HQ} = \text{FADD}/\text{SADD} \tag{4}$$

where an RfC value is unavailable for Cl, Si, or Ti, it was derived from the RfD as indicated in Equation (5) (Chalvatzaki et al. 2019).

$$\text{RfD} = \text{RfC} \times (\text{IR}/\text{BW}) \tag{5}$$

Equation (5) used the adult BW value of the USA and the adult US EPA recommended value for the inhalation rate. Cl, Si, and Ti are not human carcinogens, and their cancer risks were therefore not estimated.

Ethical approval

The Faculty of Health Science Research Ethics Committee at the University of Pretoria, approved the study (Ethics Reference No: 19/2020 and 104/2020).

Table 2. PM$_{2.5}$ and trace elemental levels (median and range) along with weather conditions from 18 April 2017 to 16 April 2018 in Kraaifontein, Cape Town, South Africa for the entire study period and by seasons and weekends/weekdays (121 sampling days).

Variables	Full study (N = 121)	Autumn (N = 31)	Winter (N = 30)	Spring (N = 30)	Summer (N = 30)	Weekdays (N = 83)	Weekends (N = 38)
PM$_{2.5}$ (μg/m^3)	10.9	9.8	13.2	18.0	8.9	9.9	14.1
	(1.2–39.1)	(1.9–21.7)	(3.2–39.1)	(1.2–32.7)	(2.0–17.3)	(1.2–32.7)	(2.7–39.1)
Cl (ng/m^3)	290	190	190	390	700	210	630
	(2.4–2500)	(2.4–1000)	(2.4–1600)	(2.5–1800)	(6.5–2500)	(2.4–2500)	(17–2100)
Si (ng/m^3)	380	550	330	390	330	340	410
	(20–3000)	(21–2600)	(52–3000)	(20–1300)	(21–910)	(20–2600)	(21–3000)
Ti (ng/m^3)	32	34	31	32	30	33	30
	(4.0–160)	(4.0–110)	(7.4–120)	(7.2–160)	(7.2–54)	(4.0–130)	(7.2–160)
Temperature (°C)	18.0	19.0	13.5	16.7	21.8	18.1	17.8
	(9.2–25.3)	(13.9–22.7)	(9.2–18.0)	(14.2–23.6)	(17.1—25.3)	(9.2–25.3)	(10.7–24.0)
Variables	Full study (N = 121)	Autumn (N = 31)	Winter (N = 30)	Spring (N = 30)	Summer (N = 30)	Weekdays (N = 83)	Weekends (N = 38)
Relative humidity (%)	68.0	68.5	73.0	66.7	62.5	68.0	68.2
	(37.3–90.7)	(37.3–89.3)	(44.2–90.7)	(50.2–81.9)	(53.9–80.9)	(37.3–90.7)	(44.2–83.6)
Wind speed (m/s)	3.4	2.6	2.5	3.9	4.8	3.3	3.6
	(1.0–8.1)	(1.0–6.2)	(1.0–5.8)	(1.2–7.7)	(2.5–8.1)	(1.0–8.1)	(1.3–7.8)
Rainfall (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	(0.0–11.4)	(0.0–1.0)	(0.0–7.8)	(0.0–11.4)	(0.0–3.2)	(0.0–11.4)	(0.0–5.5)

[1] Temperature and relative humidity had missing values for 1 day, and wind speed had missing values for 7 days

Results and discussion

Ambient $PM_{2.5}$ concentration

Williams et al. (2021) reported and discussed in detail the descriptive statistics of $PM_{2.5}$ and the weather variables for the entire 1-year study as well as by seasons, months, and weekends/weekdays. Williams et al. (2021) also compared the $PM_{2.5}$ levels to those of other African and global studies.

Tables 2and 3 recap some of the descriptive statistics (median and range) for $PM_{2.5}$ for the entire 1-year study period as well as by seasons, months, and weekends/weekdays. The yearly ambient $PM_{2.5}$ concentration was 13.4 ± 8.2 µg/m^3, ranging from 1.2 to 39.1 µg/m^3. This average $PM_{2.5}$ concentration is twice as high as the yearly WHO guideline (5 µg/m^3) (WHO 2021) but lower than the yearly South African NAAQS (20 µg/m^3) (Department Of Environment Affairs 2012). Thirty-eight samples exceeded the daily WHO guideline (15 µg/m^3) but not the daily South African NAAQS (40 µg/m^3). As discussed by Williams et al. (2021), the exceedance of the yearly and daily WHO guidelines indicate the severity of $PM_{2.5}$ pollution in Cape Town, which may result in adverse human health effects.

