RISK ASSESSMENT OF EXPOSURE TO INDOOR PARTICULATE MATTER ($PM_{2.5}$) NEAR A FERRO-MANGANESE SMELTER - MEYERTON, GAUTENG PROVINCE

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Goodwill Jopa Zimakazi Khoza

Student number: 9601106k

Supervisor: Dr Masilu Daniel Masekameni

Faculty of Health Sciences, School of Public Health, Occupational Health Division

University of the Witwatersrand

A research report submitted in the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg in partial fulfilment of the requirements for the degree of Master of Public Health (Occupational Hygiene)

27 March 2023

Declaration

I, **Goodwill Jopa Zimakazi Khoza, 6501155534085, (student no: 9601106k)** declare that the research project entitled, "*Risk assessment of exposure to indoor particulate matter (pm$_{2,5}$) near a ferro-manganese smelter - Meyerton, Gauteng Province*", is my research work undertaken under the supervision of Dr Masilu Daniel Masekameni. The work is being submitted in partial fulfilment for the degree of Master of Public Health (Occupational Hygiene) in the School of Public, Faculty of Health Science, University of the Witwatersrand, Johannesburg. This work has not been presented for examination at any other university. The author designed the study, conducted all field data collection, data analysis, and writing the research report. All the sources cited in this study have been acknowledged through comprehensive references. The senate plagiarism policy is signed and attached as an Appendix A: Plagiarism Declaration Form.

RISK ASSESSMENT OF EXPOSURE TO INDOOR PARTICULATE MATTER (PM$_{2.5}$) NEAR A FERRO¬MANGANESE SMELTER - MEYERTON, GAUTENG PROVINCE

Is authentic and original unless clearly indicated otherwise, and in such instances full reference to the source is acknowledged, and I do not pretend to receive any credit for such acknowledged quotations, and that there is no copyright infringement in my work. I declare that there is no unethical research practices were used or material gained through dishonesty. I understand that plagiarism is a serious offence. Contravention of the Plagiarism Policy notwithstanding signing this affidavit. I may be found guilty of a serious criminal offence (perjury) that would amongst other consequences compel the university of Witwatersrand to inform all other tertiary institutions of the offence and to issue a corresponding certificate of reprehensible academic conduct to whomever request such a certificate from the institution.

Signed at Johannesburg on this _27______ day of ____March___________ 2023

Khoza Goodwill Jopa Zimakazi

STAMP COMMISSIONER OF OATHS
Affidavit certified by a Commissioner of Oaths
This affidavit conforms with the requirements of the JUSTICES OF THE PEACE AND COMMISSIONERS OF OATHS ACT 16 OF 1963 and the applicable Regulations published in the GG GNR 1258 of 21 July 1972; GN 903 of 10 July 1998; GN 109 of 2 February 2001 as amended.

Declaration

I, Goodwill Jopa Zimakazi Khoza (student number: 9601106k), declare that the research project entitled "Risk Assessment Of Exposure To Indoor Particulate Matter ($PM_{2.5}$) Near A Ferro-Manganese Smelter - Meyerton, Gauteng Province." is my research work undertaken under the supervision of Dr. Daniel Masilu Masekameni. The work is being submitted in partial fulfilment for the degree of Master of Public Health in the field of Occupational Hygiene at the School of Public Health, University of the Witwatersrand, Johannesburg. This work has not been presented for examination at any other university. The author designed the study, used secondary data from the main study, data analysis, and writing the research report. Parts of this research report have been planned to be published in peer-reviewed journals and presented at conference proceedings. All the sources cited in this study have been acknowledged through comprehensive references. The senate plagiarism form is signed and attached as an Appendix A: Plagiarism Declaration Form.

Acknowledgments

I am indebted to several individuals who have made this study possible. Firstly, my sincere gratitude goes to my supervisor Dr Masilu Daniel Masekameni who has been supportive and helpful during my academic journey throughout. I am grateful of the support and mentorship he provided. As well as always availing himself on either physical or online platform even after work hours and weekends to make sure I was producing quality research. I can never thank you enough for having faith in my abilities, cheering me on and always checking up on me

I am indebted to members of University of the Witwatersrand for the assistance. Their contribution eased my academic journey, and I was able to complete my studies.

Dedication

This work is dedicated to my family for their undivided support and help throughout the study period. Many thanks to my wife Gladys Khoza and my lovely son Samuel Regomoditswe Khoza, my in-laws Bishop Peter Mosime Bodibe and Rally Pulane Bodibe, and my mother Agnes Matshidiso Khoza, my brother Abram Ramariha Khoza and sisters Jane and Geneva Khoza.

I sincerely thank you for your immeasurable level of tolerance in my period of being present but physically and emotionally absent.

Abstract

Background

Globally, over 90% of the populace have no access to clean air. Exposure to airborne contaminants is associated with adverse health risks. Studies have reported on direct correlation between industrialised settings with increased incidence of air pollution associated illnesses. Chronic exposure to $PM_{2.5}$ is linked to cardiovascular and respiratory illnesses. Exposure to particulate matter (PM) in residential settings has been studied in many big mega-cities globally. However, fewer studies were achieved in low-income settings and South Africa is no exception. Exposure and risk assessments research emanate from occupational settings with less emphasis on residential settings. Studies assessing the risk of exposure to $PM_{2.5}$ in residential settings are quite limited. This provides understanding a research knowledge gap in South African low-income societies.

Purpose

The purpose of the study is to determine indoor $PM_{2.5}$ chronic daily intake to estimate the non-carcinogenic risk in communities living adjacent industrial PM emitting sources.

Methods

Secondary data from the main study titled “Motor and cognitive health outcomes in a manganese-exposed African community” (HREC clearance certificate no. M121117), which was conducted during the period of 2019/20 was used to assess the risk of exposure to indoor $PM_{2.5}$. The secondary data used in this study was collected during winter season, and $PM_{2.5}$ was sampled using a gravimetric technique over a period of seven days. Particles were drawn into the sampling head by a Gillian Gil-Air 300plus pump (Sensidyne, St Petersburg FL, USA) which was connected using a teflon tubing. A $PM_{2.5}$ Cyclone D32 with a cut-off point of $PM_{2.5}$ attached to the sampling head to isolate larger particles from entering the inlet of the cassette. The pump was calibrated and operated at a continuous flow rate of 2.75 L/minute over a seven-days period. Pre-and-post-weighing of filters was performed to derive the final mass in a controlled laboratory environment using a micro-balance scale (model-CPA225D, Sartorius, AG, Göttingen, Germany). The pre-weight (mass) consisted only of the mass of a filter while the post mass consisted of particulate and filters.

Results

The particulate matter (PM) mass concentration for New Sicelo, Old Sicelo and Noldick was found to be 0.0125 mg/m³, 0.0115 mg/m³ and 0.0061 mg/m³ respectively. The indoor PM mass concentrations for both New and Old Sicelo was found to be doubled as compared to that of Noldick's. An increased PM mass concentrations for the New and Old Sicelo areas implied an unavoidable risk of PM exposure to the population of New and Old Sicelo, respectively. Flowing from the identified risk; sustainable mitigation plans are fundamental to curb the risk of generational poisonous exposures which will rampantly lower the populace life expectancy tremendously if not proactively addressed especially at source.

Daily intake (DI) fractions for females and males were 22.98 m^3/kg/day and 17 m^3/kg/day for all three locations, respectively. Higher DI for females corroborate and support preceding studies' findings that women spent 80% of their instances indoors. The chronic daily intake (CDI) for males at New Sicelo, Old Sicelo and Noldick were 0.21 mg/kg/day, 0.20 mg/kg/day and 0.10 mg/kg/day and females at New Sicelo, Old Sicelo and Noldick had been 0.29 mg/kg/day, 0.26 mg/kg/day and 0.14 mg/kg/day, respectively.

The difference in CDI values for females and males tells how women are over exposed compared to men. Hazard quotients (HQ) for females throughout the three locations were 261, 240 and 127 respectively while males were 193, 178 and 94. A hazard quotients (HQ) measurement means women are over exposed compared to men. $H>1$ for women means that non-carcinogenic impact has been surpassed and cancer is high while men with $H<1$ have a negligible cancer risk in the tree areas (Old and New Sicelo, Noldick).

The findings from the study positively affirm the following aspects; i) characterization of the PM mass concentration from the three locations and, ii) how impactful is the PM exposure levels to the population health status which in turn influence the concept of exposure assessment. To support the exposure assessment process; a systematic review was conducted on time-activity patterns, the demographic data for risk assessment input variables were noted and the estimation non-carcinogenic health risk of exposure to indoor PM concentration especially for the community of Meyerton.

Conclusion

The study determined indoor $PM_{2.5}$ chronic daily intake to estimate the non-carcinogenic risk in communities living adjacent to industrial PM emitting sources.

The study may want to aid in perception of exposure and development of abatement measures to decrease exposure to $PM_{2.5}$ sources and assists in performing exposure assessments.

Table of Contents

List of Figures

List of Tables

List of abbreviations

AER	Air exchange rate
AT	Years of lifetime
AQIA	Air quality indoor assessment
BW	Body weight
C	Concentration
CDI	Chronic daily intake
CR	Cancer risk
ED	Exposure days
EF	Exposure frequency
GBD	Global burden of disease
GM	Geometric mean
GPS	Geographical Positioning System
HHRA	Human Health Risk Assessment
HQ	Hazard quotient
IARC	International Agency for Research on Cancer
I/O	Indoor/outdoor
IR	Inhalation rate
I_t	Infiltration factor
NAAQS	National Ambient Air Quality Standards
NO_x	Nitrogen oxide

PAHs	Polycyclic aromatic hydrocarbons
P_f	Penetration factor
PM	Particulate matter
SO_2	Sulphur dioxide
USEPA	United State Environmental Protection Agency
YE	Years of exposure
WHO	World Health Organization
VOCs	Volatile organic compounds

CHAPTER 1: INTRODUCTION

The chapter presents an overview of particulate matter (PM), its sources and environmental impacts affecting indoor space. The chapter additionally discusses human health risk assessment of exposure to particulate matter (PM) and its health consequences in particular with reference to the indoor microenvironment in which human beings reside. The chapter also reviews previous body of research data performed on the indoor PM exposure assessments and aim to come up with improved mitigation plans that will influence objective policy decision making. The chapter outlines the aim and objectives of the study. The problem statement and the study justification are outlined. The chapter concludes by way of outlining the shape overview of the study.

Background

Urban air quality is a challenge due to the growing air pollution precipitated by industries, vehicles, and different human activity-induced emissions. In 2013, outdoor air pollution, specifically outdoor particle matter (PM), was classified as carcinogenic to human beings (Group 1) by way of the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO). Group 1 are termed to be "Carcinogenic to humans. They are agents classified as having an inherent-risk of causing cancer in humans. The evaluation is usually based on the results of epidemiological studies showing development of cancer in exposed humans (ACS, 2019).

Over 90% of the world’s population stay in areas with PM with aerodynamic diameter much less than 2.5 µm ($PM_{2.5}$) fine particulate matter), exceeding the air quality guidelines (Lim et al., 2013; Burnett., et al., 2018). Nearly 60% lives in areas that not meet even the least stringent air target from WHO (Wang et al., 2015). From The Chinese study, air pollution from PM, ozone (O3), and the home burning of stable fuels may also have brought up to 6.1 million fatalities (11% of the world total) (Shen et al., 2021).$PM_{2.5}$ is ultrafine particulate matter which can be easily deposited into the human breathing canal and be translocated into the target organs causing various diseases due to both the human short-and-long term exposure (Nishida *et al.,* 2020). In addition to the health concerns of the particulate matter irrespective of size; the composition of PM varies (Xu *et al.,* 2011). It is through complicated chemical reactions by diverse pollutants produced by fossil fuel power plants, industry, cars, and human activities (Tóth *et al.,* 2014). Other compounds of PM include black carbon (BC), polycyclic aromatic hydrocarbons (PAHs), and heavy metals, which are generally formed from transport emissions, combustion, anthropogenic activities and biomass burning emissions (Bandowe and Nkansah, 2016).

Particulate matter can be released from both natural and anthropogenic sources (Escamilla, 2015). Anthropogenic sources such as domestic stoves and industrial furnaces emit fine particles while natural sources emits particles larger than $PM_{2.5}$ (Klimont et al., 2017). Fine particles are the essential causes of various human diseases due to their ability to penetrate into the respiratory system (Leikauf, Kim and Jang, 2020). Studies proposes that inhalation is the most frequent route of entry for PM contrary to ingestion or dermal (skin) intake routes respectively (Rajan and Malathi, 2014; Debela et al., 2021).

Epidemiological studies have associated exposure to PM and respiratory ailments in areas with industrial activities (Buteau et al., 2019). Several studies have been carried out to inspect the inherent risk of exposure to PM in industrialized settings (Burns et al., 2020). Despite the penalties of PM and its related health effects, there is a lack of data linking source to receptor (Karagulian et al., 2015). Unfortunately, epidemiological studies lack statistics on exposure assessments; leading to high uncertainty on epidemiologic statistics sets, especially when health burden and mortalities are to be estimated. Lack of exposure assessment statistics suggests the need for the development of exposure evaluation criterion that will assist in growing an exposure inventory (Bruinen de Bruin et al., 2021). Exposure inventories will be a useful resource in pooling statistics together from distinct populations accordingly enhancing early detection of uncommon diseases' exposures and for measuring vulnerabilities amongst the exposed subjects (Peters et al., 2020). Human health risk assessment is dependent on these parameters – hazard identification, hazard characterization and exposure assessment (Schroeder et al., 2007).

1.1 Health effects of PM and other contaminants

The health results of exposure to PM are garnering massive attention. For instance, in China, a time-series learn about found that, a 10 $\mu g/m^3$ upward increase in $PM_{2.5}$ levels was 0.65% , 0.63%, and 1.38% increase in non-accidental death, respiratory mortality, and circulatory mortality respectively (Yanga et al., 2019). In Spain, the relative risks (RR) for an increase level of 25 $\mu g/m^3$ in $PM_{2.5}$ were 1.057 for all-cause death, 1.088 for circulatory death, and 1.122 for respiratory mortality (Chen et al., 2020). Research shown that a 10 $\mu g/m^3$ rise in fine particulate in the United States was associated with roughly 4% , 6% , and 8% increases in the hazard of all- cause, cardiopulmonary, and lung cancer mortality, respectively (Pope III *et al.*, 2002).

The cytotoxic potential of PM on respiratory health are reliant on their dwelling length in distinct areas of the airway (Poh et al., 2018). A study discovered that long-term exposure to $PM_{2.5}$ and low-grade irritation should lead to hepatic carcinogenesis and enlarge the threat of liver cancer (Zhang et al., 2018). It has been argued that exposure to different compounds of PM such as polycyclic aromatic hydrocarbons (PAHs) will set off diverse implications on human health (Rengarajan et al., 2015). Research has indicated that with long-term exposure, the outcomes include skin, lung, bladder and gastrointestinal malignancies, cataracts, kidney and liver damage, gene mutation cell harming, and cardiovascular death (Diggs et al., 2011; Låg et al., 2020). Consequently, the exposure to $PM_{2.5}$ and PAHs is a concern. Previous studies have compared $PM_{2.5}$ and PM_{10} (particulate matter with an aerodynamic diameter smaller than 10 µm) concentrations and found that the concentration response curve becomes steep for those over 65 years and living in poor conditions (Chen et al., 2020). The older one gets, the greater the risk of illnesses due to pre-existing co-morbidities as a result of the declining immune system (Hamanaka and Mutlu, 2018).

1.2 Problem statement

Globally, over 90% of the population have lack of access to clean air (Landrigan, 2017). Exposure to airborne contaminants have been associated with carcinogenic and non-carcinogenic dangers (Steinle et al., 2015). Most said cases have shown a correlation between industrialized settings with multiple occurrences of air pollution-related deaths (Lim et al., 2012). Chronic exposure to $PM_{2.5}$ been linked with high instances of morbidities such as cardiovascular and respiratory ailments (Gordon et al., 2014). Exposure to $PM_{2.5}$ in residential settings been studied in several mega-cities globally with an excessive rate of deaths reported (De Oliveira et al., 2012). Fewer researches have been carried out in low-income settings such as in South African townships (Luo et al., 2019). The World Health It is estimated that 6, 5 million global mortalities are as an outcome of exposure to indoor PM pollutants yearly. Exposure and risk assessments researches are regularly targeted in an occupational settings with much less emphasis on residential settings (Zhang et al., 2013; WHO, 2017). Therefore, research assessing the chance of exposure to $PM_{2.5}$ in residential settings is limited and presents a huge knowledge gap in low-income settings such as in

South African townships (Hamanaka and Mutlu, 2018; Zhang et al., 2018; Mbazima, Masekameni and Nelson, 2021).

1.3 Study Aim

To evaluate indoor $PM_{2,5}$ chronic daily exposure concentration to estimate the non-carcinogenic risk in a community living next to industrial PM emitting point source.

1.4 Objectives

- To characterize indoor $PM_{2.5}$ mass concentration in three residential areas in the proximity of a Ferro-manganese smelter in Meyerton;
- To conduct a systematic review on time-activity patterns and demographic data for risk assessment input variables;
- To estimate the non-carcinogenic health risk of exposure to indoor $PM_{2.5}$ concentration.

