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Indoor/Outdoor particulate matter (respirable dust) and respirable crystalline silica source tracking in households located proximal to gold mine tailings in Johannesburg, South Africa

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ABSTRACT

Introduction: This study aimed to investigate the concentration of Respirable Crystalline Silica (RCS) and respirable dust, Particulate matters (PM_4) concentration in samples measured indoors and outdoors of the nine (9) selected households located proximal to gold mine tailings in Riverlea, Johannesburg.

Materials and methods: Sampling locations were separated according to grids, based on distance from the tailings; A (<500 m from the dump), B (>500m<1 km) and C (1 km-3 km). Three households were selected from each grid zone to measure indoor and outdoor PM_4 samples continuously over 24 h using GilAir constant sampling pumps. Samples were collected during dry and wet seasons, and respirable crystalline silica in PM_4 samples were analysed by an X-ray diffraction method.

Results: The mean indoor and outdoor PM_4 mass concentrations ranged from 2.02±0.02 $\mu g/m^3$ to 2.26±0.02 $\mu g/m^3$, respectively. The dry season mean for PM_4 mass concentrations were higher than the wet season PM_4 mass concentrations in all zones. The pairwise comparison of PM_4 mass concentration for dry and wet seasons revealed no statistically significant difference ($p<0.05$). The dry season means the indoor/outdoor ratio was greater than one across all zones, suggesting indoor activities as the primary source of PM. In both seasons, the mean indoor and outdoor RCS ranged from 0.02±0.01% to 0.06±0.03%. The mean indoor and outdoor 24 h RCS concentrations in both seasons were below the California Office of Environmental Health Hazard Assessment (OEHHA) defined 24 h ambient exposure threshold of 3 $\mu g/m^3$.

Conclusion: The study found that PM_4 concentration was directly proportional to distance from the gold mine tailings. Using RCS as a signature chemical, we found a similar chemical composition in all samples collected in winter and dry season at varied distances. It is concluded that the gold mine tailings are the significant source of PM_4 emissions. Therefore, further dust control measures needs to be implemented at the gold mine tailings.

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Introduction

Air pollution is one of the greatest threats to public health. The impact of air pollution places a great burden on the healthcare system due to increased rates of mortality and morbidity. Many families in South Africa are located closer to PM emitters such as industrial areas and major roads. Most low-income households in South Africa make use of biomass fuels for cooking and heating [1]. Air pollution is associated with increased risk of lung cancer, ischemic heart disease and respirable heath problem especially amongst the vulnerable groups (pre-existing diseases and children, elderly) [2]. Air pollution is the second leading cause of death in Africa and has contributed to approximately 1.1 million deaths in 2019. Air pollution in South Africa was reported to be among the top 10 leading causes of death and outdoor air pollution was linked to 100 000 deaths [2].

Globally, air pollution is a major environmental health problem affecting everyone. Industrial activities, such as mining, food manufacturing, transportation, as well as domestic solid fuel burning, are the most common sources of air pollution [3]. Studies have shown that inhalation of PM_4 and RCS can lead to irreversible chronic health conditions such as asthma, lung cancer, cardiovascular and cognitive disorders [3, 4]. In the current decade, air pollution has contributed to about seven million premature deaths among children [3, 5].

Gold mining in South Africa has made a significant contribution to the development and sustainability of the country's Gross Domestic Product (GDP) [6]. Over the past two decades, most of the gold mines in South Africa have been closed. However, the risk of exposure to dust hasn't ceased, and in some cases might have increased, due to the reclamation process of mine tailing dumps, where the material is milled to a much finer grade, leading to the release of fine mine dust, and causing air pollution in the surrounding neighbouring communities [7].

Residents living in close proximity to gold mine tailing dumps in Johannesburg often complain of onset related to respiratory illness from the ambient dust [8]. Several community unrests have been experienced by residents in close proximity to gold mine tailings dumps over the years, triggered by concern about fine dust from gold mine tailings dumps, especially about strong wind conditions during dry seasons. Gold mine tailing dust is known to contain high concentrations of respirable crystalline silica [9]. Dust depositions vary across the seasons, with the highest levels and frequency reported in spring, and the lowest reported in autumn [10]. Approximately 40% of dust from mine dumps consists of coarse particulate matter, with the remaining proportion consisting of finer particulates [10]. Studies have reported unhealthy levels of Particulate Matter (PM_{10}) and quartz dust at distances of up to 2km downwind from mine dumps. It is estimated that over 500 000 people currently reside within this radius of three large mine tailings dumps in Gauteng [11]. Those communities have repeatedly reported exposure to dust and possible health effects as their greatest concern [7].

To apportion the source of PM_4 to which residents living in close proximity to gold mine tailing dumps may be exposed, the focus should start on source identification and tracking of PM to determine the contribution at a specific location over time. PM source tracking can be influenced by several factors, including the location of the source, the receptor's location, and meteorological conditions which sometimes vary depending on the season of the year.

Considering the limited literature on exposure to PM_4 from mine tailings in South Africa, this study aims to determine the outdoor and indoor airborne concentration levels of PM_4 and RCS of 9 selected households located closer to a gold mine tailing dumps in Johannesburg.