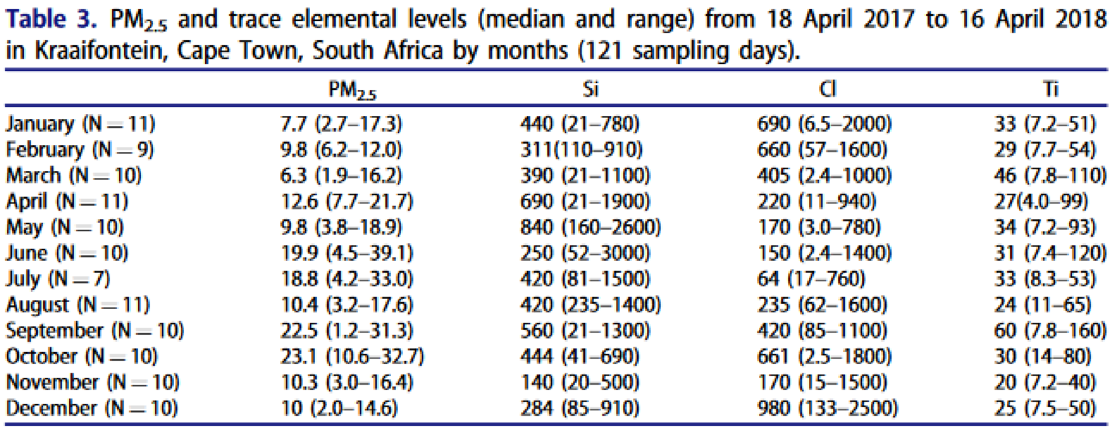


Table 3. $PM_{2.5}$ and trace elemental levels (median and range) from 18 April 2017 to 16 April 2018 in Kraaifontein, Cape Town, South Africa by months (121 sampling days).

	$PM_{2.5}$	Si	Cl	Ti
January (N = 11)	7.7 (2.7–17.3)	440 (21–780)	690 (6.5–2000)	33 (7.2–51)
February (N = 9)	9.8 (6.2–12.0)	311(110–910)	660 (57–1600)	29 (7.7–54)
March (N = 10)	6.3 (1.9–16.2)	390 (21–1100)	405 (2.4–1000)	46 (7.8–110)
April (N = 11)	12.6 (7.7–21.7)	690 (21–1900)	220 (11–940)	27(4.0–99)
May (N = 10)	9.8 (3.8–18.9)	840 (160–2600)	170 (3.0–780)	34 (7.2–93)
June (N = 10)	19.9 (4.5–39.1)	250 (52–3000)	150 (2.4–1400)	31 (7.4–120)
July (N = 7)	18.8 (4.2–33.0)	420 (81–1500)	64 (17–760)	33 (8.3–53)
August (N = 11)	10.4 (3.2–17.6)	420 (235–1400)	235 (62–1600)	24 (11–65)
September (N = 10)	22.5 (1.2–31.3)	560 (21–1300)	420 (85–1100)	60 (7.8–160)
October (N = 10)	23.1 (10.6–32.7)	444 (41–690)	661 (2.5–1800)	30 (14–80)
November (N = 10)	10.3 (3.0–16.4)	140 (20–500)	170 (15–1500)	20 (7.2–40)
December (N = 10)	10 (2.0–14.6)	284 (85–910)	980 (133–2500)	25 (7.5–50)

Trace elemental concentration in ambient $PM_{2.5}$ samples

Williams et al. (2021) did not analyze all 121 $PM_{2.5}$ filter samples for trace elements but collected four composite $PM_{2.5}$ filter samples during 96 hours in September 2017 and January 2018. The analysis of these four 96-hour samples was for Al, Ca, Fe, Mg, Na, and Zn. Williams et al. (2021) discussed the trace element results of the four 96-hour samples.

The detected trace elements contributed 2.6% of the total $PM_{2.5}$ mass. Tables 2 and 3 indicate the descriptive statistics (median and range) of the Cl, Si, and Ti levels during the entire 1-year study, as well as by seasons, months, and weekends/weekdays. Si had the highest median concentration (380 ng/m^3), followed by Cl (290 ng/m^3) and Ti (33 ng/m^3). Similarly, Si levels in other areas in South Africa were higher than those of Cl and Ti, namely the administrative capital Pretoria (Adeyemi et al. 2022; Howlett-Downing et al. 2022), Thohoyandou in a rural area (Edlund et al. 2021), and the heavily industrialized Vaal Triangle area (Muyemeki et al. 2021).