1.5 Justification

The current study provides information on the risk factors associated with exposure to indoor $PM_{2.5}$ in communities living next to primary emitting sources (Jiřík *et al.*, 2016). Indoor $PM_{2.5}$ is currently classified as a major contributor to cardiovascular and respiratory diseases and high mortality rate contributor among males and females living near air polluting plants (Hodas *et al.*, 2016). Studies focusing on estimating indoor $PM_{2,5}$ life-time exposure of adult male and female residents are important in estimating the non-carcinogenic health risk of exposure to indoor $PM_{2,5}$ concentration (Melki, 2019). Outdoor air inflow into the indoor micro-environment plays an integral part to the indoor outdoor (I/O) ratio and has been found to be etiologic in indoor air pollution in terms of the WHO air quality guidelines (Edlund *et al.*, 2021). Indoor outdoor ratio is the rate at which ambient pollutants are transferred into the indoor micro-environment for which literature has proved that there was a correlation between outdoor and indoor particulate concentration and two-thirds variation of daily indoor pollution is explainable by the daily outdoor pollution variation (Leung, 2015; Mbazima, Masekameni and Nelson, 2021).

1.6 Structure of the report overview

Chapter 1 outlines the human health risk of exposure to PM and associated its health effects especially with reference to the indoor microenvironment in which people spend most of their times. In this chapter, the problem statement was formulated, the domain of the study specified, and the aim and objectives set out. The chapter also provides the justification of the study and the general approach to the study outlined.

Chapter 2 presents the literature review on risk assessment of exposure to indoor particulate matter (PM) from global, regional, and local perspectives. This provided viewpoints on human health impacts for those exposed to indoor PM. It also examines the sources of PM both natural and anthropogenic sources that have causal-link to indoor PM pollution. The main intention was to provide enough data for governmental policy making as well as regulatory decision-making within Africa.

Chapter 3 outlines methods and materials employed in the main study, the process used for collecting field data and analyzing the data in a controlled laboratory environment. Since the study flows from the main study, secondary data was used in the current study and the analyzed information provided details on outdoor and indoor calculations. Only indoor PM concentrations for the three locations was used.

Chapter 4 presents results from the three locations in Meyerton located within Midvaal Local Municipality with reference to indoor mass concentration of PM, exposure assessment for indoor PM and how systematic review of various indoor PM exposure found.

Chapter 5 presents and discusses the synopsis of the study findings providing details, mass concentration of the three areas, and estimation of life time exposure to PM for both males and females as well as its non-carcinogenic human health risk of exposure. The chapter concludes with an explanation of the limitations of the study, future research and its significance.

CHAPTER 2: LITERATURE REVIEW

The chapter presents the literature review on risk assessment of exposure to indoor particulate matter (PM) from global, regional, and local perspectives. This provided viewpoints on human health impacts for those exposed to indoor PM. It also examines the sources of PM (both natural and anthropogenic sources) that have causal-link to indoor PM pollution. The main intention was to provide enough data for governmental policy making as well as regulatory decision-making within Africa.

Particulate matter (PM) defined: "is classified and they are ultrafine particles (nucleation and Aitken mode, diameter less than 0.1 µm), fine particles (mainly accumulation mode, aerodynamic diameter between 0 and 2.5 µm) and coarse particles (aerodynamic diameter between 2.5 and 10 µm) (Zhang *et al.*, 2016)." was used to assess whether a citation pertained to PM exposure. Globally, it is noted that inhalation of contaminated air has resulted in over 7 million deaths (Forouzanfar et al., 2015), of which around 4.3 million deaths is attributed to indoor air pollution while 3.7 million deaths occur due to ambient air pollution (Burnett, Chen, Mieczysław Szys*zkowicz, et al*., 2018). The World Health Organization (WHO) noted that 90% of the global population live in areas where the ambient air quality levels are exceeded and this was supported by a South African study (Olufemi and Mji, 2019). There is dearth amount of literature from epidemiological studies regarding the health effects associated with exposure to PM (Hobson and Guy, 2014). It is suggested that the mechanisms on how the diseases evolve from exposure to diagnosis are largely unknown (Smith et al., 2007). This is an area lacking more research.

Literature suggest that the harmful effects of PM depend on several factors such as its particle diameter, chemical composition and concentration (Hobson and Guy, 2014). Particulate matter can be emitted from either natural or man-made sources (Santos *et al.*, 2017). Types of natural sources are earthquakes and cyclones while anthropogenic sources are mining operations and steel production smelters, which are regarded as primary sources in terms of source apportionment (Santos *et al.*, 2017).

It is projected that by 2060, outdoor air pollution will cause up to 9 million deaths annually (Landrigan, 2017). Continuous exposure to indoor PM from fugitive emitters such as ferro-manganese smelters located in close proximity to residential zones remains a direct cause of illness (Hayes *et al.*, 2020). Such industrial processes involve extremely high temperature between 1000 - 1400^{o}C, resulting in submicron PM emitted (Marris *et al.*, 2012).

Submicron PM can easily translocate from source to receptor due to its size and aerodynamic nature as it has a longer atmospheric residence time (Lowther *et al.*, 2019). $PM_{2.5}$ released by ferromanganese smelter into the atmosphere poses adverse health risks to the community located nearer to it (Mbazima, Masekameni and Nelson, 2021).

The relationship between $PM_{1.0}$ and $PM_{2.5}$ will be aggregated as they have found to have similar physico-chemical composition (Lee *et al.*, 2006) and their associated health outcomes yield the same lethal outcomes irrespective of the particle size where source apportionment might as well be problematic to pinpoint objectively (Wang *et al.*, 2015). The said contaminants pose adverse human health due to its carcinogenic effects (Olawoyin, 2018). Ambient and indoor air are potential sources of toxic airborne substances (Palmiotto *et al.*, 2014). Ambient PM sources in the low-income community context are related to emissions from motor vehicles, dust from untarred roads, wind-blown dust, industries burning contaminated fossil fuels, waste burning activities and domestic use of highly polluting fuel types (Wiston, 2017).

Indoor PM concentrations are defined as sources such as sand, clay, soil, smoke residuals from heating, cooking or smoking, cleaning agents, residues from synthetic fibres, building materials (mostly corrugated sheet metal structures) and a multitude of other material s created in the home or transported from the outside either manually or through infiltration or penetration (Khallaf, 2011; Tran, Ngoh and Balasubramanian, 2020). (Khallaf, 2011; Tran, Ngoh and Balasubramanian, 2020).

Studies have shown that coal burning activities such as cooking and heating activities represents one of the largest source contributors to ambient and indoor PM concentrations (Melki, 2019).The type of building structures leave more room for outdoor particulate matter to infiltrate into the indoor space through the openings and cracks. PM can also be easily foot-tracked into the indoor living space (Mitali Parvin Promoter, 2014; Chalvatzaki *et al.*, 2019). Once brought into the domestic micro-environment, daily activities like cleaning, cooking and heating will re-suspend or re-stimulate formation of PM from time to time, thus worsening human exposure to these pollutants (Vardoulakis *et al.*, 2020)..

2.1 Particulate matter (PM)

PM is a mixture of suspended atmospheric particles either in solid or liquid state which are seen as dust, smoke or haze (Lowther *et al.*, 2019). PM is categorized into three classes namely PM_1 (<1 µm), $PM_{2.5}$ (<2.5 µm) and PM10 (<10 µm) and it is the size that is aerodynamic e.g. aerodynamic diameter of 2.5 microns ($PM_{2.5}$) (Hoeflinger and Laminger, 2019). The WHO guidelines regard PM as a Group 1 carcinogen for indoor air quality selected pollutants and it undoubtedly shows how catastrophic this toxicant can be to human health (WHO, 1998).

The Global Burden of Disease (WHO, 2017) authority reported that exposure to ambient air pollution and household air pollution (HAP) from usage of solid fuel are the leading environmental risk factors in developing countries such as China (World Health Organization, 2014). This is due to increased ambient air pollution from Chinese mega-cities. Studies have noted that this was a major public health concern (Ethan, Mokoena and Yu, 2021). $PM_{2.5}$ levels are found to excessively exceed the acceptable limits set by WHO air quality guidelines globally. To aggravate this further, primary and secondary emitting sources are having a devastative and catastrophic causal-link to high pollution episodes experienced by communities which consequently have a negative health impact on the exposed population (Bandowe *et al.*, 2014).

2.2 Formation of PM

PM formation is mainly influenced by various emitting sources. These sources can be local, stationary, and vehicular in nature releasing distinct particles which depends on their combustion state. Combustion can also be in a nuclei mode especially those from smelters, vehicles and coal-fired power generating plants (Khillare and Sarkar, 2012). Particulate matter is primarily emitted while secondary is transformational formed and each particle mode has its specific sources within the biosphere (Bandowe *et al.*, 2014).

Particulate matter (PM) is classified as ultrafine particles (nucleation and Aitken mode, diameter less than 0.1 µm), fine particles (mainly accumulation mode, aerodynamic diameter between 0 and 2.5 µm) and coarse particles (aerodynamic diameter between 2.5 and 10 µm) (Viana *et al.*, 2014). Generally, fine and ultrafine PM are formed from high temperature processes such as vehicular exhaust, oil and coal combustion, biomass burning, industrial processes, and chemical reactions in the atmosphere (Taiwo *et al.*, 2014). Evolution of coarse particle is mostly due to attrition processes including mechanical abrasions and re-suspended dust generated from roads used by auto-vehicular means and from their tyre wear and tear (Sommer *et al.*, 2018). Tyre wear particles is one of the primary source of micro plastic emissions (Gehrke, Dresen and Blömer, 2020). Micro plastic waste incineration is euphemistically dubbed toxic and deadly to human health. Pollutants such polychlorinated biphenyls (PCBs), PAHs and nitrogen oxide (NOX) are the emitted toxicants from source and have adverse health effects on the exposed population (Da Costa, 2020).

Figure 1 illustrates that Aitken particles in a nucleation mode or incomplete combustion are formed by condensation of super-saturated gases while accumulation mode can either be through extreme or moderate mechanical processes (Taiwo *et al.*, 2014). These are the different modes by which PM formation becomes successful. Consistent burning of both biomass and fossil fuel (coal) is the greatest contributor to PM formation from an anthropogenic point of source (Melki, 2019). Particles in accumulation mode (diameter 0.1–1 µm) possess the lowest deposition velocity, and have the longest resident time and can travel over a large spatial scale. Aerosols vary in composition, size, concentration, and source. They profoundly affect climate, visibility, human health, and biogeochemical cycling (Griffin, 2013). Airborne dust aerosols can be found in accumulation mode due to their particle size diameter. Aerosol components of accumulation mode are formed through direct emissions and during condensation and coagulation (Hussein *et al.*, 2018).

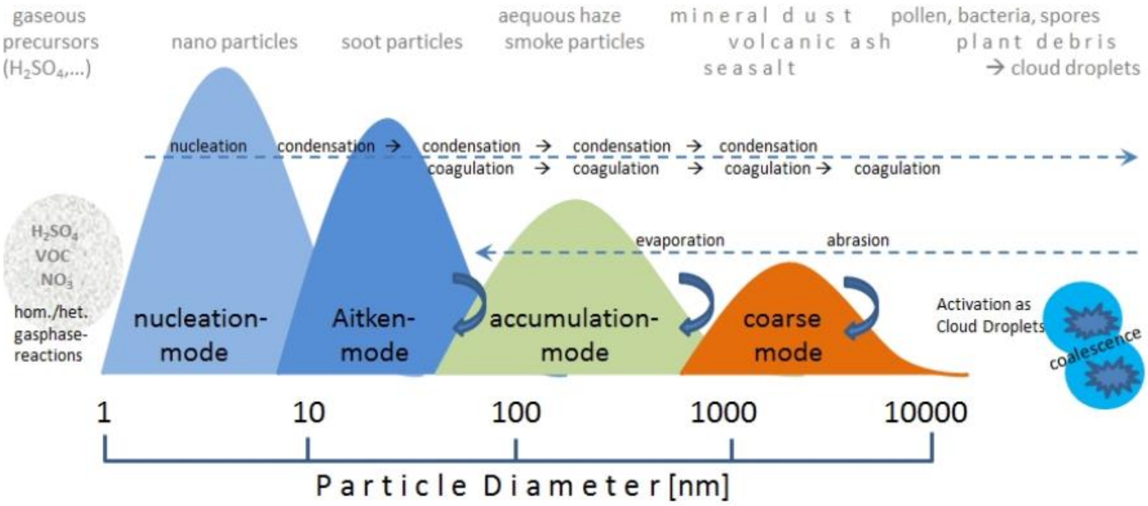


Figure 1: Schematic multi-modal particle size distribution with typical transformations and example particle types within each mode.

Particles emitted from a heat/ combustion dependent activities are often spherical and often of smaller aerodynamic diameter (Hussein *et al.*, 2018). However, most of the spherical emitted particles often comprises of agglomerates resulting from particle formation processes as shown in Figure 2.

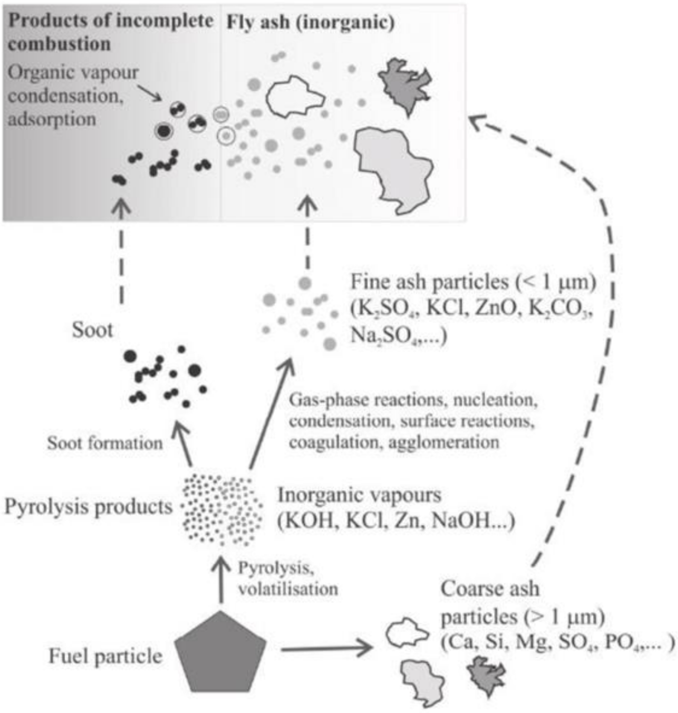


Figure 2: Particle formation pathways from biomass wood combustion

Error! Reference source not found. above depicts that the particulate matter formation flows from various pathways. These pathways can lead to particle size distribution consisting of bimodal characteristics. Fine mode (< 1 µm) is the first one and its formation is through nucleation and condensation from the gas phase. The second is the coarse mode (>1.0 µm) and it is made up of non-volatilized ash residuals mostly resulting in fly-ash particles. Whereas fine particles are primarily formed of potassium salts like potassium sulphate (K_2SO_4) and potassium chloride (KCl) (Obaidullah *et al.*, 2012).

2.3 Sources of outdoor and indoor PM

Sources of outdoor PM are industrial emissions such as industrial processes or vehicular fumes (Bowler *et al.*, 2012; Salvador and Salvador, 2012). Poor communities living nearer industrial sites are the mostly affected (Dong *et al.*, 2020). Outdoor PM have is directly proportional to the increase of communal subjects adverse health effects. This increased pollution haze and plume is a major concern from a research and regulatory framework perspectives (Steinle *et al.*, 2015). Transportation of outdoor $PM_{2.5}$ can either be through foot tracking and infiltration through cracks or holes in the building structures especially if homes such as shacks are constructed from corrugated zinc (Bo *et al.*, 2017). Lack of comprehensive research about outdoor $PM_{2.5}$ remains a challenge to public health policy and decision-making platforms. Contrastingly, indoor PM studies has gained more attention and some findings are that their sources can either be from particles or indoor activities such as cooking, heating and smoking with the potential that indoor PM is always in excessive volumes compared to outdoor PM levels (Chang *et al.*, 2019). Since most outdoor sources are influenced by meteorological factors, indoor sources are mostly dependent on both relative humidity and the temperature as catalytic contributors to exposure to toxic ultra-fine particles (UFP) (Yang *et al.*, 2017). Anthropogenic sources are the causes of high indoor PM in enclosed micro-environments and such fine particles re-suspends due to domestic human activities, and ventilation methods whether mechanical or natural (Zhang *et al.*, 2014). Indoor air pollutants can be classified as organic, inorganic, radioactive as well as biological (Van Tran, Park and Lee, 2020).

The hazard associated to air pollutants depends on their toxicity level, time of exposure and concentration varies from person to person (Hodas *et al.*, 2016). Close to 9 billion of the world population use wood for cooking activities in their residential space and these solid fuels are the emitters of toxic gases such as SO_2, NO_x and PM (Vardoulakis *et al.*, 2020). To make matters worse, these toxicants when emitted, have a longer accumulation period indoors even when the ventilation system is good enough to eradicate them. Indoor air quality is mostly influenced by outdoor sources such as factory furnaces, vehicular exhaust smokes etc., (Leung, 2015).

Outdoor sources emissions are mostly dependent on the geographical location, meteorological conditions, and the mass concentration of the $PM_{2,5}$. Some of the determining factors that influence exposure assessment is PM with less than 2.5 μm which have a longer suspension period time-lag from source and can travel airborne for great distance (Cities and Martins, 2018) while the heavier PM will be deposited nearer and faster once released into the biosphere except if it agglomerate due to external meteorological forces acting on it while airborne (Zhao *et al.*, 2020).