Materials and methods

Study design and sample size

This was a cross-sectional study aimed at evaluating the concentrations of PM_4 and RCS in PM_4 mass samples, taken outdoors and indoors of the 9 selected households located in close proximity to Johannesburg gold mine tailing dumps. A total of 36 samples were obtained in both seasons (wet and dry), excluding control bank samples. On each resident, two samples (indoor and outdoor) were taken for 24 h.

Description of the study area

The study was carried out in a community living near a gold mine tailing dumps during the dry and wet seasons in Johannesburg. In South Africa, the dry season is considered a season having strong wind conditions and high dust levels, whereas the wet season is considered a season having substantial rainfalls. The data collection for the dry season was collected in July while for the wet season, it was in November. The target area includes households within the Riverlea community, located near gold mine tailings dumps.

The Riverlea community is in the southern portion of Johannesburg, between two gold mine tailings dumps that resemble yellow mountains, Mooifontein and 2L3 (Fig. 1: Geographical map of the research region). The gold mine tailings were created in the early 90’s in Johannesburg. Riverlea is predominantly a coloured community of 3.40 km² area in size. According to the 2011 census [12], the Riverlea community had an estimated population of 16,226 (4,771.91/km²) and 4208 households (1,237.53/km²). The housing structure types include formal and informal houses as well as apartheid-era low-cost houses made of bricks with asbestos roofs.

Fig. 1. Geographical map of the study area: imagery ©2022 CNES/ Aorbus, Landsat/Copernicus, Maxar Technologies, map data © 2022 AfriGis (Pty) Ltd

Description of the sampling locations

The households were randomly selected by drawing a grid zone based on the distance between the household's location and the gold mine tailings dumps. The grid zones were classified as zones A, B and C (see Fig. 1). A total of nine households were selected in consultation with the Riverlea committee mine forum. Three households were selected from each grid zone. Zone A of the grid included households located 500 m away from the gold mine tailing's boundary and they were considered as a near-field resolution. Zone B included households located between 500 m – 1 km away from the mine tailings and was considered an intermediate field zone, and zone C included houses located between 1 km - 1.5 km away from the gold mine tailings and was considered as the far field- zone in relation to the gold mine tailings dumps. The highest concentrations of PM_4 mass were expected in Zone A households. Households in Zone A were near the Mooifontein gold mine tailings dump.

Indoor and outdoor sampling

For both seasons, sampling was carried out in July and November 2022. Both outdoor and indoor sampling pumps were placed inside the house for security purposes and to protect them from harsh climatic conditions such as rainfall, which can cause the pump to malfunction. In some households where access for placing the outdoor sample train was not easy, the sample train was placed in an outdoor safe location with a roof structure.

Indoor PM_4 samples were collected at a height between 1.2 and 1.5 m above the ground. In addition, indoor samples were placed in either the sitting room or kitchen area. There were no limits on the activities carried out during the sample in either environmental space. As a result, individuals from the selected households went about their typical daily household routines.

Indoor and outdoor samples were collected in the nine selected households during the dry and wet seasons for the period of ±24 h. Approximately, 36 samples were collected in both seasons, excluding blank sample filters. Indoor samples were placed on a stable platform such as a fridge, TV stand or table at a height between 1.2 and 1.5 m above the ground. Outdoor sampling pumps were placed on a table or window panel with the sampling media and extended outside through a window or broken portion of the window at the height between 1.2-1.5 m above the ground for a period of ±24 h, taking the necessary precautions to ensure equipment security. Samples were labelled as per the selected households within their grid zones. Sample records were noted on the National Institute of Occupational Health (NIOH) Occupational Hygiene environmental sampling sheet.

Meteorological conditions in the study

Meteoblue weather provided historical meteorological weather conditions data, indicating that strong wind speeds, which may lead to spreading dust particles from mine tailings dumps, are generally northerly, with dominant maximum wind speeds of 28 km/h during dry times. Southerly winds, on the other hand, were a stronger indicator of worst-case conditions in Riverlea, as they increased the probability of mining tailings dust reaching people. The dry season, which occurs between July and August, is expected to be associated with high dust levels, while the wet season is expected to be associated with low dust levels. Riverlea's historical meteorological data showed that November had the most precipitation. This was considered to represent the wet season in this study [13].

Sample duration

Air sampling pumps were positioned inside and outside the selected households based on the sample grid zones. PM_4 mass concentrations were sampled over 24 h. The 24-h airborne mass concentrations of PM_4 were analysed gravimetrically while the RCS concentrations were determined through an X-Ray Diffraction (XRD) technique. The derived 24-h RCS concentrations were compared to the ambient limit of 3 µg/m^3 as determined by OEHHA, California EPA.

Sampling train description

Indoor and outdoor PM$_4$ were sampled using GilAir sampling pumps that were set at the flow rate of 2.2 L/min. The PM$_4$ dust fraction were collected on 25 mm diameter PVC filters, assembled in Higgins-Dewell (HD) cyclones with filter pads. The HD cyclone sampler is an air sampling equipment that is designed with a 50% cut point sampling efficiency for a particle of 4-µm. The rapid air circulation of the HD cyclone allows larger particles to fall into a grit pot while respirable-size particles remain captured on the filter cassette. The sampling media were attached to sampling tubes and the standard sampling pumps were calibrated at a flow rate of 2.2 L/min. The sampling information was recorded on NIOH standard Occupational Hygiene sampling sheet.