Cl levels in Cape Town were higher than in Pretoria or the Vaal Triangle area (an industrial area located inland about 600 km from the Indian Ocean), or in Thohoyandou (a rural area located inland about 2000 km north from Cape Town) (Adeyemi et al. 2022; Edlund et al. 2021; Howlett-Downing et al. 2022; Muyemeki et al. 2021). The most likely sources of the Cl in the $PM_{2.5}$ filter samples in Cape Town are the Atlantic Ocean (20 km west from the Kraaifontein study site) and the Indian Ocean (25 km south from the study site) (Williams et al. 2021; Alfeus 2021). Cl levels were similar to those observed in Kenya, attributable to the marine influence of air masses from the Indian Ocean (Gaita et al. 2014). Cl levels in this study were lower than concentrations reported in Burkina Faso and Cairo, Egypt (Boman et al. 2009; Shaltout et al. 2020). Cl levels observed in this study were higher than those reported in Venice, Italy, and Gothenburg, Sweden (Boman et al. 2010; Masiol et al. 2014).

Cl levels differed significantly ($p < 0.05$) between the four seasons in this study. The median Cl level was highest in summer (700 ng/m^3), specifically in December (980 ng/m^3), and lowest in winter (190 ng/m^3), specifically in July (64 ng/m^3). The wind speed was also highest in summer and lowest in winter ($p < 0.05$). During summer, the strong southeaster wind carries sea spray to areas of the city that are not directly next to the sea, such as the Kraaifontein study site. Median Cl levels were significantly higher over weekends (630 ng/m^3) than on weekdays (210 ng/m^3) and also varied significantly by day of the week ($p < 0.05$), with the highest median level observed on Saturdays (780 ng/m^3) (Tables 1 and 3S). Biomass burning (combustion processes) is an alternative source of Cl emission, which could explain its variation by days of the weeks, especially over weekends and during summer holidays when many households barbeque outdoors (Boman et al. 2009; Gaita et al. 2014). To support our findings, Mmari et al. (2020) reported an enrichment factor for Cl in the range of 40–100, attributing it to anthropogenic sources. Cl is a secondary sulfate aerosol precursor formed when Cl reacts with sulfuric acid during atmospheric transport (Gaita et al. 2014).

Median Si and Ti levels in Cape Town did not differ across seasons, months, day of the week, or weekends/weekdays ($p > 0.05$), except for Ti by day of the week. The median Ti level was highest on Fridays (38 ng/m^3) and the lowest on Saturdays (18 ng/m^3) ($p < 0.05$) (Tables 4S and 5S). Various studies attributed Si and Ti to either sea sand, soil, or mineral dust due to traffic or wind (Adeyemi et al. 2021; Alfeus 2021; Gaita et al. 2014; Mmari et al. 2020; Muyemeki et al. 2021; Yu et al. 2019). Source apportionment studies indicate that crustal elements contribute 0.91 and 1.4 µg/m^3 toward $PM_{2.5}$ levels in Cape Town and Pretoria, respectively (Adeyemi et al. 2021; Alfeus 2021).

This study's median Ti level was similar to that of Nairobi, Kenya (Gaita et al. 2014), Pretoria, and Thohoyandou (Adeyemi et al. 2022; Edlund et al. 2021; Howlett-Downing et al. 2022). Ti levels were higher in Burkina Faso and Cairo, Egypt (Boman et al. 2009; Shaltout et al. 2020), and much lower in Venice, Nanjing City in China, or Gothenburg compared to this study (Boman et al. 2010; Masiol et al. 2014; Yu et al. 2019). It is necessary to conduct a complete source apportionment study to quantify the various sources' contribution to $PM_{2.5}$ in Cape Town.

Correlations between $PM_{2.5}$ and trace elements

Table 4 shows the correlations between $PM_{2.5}$, Cl, Ti, and Si. William et al. (2021) found a significant correlation between $PM_{2.5}$ with temperature and wind speed, but not relative humidity. Si and Ti were highly correlated (0.61), suggesting common crustal sources of Si and Ti in $PM_{2.5}$ (Zheng et al. 2016). Similarly, Ti and Si exhibited strong correlations in

Pretoria and Thohoyandou (Adeyemi et al. 2022; Edlund et al. 2021; Howlett-Downing et al. 2022). Cl was weaker and not significantly correlated with Si or Ti. Lastly, Cl, Si, and Ti correlated with $PM_{2.5}$, indicating that sea salt and crustal sources contribute to $PM_{2.5}$ mass in Cape Town.