2.3 Time activity data and demographics as variables for risk assessment

The success of human health risk assessment depends on the need to estimate the total population exposure. Exposure assessment at population level requires time-activity patterns to map the distributions for exposure. In the Canadian CHAPS 2 study, the predictors in time-activity patterns were season, age, gender, and rurality. The study found that almost 88% of the time was spent indoor, 5% outdoors and 7% in transit (Matz *et al.*, 2014).

Studies lack information on receptor characteristic during risk estimation. In other studies, there is a lack of demographic data included such age, body weight and life expectancy. A recent study conducted to attempt to use demographic data, however, the study used default values from the US EPA database (USEPA, 2012). The reason using the US EPA defaults is that South Africa has no such data available to be used as reference framework. Exposure to coal burning fumes from the same study found that both adult females and males had a higher cancer risk than the US EPA designated severity risk (Masekameni, 2017). The attributable risk of exposure to fossil fuel fumes has been found to be etiologic to the disease burden over time to the exposed population.

Time-activity pattern is mostly determined by gender, age, body weight, season, time spent indoor and time-spent outdoor. Mostly females spent about 59% of their day indoors compared to 41% of their male counterparts. Females spent more time in the kitchen and other indoor microenvironments while males spent their time in transit and outdoors (Zhao et al., 2009). This is was in agreement with previous study by Power et al., (2011). Exposure for age groups 20-59 years and 60+ years, the daily time-spent indoors has been found to be 15.5 and 18.6 weighted average hours per day respectively (Matz et al., 2015).

Women and school children also spent more time at homes on weekdays in winter as the seasonal school holidays overlapped with their winter break for the three locations under study (Fan, Wu and Ohman-Strickland, 2010). Total exposure of the population has been found to be higher in areas where solid fuel is used as source of energy and the elderly have a high prevalence of exposure to having adverse health effects than adults and kids (Wang et al., 2008). Overweight and obesity have been associated with continuous exposure to PM polluted residential and work microenvironments. The PM concentrations had a higher hazard ratio than the annual acceptable limit were based on the exposure models employed that males especially are at the highest risk of exposure to developing obese characteristics and an increased body mass index (BMI) (Bowe et al., 2021).

Exposure model for individuals was mostly dependent on the parameters such as house type, meteorological variations, indoor domestic activities, and the type of cooking stoves. AER which is also a driving force in exposure assessment mostly accounts for daily indoor domestic ambient infiltration and the time spent in various locations either indoors or outdoors (Breen *et al.*, 2015). From the studies the National Particle Component Toxicity (NPACT), fossil fuel modes were found to have both short-and-long-term adverse health effects to exposed communities; leading to increased morbidity and mortality related cardiovascular complications due to quality of both the ambient and indoor air (Bevan, 2021).

Another direct causes increasing personal exposure to outdoor and indoor polluted $PM_{2.5}$ is the type of building structure, which either have leakages or air-tight and with most residents spending more than 80% of their life-time indoors rather than outdoors (Kim, Kang and Kim, 2020). As study (Park *et al.*, 2021) observed that the infiltration factor into leaky units is 1.59 times which are similar to the ones from the locations of Old and New Sicelo as opposed to the up-market Noldick (air-tight facilities). Interestingly, both Old and New Sicelo areas have no electricity supply. All of them have being classified as a Low Income (LI) settlement, with a higher unemployment. This socio-economic status means only solid and fossil fuel is used for heating and cooking purposes in all the households and kitchen. As such particulate matter resuspension of $PM_{2.5}$ (VOCs and PAHs) concentration might occur exceeding the WHO values *(Alves et al*>, no date). Another perspective that one can employ on the current study is the Life-Cycle Assessment (LCA) as the indoor compartment was used as the micro-environment of interest, the selected residential households were located in the same locality. Various parameters such as I/O ratios were studied holistically taking into account household structural characteristics in decision making. LCA will also help to strengthen the study results as it looks in detail at both cumulative outdoor and indoor exposure more especially as indoor polluted $PM_{2.5}$ emissions and assist in comprehending personal health effects of exposure and environmental implications (Rosenbaum *et al.*, 2015)

Indoor environmental air quality (IEAQ) is paramount to the residential quality of life but mostly dependent on the building structural characteristics. The bias of IEAQ often includes various parameters such as illumination, air quality conditions and thermal comfort and sound.

Poor IEAQ in indoor living environments is attributable to adverse health effects especially towards the elderly population with comorbidities, women of child-bearing age and infants. Looking at New and Old Sicelo, these parameters of concern previously alluded to, are present in those residential settings. Since then, their level of IEQ will be deficient, thus negatively impacting the residents due to toxic $PM_{2.5}$ (Marques *et al*>, no date). The three locations are composed of a multicultural population and different lifestyles. With reference to the studies by NHAPS and CHAPS, time-micro-environment activity patterns is driven by the community characteristics discussed above. Various cultural activities and familial lifestyles are some of the direct and contributing factors to toxic exposure to indoor $PM_{2.5}$ (Leech *et al.*, 2002).

As for the two residential settings (Old and New Sicelo) in Meyerton, seasonal conditions and gender were primary parameters that were determinants of time-microenvironment-activity patterns which are drivers of personal exposure, thus adversely impacting on the health of residents due to inhalable airborne toxins such as $PM_{2.5}$ (Hwang *et al.*, 2016). Another concurring factor to support the research aim is from the Fresno 1 & 2 studies where indoor micro-environmental concentration and the influencing factors are synonymous to the findings from recent research conducted (Mbazima, Masekameni and Nelson, 2021).

Even short-term exposure to $PM_{2.5}$ has been found to be detrimental to health of children and adults where the daily exposure concentration is merely 10 $\mu g/m^3$ and found to contributing up 32% to the total burden of disease. Children and aged adults spend almost 80% of their time in doors (Horne *et al.*, 2018).

2.3.1 Time activity pattern

Time-activity pattern is dependent to multiple factors that may be associated with adverse health effects due to indoor exposure to particulate matter (PM) of outdoor origin. Indoor air quality concentration is also influenced by other sources found in the microenvironment such cooking tools (activities??) and cleaning equipment (Burke, Zufall and Özkaynak, 2001). Other contributing factors are causal to the various ailments resulting in increased death rate, accounting for approximately 81% to 89% due to indoor PM of exposure and these are the infiltration rate of buildings and the time spent indoor by those exposed (Ji and Zhao, 2015). A study by (Mbazima, Masekameni and Nelson, 2021) these structural characteristics can be found some areas of Old Sicelo and New Sicelo, especially shacks and structures constructed from boards. It has been found that activities such as eating, cooking and heating can mainly affect exposure to indoor particulate matter (PM) and the longer the occupancy period within the same microenvironment, the higher the risk of exposure to indoor PM (Cities and Martins, 2018). Higher indoor concentrations can be experienced during occupancy periods than during non-occupant one. It is suggested that temporal variations plays a vital part in the final condition of the indoor air quality (Bo *et al.*, 2017).

2.3.2 Demographic data

2.3.2.1 Globally

Studies such as the Canadian CHAPS 2, used the following variables such as age, seasonal variations, gender, and rurality to study time-activity patterns to expand the knowledge base of human health risk assessment with reference to population exposure in general. These are viewed as some of the characteristics influencing time-activity patterns (Matz *et al.*, 2014).

2.3.2.2 Regionally

Sub-Saharan Africa's economic boom has seen an increase in economic initiatives taking place in many cities where industrial activities run 24 hours round the clock. As such, the environmental impacts are experienced in general and exposure to PM pollution air quality data has been increasing at an alarming space (Green *et al.*, 2022). Environmental pollution in African cities has been exacerbated by the continuous usage of biomass and fossil fuel as sources of energy where both short-and-long-term air monitoring have shown that African pollution levels exceeded international limits (Petkova et al., 2013). Research in African countries is lacking on this subject of exposure to PM. Meanwhile South Africa is the only country in the continent that has progress researching on this subject dues to its health effects that adversely contribute to increased morbidity and mortality rates respectively (Katoto *et al.*, 2019).

2.3.2.3 Locally

Since South African does not have exposure guidelines, a study done in Limpopo used the US Agency for International Development (USAID) guidelines to do a human health risk assessment (HHRA) of exposure in evaluating indoor PM risk of exposure. The US EPA HHRA model was used in assessing the health risks of exposure for the population concerned (Edlund *et al.*, 2021). Even though there is progress in research on exposure to PM in South Africa in the African continent, further research is needed to match the European counterparts in the field of exposure science (Cai, Gibson and Rahimi, 2021).

2.4 Health risks associated with exposure to PM

Epidemiological studies has shown that exposure to PM is associated with adverse health effects (Butler, Madhavan, 2016). It is noted that ambient and indoor air pollution is associated with high incidence rate of pre-term birth. Recent studies have proven that there is an association between $PM_{2.5}$ exposure during pregnancy and pre-term birth (Sun *et al.*, 2015). $PM_{2.5}$ has a longer atmospheric resident time and can travel over a greater distance before being deposited (Lin *et al.*, 2018). Activities such as walking and domestic cleaning contribute more than 2.3 times incremental to $PM_{2.5}$ indoor concentration which is above both WHO annual and 24 hours atmospheric air quality limits (Li *et al.*, 2021).

Those exposed to PM can either have an exacerbated or a new health condition developing as individual vulnerability varies tremendously and plays an important part due to pre-existing diseases. Moreover it also forms part of the GBD as it impacts on both morbidity and mortality rates respectively (Yanga *et al.*, 2019). The exposure to inhalable PM can either be short-term (Days/Hours) or long-term (Years/Months) which can results in respiratory and cardiovascular morbidity (aggravated asthma) and mortality (lung cancer) (Cantone *et al.*, 2011). PM has devastating adverse health effects on human health such as the risk of heart failure, ischemic or thrombotic stroke, cardiovascular death, and ischemic heart diseases. It is show that PM is one of endocrine system disrupters which consequently become a precursor for both diabetic mellitus and obesity amongst the exposed population (Darbre, 2018).

As per the findings from the Harvard Six Cities study, long-term exposure to PM has been linked to an increased death rate amongst susceptible individual with health risk factors such as hypertension, diabetes, and smoking. Cancer and cardiopulmonary conditions were etiological to mortality (Hamanaka and Mutlu, 2018).

Exposure to contaminated air can cause several diseases including respiratory, cardiovascular, neurological and systemic illnesses (Manisalidis et al., 2020). Studies have shown that exposure to particulate matter and volatile organic compounds leads to the development of carcinogenic and non-carcinogenic effects (Masekameni et al., 2019). Prolonged exposures even at low level concentration might also lead to the development of chronic health effects (Liu et al., 2021). In order, to understand the burden of air pollution, future research is suggested to determine the depth of the problem (Lowther et al., 2019).

To reiterate the status quo as narrated above, the longer one is exposed to PM, there is a downside about possible development of black carbon emanating from incomplete combustion from industrial processes or even domestic heating and cooking activities especially from fossil fuel such as coal (Olufemi and Mji, 2019) which have proven to have detrimental health effects to exposed communities (Hodas *et al.*, 2016; Moletsane *et al.*, 2021).

2.5 Exposure assessment methods of PM

Exposure is the amount or concentration of a particular agent that reaches an organism, system or (sub) population in a specific frequency over a defined duration period. Exposure has various meaning within multiple contexts either linguistically or discipline-oriented. Personal and pollution exposures vary greatly where individual's exposure depends on daily activity patterns and the pollution exposure is an non-static phenomenon hence the distinction between them (Dias and Tchepel, 2018).

The availability of an exposure assessment inventory is essential in that input parameters for risk assessment can be easily accessed. Human health risk assessment is an essential process where hazards can be identified and evaluated in order to determine the status of a targeted population (Chalvatzaki et al., 2019). Risk assessment is a complex process requiring various data set to ensure that the output of the risk assessment is scientifically sound (Aven, 2016).

Exposure assessment of PM concentrations require continuous monitoring for 24 hours daily per annum and the applicable methods must be applied against an equivalent Golden Standard. A body of knowledge on quantitative data must be amassed in relation to sources, levels and trends of emissions of both precursor gases and primary particles in helping the best fit risk reduction control strategy being implemented (Koenig, 2000). To clearly understand the relationship between indoor and outdoor PM, there are six parameters in exposure assessment development which are as follows:

- Indoor/Outdoor ratio (I/O);
- infiltration factor and;
- Penetration factor
- Time activity pattern
- Demographic information of the exposed individuals
- Intensity of PM in the air compartment.

I/O ratio depends on the size of the indoor particles' rate of emission from source and building structural geometry of cracks and the air exchange rate (AER) (Hodas *et al.*, 2016).

Infiltration factor (I_f) deals with the equilibrium fraction where their penetration airborne indoor particles and how they remain suspended for a certain time period and there is an endless avoidance of mixture with indoor particles (Vardoulakis *et al.*, 2020). Penetration factor (P_f) refers to the fraction ability of particles infiltrating of air penetration efficiency through the structural cracks and the leaks in the building envelopes (Lowther *et al.*, 2019).

Several ways exist to determine human exposure levels. These include, using satellite observations (Van Donkelaar *et al.*, 2015). Personal monitoring is another useful instrument to measure PM. A fixed-site monitoring instrument can be used for both indoor and outdoor PM measurements (Liu *et al.*, 2003). Furthermore, one can use the artificial neutral network (ANN) as previously adopted in Mainland China exposure assessment. Remote sensing study can also be used where PM estimation concentration model was built from (Yao and Lu, 2014). The application and usage of these instruments help in being decisive in minimizing personal exposure to PM which has proven to be detrimental to health and to continuously monitor their residential indoor air quality (IAQ) proactively. Monitoring indoor and outdoor PM infiltration and penetration had its advantages and disadvantages.

This pre-knowledge stance will further help and empower residents in advancing health promotion and making informed lifestyle decisions (Lowther *et al.*, 2019). The knowledge and empowerment of residents will come as a mutual resolution to the dichotomous relationship between both health promotion and lifestyle decision-making. The approach will come with an objective paradigm shift in terms of PM exposure assessment i.e. from old to new, which will be preventive or proactive from an exposure science world view rather than from an epidemiological way thereby advocating pre-exposure prevention rather than the opposite (Sethi and Di Molfetta, 2019). The benefit of fixed monitoring tools and indoor air quality was confirmed in the 72 only 19 in full reviewed studies where an orchestral agreement has indicated that spatial-temporal variations both indoors and outdoors are the key elements in determining personal exposure assessment to PM (Dias and Tchepel, 2018).

2.6 Determinants of PM toxicity

Depending on the emitting source, PM concentration might be dominated by variety of chemicals and physical properties. In the Vaal region as declared air pollution priority area most of the emissions are from industrial sources. In the Vaal air pollution priority region, there is a high concentrated industrial activity such as steel manufacturing, cement kilns, power generation and foundries. Therefore, the toxicity of PM depends on the physicochemical properties which is often influenced by various release mechanisms such as mechanical, thermal, and physical processes. Most industrial activities in the Vaal region are dependent on the use of solid fuels such as biomass and coal. Common pollutants commonly released during industrial activities includes manganese, lead, chromium, mercury etc.

2.6.1 Manganese

Manganese (Mn) has a biological half-life between 36 and 41 days (O'Neal *et al.*, 2014). It can be in these forms: Oxide, sulphide, silicate and carbonate and used for alloys such as steel to impact hardness as well as dry cell batteries (Lyon, 2010). Health effects of exposure to Mn are metal fumes fever (MFF) and chronic central nervous system effects from Mn dust and its compounds) psychosis (Verhoeven, Egger and Kuijpers, 2011).

Characteristics of this sickness are slow speech, slow spasmodic gait and severe cases are irreversible but not fatal. Pulmonary effects are rare and include fibrotic changes but unclear whether these are because of Mn itself or to high levels of silica and symptoms of pneumonitis may be experienced (Riccelli *et al.*, 2020).

2.6.2 Lead

Exposure to lead (Pb) has been a huge public health challenges for over 2000 years where humans, children and infants suffered adverse health effects from immunological, reproductive and .neurological perspectives. Internal dose metric for Pb is the concentration of Pb in blood (PbB, typically expressed in terms of µg/dL) and have shown cumulative effects through the application of longitudinal measurements. The most prevalent health effect is neurological in infants and a greater amount of literature supports this view in terms of the life-time exposure to Pb (Abadin *et al.*, 2020). Hematological and immunological effects are mostly experienced in adults and children respectively while reproductive effects in males (Frey, 2014).

2.6.3 Chromium

Steel production industries uses chromium as one the reductant, wood preserver and for chrome plating. Emission of the pollutant can occur within work or residential environments but less priority has been given to the community living in close proximity to the source and time has come that from an exposure point of departure, emission is dealt with proactively at source. Minimizing chromium compounds emission from source such as dichromate, chromates and chromic acid will successfully prevent and protect the receptor from deadly and toxic exposures. Continuous exposure to chromium and its compounds is health hazard which causes diseases like weakened immune system, liver and kidney damage, lung cancer and alteration of the genetic material which is not the only physiological effects that can experienced once exposed (Teklay, 2016).