Gravimetric analysis

The PM$_4$ mass concentration was determined by a gravimetric method following the UK MDHS 14/4 [14]. The filters were weighed before and after sampling to determine the PM$_4$ gravimetric mass.

Preparation of filters

All sampling filters, including laboratory blank reference filters, were placed in a petri dish for a minimum of 12 h overnight to stabilize, and each filter was assigned a unique identification number. The relative humidity (RH%) was controlled within ±5% of the recorded pre-weight and the temperature was between 18ºC and 30ºC during weighing.

Pre weighing

After filters were pre-weighed, they were inserted into a three-piece sampling cassette, closed with a blue and red cap ready to be used for sampling of PM$_4$ mass. The PM$_4$ mass fraction on the filter was determined by a gravimetric method using a microbalance. The range of the balance was set between 0.001 to 2000 g. An antistatic eliminator was used to remove static charge before each filter was weighed. The analysis was carried out by a SANAS 17025 accredited laboratory of the NIOH, using the UK Method for the Determination of Hazardous Substances MDHS 14/4 [14].

Post weighing

Post-weighing was performed after sampling to determine the PM$_4$ mass. The filters were removed from the sampling cassette after sampling placed in a petri-dish, and thereafter reconditioned for 12 h overnight before reweighing. All sampled filters were weighed to derive the post-sampling mass. The analysis was carried out by the NIOH Occupational Hygiene section's SANAS 17025-approved laboratory, using an in-house procedure based on the MDHS 14/4 [14].

The corrected final mass was determined using Eq. 1.

$$\text{Corrected Final mass} = M1\ (PM-PrM) - M2\ (PM-PrM) \tag{1}$$

Where M1 is the mass of the field filter, PM is the post mass, PrM is the pre mass and M2 is the mass of the control filter.

The airborne dust concentration was determined using Eq. 2.

$$C=M/V \tag{2}$$

Where: C is the measured concentration in μg/m^3, M is the Corrected Final mass (μg), and V is the volume of air sampled (m3).

Respirable crystalline silica (quartz) determination

The samples were analyzed using X-Ray Diffraction (XRD) which is a versatile, non-destructive direct-on filter technique. The analysis was performed by a SANAS 17025 accredited laboratory of the NIOH Occupational Hygiene section, using the UK Method for the Determination of Hazardous Substances MDHS 101/2 [15].

Data analysis

This section gives an overview of data analysis and how PM_4 mass, crystalline silica, indoor/outdoor ratio as well as the RCS 24-h time-weighted average concentration were determined using equations.

Objective 1: Determination of PM_4 mass

The PM_4 mass was determined using Eq. 3

$$PM_4 \text{ mass} = (M2 - M1 - B) \tag{3}$$

Where: M1 = mass of filter before sampling (μg), M2 = mass of filter after sampling (μg), B = average mass change of blanks (μg

Objective 2: Determination of the free crystalline silica percentage

This was done to determine the percentage of free crystalline silica content in the PM_4 gravimetric mass weight using the fraction mass of the silica weight detected on each sample. The percentage of crystalline silica was determined by the following:

$$(PM_4)) \text{ x } 100\% \tag{4}$$

The XRD mass of the free crystalline silica refers to the content of crystalline silica detected by the XRD analytical technique in each PM_4 gravimetric sample weight. The gravimetric mass of the respirable dust refers to the PM_4 gravimetric weight or respirable dust mass weight. The percentage of the crystalline silica was derived from the Below Detection Limit (BDL) mass and the PM_4 mass concentration.

Objective 3: Determination of the indoor and outdoor PM_4 ratio

Indoor-outdoor ratios (I/O) were determined to check whether there is a contribution of outdoor PM_4 to the indoor environment. An I/O ratio of one indicates unity between indoor and outdoor PM concentration. An I/O ratio of less than one implies that the source of PM_4 is from an outdoor environmental activity or source. A ratio greater than one indicates a significant indoor source contributing to the indoor air quality.

The I/O ratio was obtained using Eq. 5.

$$Ci = C \text{ in}/C \text{ out} \tag{5}$$

Where Ci is the indoor/outdoor concentration ratio, C in is the indoor PM_4 concentration, and C out is the outdoor PM_4 concentration [16].

Determination of the RCS 24 h time-weighted average concentration (TWA)

The 24-h TWA for RCS was determined and compared to the 24-h ambient exposure level of the OEHHA, California EPA ambient environment limit of 3 μg/m^3. The following equation was used to determine the 24-h TWA for RCS:

The RCS 24 h TWA air concentration (C) was calculated following Eq. 6:

$$TWA = (C \text{ X } T)/(1440), \ \mu g/m^3 \tag{6}$$

Where:

C - Air concentration of RCS

T – Sample duration

1440 - Reference 24-h (in min)

Data management

Data processing

Collected data that includes sample field sheets, laboratory results, pre-post calibration results, pre-post mass weight of PM_4, RCS results, and the controlled calculation concentration spreadsheets were recorded on the controlled share driver. Additionally, the raw data was first entered into a Microsoft Excel spreadsheet for cleaning and processing. The data was also exported onto statistical software for analysis.