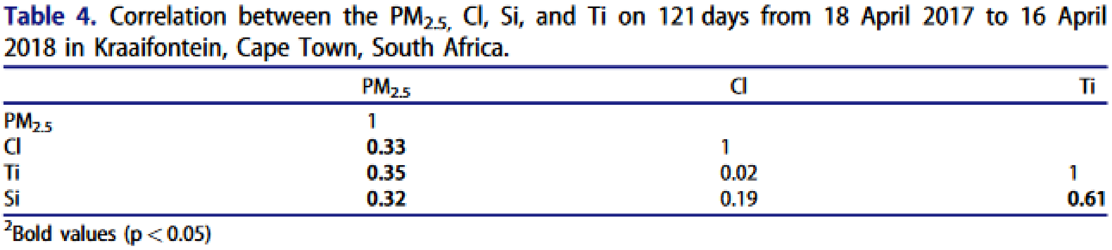


Table 4. Correlation between the $PM_{2.5}$, Cl, Si, and Ti on 121 days from 18 April 2017 to 16 April 2018 in Kraaifontein, Cape Town, South Africa.

	$PM_{2.5}$	Cl	Ti
$PM_{2.5}$	1		
Cl	**0.33**	1	
Ti	**0.35**	0.02	1
Si	**0.32**	0.19	**0.61**

[2] Bold values ($p < 0.05$)

Health risk assessment of $PM_{2.5}$ and associated trace elements

The HQs of $PM_{2.5}$ presented in Table 5 show the probability of health risks in adults, children, and infants. Using the WHO guideline as the safe concentration, the HQ for adults, children, and infants were 2.72, 8.02, and 8.73, respectively. This study shows that children and infants are more vulnerable to $PM_{2.5}$ than adults when exposed to the same concentration. Other local studies confirm this finding (Edlund et al. 2021; Morakinyo et al. 2017; Thabethe et al. 2014). Children and infants have a higher inhalation rate, small body weight, and a larger surface area of the lungs, resulting in a higher internal dose (USEPA. 2011). The higher inhalation rate-to-body weight ratio makes them highly susceptible, especially during barbequing events emitting higher $PM_{2.5}$ concentrations. Moreover, children spend more time in outdoor activities such as playing on the ground, walking to school, or sports activities after school, increasing their exposure to $PM_{2.5}$ (Edlund et al. 2021; Thabethe et al. 2014; USEPA. 2011). A study in Thohoyandou, South Africa, also reported adult health risks (HQ 1.18). However, the outdated annual WHO guideline of 10 $\mu g/m^3$ was still applicable and thus applied (Edlund et al. 2021).

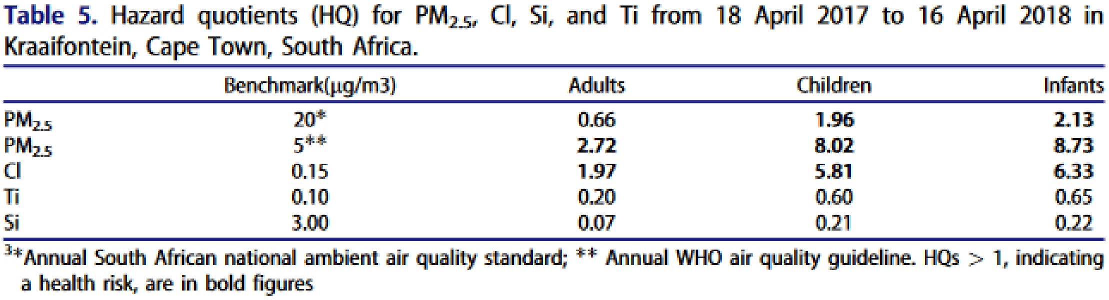


Table 5. Hazard quotients (HQ) for $PM_{2.5}$, Cl, Si, and Ti from 18 April 2017 to 16 April 2018 in Kraaifontein, Cape Town, South Africa.