2.6.4 Mercury

Mercury (Hg) is found in rocks of the sulphate ore cinnabar. It is extracted by roasting the ore and condensing the Hg vapor emitted. Mercury is different in that at room temperature. Mercury exists naturally and as an anthropogenic contaminant (USEPA, 1997). Processed mercury release can lead to a progressive increase in the amount of ambient mercury, which enters the atmospheric-soil-water distribution cycles where it can remain in circulation for years. Mercury poisoning is the result of exposure to mercury or mercury compounds resulting in various toxic effects depend on its chemical form and route of exposure (Rice *et al.*, 2014). Exposure to Hg is associated with an increased risk of atherosclerosis, coronary dysfunction myocardial infarction and hypertension (Zulaikhah, Wahyuwibowo and Pratama, 2020).

Mercury (Hg) is a heavy metal which can be metallic liquid when transformed. Hg can have the health hazards impacting on those exposed where exposure to compounds is mostly through inhalation of the dust and Hg spillage is the main nuisance for exposure. There are two toxic derivatives namely Alkyl (methyl and ethyl) and phenyl mercury acetate. These derivatives causes sensitization and blistering. Hg exposure can either be acute (rare or likely) or chronic (more likely) poisoning and have adverse health effects such muscular tremors emanating from both the organic and inorganic states (Rice *et al.*, 2014).

2.7 Human health risk assessment of PM

South Africa has more than fourteen (14) coal-fired power generation stations throughout the various provinces like Mpumalanga, Limpopo, Free State etc. With Mpumalanga being the epicenter of power generation and most affected by fugitive emissions from these plants. It is also has various activities like mining and metallurgical processing of steelworks which are consequently the sources of high natural dust levels. Excessive high PM has been linked to both urban areas and densely industrialized settings in South Africa (Morakinyo *et al.*, 2017).

Consistent toxic emissions from source present a detrimental effect from health and environmental perspectives. Such detrimental effects of indoor and outdoor PM air quality contribute to the GBD of those exposed over time, hence it is categorized as one of the carcinogen (Zhang *et al.*, 2018; Edlund *et al.*, 2021). From a study of European cities, it was confirmed that long-term exposure to PM, especially to the elderly, frail and co-morbid adult populations pose a high mortality and hospitalization from diseases due to their vulnerability. There is also a linear and inclined risk of exposure to PM concentration pollution and no specific threshold limit exists (Fortoul *et al.*, 2011).

2.7.1 Human health risk assessment

Human health risk assessment (HHRA) is the scientific evaluation of adverse health effects resulting from a personal exposure to a particular contaminant or hazard (Morakinyo et al., 2017).

2.7.1.1 Risk assessment methods

Risk assessment is the determination of quantitative or qualitative estimate of risk related to a well-defined situation and a recognized threat i.e., also called a hazard.

Quantitative risk assessment requires calculations of two components of risk (R) -

- The magnitude of the potential loss (L), and
- The probability (p) that the loss will occur.

In summary, to conduct risk assessment, 5 main steps are always adopted (Matz *et al.*, 2014).

i) Identify the hazard: Be it physical, mental, chemical, or biological.

ii) Decide who could be harm

iii) Assess the risk

iv) Make record of findings

v) Review

In the engineering of complex systems, sophisticated risk assessments are often made within safety engineering and reliability engineering when it concerns threats to life, environment, or machine functioning (Bruinen de Bruin *et al.,* 2021).

Risk assessment methodologies differ by industries. Several methods of risk assessment that help identify risk, assess the risk appropriately and help in the risk management (Giannopoulos, Filippini and Schimmer, 2012).

There are two health risk assessment indicators that will discuss and unpack relative to PM exposure in general (U. S. Environmental Protection Agency, 2010; WHO Regional Office for Europe, 2016).

There are types of pathways of PM exposure namely inhalation, dermal and ingestion. Exposure to toxic chemicals is found to be 3-fold through dermal route than by ingestion and inhalation pathways for employees working with polychlorinated biphenyls which has a probability of carcinogenic risk (Debela *et al.*, 2021).

Cancer risk (CR) is the second indicator of the health risk assessment in PM exposure and describes the chance of a person developing cancer. Cancer risk can be either relative or absolute. Since 70% of ambient PM pollution can infiltrate indoor space for the time activity periods resulting in adverse health effects (Chalvatzaki *et al.,* 2019).

Hazard quotient (HQ) is the ratio of the potential exposure to a substance and the level at which no adverse effects are expected. HQ aims at establishing the characterized cancer risk due to PM personal exposure to toxic metals or chemical or fumes such as Cadmium through the route of inhalation. If the Hazard Quotient is calculated to be less than 1 (HQ<1), it means that the risk is tolerable (Pongpiachan, Iijima and Cao, 2018).

By application of Monte Carlo simulation; it was detected that chemical exposure was in excess of the acceptable limit (10^{-4}) especially for the adult population (Chen *et al.*, 2022). HQ has shown high levels during annual celebrations especially with fireworks (Cr, Mn and Pb) and bonfires from a study in Thailand, where the USEPA guidelines was exceeded and may expose the population to an elevated cancer risk (Pongpiachan, Iijima and Cao, 2018).

CHAPTER 3: METHODOLOGY

This chapter outlines materials and methods used in the main study for collecting field data and analysing the data in a controlled laboratory environment. Detailed explanation of the processes is described in this chapter. Since the study follows from the main study, secondary data used in the current study and the analyses for the study encompass estimates on outdoor and indoor concentrations. Only indoor PM mass concentrations for the three locations was used for this study. The study area comprised of the three areas in Meyerton namely Old Sicelo, New Sicelo and Noldick respectively.

The current study estimated time spent indoor patterns and its demographics. The chapter further explains the systematic review process to synthesize relevant literature on the topic of the study and show schematically how the data was processed. This also covered information on inclusion and exclusion criteria for the study. The chapter attempts to perform risk assessment and human health risk assessment of exposure to indoor PM. The chapter ends by describing the ICP-MS used to study the elemental composition of the sampled indoor and outdoor $PM_{2.5}$.

3. Methods and materials

3.1 Study design

This study is based on data gathered through household physical measurements from the main study where the 3 locations are situated in Meyerton, Gauteng: Old Sicelo, New Sicelo and Noldick. Support, re-enforcement, and contextualization of the findings has been validated by data collected from these 3 locations. A summary overview of both ambient and indoor PM concentrations is presented as an introduction to the reader on the physical measurements conducted for the period of the data collection. Measurements carried out in line and compared with the National Ambient Air Quality Standards (NAAQS) protocols to comply with standards and validate research findings. Considerations of variability factors of PM concentrations and personal exposure within distinct microenvironments is evaluated using the secondary data. In conclusion, statements are made to draw deductive reasoning on the health risk of the population exposed to PM indoor pollution in Old Sicelo, New Sicelo and Noldick, which could be used as surrogate values for personal exposure assessments and influence human health risk assessment of exposure to PM.

3.2 Study area

The study was conducted in Meyerton. Meyerton is located 15 kilometres from Vereeniging in the Northern direction, Gauteng Province with GPS coordinates 26.5854° S and 28.0069° E. Meyerton falls under the geographical jurisdiction of the Midvaal Local Municipality within the Sedibeng District as in Figure 3. Midvaal is famous for its farming activities that supply most parts of Gauteng Province. There is approximately 77.5% households which are formal dwellings constructed using bricks and cement while 22.5% constitute informal settlements, with housing structures constructed from corrugated iron and boards (Ngyende, 2012; Housing Development Agency, 2013).

Field data was collected at Meyerton area in three local settlements (New Sicelo, Noldick and the Old Sicelo) (Mbazima, Masekameni and Nelson, 2021). These three residential areas are in the same geographical space with varying and distinctive characteristics and are differently distant from the emitting source i.e., Samancor Ferromanganese smelter. Noldick and New Sicelo are

Closely nearer to the smelter is New Sicelo and Noldick areas, respectively which are located approximately 2.5 km away from the smelter while Old Sicelo is 4 km farther. Old-and-New Sicelo have are densely populated compared to a less densely inhabited, Noldick. Noldick consists of buildings made of cement bricks, fitted with ceilings, and routinely well maintained while Old-and New Sicelo are shacks constructed from corrugated sheet metals and facial boards. These structures are in a state of dilapidation due to higher unemployment where many households leave below the poverty datum line.

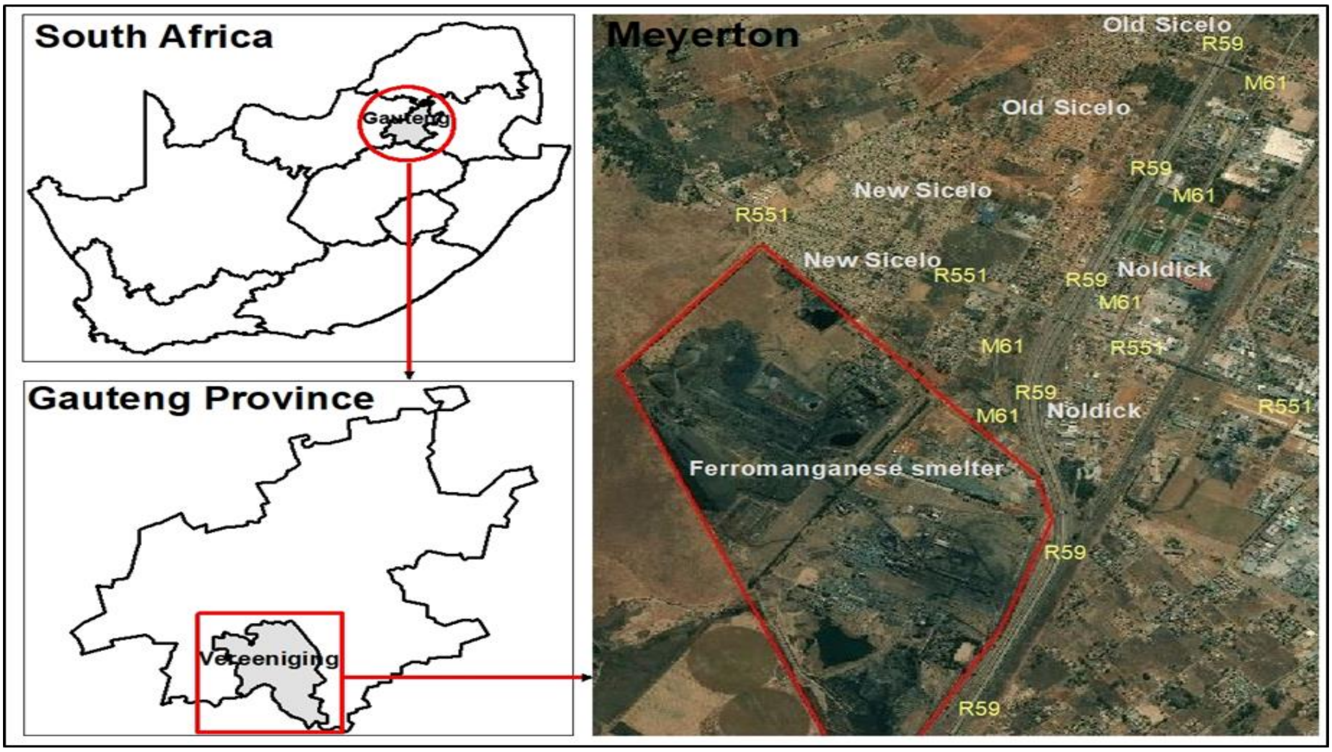


Figure 3: A geographical map of the study area

3.3 Data collection

A gravimetric sampling technique was adopted for this study using GillAir pumps and polycarbonate filters.

3.3.1 Preparation of filters

Polycarbonate membrane (PCTE) filters (Zefon, Ocala, FL, USA) of 37 mm in diameter and pore size of 0.08 µm were conditioned in a controlled laboratory environment over 24 hours and pre-weighed gravimetrically at the occupational health laboratory at the University of the Witwatersrand. The weighing was done under laboratory conditions (@ 21 ± 1˚C temperature and 35 ± 2% humidity) using a model CPA225D electronic microbalance scale (Sartorius, AG, Göttingen, Germany) that has a minimum resolution of 0.001 mg. The microbalance scale was calibrated internally by pressing the CAL button before weighing the filters. Before sampling, the filters were stored in a controlled laboratory environment with the temperature recorded at 22˚C and humidity 35%. Before and after sampling each filter was weighed three times and the average mass was used.

3.3.2 Sampling

Sampling is a critical phase that can determine the success or failure of the experimental work, therefore the sampling equipment must be chosen carefully to achieve reliable results (Meri *et al.*, 2018). The sampling of airborne PM has been conventionally done using active samplers and the most used method of active sampling is by passing air through a filtering media using a pump (Elmes and Gasparon, 2017).

The active sampling technique ensures enough accumulation of PM on the filter for a statistically robust determination of the mass concentration thus providing reliable quantitative data (Elmes and Gasparon, 2017). It further allows accurate measurement of the air pumped through the filter so that the mass concentration can be calculated and reported as mass per cubic metre of air (Elmes and Gasparon, 2017).

In this study, indoor $PM_{2.5}$ was sampled using two identical Gilian GilAir 300plus pumps (Sensidyne, St Petersburg FL, USA) (Stanislawska *et al.*, 2017), connected to a Teflon tube that joins the pump and a 37 mm cassette (SKC Inc., Eighty-Four, PA, USA) fitted with a PCTE filter. The cassette was coupled with a 37 mm $PM_{2.5}$ Gs-3 multiple-inlet cyclone (SKC Inc., Eighty-Four, PA, USA) that separated the coarse and fine particles using centrifugal force (Boudissa *et al.*, 2006; Panda and Shiva Nagendra, 2018).

One pump was used to sample the outdoor $PM_{2.5}$ while the other was used to sample indoor $PM_{2.5}$ in the main activity room. Both pumps were placed indoors for security purposes and to protect them from harsh environmental conditions such as rain and direct sunlight, which can damage the pumps and affect their functionality. The pump collected samples will give the exposure data required for the study once analysed. The samples were collected at a height of ~1.5 m, ~1 m away from walls, and ~1.2 m away from windows, doors, and ventilation inlets (Hoek *et al.*, 2008). Although the pumps are fitted with a battery with a life span of 8 hours, they were connected to an electric charger as a backup. The pumps were continuously monitored to ensure that they are sampling effectively.

Indoor samples were collected in the sitting rooms; where impossible (e.g., one-room houses) indoor samples were collected in the middle of the room. There were no restrictions on the activities undertaken during the sampling, therefore, participants carried out their normal activities.

For outdoor samples, the 1.5 m height could not be used in most cases due to the difference in the house structures. Therefore, outdoor samples were sometimes collected at a height below or above 1.5 m.

The airborne $PM_{2.5}$ was sampled at a constant flow rate of 2.75 L/min and the particles deposited on the PCTE filters (Boudissa *et al.*, 2006) and the flow rate was checked before and after sampling using a Gilibrator (Sensidyne, St Petersburg FL, USA) for quality control. The 2.75L/min flow rate was used so as to meet the ISO 7708 criteria. The pumps provided the relapsed time in minutes and calculated the volume of air sampled. However, the volume was in litres per minute (L/min). Therefore, the volume was divided by a thousand to convert it into cubic metres (m^3).

3.4 Systematic review process

Titles and abstracts of all studies were screened. Fine particulate matter and human Health risk assessment (HHRA) were phrases for exclusion.

In Figure 4 a schematic illustration of the systematic search process is outlined. A total of two hundred and forty (240) articles from the year 2000 - 2022 were systematically reviewed from four (4) data bases namely Pubmed, Scopus, Science Direct and Google Scholar. The period range was influenced by the date of the main study which was within the same period. Only forty (40) articles were included as part of the qualifying literatures and the criteria was based on exposure of interest, geographic location of study, peer reviews, reported outcomes nad participants. Multiple primary search criteria for publications included keywords from the publications (title, abstract and text) that refers to PM (including subtypes and synonyms) and indoor environment (and synonyms). The search strategies used combinations of the following keywords: ‘indoor environment’, “air pollution”, “particulate matter”, “fine particulate matter”, “fine particles”, “PM”, “$PM_{2.5}$”, “health risk assessment”, human health risk assessment- (HHRA)”. Only publications in English and from a peer reviewed articles were considered.