Statistical analysis

Microsoft Excel 2016 version was used for descriptive data analysis such as minimum, mean, median, maximum, standard deviation and comparison of the outdoor and indoor PM_4 mass concentrations. An F-test was used to determine the normality of the data and the type of t-test to employ. Based on the outcome of the F-test, Student's t-test was used to test for a statistically significant difference between the means of outdoor/indoor PM_4 mass concentrations, RCS percentage, I/O ratio and 24-h RCS concentration. The student's t-test was performed at a 95% confidence level and a p-value greater than 0.05 indicated a weak statistically significant/ weak association and the p-value of less than 0.05 indicated a strong association. A pairwise comparison was used to assess the relationship between the mean outdoor and indoor PM_4 concentration, I/O ratio, 24-h RCS and RCS percentage.

Quality assurance

Calibration of sampling pumps

The GilAir air sampling pumps were pre- and post-calibrated at a flow rate of 2.2 l/min using a primary flow-bubble generator standard flow calibrator traceable to the National Institute for Standards and Technology (NIST), serial number 0609056. The post-calibration checks were considered acceptable when the averaged pre- and post-calibration flow rates were within ±5% of the pre-sampling targeted flow rate. All calibration checks were within the allowable limit of ±5%. Pumps were collected after 24 h of sampling and taken to the NIOH Occupational Hygiene section for post-calibration airflow verification using a calibrated primary bubble flow generator.

The analysis of PM_4 and crystalline silica was performed by a SANAS 17025 accredited laboratory of the NIOH Occupational Hygiene section, using the UK Method for the Determination of Hazardous Substances MDHS14/4 and 101/2, respectively (See appendix 3 for the laboratory test report) [14-15].

Gravimetric analysis

Gravimetric weighing of filters was done prior to sampling using a calibrated microbalance. All filters were prepared in a dust-free environment. The 25 mm filters were placed pre-sampling in a petri dish for a minimum of 12 h overnight to stabilize in the laboratory within the controlled indoor temperature of between 18ºC and 30ºC and relative humidity controlled within ±5% of the RH% recorded pre-weight. After sample collection, the filters were removed from the sampling cassettes and placed in petri dishes to stabilize and re-weighed to obtain the PM_4 post-mass weight gain. A blank filter was prepared for each sampling batch and transported to the laboratory with the field filters. The analysis was performed by a SANAS 17025 accredited laboratory of the NIOH Occupational Hygiene section, following an in-house method using the United Kingdom Health and Safety Executive (HSE) Method for the Determination of Hazardous Substance (MDHS) 14/4 [14].

Results and discussion

Indoor and outdoor PM_4 mass concentration

Results presented in Table 1 show the mean indoor and outdoor PM_4 mass concentration for both dry and wet season. The dry season mean indoor PM_4 concentration ranged from 2.23±0.03 $\mu g/m^3$ to 2.26±0.02 $\mu g/m^3$, whereas the outdoor PM_4 mass concentration ranged from 2.22±0.02 $\mu g/m^3$ to 2.24±0.02 $\mu g/m^3$. The mean dry season indoor PM_4 mass concentrations were higher than the mean outdoor PM_4 mass concentration. The wet season mean indoor and outdoor PM_4 mass concentrations ranged from 0.02±0.00 $\mu g/m^3$ to 0.05±0.02 $\mu g/m^3$.

The dry season mean PM_4 mass concentrations across all zones were higher than the wet season PM_4 mass concentrations. The higher indoor mean PM_4 mass concentration might have been due to activities such as cleaning, cooking, and the infiltration of outdoor PM. This finding was expected due to poorly maintained dust source from gold mine tailings and dust storms experienced during dry seasons. The finding is similar to a study where surface moisture was found to reduce dust emissions by almost 80% in communities proximate to gold mine tailings [16, 17].

Results presented in Fig. 2 depict the mean outdoor PM_4 mass concentration distribution for dry season. Zone A had the highest mean outdoor PM_4 mass concentration followed by zone B, this suggests that the primary source of PM is from the mine tailings dump, as the mean outdoor PM_4 concentration in zone C was the lowest. In a separate study focusing on environmental exposure to uranium in a population living in close proximity to gold mine tailings in South Africa, exposure dosage to PM bound Uranium was found to decline with a decrease with distance from the gold mine tailings [18].

Table 1. The dry and wet season mean indoor and outdoor PM_4 concentrations

	Zone	Indoor N=9 ***($\mu g/m^3$)***	Outdoor N=9 ***($\mu g/m^3$)***
Dry season	A	2.26±0.02	2.24±0.02
	B	2.25±0.02	2.23±0.03
	C	2.23±0.01	2.22±0.02

	Zone	Indoor N=19	Outdoor N=9
Wet season	A	0.05±0.02	0.03±0.01
	B	0.03±0.01	0.03±0.01
	C	0.03±0.02	0.02±0.01