	Benchmark(µg/m3)	Adults	Children	Infants
$PM_{2.5}$	20*	0.66	**1.96**	**2.13**
$PM_{2.5}$	5**	**2.72**	**8.02**	**8.73**
Cl	0.15	**1.97**	**5.81**	**6.33**
Ti	0.10	0.20	0.60	0.65
Si	3.00	0.07	0.21	0.22

[3] *Annual South African national ambient air quality standard; ** Annual WHO air quality guideline. HQs > 1, indicating a health risk, are in bold figures

Using the SA NAAQS, the probability of health risks for children (HQ 1.96) and infants (HQ 2.13) is higher than for adults (HQ 0.66). Edlund et al. (2021) reported an HQ of 0.54 for adults in Thohoyandou. These low HQs do not imply the absence of adverse health effects, seeing that the SA NAAQS is more lenient than the more protective WHO guideline (Department Of Environment Affairs 2012; WHO 2021). As mentioned earlier, numerous epidemiological studies globally reported on the association between $PM_{2.5}$ and various health outcomes amongst adults.

Our results suggest the revision of the current South African NAAQS (20 $\mu g/m^3$) to an exposure limit of 5 $\mu g/m^3$ to align with the revised WHO guideline sooner than the scheduled revision in 2030 (15 $\mu g/m^3$) (Department Of Environment Affairs 2012). Edlund et al. (2021)

recommended adjusting the current SA standard to 9.2 $\mu g/m^3$; despite employing the outdated WHO guideline. Lowering $PM_{2.5}$ standards would ensure accepted health risks ($HQ < 1$) are no longer exceeded in adults, children, and infants and further contributes to reducing the burden of disease and improving life expectancy (Edlund et al. 2021; WHO 2013).

Cl posed a significant health risk as the HQs were above 1 for adults (1.97), children (5.81), and infants (6.33). Similarly, Edlund et al. (2021) reported a higher HQ in children (1.23) and infants (1.33) as a result of exposure to Cl than in adults (0.44). As mentioned, probably sources of Cl in Cape Town are sea spray or combustion. Sea salt was an air pollution source discussed in a WHO report, which summarized epidemiological evidence of long-term and short-term PM exposure since 2005 (WHO 2013). However, the report concluded that the current evidence indicates no harmful health effects from exposure to sea salt (WHO 2013).

This study reported no significant health risks ($HQ < 1$) in adults, children, and infants due to exposure to Ti and Si. The 2013 WHO report concluded that there was little epidemiological evidence available on the risk of Sahara Desert dust on hospital admissions from studies published until June 2012 (WHO 2013). A study from Hong Kong reported that episodic dust storm events were associated with an increase (RR:1.04) in hospital admission for ischemic heart disease in all age groups (Tam et al. 2012). A cohort study conducted at the Barcelona university hospital observed a statistically significant association between gestational age at delivery and the number of episodic days during the third trimester and whole pregnancy ($p < 0.01$) in Barcelona, Spain (Dadvand et al. 2011). However, the HRA method is limited in estimating health risks for pregnant mothers, although they are most susceptible to $PM_{2.5}$ impact.

The findings of an epidemiological study conducted in the Free State province in South Africa reported elevated hospital admissions for respiratory and cardiovascular diseases, eye irritation, and motor vehicle accidents in the range of 3–40 days after dust storms with no statistical significance ($p > 0.05$) (Nkosi et al. 2022). The lack of substantial evidence on human health effects associated with dust storms warrants additional research. No dust storm has been reported in Cape Town yet; however, climate change's effect is likely to lead to an increase in extreme events such as dust storms.

Conclusion

This paper is the first to conduct a human health risk assessment on $PM_{2.5}$, Cl, Si, and Ti in Cape Town, South Africa. The results indicate that $PM_{2.5}$ and trace elements pose significant risks across all age groups. This study recommends a source apportionment study to determine the toxic elements of $PM_{2.5}$ and inform its management.

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Disclosure statement

The authors declare no conflict of interest.

Authors' contribution

This manuscript was part of the Ph.D. project of Anna Alfeus. Prof Janine Wichmann and Dr. Joyce Shirinde supervised the Ph.D. thesis. Anna Alfeus (AA*), Joyce Shirinde (JS), Peter Molnar (PM), Johan Boman (JB), and Janine Wichmann (JW) are the authors of this manuscript. AA* wrote the draft manuscript. PM and JB did data curation. The current version of the manuscript was approved by all authors.

Data availability

The authors are working on other manuscripts with the data, hence the data is not available to the public.

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