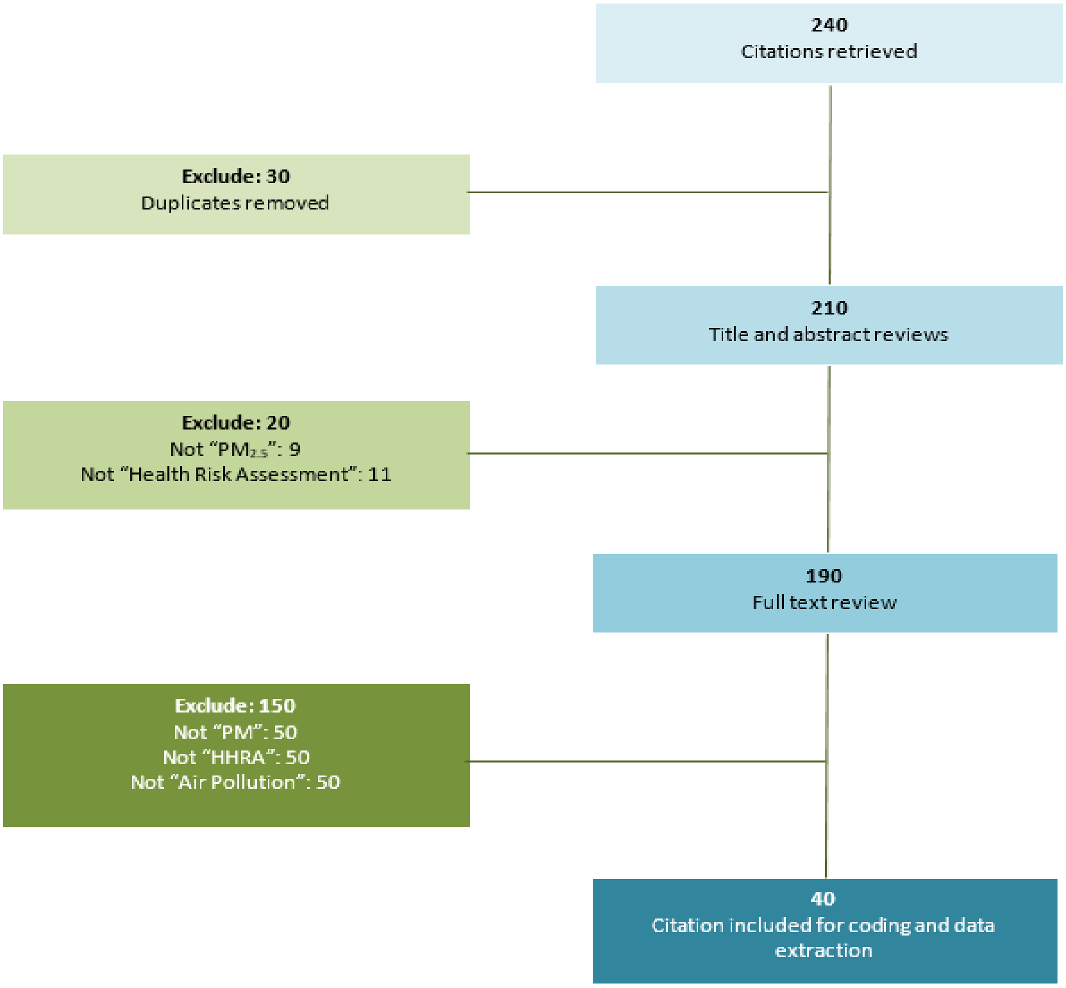


Figure 4: Schematic illustration of the systematic search process

Inclusion criteria

Inclusion of eligible studies was finalised and validated by two independent peers. The studies were included in the meta-analysis if they met the following criteria:

(i) studies included population exposed to $PM_{2.5}$;

(ii) studies presented sample sizes and odds ratios (OR) with 95 % confidence intervals (CI) or information that could be used to infer these results;

(iii) If more than one study identified for the same population, only the study that included the most recent population or the most information passed the inclusion criterion. Studies that did not meet the above criteria failed the inclusion criterion.

3.5 Processing of raw data

In this study, the two stage approaches were used in the analysis:

This study was nested in the main study, which investigated the similarities between indoor and outdoor $PM_{2.5}$ in three residential areas near a ferromanganese smelter in Meyerton to apportion the emission source(s). In the primary study, indoor and outdoor $PM_{2.5}$ samples were collected concurrently, using GilAir300 plus samplers, at a flow rate of 2.75 L/min. $PM_{2.5}$ was collected on polycarbonate membrane filters housed in 37 mm cassettes coupled with $PM_{2.5}$ cyclones. In this study, secondary data extracted from the primary study data was used to estimate indoor $PM_{2,5}$ from households.

3.5.1 Determination of the mass concentration

The mass concentration in µg/m^3 was derived using equation 1.

$$C = \frac{m\ x\ 0.001}{V} \qquad \text{Equation 1}$$

Where (m) is the final mass PM (post mass-pre mass) in milligrams, 0.001 is the conversion factor (from milligram to microgram) and v (m^3) is the volume of air over the entire sampling period~~.~~ In this study, the mass concentration was reported in µg/m^3.

3.5.2 Calculation of the geometric mean (GM)

Since this is anticipated to be a skewed data, the GM was calculated to derive an input value to calculate the chronic daily intake (CDI). GM was calculated using equation 2

$$GM = \sqrt[n]{x_1 \times \cdots \times x_n} \qquad \text{Equation 2}$$

Where X_1,..etc, represent individual data points, and n is the total number of data points used in the calculation.

3.5.3 Indoor–Outdoor Ratio

Indoor–outdoor ratios (I/O) were calculated to determine the difference between indoor and outdoor $PM_{2.5}$ mass concentration and to determine whether there is a contribution of outdoor $PM_{2.5}$ to the indoor environment. An I/O ratio of one indicates unity between the $PM_{2.5}$ in the indoor and outdoor environment. An I/O ratio of less than one indicates a contribution of outdoor PM to the indoor environment. A ratio greater than one indicates a significant indoor source that is contributing to indoor air quality. The I/O ratio was obtained using Equation (3).

$$Ci = \frac{Cin}{Cout} \qquad \text{Equation 3}$$

where C_i is the indoor-outdoor ratio, C_{in} the indoor $PM_{.2.5}$ mass concentration, and C_{out} is the outdoor $PM_{2.5}$ mass concentration

3.6 Estimation of exposure to indoor $PM_{2.5}$

3.6.1 Risk assessment

Estimation of exposure of the population is a primary element of human health risk assessment for environmental pollutants. At population-level exposure assessments require time-activity pattern, which are relative to microenvironments where people spend their time. Societal exposure mapping models may have influence on time-activity patterns as shown by the previous study conducted in Canada (Matz *et al.*, 2014). Available risk assessment techniques promotes risk-based approaches used in investigating occupational exposures (Zhang *et al.*, 2012). In general human health risk assessment is conducted to estimate the potential risk of exposure to incidental $PM_{2,5}$ (Moolla *et al.*, 2013; Karachaliou *et al.*, 2016; Masekameni *et al.*, 2018). Risk assessment is a comprehensive process, which includes hazard source identification, evaluation, characterization and control, aiming at prevention of possible health outcomes (Forouzanfar *et al.*, 2015). The approach is separated into processes which includes hazard identification, exposure scenario determination and consideration of the human behaviour; data collection, exposure and risk characterization (Chalvatzaki *et al.*, 2019).

3.6.2 Human exposure assessment to indoor $PM_{2.5}$

For the exposure assessment, the estimated dose expressed as chronic daily intake (mg/kg/day) is considered. The driving factors in dose estimation is exposure pathway (air) including route of entry which commonly is (inhalation), frequency of exposure (activity based), and duration of exposure (working years expected) and population age group (adults, males, and females). In the absence of the local database regarding exposure assessment factors, the study adopted parameters for exposure assessment from the USEPA risk assessment guidelines and South African statistics as shown in **Table 1.**

Table 1: **Summary of exposure factors**

Parameter	Description	Value	Unit
C	Room concentration	-	mg/m^3
IR	Inhalation rate	30	m^3/day
BW	Body weight	60 kg/ 70 kg Females & Males	Kg
ED	Exposure days	289 (19 hours-a day for 7 days a week)	Days/ year
YE	Years of exposure	30 (residential)	Years
AT	Years in lifetime	67/63	Years

Dose response relationship was used to estimate potential biological response for each pollutant. Similar to Masih *et al.* (2016; 2017) and the average concentration for the entire exposure day was used to calculate the pollutant intake concentration. Chronic daily intake (CDI) for $PM_{2.5}$ concentration was calculated using Equation 4.

$$CDI = \frac{C \times CF \times IR \times EF \times ED}{BW \times AT} \qquad \text{Equation 4}$$

Where CDI is the dose $PM_{2.5}$ *intake;*

C is the concentration of a PM pollutant in ($\mu g/m^3$)*;*

CF is the concentration conversion (mg/ µg= 0.001 or 1 µg) factor;

IR is the inhalation rate (adults 14.9 m^3*/day);*

EF is the exposure frequency (day/year= 0.59 Female and 0.41 males) - equation 3;

ED is the exposure duration as in equation 5;

BW is the average body weight (68.1 kg);

AT is the average years in life-time (67 and 63 for females and males, respectively).

Equation 4 was used to determine a procedure to estimate exposure duration in a typical 19-hour time spent indoors.

$$TWA_{19\text{-Hour}} = TWA \text{ x } \frac{t}{T} \qquad \text{Equation 4}$$

Where $TWA_{19\text{-hour}}$ *is the average exposure duration over a 24-hour period assuming that an adult females and males spends around 59% and 41%of their time indoors, respectively.*

TWA is the average exposure concentration,

t is the actual exposure time while

T is the standard 24-hour day period (Breysse and Lees, 2006).

The exposure duration obtained from equation 4 was used as daily average exposure; therefore, a yearly average exposure was calculated given that exposure cover 14.16-hours (females) and 9.84 hours (males) a day duration over 365 days in a year from this exposure scenario. It is estimated that adult people spent approximately 2 weeks outside the exposure boundary per year (Mioduszewski *et al.*, 2002). Therefore, annual exposure duration was derived using equation 3.

$$ED = \frac{Actual\ exposure\ duration}{24\ hours\ per\ day} \text{ x 365 days in a year} \qquad \text{Equation 5}$$

ED is the exposure duration (days/year);

Actual exposure duration is the 14.16-hours (females) and 9.84 hours (males) yearly exposure scenario;

24 hours is the total hours in a day; and

365 days is the number of exposure days in a year.

Average exposure duration will be the duration of incidental exposure to $PM_{2.5}$ *(converted from minutes to hours);*

14.16-hours (females) and 9.84 hours (males) will be the averaged total hours spent indoors by the study subject per day;

365 days will be the number of exposure days in a year (7 days per week x 52 weeks per year), minus 14 days (assuming that people are outside the residential boundary).

In addition to the $\mathrm{CDI}_{\text{(average daily intake)}}$, the cumulative lifetime exposure concentration intake for 30 years will be calculated using equation 6.

$$CDI\ (30\ years\ dose) = \frac{\sum CDI\ x\ 117\ x\ YE}{67/63} \qquad \text{Equation 6}$$

$CDI_{(30\ years\ dose)}$ *the cumulative average 30-year dose in mg/kg,*

CDI the chronic daily intake (mg/kg/day),

YE estimated lifetime exposure duration equivalent to 30 years for residential exposures,

365 the total number of days in a year and 67/63 years female and male life expectancy in South Africa, respectively.

The adjusted lifetime chronic daily intake (CDI_{adj}) *will be calculated accounting for the life expectancy in for a South African female and male.*

The $\mathrm{CDI}_{\mathrm{adj}}$ was calculated using equation 7.

$$CDI\ adj = \frac{CDI\ (25\ years\ average\ dose)}{life\ expectency\ in\ days} \qquad \text{Equation 7}$$

CDI adj is the lifetime chronic daily intake; $CDI_{(30\ years\ dose)}$ *which is the cumulative average 30-year dose (mg/kg) and Life expectancy in days (67/63 years x 365 days per year).*

Risk characterisation is the last step in risk assessment, which provide information on the hazard status of a contaminant. For non-carcinogenic pollutants hazard quotient (HQ) was used to estimate the risk. Where a HQ of >1 is regarded as hazardous exposure while HQ of <1 means that the exposure is less hazardous. In equation 7, the procedure for calculating HQ as shown in Equation 8.

$$HQ=\frac{CDI}{RfD} \qquad \text{Equation 8}$$

The RfC for diesel particulate matter (DPM) (5 µg/m^3) was used to derive an RfD. To date there is not a concise RfD for particulate matter ($PM_{2.5}$). The only available data is for DPM, which is only provided as an RfC, body weight, and the inhalation rate was used together with the RfC to calculate the RfD for $PM_{2.5}$. In equation 9, a procedure to calculate the RfD is shown.

$$RFD= RFC/1000 \text{ x } \frac{Inhalation\ rate}{Body\ weight} \qquad \text{Equation 9}$$

Reference dose (RfD): An estimate (with uncertainty spanning perhaps an order of magnitude ratio) of a daily oral or dermal exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Its unit is usually expressed as **mg/kg/day.**

CHAPTER 4: RESULTS

This chapter presents the mathematical computation of the secondary data collated to provide an understating of the impacts of exposure to pollutants emitted from smelter processing in terms of the concentration threshold limit as per USEPA and WHO guidelines. To sum the results up, pairwise comparison of $PM_{2.5}$ *is explained to answer the objectives of the study.*

4.1. Indoor $PM_{2.5}$ concentrations for the 3 different locations

Figure 5 shows the variation between indoor and ambient $PM_{2.5}$ mass concentrations for Old Sicelo, New Sicelo and Noldick residential areas. Indoor mass concentration PM was lower than the outdoor mass concentration. Old Sicelo presented higher average indoor $PM_{2.5}$ mass concentration of 2.62 µg/m^3. Meanwhile the highest average outdoor $PM_{2.5}$ mass concentration of 21.66 µg/m^3 was for Noldick (Mbazima et al., 2021).

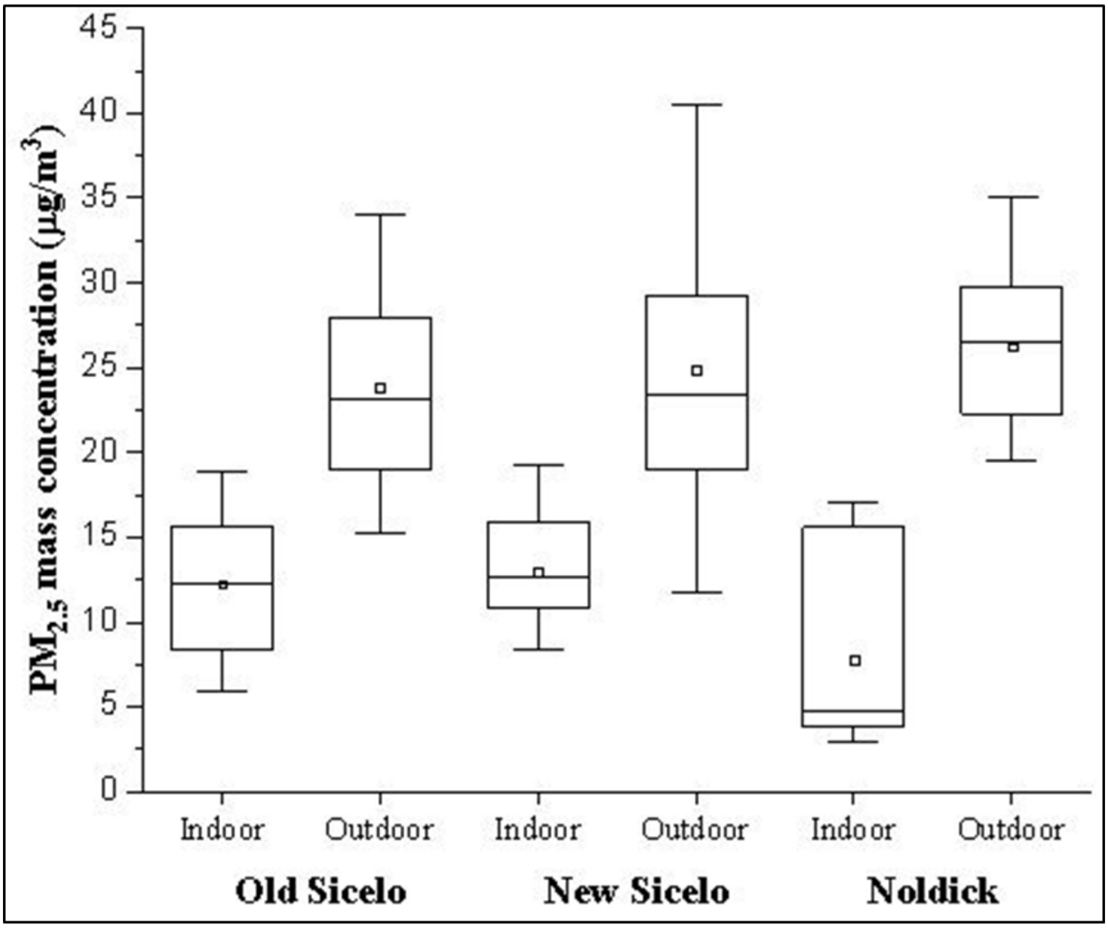


Figure 5: Box and whisker plots comparing indoor and outdoor $PM_{2.5}$ mass concentrations (µg/m3) across the three residential areas**.**

Table 2 present I/O ratios (using Equation 3) of the three residential areas. It has been noted that I/O ratios of Old Sicelo, New Sicelo and Noldick was 50 ± 0.07, 0.54 ± 0.10, and 0.27 ± 0.17, respectively. Outdoor mass concentration was higher than indoor concentration in the three residential areas (Mbazima et al., 2021)**.**

Table 2: Descriptive statistics of indoor-outdoor ratios across the three residential areas.

Parameter	Old Sicelo	New Sicelo	Noldick
Minimum	0.39	0.39	0.14
Maximum	0.60	0.71	0.54
Mean	0.50	0.54	0.27
Standard deviation	0.07	0.10	0.17

4.2 Exposure assessment to indoor PM

Table 3 shows a pairwise comparison of $PM_{2.5}$ concentrations sampled in indoor environment. Two of the three possible pairings show significant statistical differences. This finding was expected since both settlements share the same characteristics compared to a more affluent Noldick. Noldick is mostly vegetated while Old and New Sicelo are without any possibility of occult deposition. Furthermore, most part of Noldick is paved and tarred while Old and New Sicelo comprises of gravel roads. Therefore, one could anticipate a higher PM fraction at Old and New Sicelo as opposed to Noldick.