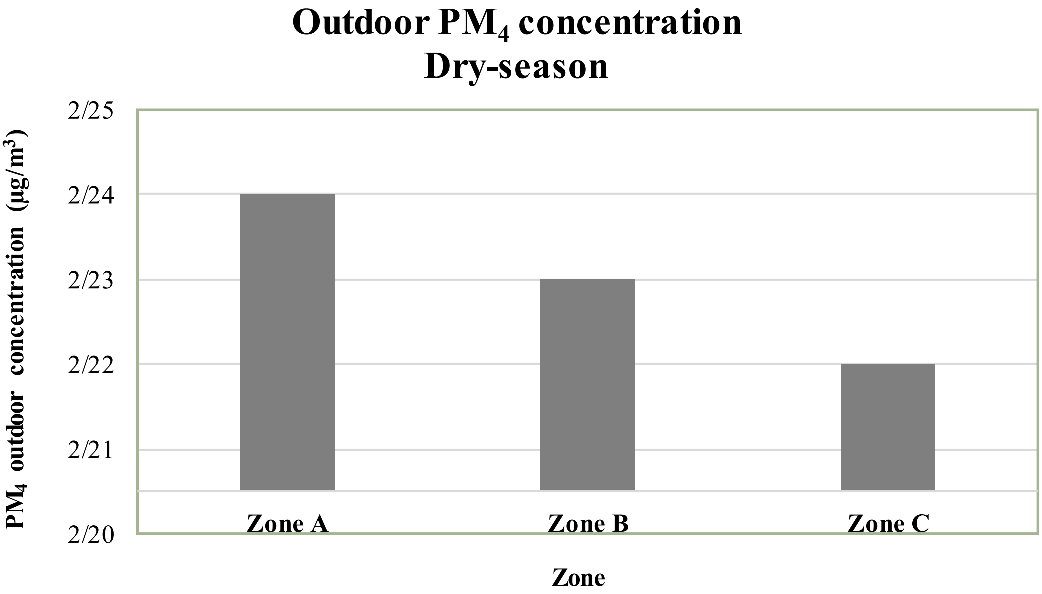

Fig. 2. The dry season mean outdoor PM_4 concentration distribution

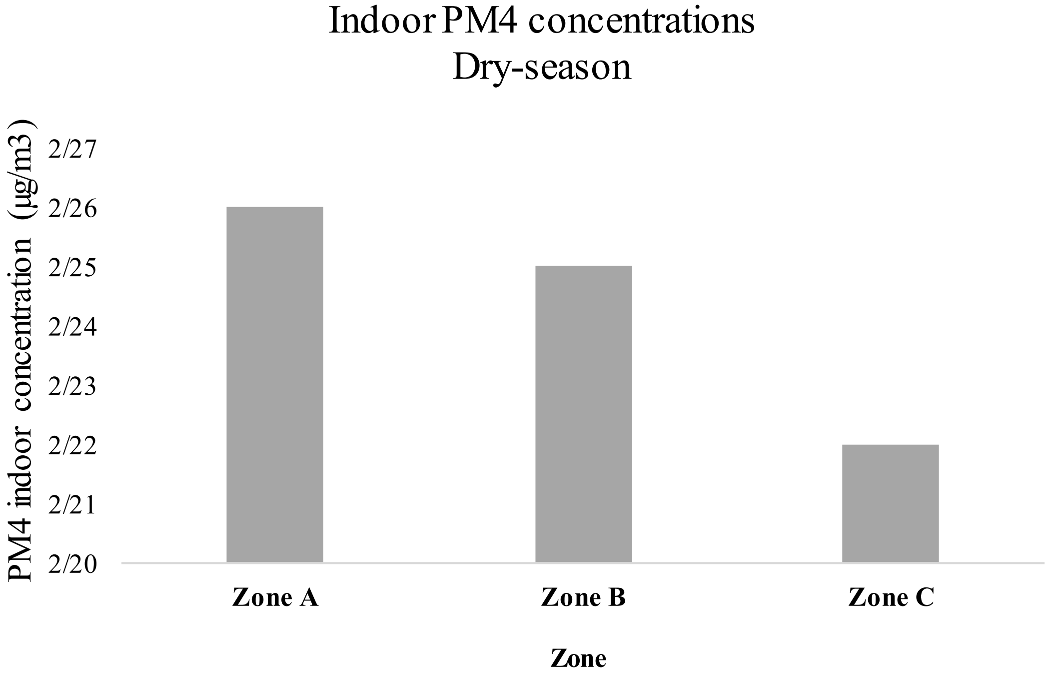

Fig. 3. The dry season mean indoor PM_4 concentration distribution

Results presented in Fig. 3 depict the mean indoor PM_4 mass concentration distribution for the dry season. Zone A had the highest mean indoor PM_4 mass concentration was zone A, followed by zone B. Since the mean outdoor PM_4 concentration in zone C was the lowest, this suggests that the mine tailings dumps were the primary source of PM.

Results presented in Fig. 4 depict the mean outdoor PM_4 mass concentration distribution for the wet season. Zone A & B had the highest mean outdoor PM_4 mass concentration; this also suggests that the mine tailings dumps were the primary source of PM.