Both Old and New Sicelo are situated near the emitting source hence the comparable concentration figures while Noldick is located a distance from the ferro-manganese smelter plant. High PM concentration values for both Old and New Sicelo proves that the type of homes made with corrugated sheets and fascia-boards experience easier particle infiltration and deposition compared to Noldick, whose deposition potential is difficult as the houses are constructed from bricks and fitted with entry ceilings (Hernández-Pellón and Fernández-Olmo, 2019). The socioeconomic status of the community plays a vital part in the household lifestyle. Old and New Sicelo falls amongst poverty stricken communities where there is a high rate of unemployment which impact on the affordability of modern energy like electricity (Ferguson *et al.*, 2020).

Unaffordability of clean energy means reliance on both fossil fuels and biomass energy generation for both cooking and heating purposes. Fossil and biomass energy sources have been found to be equally responsible for air pollution while the population from Noldick are mostly affluent and of middle-class status, that is, in a better position to afford electricity and thus enjoy cleaner indoor air quality and living spaces

Additional to this point of source, some sources such as the Route 59 (R59) provincial and economic road and the Hullet Tongaat Mills in Meyerton are indirect contributors to ambient pollution. This was however not considered in this study. With the mass concentration of PM falling between 11.5 – 12.6 µg/m3, this clearly shows risk of exposure to hazardous emissions especially the residents of both Old and New Sicelo areas. According to the National Ambient Air Quality Standards (NAAQS) the figures falls within the set standards by the regulatory authority in terms of the toxicity of the agents of exposure (Kumar *et al.*, 2014). Interestingly, these readings were taken over a period 7 days in 24 hours rather than annually same as US EPA and NAAQS.

Table 3: Pairwise comparison of indoor $PM_{2.5}$ concentrations for the three study areas

Area	$PM_{2.5}$ Conc. N=10 (µg/m^3)	GSD	F-test	P-value	Statistical sig. @ 95%
Old Sicelo vs	11.5	4.1	0.43	0.29	No
New Sicelo	12.6	3.1			
New Sicelo vs	12.6	3.1	0.08	0.014	Yes
Noldick	6.1	5.8			
Old Sicelo vs	11.5	4.1	0.33	0.031	Yes
Noldick	6.1	5.8			

4.3 Results of the systematic review

From the total of 240 reviewed publications, 210 were excluded and only 40 were included in the final sample and the following key words were used - “air pollution”, “particulate matter”, “fine particulate matter”, “fine particles”, “PM”, “$PM_{2.5}$”, “health risk assessment”, human health risk assessment- (HHRA)”.

Parameters presented in **Table 1**, provide a summary of key input values for human health risk assessment estimation. Based on various searched databases it has being found that people spend varied time periods indoors and outdoors. Data from a consolidated human activity database (CHAD) it has been indicated that time spent indoors and outdoors are influenced by activities, season and gender (USEPA CHAD, 2012). It can now be drawn that women spend a larger proportion of their time indoors compared to male counterparts as shown in Table 3. This finding was supported by Taiwanese time-activity pattern studies for people over the age of 65 years. The study showed higher relative risk (RR) of exposure to $PM_{2.5}$ and mostly women with an Odds Ratio (OR= 3.94) which was two-fold as compared to males. The outcome of interest was cardio-vascular diseases (CVDs) and respiratory diseases (RD). An increase of exposure to the $PM_{2.5}$ concentration increased the number of emergency room visits (Liu et al., 2017). However, in contrary to other databases it has been reported that women spend about 80% of their time spent mostly indoors (Rappazzo et al., 2014).

Life expectancy was found to be different based on country's specific gross domestic income. It has been established that high income countries or developed countries often have a higher life expectancy than developing countries. In South Africa it has been reported that women are likely to live longer than male. Moreover, women lives about 67 years as compared to males with an average life expectancy of 63 years (StatsSA, 2017). This finding is in contrary with reported life expectancy of males and females from the USEPA database. Based on the USEPA on average American population live 70 years (EPA, 2012). Few databases exits reporting on inhalation rate for different age groups. The average inhalation rate for a South African adult is reportedly at 14.9 m^3/day. However, the USEPA suggests that an average adult has an inhalation rate of about 20 m^3/day (USEPA, 2004).

Table 3: Human Health Risk Assessment inputs parameters from various databases

Population characteristics obtained from various literature sources

Variable	**Male**	**Female**	**Source**
Time spend indoor	41%	59%	CHAD
Time spend outdoor	59%	41%	CHAD
Life expectancy	63 years	67 years	StatsSA
Inhalation rate	14.9 m^3	14.9 m^3	StatsSA

Results shown in **Error! Reference source not found.** shows the non-carcinogenic health effects of exposure to PM at the three study locations. The hazard quotient is above 1 for the three study areas, suggesting a greater risk of residents to contract PM associated health effects.

Table 4: Non-carcinogenic risks of exposure to PM

Area	Daily Average Concentration (μg/m³)	Day average Concentration (mg/m³)	DI Females m³/kg/day	DI Males m³/kg/day	CDI Female mg/kg/day	CDI male mg/kg/day	RfD mg/kg/day	HQ Female	HQ Male
Old Sicelo	12.5	0.0125	22.98	17.00	0.29	0.21	0.0011	261	193
New Sicelo	11.5	0.0115	22.98	17.00	0.26	0.20	0.0011	240	178
Noldick	6.1	0.0061	22.98	17.00	0.14	0.10	0.0011	127	94

CHAPTER 5: DISCUSSION

This chapter summarises the conclusions and recommendations for further studies. The aim and objectives of the study are evaluated against the findings. From the findings, opportunities for further investigation of sustainable mitigation methods to minimize exposure to PM. Recommendations are made for additional systematic studies to explore these parameters

5.1 Synopsis of study findings

5.1.1 Indoor $PM_{2.5}$ mass concentrations for three areas

From the pairwise comparison Table 1, the indoor of $PM_{2.5}$ mass concentrations were compared statistically using an F-test and a standard deviation.

The null hypothesis for the F-test was that there is an equal variance between the standard deviations of indoor and outdoor $PM_{2.5}$ concentrations. Where a $p<0.05$ indicates a significant difference and the null hypothesis was rejected. For a non-significant difference and an acceptable null hypothesis, $p>0.05$. The pairwise calculation showed that both Old Sicelo and New Sicelo (11.5 ± 4.1µg/m^3) and (12.6 ± 3.1µg/m^3) indoor particle mass concentration is attributed to the emissions from source due to their proximal location, and meteorological conditions and were not statistically significant for Old Sicelo and Noldick as well as New Sicelo and Noldick (11.5 ± 4.1 µg/m^3) and (6.1 ± 5.8 µg/m^3) ; (12.6 ± 3.1 µg/m^3) and (6.1 ± 5.8 µg/m^3) were statistically significant ($p<0.05$) respectively (Abdel-Salam, 2015).

Higher $PM_{2.5}$ mass concentration for Old-and-New Sicelo can be attributed to various emission sources both stationary and non-stationary such as the Ferro-manganese smelter plant and the carbon dioxide fumes from the vehicular traffic using the Route 59 (R59) (Li *et al.*, 2021). In addition to the possible contributing sources, indoor human activities such as cooking, heating and domestic cleaning that can re-suspend the $PM_{2.5}$ (Zauli-Sajani *et al.*, 2018). Dust foot tracking from the outdoor into the indoor micro-environment increases both convection and infiltration rates especially for shacks (Butler, Madhavan, 2016). As for Noldick, the low particle mass concentration values indicate that both $PM_{2.5}$ convection and infiltration rates of outdoor air into the indoor environment was minimal due to the characteristics of the structure since the houses are constructed with cement bricks, tiled roofing and fitted with wall-to-wall ceilings (Zhang *et al.*, 2021).

5.2 Indoor $PM_{2.5}$ mass concentration

Based on calculations from the pairwise particulate matter I/O mass concentration, there was no statistically significant difference ($p<0.292$) in terms of Old Sicelo and New Sicelo where the daily mean decreased incrementally. As for the two paired areas of New Sicelo and Noldick, Old Sicelo and Noldick shows an increase in their means and are both statistically significant ($p<0.014$ & $p<0.031$) respectively. ~~An increase in the ambient concentration mean has a confidence of 95%, indicating that the exposed population will develop adverse health effects. There is a 95% probability that those exposed in the three locations will develop adverse health effects associated with either short-term or long-term exposure to $PM_{2.5}$ (Dominici *et al.*, 2019).~~

From the ESCALA (Estudio de Salud y Contaminación del Aire en Latinoamérica) study, exposure to $PM_{2.5}$ has been significantly associated to high death rate because of respiratory or cardiovascular metabolic failures (Romieu I et al, 2012). This also confirmed by the findings from the Hamanaka and Mutlu (2018) study, which confirmed that both the annual and daily means of exposure to indoor particle concentration may be lethal and detrimental to human health, and ultimately increase in mortality and aggravate the rate of morbidity for those already vulnerable. Since the Meyerton study areas were in close proximity to the emitting source and other indirect sources within the area, there is a likelihood that a higher number of pollutants released into the environment increased the risk of exposure to the population under study and consequently, having a worsening effect on their health status over time (Jiřík *et al.*, 2016).

5.3 Estimated non-carcinogenic human health risk of exposure to indoor $PM_{2.5}$

From the pairwise comparisons on the Table 1, both Old-and-New Sicelo ($p>0.05$) residential areas are more polluted than Noldick. The two highly polluted areas were however found to be statistically insignificant. This is supported by previous studies that showed that exposure to indoor $PM_{2.5}$ concentration for people living nearer industrial plants where their exposure was associated to lung impairment conditions (Pramitha and Haryanto, 2019). In terms of the health effects from being exposed to higher $PM_{2.5}$ concentrations, both the infiltration and exposure factors need to be considered as they do not occur in isolation and without etiologic drivers such as age, geographical settings, socio-economic status, gender, and seasonal meteorological variations. Furthermore, air exchange rate, daily opening of windows and time-spent indoors and outdoors impacts on the health outcomes where $PM_{2.5}$ is responsible for almost 68% of the total exposure from the studied areas (Hamanaka and Mutlu, 2018).

5.5 Limitations of the study

Since secondary data from the main study was used, which had a small sample (N=10), the results might have bias. Any limitations picked up from the main study will also be influential to the present study. The data from the main study was used to do a pairwise comparison calculation for the three areas (Old Sicelo, New Sicelo and Noldick) to understand mass concentration of both indoor and outdoor $PM_{2.5}$. The initial data collection from households was never supported by weather monitoring stations and thus it did not consider meteorological impact which would explain both the dispersion models and transportation of all fugitive pollutants. Therefore, this type of limitation presented challenges in correlating $PM_{2.5}$ concentration with meteorological factors such humidity, temperature, wind -speed and wind direction.

Furthermore, time-activity based patterns was never considered when the data was collected. This would have amplified the $PM_{2.5}$ mass concentrations' contribution to indoor sources. Data was also collected during the winter season where there was a likelihood that the weather conditions was unstable most of the times thus influencing variability in emission patterns from the smelter. This high degree of emission variability of PM indoor concentrations as compared to outdoor concentrations demonstrate a probability for exposure misclassification when employing outdoor PM concentrations when both indoor exposures and risks estimation are computed. Production schedules of the smelter were unavailable and could have impacted the results of the original study.

5.6 Strengths of the study

The study aimed at determining indoor $PM_{2.5}$ chronic daily intake to estimate the non-carcinogenic risk of exposure to people living in a residential areas near a ferro-manganese smelter. Source characterization has been managed to provide an understanding of emission, and potential major emitting sources of both indoor and outdoor $PM_{2.5.}$ Outdoor air pollution remains a major contributor to indoor PM concentrations of all sizes. Further studies will give affirmation of all sources or identifying major emitting sources of indoor and outdoor $PM_{2.5}$ in Meyerton. Only indoor PM will be considered for this study.

5.7 Future research

Prospective studies carrying out exposure risk assessment in Meyerton are necessary since this directed and focused to risk assessment of exposure to indoor $PM_{2.5}$.

Since it was found that the concentration of the elements increased as the distance from the source increased (Mbazima et al., 2021), future studies can investigate the impact of the ferro-manganese smelter beyond the three residential areas studied. Furthermore, studies focusing on possibility of the $PM_{2.5}$ transforming from the air compartment to water and soil.

Time-activity pattern studies are key in quantifying how much time the residents spend indoors, outdoors, and external to the border lines of their microenvironment. Time-activity pattern studies are necessary since the development of adverse health outcomes depends on the time of exposure. Time-activity patterns can be used to collect data that will be useful for exposure risk assessment and modeling the intake and uptake of $PM_{2.5.}$

Personal exposure studies and concentration in the breathing zone should be carried out for risk assessment in residential areas. Breathing zone concentration is believed to be an accurate estimation of how much the receptor is exposed to ambient and indoor concentration. Future studies should also investigate particulate matter (PM) number concentration since this study reported estimates of both non-carcinogenic and the chronic daily intake of indoor and outdoor $PM_{2.5}$. The bioavailability and bio-accessibility of the indoor $PM_{2.5}$ should be studied in future studies. There is a need for additional investigation to improve our understanding of exposure response function(s) for mortality and morbidity at low levels of $PM_{2.5}$, ozone (O_3), and other ambient air pollutants generally found present in the environment. Infiltration-based mobile indoor air cleaners' usage can act as IAQ intervention with the objective to have a major improvement to IAQ PM by reducing indoor particles concentrations variably. These pollution reduction interventions can be subsidized by the government as part of tax rebates per household. Main polluters (mostly industries) will fund the pool in accordance their ongoing environmental degradation activities as measured by authorities through scientific means. The Polluter Principle will apply to each environmental penalty.

5.8 Significance and conclusion

This is a sub-study nested under the main study titled "motor and cognitive health outcomes in a manganese-exposed African community". The main study has obtained ethical clearance (HREC clearance certificate no. M121117) and consent was also obtained from the participants. Since the main study has already obtained ethical clearance, the sub-study was given a waiver for ethical clearance by the University of the Witwatersrand's Human Research Ethics Committee.

This study initially aimed at characterize indoor $PM_{2.5}$ mass concentration in three residential area in the proximity of a Ferro-manganese smelter in Meyerton; secondly, to conduct a systematic review on time-activity patterns and demographic data for risk assessment input variables and lastly, to estimate the non-carcinogenic health risk of exposure to indoor $PM_{2.5}$ concentration.

The findings from the study will influence public policy reforms and decision-making for legislation and improving future urban planning and to stimulate future studies. Findings will also add a voice to the ongoing call by environmentalists and toxicologists that all regions to increase their research knowledge base by conducting population-representative studies. Once these population-representative studies are maximized by all the scientific community, the conundrum about indoor exposure PM will be solved.

The government should improve on enforcement of air quality guidelines for household purposes with reference to domestic activities especially for cleaning and cooking tasks as equally as they do for companies that are having atmospheric emission licenses. There is need for more research on indoor emissions especially in communities living within the vicinity of smelter. This research could provide an understanding on $PM_{2.5}$ concentration which can help to develop control strategies.

REFERENCES

Abadin, H. *et al.* (2020) 'Toxicological profile for lead', (August), p. 582. Available at: http://arxiv.org/abs/1011.1669%0Ahttp://www.ncbi.nlm.nih.gov/pubmed/24049859%0Ahttps://stacks.cdc.gov/view/cdc/95222.

Abdel-Salam, M. M. M. (2015) 'Investigation of PM2.5 and carbon dioxide levels in urban homes', *Journal of the Air and Waste Management Association*, 65(8), pp. 930–936. doi: 10.1080/10962247.2015.1040138.

Alves, C. *et al.* (2020) 'Fine Particulate Matter and Gaseous Compounds in Kitchens and Outdoor Air of Different Dwellings', pp. 1–19.

Bandowe, B. A. M. *et al.* (2014) 'PM2.5-bound oxygenated PAHs, nitro-PAHs and parent-PAHs from the atmosphere of a Chinese megacity: Seasonal variation, sources and cancer risk assessment', *Science of the Total Environment*, 473–474, pp. 77–87. doi: 10.1016/j.scitotenv.2013.11.108.

Bandowe, B. A. M. and Nkansah, M. A. (2016) 'Occurrence, distribution and health risk from polycyclic aromatic compounds (PAHs, oxygenated-PAHs and azaarenes) in street dust from a major West African Metropolis', *Science of the Total Environment*, 553, pp. 439–449. doi: 10.1016/j.scitotenv.2016.02.142.

Bevan, G. H. (2021) 'Ambient Air Pollution and Atherosclerosis : Recent Updates'.

Bo, M. *et al.* (2017) 'Assessment of indoor-outdoor particulate matter air pollution: A review', *Atmosphere*, 8(8). doi: 10.3390/atmos8080136.

Boudissa, S. M. *et al.* (2006) 'Manganese concentrations in the soil and air in the vicinity of a closed manganese alloy production plant', *Science of The Total Environment*, 361(1–3), pp. 67–72. doi: 10.1016/j.scitotenv.2005.05.001.

Bowler, R. M. *et al.* (2012) 'Anxiety affecting parkinsonian outcome and motor efficiency in adults of an Ohio community with environmental airborne manganese exposure', *International Journal of Hygiene and Environmental Health*, 215(3), pp. 393–405. doi: 10.1016/j.ijheh.2011.10.005.

Breen, M. S. *et al.* (2015) 'Air Pollution Exposure Model for Individuals (EMI) in Health Studies: Evaluation for Ambient PM2.5 in Central North Carolina', *Environmental Science and Technology*, 49(24), pp. 14184–14194. doi: 10.1021/acs.est.5b02765.

Breysse, P. N. and Lees, P. S. J. (2006) 'Industrial Hygiene Concept'.

Bruinen de Bruin, Y. *et al.* (2021) 'Enhancing the use of exposure science across EU chemical policies as part of the European Exposure Science Strategy 2020–2030', *Journal of*

Exposure Science and Environmental Epidemiology, (April). doi: 10.1038/s41370-021-00388-4.

Burke, J. M., Zufall, M. J. and Özkaynak, H. (2001) ‘A population exposure model for particulate matter: Case study results for PM2.5 in Philadelphia, PA’, *Journal of Exposure Analysis and Environmental Epidemiology*, 11(6), pp. 470–489. doi: 10.1038/sj.jea.7500188.

Burnett, R. *et al.* (2018) ‘Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter’, *Proceedings of the National Academy of Sciences*, 115(38), pp. 9592–9597. doi: 10.1073/pnas.1803222115.

Butler, Madhavan, and A. (2016) *Health Risks of Indoor Exposure to Particulate Matter, Health Risks of Indoor Exposure to Particulate Matter*. doi: 10.17226/23531.

Cai, Y. S., Gibson, H. and Rahimi, K. (2021) ‘Ambient air pollution and respiratory health in sub-Saharan African children: a cross-sectional analysis’, *ISEE Conference Abstracts*, 2021(1). doi: 10.1289/isee.2021.p-273.

Cantone, L. *et al.* (2011) ‘Inhalable metal-rich air particles and histone H3K4 dimethylation and H3K9 Acetylation in a Cross-sectional Study of Steel Workers’, *Environmental Health Perspectives*, 119(7), pp. 964–969. doi: 10.1289/ehp.1002955.

Chalvatzaki, E. *et al.* (2019) ‘Characterization of human health risks from particulate air pollution in selected European cities’, *Atmosphere*, 10(2), pp. 1–16. doi: 10.3390/ATMOS10020096.

Chang, L. T. C. *et al.* (2019) ‘Major source contributions to ambient PM2.5 and exposures within the New South Wales Greater Metropolitan Region’, *Atmosphere*, 10(3). doi: 10.3390/atmos10030138.

Chen, X. *et al.* (2022) ‘Health risks of adults in Hong Kong related to inhalation of particle-bound heavy metal(loid)s’, *Air Quality, Atmosphere and Health*, 15(4), pp. 691–706. doi: 10.1007/s11869-021-01115-6.

Cities, S. and Martins, N. R. (2018) ‘Impact of PM2 . 5 in indoor urban environments : A review’, (July). doi: 10.1016/j.scs.2018.07.011.

Da Costa (2020) ‘Requested by the PETI committee The environmental impacts of plastics and micro-plastics use , waste and pollution : EU and national measures’, (October).

Darbre, P. D. (2018) ‘Overview of air pollution and endocrine disorders’, *International Journal of General Medicine*, 11, pp. 191–207. doi: 10.2147/IJGM.S102230.

Debela, S. A. *et al.* (2021) ‘Assessment of Perceptions and Cancer Risks of Workers at a Polychlorinated Biphenyl-Contaminated Hotspot in Ethiopia’, *Journal of Health and Pollution*, 11(30), pp. 1–19. doi: 10.5696/2156-9614-11.30.210609.

Dias, D. and Tchepel, O. (2018) ‘Spatial and Temporal Dynamics in Air Pollution Exposure Assessment’. doi: 10.3390/ijerph15030558.

Dominici, F. *et al.* (2019) ‘R E S E A R C H R E P O RT’, 5505(200).

Dong, X. *et al.* (2020) ‘Population based Air Pollution Exposure and its influence factors by Integrating Air Dispersion Modeling with GIS Spatial Analysis’, *Scientific Reports*, 10(1), pp. 1–12. doi: 10.1038/s41598-019-57385-9.

Van Donkelaar, A. *et al.* (2015) ‘Use of satellite observations for long-term exposure assessment of global concentrations of fine particulate matter’, *Environmental Health Perspectives*, 123(2), pp. 135–143. doi: 10.1289/ehp.1408646.

Edlund, K. K. *et al.* (2021) ‘Health risk assessment of pm2.5 and pm2.5-bound trace elements in thohoyandou, south africa’, *International Journal of Environmental Research and Public Health*, 18(3), pp. 1–12. doi: 10.3390/ijerph18031359.

Elmes, M. and Gasparon, M. (2017) ‘Sampling and single particle analysis for the chemical characterisation of fine atmospheric particulates: A review’, *Journal of Environmental Management*, 202, pp. 137–150. doi: 10.1016/j.jenvman.2017.06.067.

EPA, U. (2012) ‘Environmental Health Risk Assessment’, *Environmetal Protection Agency*.

Ethan, C. J., Mokoena, K. K. and Yu, Y. (2021) ‘Air pollution status in 10 mega-cities in china during the initial phase of the covid-19 outbreak’, *International Journal of Environmental Research and Public Health*, 18(6), pp. 1–15. doi: 10.3390/ijerph18063172.

Ferguson, L. *et al.* (2020) ‘Exposure to indoor air pollution across socio-economic groups in high-income countries: A scoping review of the literature and a modelling methodology’, *Environment International*, 143(April), p. 105748. doi: 10.1016/j.envint.2020.105748.

Forouzanfar, M. H. *et al.* (2015) ‘Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: A systematic analysis for the Global Burden of Disease Study 2013’, *The Lancet*, 386(10010), pp. 2287–2323. doi: 10.1016/S0140-6736(15)00128-2.

Fortoul *et al.* (2011) *Air Pollution and Its Effects in the Respiratory System.* INTECH Open Access Publisher.

Frey (2014) ‘United States Environmental Protection Agency’, *Proceedings of the Water Environment Federation*, 2005(16), pp. 726–737. doi: 10.2175/193864705783867675.

Gehrke, I., Dresen, B. and Blömer, J. (2020) ‘Modelling the distribution of tyre wear particles in Germany’, *29th Aachen Colloquium Sustainable Mobility 2020*, p. 10.

Giannopoulos, G., Filippini, R. and Schimmer, M. (2012) *Risk assessment methodologies for Critical Infrastructure Protection. Part I: A state of the art.*, *European Commission JRC*

(Joint Research Center) Technical notes. doi: 10.2788/22260.

Green, P. *et al.* (2022) ‘Exploring PM2.5 variations from a low-cost sensor network in Greater Kampala, during COVID-19 imposed lockdown restrictions: Lessons for policy’, *Clean Air Journal*, 32(1), pp. 1–14. doi: 10.17159/caj/2022/32/1.10906.

Griffin, R. J. (2013) ‘The Sources and Impacts of Tropospheric Particulate Matter’, *Nature Education Knowledge*, 4(5), p. 1. Available at: http://www.nature.com/scitable/knowledge/library/the-sources-and-impacts-of-tropospheric-particulate-102760478.

Hamanaka, R. B. and Mutlu, G. M. (2018) ‘Particulate Matter Air Pollution: Effects on the Cardiovascular System’, *Frontiers in Endocrinology*, 9(November), pp. 1–15. doi: 10.3389/fendo.2018.00680.

Hayes, R. B. *et al.* (2020) ‘PM2.5 air pollution and cause-specific cardiovascular disease mortality’, *International Journal of Epidemiology*, 49(1), pp. 25–35. doi: 10.1093/ije/dyz114.

Hernández-Pellón, A. and Fernández-Olmo, I. (2019) ‘Airborne concentration and deposition of trace metals and metalloids in an urban area downwind of a manganese alloy plant’, *Atmospheric Pollution Research*, 10(3), pp. 712–721. doi: 10.1016/j.apr.2018.11.009.

Hobson, D. W. and Guy, R. C. (2014) ‘Nanotoxicology’, *Encyclopedia of Toxicology: Third Edition*, pp. 434–436. doi: 10.1016/B978-0-12-386454-3.01045-9.

Hodas, N. *et al.* (2016) ‘Indoor inhalation intake fractions of fine particulate matter: review of influencing factors’, *Indoor Air*. doi: 10.1111/ina.12268.

Hoeflinger, W. and Laminger, T. (2019) ‘Journal of the Taiwan Institute of Chemical Engineers PM2 . 5 or respirable dust measurement and their use for assessment of dust separators’, *Journal of the Taiwan Institute of Chemical Engineers*, 94, pp. 53–61. doi: 10.1016/j.jtice.2017.07.035.

Hoek, G. *et al.* (2008) ‘Indoor-outdoor relationships of particle number and mass in four European cities’, *Atmospheric Environment*, 42(1), pp. 156–169. doi: 10.1016/j.atmosenv.2007.09.026.

Horne, B. D. *et al.* (2018) ‘Short-Term Elevation of Fine Particulate Matter Air Pollution and Acute Lower Respiratory Infection’, 198, pp. 759–766. doi: 10.1164/rccm.201709-1883OC.

Housing Development Agency (2013) ‘South Africa: Informal settlements status 2013’, (August), pp. 1–61. Available at: http://www.thehda.co.za/uploads/files/HDA_South_Africa_Report_lr.pdf.

Hussein, T. *et al.* (2018) ‘Accumulation and coarse mode aerosol concentrations and carbonaceous contents in the urban background atmosphere in Amman, Jordan’, *Arabian*

Journal of Geosciences, 11(20). doi: 10.1007/s12517-018-3970-z.

Hwang, Y. *et al.* (2016) ‘Determination of Similar Exposure Groups Using Weekday Time Activity Patterns of Urban Populations’, 42(December), pp. 353–364.

Ji, W. and Zhao, B. (2015) ‘Estimating mortality derived from indoor exposure to particles of outdoor origin’, *PLoS ONE*, 10(4), pp. 1–15. doi: 10.1371/journal.pone.0124238.

Jiřík, V. *et al.* (2016) ‘Air pollution and potential health risk in Ostrava region – A review’, *Central European Journal of Public Health*, 24(88), pp. S4–S17. doi: 10.21101/cejph.a4533.

Karachaliou, T. *et al.* (2016) ‘Using Risk Assessment and Management Approaches to Develop Cost-Effective and Sustainable Mine Waste Management Strategies’, *Recycling*, 1(3), pp. 328–342. doi: 10.3390/recycling1030328.

Katoto, P. D. M. C. *et al.* (2019) ‘Ambient air pollution and health in Sub-Saharan Africa: Current evidence, perspectives and a call to action.’, *Environmental Research*, 173(March), pp. 174–188. doi: 10.1016/j.envres.2019.03.029.

Khallaf, M. K. (2011) *THE IMPACT OF AIR POLLUTION ON HEALTH , ECONOMY , ENVIRONMENT AND.*

Khillare, P. S. and Sarkar, S. (2012) ‘Atmospheric Pollution Research Airborne inhalable metals in residential areas of Delhi , India : distribution , source apportionment and health risks’, *Atmospheric Pollution Research*, 3(1), pp. 46–54. doi: 10.5094/APR.2012.004.

Kim, H., Kang, K. and Kim, T. (2020) ‘Effect of occupant activity on indoor particle concentrations in Korean residential buildings’, *Sustainability (Switzerland)*, 12(21), pp. 1–19. doi: 10.3390/su12219201.

Koenig, J. Q. (2000) ‘Health Effects of Particulate Matter’, *Health Effects of Ambient Air Pollution*, pp. 115–137. doi: 10.1007/978-1-4615-4569-9_10.

Kumar, A. *et al.* (2014) ‘Assessment of indoor air concentrations of VOCs and their associated health risks in the library of Jawaharlal Nehru University, New Delhi’, *Environmental Science and Pollution Research*, 21(3), pp. 2240–2248. doi: 10.1007/s11356-013-2150-7.

Landrigan, P. J. (2017) ‘Air pollution and health’, *The Lancet*, 2. doi: http://dx.doi.org/10.1016/.

Lee, S. C. *et al.* (2006) ‘PM1.0 and PM2.5 characteristics in the roadside environment of Hong Kong’, *Aerosol Science and Technology*, 40(3), pp. 157–165. doi: 10.1080/02786820500494544.

Leech, J. A. *et al.* (2002) ‘It ’ s about time : A comparison of Canadian and American time – activity patterns y’, pp. 427–432. doi: 10.1038/sj.jea.7500244.

Leung, D. Y. C. (2015) ‘Outdoor-indoor air pollution in urban environment: Challenges and opportunity’, *Frontiers in Environmental Science*, 2(JAN), pp. 1–7. doi: 10.3389/fenvs.2014.00069.

Li, J. *et al.* (2021) ‘Field-based evidence of changes in household PM2.5 and exposure during the 2020 national quarantine in China’, *Environmental Research Letters*, 16(9). doi: 10.1088/1748-9326/ac1014.

Lin, Y. *et al.* (2018) ‘A review of recent advances in research on PM2.5 in China’, *International Journal of Environmental Research and Public Health*, 15(3). doi: 10.3390/ijerph15030438.

Liu, L. J. S. *et al.* (2003) ‘Exposure assessment of particulate matter for susceptible populations in Seattle’, *Environmental Health Perspectives*. Public Health Services, US Dept of Health and Human Services, pp. 909–918. doi: 10.1289/ehp.6011.

Lowther, S. D. *et al.* (2019) ‘Particulate Matter Measurement Indoors : A Review of Metrics , Sensors , Needs , and Applications’. doi: 10.1021/acs.est.9b03425.

Lyon, S. B. (2010) ‘Corrosion of lead and its alloys’, *Shreir’s Corrosion*, (June), pp. 2053–2067. doi: 10.1016/B978-044452787-5.00098-6.

Marques, G. *et al.* (2020) ‘Indoor Air Quality Monitoring Systems for Enhanced Living Environments : A Review toward Sustainable Smart Cities’.

Marris, H. *et al.* (2012) ‘Science of the Total Environment Fast changes in chemical composition and size distribution of fi ne particles during the near- fi eld transport of industrial plumes’, *Science of the Total Environment, The*, 427–428, pp. 126–138. doi: 10.1016/j.scitotenv.2012.03.068.

Masekameni *et al.* (2018) ‘Risk Assessment of Benzene, Toluene, Ethyl Benzene, and Xylene Concentrations from the Combustion of Coal in a Controlled Laboratory Environment’, *International Journal of Environmental Research and Public Health*, 16(1), p. 95. doi: 10.3390/ijerph16010095.

Masekameni, D. (2017) ‘Xenobiotic Particle Emission Formation in Fixed-Bed Domestic Coal Combustion Daniel Masilu Masekameni’, 0002(August).

Masih, A. *et al.* (2016) ‘Inhalation exposure and related health risks of BTEX in ambient air at different microenvironments of a terai zone in north India’, *Atmospheric Environment*, 147, pp. 55–66. doi: 10.1016/j.atmosenv.2016.09.067.

Masih, A. *et al.* (2017) ‘Exposure profiles, seasonal variation and health risk assessment of BTEX in indoor air of homes at different microenvironments of a terai province of northern India’, *Chemosphere*, 176, pp. 8–17. doi: 10.1016/j.chemosphere.2017.02.105.

Matz, C. J. *et al.* (2014) ‘Effects of age, season, gender and urban-rural status on time-activity: Canadian human activity pattern survey 2 (CHAPS 2)’, *International Journal of Environmental Research and Public Health*, 11(2), pp. 2108–2124. doi: 10.3390/ijerph110202108.

Mbazima, S. J., Masekameni, M. D. and Nelson, G. (2021) ‘Physicochemical Properties of Indoor and Outdoor Particulate Matter 2.5 in Selected Residential Areas near a Ferromanganese Smelter’, *International Journal of Environmental Research and Public Health*, 18(17), p. 8900. doi: 10.3390/ijerph18178900.

Melki, P. (2019) ‘Health impact of airborne particulate matter in Northern Lebanon : from a pilot epidemiological study to physico-chemical characterization and toxicological effects assessment To cite this version : HAL Id : tel-02088915 by NORTHERN LEBANON : FROM A PILOT’.

Meri, J. *et al.* (2018) ‘Chemosphere Trends in analytical techniques applied to particulate matter characterization : A critical review of fundaments and applications’, 199. doi: 10.1016/j.chemosphere.2018.02.034.

Mioduszewski, R. *et al.* (2002) ‘Interaction of exposure concentration and duration in determining acute toxic effects of sarin vapor in rats’, *Toxicological Sciences*, 66(2), pp. 176–184. doi: 10.1093/toxsci/66.2.176.

Mitali Parvin Promoter (2014) ‘Mitali Parvin’, *Indoor-Outdoor Volatile Organic Compounds (VOCs) levels in Urban and Industrial Area of Dhaka City, Bangladesh*.

Moletsane, S. D. *et al.* (2021) ‘Research article Intra-urban variability of PM2.5in a dense, low-income settlement on the South African Highveld’, *Clean Air Journal*, 31(1), pp. 1–9. doi: 10.17159/CAJ/2021/31/1.9413.

Moolla, R. *et al.* (2013) ‘Occupational health risk assessment of benzene and toluene at a landfill site in Johannesburg, South Africa’, *WIT Transactions on the Built Environment*, 134, pp. 701–712. doi: 10.2495/SAFE130631.