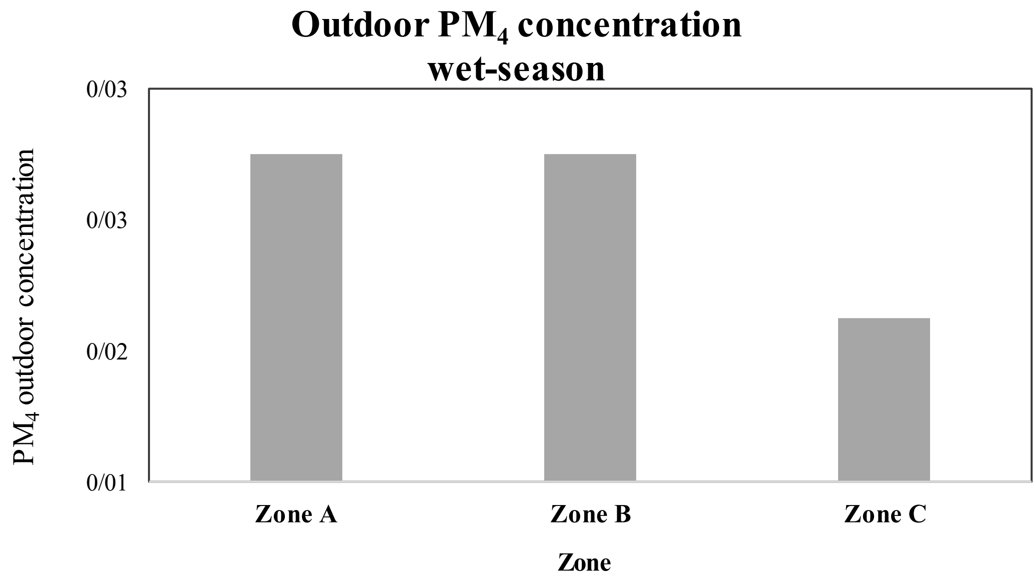

Fig.4. The wet season means outdoor PM_4 concentration distribution

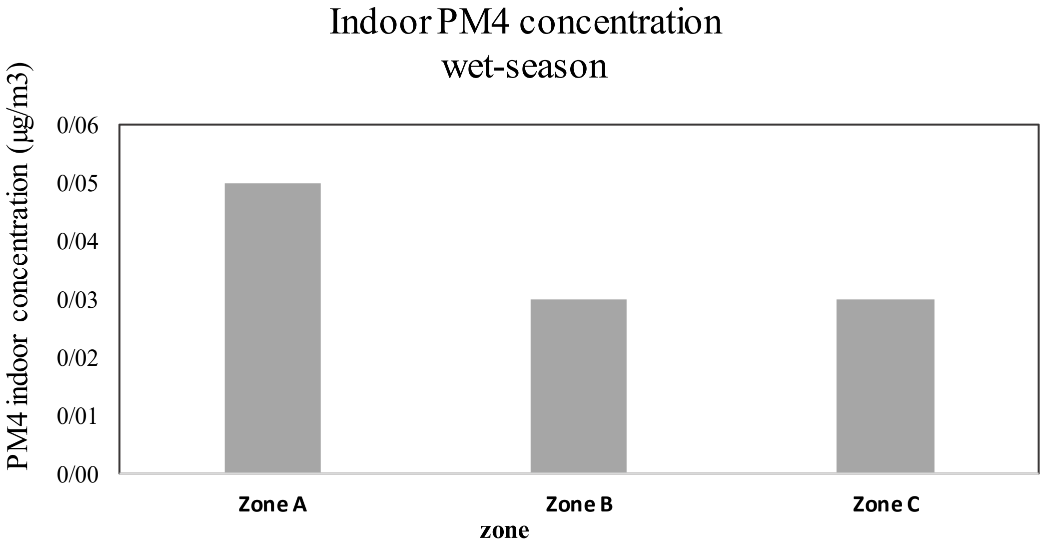

Fig. 5. Indoor PM_4 concentration for wet-season distribution

Results presented in Fig. 5 depict the mean indoor PM_4 mass concentration distribution for wet season. Zone A had the highest mean indoor PM_4 mass concentration. Zone B and C had the same levels of PM_4 concentration.

Indoor and outdoor RCS percentage

Results presented in Table 2 show the descriptive statistics for the indoor and outdoor percentage of free crystalline silica in respirable (PM_4) samples for both dry and wet season. The mean indoor and outdoor percentage of crystalline silica in both seasons ranged from 0.02±0.01% to 0.08±0.01%.

Similar study by researchers measured the mean 24-h average ambient crystalline silica concentrations in 22 urban areas, the study found has found the mean percentage of RCS that ranged from 0% up to 2.6% [16]. Another study by researchers that has focused on a residential PM exposure outside 17 households within 800 m of sand mining activities, has found the percentage of crystalline silica in the PM$_4$ mass concentration that ranged from 2% to 4% [19].

Indoor/outdoor PM$_4$ (I/O) ratio

Results presented in Table 3 show the descriptive statistics for the mean I/O ratio for both dry and wet season. Studies that focus on investigation of PM$_4$ I/O ratio in residents located near PM emitters are limited. However, the dry season I/O ratios across all zones were ≥1. A similar study that focused on PM$_{2.5}$ indoor/outdoor ratio by many researchers [22] has also found no statistically significant difference at 95% confidence interval. The dry season higher PM$_4$ levels are associated with strong wind conditions. Studies by other researchers [23], Martins et al [24] found that structures with building openings such as windows and doors tend to have a higher penetration of outdoor PM [22]. Another study by researchers [25] has shown that the I/O ratios for particulate matters were higher in warmer and mild seasons due to penetration of outdoor particles by means of natural ventilation [23].

Table 2. The dry and wet season mean indoor and outdoor RCS percentage in PM$_4$ samples

	Dry season		Wet season	
Zone	Indoor N=9 (%)	Outdoor N=9 (%)	Indoor N=9 %	Outdoor N=9 %
A	0.04±0.01	0.05±0.02	0.06±0.01	0.05±0.03
B	0.05±0.01	0.06±0.03	0.06±0.01	0.05±0.01
C	0.02±0.01	0.05±0.02	0.08±0.01	0.04±0.01

Table 3. The dry season means I/O ratio

	Zone	I/O Ratio **Unitless**		Zone	I/O Ratio **Unitless**
Dry season	A	1.01 ± 0.02	Wet season	A	1.00 ± 0.01
	B	1.01 ± 0.01		B	1.00 ± 0.01
	C	1.00 ± 0.01		C	1.00 ± 0.01

Table 4. The dry season means indoor and outdoor 24-h RCS concentration

	Zone	Indoor N=9 *(µg/m^3)*	Outdoor N=9 *(µg/m^3)*		Zone	Indoor N=9 *(µg/m^3)*	Outdoor N=9 (µg/m^3)
Dry season	A	2.23±0.02	2.22±0.02	Wet season	A	2.10±0.10	2.14±0.11
	B	2.26±0.02	2.24±0.02		B	2.14±0.11	2.13±0.10
	C	2.25±0.03	2.23±0.03		C	2.57±0.19	2.66±0.24

Indoor and outdoor 24 h RCS concentration

Results presented in Table 4 depict the 24 h RCS concentration descriptive statistics for both dry and wet season. The dry season mean indoor and outdoor 24 h RCS concentrations ranged from 2.22±0.02 µg/m^3 to 2.26±0.02 µg/m^3, whereas the wet season the mean indoor and outdoor 24 h RCS concentrations ranged from 2.10±0.10 µg/m^3 to 2.66±0.24 µg/m^3. The mean 24 h RCS indoor concentrations were higher than the outdoor 24 h RCS concentration which suggest that the source of PM$_4$ may be from the indoor household activities.

The mean indoor and outdoor 24 h RCS concentrations in both seasons were below the 24 h ambient exposurelevel of 3 $\mu g/m^3$ set by OEHHA, California EPA. Similar study by Richards et al. [26], has found the levels of environmental exposure to RCS below OEHHA ambient threshold limit of 3 $\mu g/m^3$ [26]. Another study conducted by researchers [27] measured ambient respirable crystalline silica in residence surrounding gold mine tailing storage facilities. The study has found ambient crystalline silica levels that were above 3 $\mu g/m^3$ during the dry season in residences that were in close proximity to mine tailings [23].

Pairwise comparison for the dry and wet season

Results presented in Table 5 show the indoor and outdoor dry season pairwise comparison for PM_4 mass concentration within all zones. The zones were paired based on the outdoor and indoor PM_4 mass concentration. The PM_4 mass concentration were expressed in micrograms per cubic meters ($\mu g/m^3$). Studies that focus on investigation of PM_4 indoor and outdoor in resident located near PM emitters are limited. However, the dry season results revealed no statistically significant difference ($p<0.05$) at 95% confidence interval in PM_4 mass concentration between all zones. This suggests that the PM source strength in both indoor and outdoor is the same.

Table 5. Pairwise comparison of the PM_4 Mass concentrations (dry season)

Zone	Location	Average Conc. ($\mu g/m^3$)	Statistical analysis		
			F-Test	P-Value	95% Cl
Zone A vs Zone B	Outdoor	2.24 ± 0.02 2.23 ± 0.03	0.64	0.54	No
Zone A vs Zone C		2.24 ± 0.02 2.22 ± 0.02	0.92	0.29	No
Zone B vs Zone C		2.23 ± 0.03 2.22 ± 0.02	0.57	0.75	No
Zone A vs Zone B	Indoor	2.26 ± 0.02 2.25 ± 0.02	0.94	0.63	No
Zone A vs Zone C		2.26 ± 0.02 2.23 ± 0.01	0.53	0.63	No
Zone B vs Zone C		2.26 ± 0.02 2.23± 0.01	0.58	0.41	No

Results presented in Table 6 show the indoor and outdoor wet season pairwise comparison for PM_4 mass concentrations within all zones. The wet season results revealed no statistically significant difference ($p<0.05$) at 95% confidence interval in PM_4 mass concentrations between all zones. This also suggests that the PM source strength in both indoor and outdoor is the same. The results revealed no statistically significant difference ($p<0.05$) at the 95% confidence interval in PM_4 I/O ratios comparison. The pairwise comparison between indoor zone A vs C and B vs C showed a strong association/ statistically significant difference ($p>0.05$) at the 95% confidence interval. The outdoor pairwise comparison indicated no statistically significant difference ($p<0.05$) between the zones. Additionally, the indoor pairwise comparison between zones A vs B indicated no statistically significant difference.

Results presented in Table 7 shows the indoor and outdoor dry season pairwise comparison for 24 h RCS concentrations within all zones. The zones were paired based on the indoor and outdoor 24 RCS percentage The results showed no statistically significant differences ($p<0.05$) at the 95% confidence interval in the 24 h RCS concentrations comparison.

Results presented in Table 8 shows the indoor and outdoor wet season pairwise comparison for the 24 h RCS concentrations with all zones. The pairwise comparison between indoor zone A vs C and B vs C showed a strong association/ statistically significant difference ($p>0.05$) at the 95% confidence interval. The outdoor pairwise comparison indicated no statistically significant difference ($p<0.05$) between the zones. Additionally, the indoor pairwise comparison between zones A vs B indicated no statistically significant difference.

Table 6. Pairwise comparison of the PM_4 mass concentrations (wet season)

Zone	Location	Average Conc. ($\mu g/m^3$)	Statistical analysis		
			F-Test	P-Value	95% Cl
Zone A vs Zone B	Outdoor	0.05 ± 0.02 0.03 ± 0.01	0.76	0.46	No
Zone A vs Zone C		0.05 ± 0.03 0.03 ± 0.02	0.36	0.90	No
Zone B vs Zone C		0.03 ± 0.01 0.03 ± 0.02	0.25	0.43	No
Zone A vs Zone B	Indoor	0.03 ± 0.01 0.03 ± 0.01	0.35	0.76	No
Zone A vs Zone C		0.03 ± 0.01 0.02 ± 0.00	0.93	0.11	No
Zone B vs Zone C		0.03 ± 0.01 0.02 ± 0.01	0.39	0.08	No

Table 7. Pairwise comparison of the 24-h RCS concentrations (dry season)

Zone	Location	Average Conc. (µg/m^3)	Statistical analysis		
			F-Test	P-Value	95% Cl
Zone A vs Zone B	Outdoor	2.24 ± 0.02 2.23 ± 0.03	0.64	0.58	No
Zone A vs Zone C		2.24 ± 0.02 2.22 ± 0.02	0.92	0.29	No
Zone B vs Zone C		2.23 ± 0.03 2.22 ± 0.02	0.57	0.74	No
Zone A vs Zone B	Indoor	2.26 ± 0.02 2.25 ± 0.02	0.44	0.63	No
Zone A vs Zone C		2.26 ± 0.02 2.23 ± 0.01	0.63	0.21	No
Zone B vs Zone C		2.25 ± 0.02 2.23 ± 0.01	0.58	0.41	No

Table 8. Pairwise comparison of the 24 h RCS concentrations (wet season)

Zone	Location	Average Conc. (µg/m^3)	Statistical analysis		
			F-Test	P-Value	95% Cl
Zone A vs Zone B	Outdoor	2.14 ± 0.11 2.13± 0.10	0.95	0.93	No
Zone A vs Zone C		2.14 ± 0.11 2.66 ± 0.24	0.33	0.07	No
Zone B vs Zone C		2.13 ± 0.10 2.66 ± 0.24	0.31	0.06	No
Zone A vs Zone B	Indoor	2.10 ± 0.10 2.14 ± 0.11	0.95	0.71	No
Zone A vs Zone C		2.10 ± 0.10 2.57 ± 0.19	0.44	0.04	Yes
Zone B vs Zone C		2.14 ± 0.11 2.57 ± 0.19	0.47	0.05	Yes

Conclusion

The aim of the study was to determine the concentrations of RCS and PM_4, in samples collected indoor and outdoor of 9 selected households located in close proximity to gold mines tailings dumps, in Johannesburg. In the South African context, studies that focus on investigation of indoor and outdoor PM_4 concentration in households located in close proximity to gold mine tailings are limited. Therefore, the findings of this study can be used to provide valuable information on the indoor and outdoor PM_4 concentrations, which can be used in modelling exposure and conducting a probabilistic health risk assessment. High PM_4 levels are related to dry season weather conditions due to strong winds conditions. Therefore, the PM_4 mass concentrations in all zones were higher during the dry season than during wet season.

It can be concluded that the gold mine tailings are the primary source of PM emission in and around the community proximate. The PM concentration reduces as community reside further away from the gold mine tailings. Using RCS as a chemical signature to identify the source, our results showed a similar chemical profile on the dust sample irrespective of the distance. We also used the I/O ratio to investigate the indoor source of PM. The results showed an I/O ratio of greater than one suggesting that the source of indoor PM enriched with RCS is from outdoor sources. Therefore, it is recommended that dust suppression intervention be applied around the gold mine tailings in order to reduce the community PM_4 and RCS exposures. Furthermore, source apportionment studies are required to accurately determine the contribution level of the TSF on local air pollution.

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Competing interests

The authors declare no conflicts of interest.

Author Contributions

Conceptualization, Nkateko Makhubele, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni; methodology, Nkateko Makhubele, Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni software, Nkateko Makhubele, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni; formal analysis, Nkateko Makhubele, Phoka Rathebe and Thokozani Mbonane, investigation, Nkateko Makhubele, Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; resources, Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; data curation, , Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; writing—original draft preparation, Nkateko Makhubele; writing—review and editing, Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni; visualization, Nkateko Makhubele, Phoka Rathebe, Thokozani Mbonane, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; supervision, Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; project administration: Jeanneth Manganyi, Gabriel Mizan and Masilu Daniel Masekameni.; funding acquisition, Jeanneth Manganyi and Masilu Daniel Masekameni. All authors have read and agreed to the published version of the manuscript

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We appreciated the household owner who

allowed us to take samples in their household.

Ethical considerations

This study did not involve humans or animals as subjects, there was no harm anticipated to human or animal life, therefore an ethics waiver was granted by the University of the Witwatersrand ethics committee (medical) Ref W-CBP-220120-01.

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