Morakinyo, O. M. *et al.* (2017) ‘Health risk of inhalation exposure to sub-10 µm particulate matter and gaseous pollutants in an urban-industrial area in South Africa : an ecological study’, pp. 1–9. doi: 10.1136/bmjopen-2016-013941.

Ngyende, A. (2012) ‘Statistical Release’, *The Journal of Thoracic and Cardiovascular Surgery*, 143(1), pp. A27–A28. doi: 10.1016/s0022-5223(11)01322-5.

Nishida, R. T. *et al.* (2020) ‘A Simple Method for Measuring Fine-to-Ultrafine Aerosols Using Bipolar Charge Equilibrium’, *ACS Sensors*, 5(2), pp. 447–453. doi: 10.1021/acssensors.9b02143.

O’Neal, S. L. *et al.* (2014) ‘Manganese accumulation in bone following chronic exposure in rats: Steady-state concentration and half-life in bone’, *Toxicology Letters*, 229(1), pp. 93–100. doi: 10.1016/j.toxlet.2014.06.019.

Obaidullah, M. *et al.* (2012) ‘A review on particle emissions from small scale biomass combustion’, *International Journal of Renewable Energy Research*, 2(1), pp. 147–159.

Olawoyin, R. (2018) ‘Adverse Human Health Impacts in the Anthropocene’, *Environmental Health Insights*, 12. doi: 10.1177/1178630218812791.

Olufemi, A. C. and Mji, A. (2019) ‘Health risks of exposure to air pollutants among students in schools in the vicinities of coal mines’. doi: 10.1177/0144598718765489.

Palmiotto, M. *et al.* (2014) ‘Influence of a municipal solid waste landfill in the surrounding environment: Toxicological risk and odor nuisance effects’, *Environment International*, 68, pp. 16–24. doi: 10.1016/J.ENVINT.2014.03.004.

Panda, S. and Shiva Nagendra, S. M. (2018) ‘Chemical and morphological characterization of respirable suspended particulate matter (PM10) and associated heath risk at a critically polluted industrial cluster’, *Atmospheric Pollution Research*, 9(5), pp. 791–803. doi: 10.1016/j.apr.2018.01.011.

Park, B. R. *et al.* (2021) ‘Estimation of Outdoor PM 2 . 5 Infiltration into Multifamily Homes Depending on Building Characteristics Using Regression Models’.

Pongpiachan, S., Iijima, A. and Cao, J. (2018) ‘Hazard quotients, hazard indexes, and cancer risks of toxic metals in PM10 during firework displays’, *Atmosphere*, 9(4), pp. 1–18. doi: 10.3390/atmos9040144.

Pope III, C. A. *et al.* (2002) ‘to Fine Particulate Air Pollution’, *The Journal of the American Medical Association*, 287(9), pp. 1132–1141. Available at: http://jama.jamanetwork.com/article.aspx?doi=10.1001/jama.287.9.1132.

Pramitha, E. and Haryanto, B. (2019) ‘Original article effect of exposure to 2.5 µm indoor particulate matter on adult lung function in Jakarta’, *Osong Public Health and Research Perspectives*, 10(2), pp. 51–55. doi: 10.24171/j.phrp.2019.10.2.02.

Riccelli, M. G. *et al.* (2020) ‘Welding fumes, a risk factor for lung diseases’, *International Journal of Environmental Research and Public Health*, 17(7). doi: 10.3390/ijerph17072552.

Rice, K. M. *et al.* (2014) ‘Environmental mercury and its toxic effects’, *Journal of Preventive Medicine and Public Health*, 47(2), pp. 74–83. doi: 10.3961/jpmph.2014.47.2.74.

Rosenbaum, R. K. *et al.* (2015) ‘Indoor Air Pollutant Exposure for Life Cycle Assessment: Regional Health Impact Factors for Households’. doi: 10.1021/acs.est.5b00890.

Salvador, S. and Salvador, E. (2012) ‘Overview of Particle Air Pollution Air Quality

Communication Workshop’.

Santos, J. M. *et al.* (2017) ‘Source apportionment of settleable particles in an impacted urban and industrialized region in Brazil’, pp. 22026–22039. doi: 10.1007/s11356-017-9677-y.

Sethi, R. and Di Molfetta, A. (2019) ‘Human Health Risk Assessment’, in *Springer Tracts in Civil Engineering*. doi: 10.1007/978-3-030-20516-4_16.

Sommer, F. *et al.* (2018) ‘Tire abrasion as a major source of microplastics in the environment’, *Aerosol and Air Quality Research*, 18(8), pp. 2014–2028. doi: 10.4209/aaqr.2018.03.0099.

Stanislawska, M. *et al.* (2017) ‘Coarse, fine and ultrafine particles arising during welding - Analysis of occupational exposure’, *Microchemical Journal*, 135, pp. 1–9. doi: 10.1016/j.microc.2017.06.021.

StatsSA (2017) ‘P0302: Mid-year population estimates 2017’, *Stats Sa*, (July), p. 10. doi: Statistical release P0302.

Steinle, S. *et al.* (2015) ‘Personal exposure monitoring of PM2.5 in indoor and outdoor microenvironments’, *Science of the Total Environment*, 508, pp. 383–394. doi: 10.1016/j.scitotenv.2014.12.003.

Sun, X. *et al.* (2015) ‘The association between fine particulate matter exposure during pregnancy and preterm birth : a meta-analysis’, *BMC Pregnancy and Childbirth*, pp. 1–12. doi: 10.1186/s12884-015-0738-2.

Taiwo, A. M. *et al.* (2014) ‘Science of the Total Environment Mass and number size distributions of particulate matter components : Comparison of an industrial site and an urban background site’, *Science of the Total Environment, The*, 475, pp. 29–38. doi: 10.1016/j.scitotenv.2013.12.076.

Teklay (2016) ‘Physiological Effect of Chromium Exposure: A Review’, *International Journal of Food Science, Nutrition and Dietetics*, pp. 1–11. doi: 10.19070/2326-3350-si07001.

Tóth, A. *et al.* (2014) ‘Atmospheric tar balls: Aged primary droplets from biomass burning?’, *Atmospheric Chemistry and Physics*, 14(13), pp. 6669–6675. doi: 10.5194/acp-14-6669-2014.

Tran, P. T. M., Ngoh, J. R. and Balasubramanian, R. (2020) ‘Assessment of the integrated personal exposure to particulate emissions in urban micro-environments: A pilot study’, *Aerosol and Air Quality Research*, 20(2), pp. 341–357. doi: 10.4209/aaqr.2019.04.0201.

Van Tran, V., Park, D. and Lee, Y. C. (2020) ‘Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality’, *International Journal of Environmental Research and Public Health*, 17(8). doi: 10.3390/ijerph17082927.

U. S. Environmental Protection Agency (2010) ‘Quantitative Health Risk Assessment for Particulate Matter’, *U. S. Environmental Protection Agency*, pp. 1–596. Available at: http://www.epa.gov/ttn/naaqs/standards/pm/data/PM_RA_FINAL_June_2010.pdf%5Cnpapers2://publication/uuid/36AC0D6B-29A0-4A0F-A8B5-699617A33A15.

USEPA (1997) ‘Locating and estimating air emissions from sources of mercury and mercury compounds’, (December).

USEPA (2004) ‘Risk assessment guidance for superfund (RAGS). Volume I. Human health evaluation manual (HHEM). Part E. Supplemental guidance for dermal risk assessmentUSEPA, 2004. Risk assessment guidance for superfund (RAGS). Volume I. Human health evaluation manual (H’, *US Epa*, 1(540/R/99/005), pp. 1–156. doi: EPA/540/1-89/002.

USEPA (2012) *Existing Default Values and Recommendations for Exposure Assessment A Nordic Exposure Group Project 2011*.

USEPA CHAD (2012) ‘THE CONSOLIDATED HUMAN ACTIVITY’.

Vardoulakis, S. *et al.* (2020) ‘Indoor exposure to selected air pollutants in the home environment: A systematic review’, *International Journal of Environmental Research and Public Health*. MDPI AG, pp. 1–24. doi: 10.3390/ijerph17238972.

Verhoeven, W. M., Egger, J. I. and Kuijpers, H. J. (2011) ‘Manganese and acute paranoid psychosis: A case report’, *Journal of Medical Case Reports*, 5(1), p. 146. doi: 10.1186/1752-1947-5-146.

Viana, M. *et al.* (2014) ‘Indoor / outdoor relationships and mass closure of quasi-ultrafine , accumulation and coarse particles in Barcelona schools’, pp. 4459–4472. doi: 10.5194/acp-14-4459-2014.

Wang, J. *et al.* (2015) ‘Assessment of short-term PM2.5-related mortality due to different emission sources in the Yangtze River Delta, China’, *Atmospheric Environment*, 123, pp. 440–448. doi: 10.1016/j.atmosenv.2015.05.060.

WHO (1998) ‘WHO guidelines for air quality.’, *Indian pediatrics*, 35(8), pp. 812–815.

WHO (2017) ‘Global Burden of Disease Study 2017’, *The Lancet*, pp. 1–7.

WHO Regional Office for Europe (2016) ‘Health Risk Assessment of air pollution’, *World Health Organization*, pp. 1–40. Available at: https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution%0Ahttp://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-t.

Wiston, M. (2017) ‘Status of Air Pollution in Botswana and Significance to Air Quality and

Human Health', 7(15).

World Health Organization (2014) 'Burden of disease from household air pollution for 2012. Summary of results', *World Health Organization*, 35(February), pp. 2012–2014. Available at: http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf.

Xu, M. *et al.* (2011) 'Coal combustion-generated aerosols: Formation and properties', *Proceedings of the Combustion Institute*, 33(1), pp. 1681–1697. doi: 10.1016/j.proci.2010.09.014.

Yang, L. *et al.* (2017) 'The Correlation between Indoor and Outdoor Particulate Matter of Different Building Types in Daqing, China', *Procedia Engineering*, 205, pp. 360–367. doi: 10.1016/j.proeng.2017.10.002.

Yanga, B.-Y. *et al.* (2019) 'Ambient PM1 air pollution and cardiovascular disease prevalence: Insights from the 33 Communities Chinese Health Study', *Environmental International*, 123, pp. 310–317.

Yao, L. and Lu, N. (2014) 'Particulate matter pollution and population exposure assessment over Mainland China in 2010 with remote sensing', *International Journal of Environmental Research and Public Health*, 11(5), pp. 5241–5250. doi: 10.3390/ijerph110505241.

Zauli-Sajani, S. *et al.* (2018) 'Higher health effects of ambient particles during the warm season: The role of infiltration factors', *Science of the Total Environment*, 627, pp. 67–77. doi: 10.1016/j.scitotenv.2018.01.217.

Zhang, H. *et al.* (2014) 'Anthropogenic mercury enrichment factors and contributions in soils of Guangdong Province, South China', *Journal of Geochemical Exploration*, 144, pp. 312–319. doi: 10.1016/j.gexplo.2014.01.031.

Zhang, L. *et al.* (2021) 'Indoor particulate matter in urban households: Sources, pathways, characteristics, health effects, and exposure mitigation', *International Journal of Environmental Research and Public Health*, 18(21). doi: 10.3390/ijerph182111055.

Zhang, T. *et al.* (2016) 'Characteristics of Fine Particles in an Urban Atmosphere — Relationships with Meteorological Parameters and Trace Gases', pp. 1–16. doi: 10.3390/ijerph13080807.

Zhang, Y. *et al.* (2012) 'Levels , sources and health risks of carbonyls and BTEX in the ambient air of', *Journal of Environmental Sciences*, 24(1), pp. 124–130. doi: 10.1016/S1001-0742(11)60735-3.

Zhang, Z. *et al.* (2018) 'Long-term exposure to fine particulate matter, blood pressure, and incident hypertension in taiwanese adults’, *Environmental Health Perspectives*, 126(1), pp. 1–8. doi: 10.1289/EHP2466.

Zhao, J. *et al.* (2020) ‘Particle mass concentrations and number size distributions in 40 homes in germany: Indoor-to-outdoor relationships, diurnal and seasonal variation’, *Aerosol and Air Quality Research,* 20(3), pp. 576–589. doi: 10.4209/aaqr.2019.09.0444.

Zulaikhah, S. T., Wahyuwibowo, J. and Pratama, A. A. (2020) ‘Mercury and its effect on human health : a review of the literature Mercury and its effect on human health : a review of the literature’, (June). doi: 10.11591/ijphs.v9i2.20416.

Appendix A: Plagiarism declaration form

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

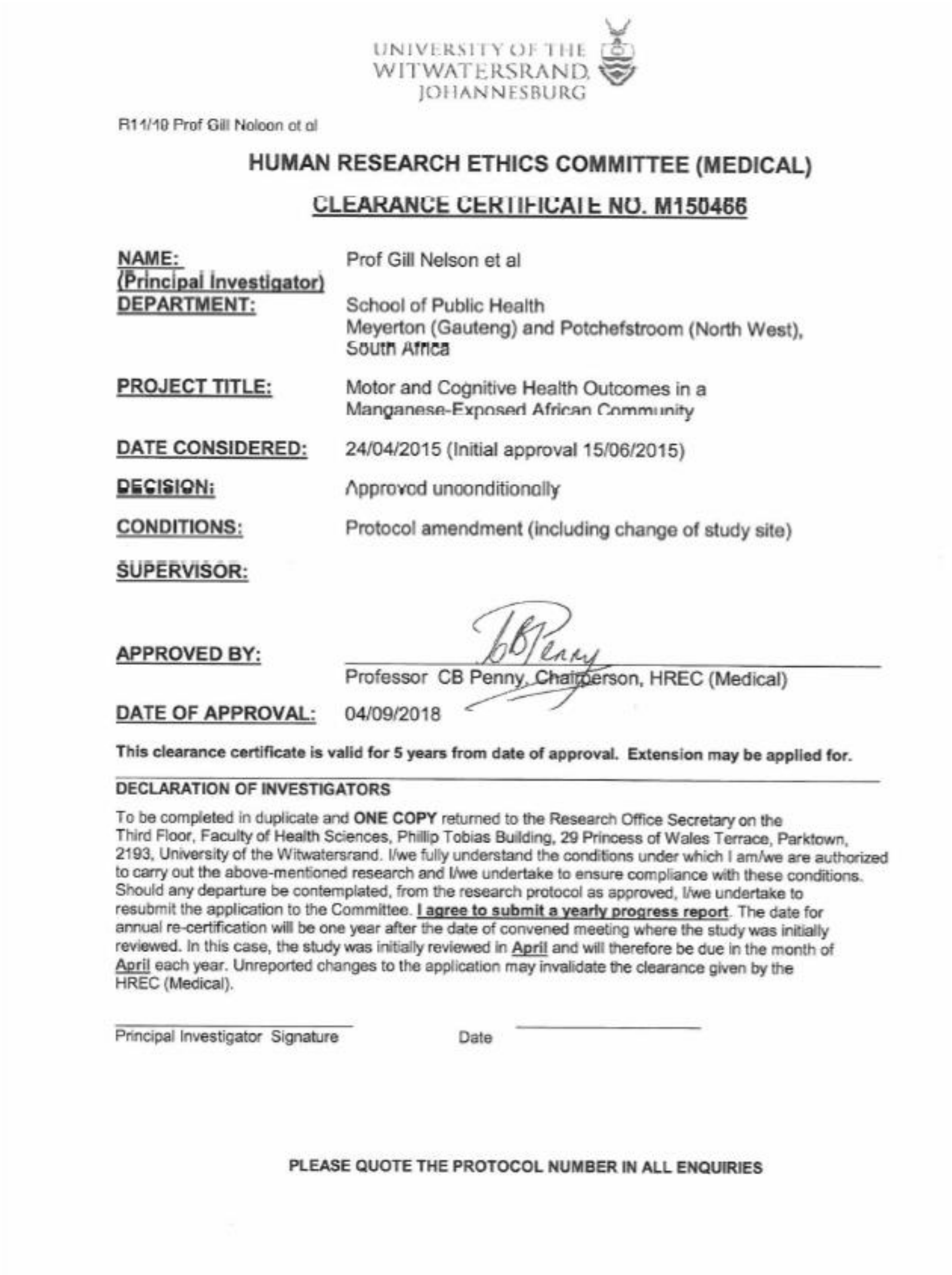
I **GOODWILL JOPA ZIMAKAZI KHOZA** (Student number: **9601106K**) am a student registered for the degree of **MASTER OF PUBLIC HEALTH (OH)** in the academic year **2022**.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.

Signature: Goodwill Khoiza Date: **22 August 2022**

Appendix B: Research ethics clearance certificate



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

R14/49 Prof Gill Nelson et al

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M150466

NAME: **(Principal Investigator)**	Prof Gill Nelson et al
DEPARTMENT:	School of Public Health Meyerton (Gauteng) and Potchefstroom (North West), South Africa
PROJECT TITLE:	Motor and Cognitive Health Outcomes in a Manganese-Exposed African Community
DATE CONSIDERED:	24/04/2015 (Initial approval 15/06/2015)
DECISION:	Approved unconditionally
CONDITIONS:	Protocol amendment (including change of study site)
SUPERVISOR:	
APPROVED BY:	CB Penny Professor CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL:	04/09/2018

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**. The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **April** and will therefore be due in the month of **April** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature ____________ Date ____________

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES