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Reporting Silica Dust Exposure Measurements in South African Gold and Coal Mines: 2005 to 2016

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Mongoma, Brian Tshepo. (2023). Reporting Silica Dust Exposure Measurements in South African Gold and Coal Mines: 2005 to 2016. [Masters dissertation, University of the Witwatersrand, Johannesburg]. WIReDSpace. https://hdl.handle.net/10539/44824

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REPORTING SILICA DUST EXPOSURE CONCENTRATIONS IN SOUTH AFRICAN GOLD AND COAL MINES: 2005 TO 2016

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A Research report submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Public Health

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Supervisor 2: Prof. Derk Brouwer

Johannesburg, October 2023

DECLARATION

I, **Brian Tshepo Mongoma**, student number 330338, hereby declare that **Reporting Silica Dust Exposure Measurements in South African Gold and Coal Mines: 2005 to 2016** is entirely my own and has not received any outside assistance. I am submitting it for consideration for the degree of Master of Public Health with a focus on occupational hygiene at the University of the Witwatersrand in Johannesburg. This particular piece of work has not been presented for assessment or certification at any other academic institution before. Any sources from external authors that have been incorporated into this research have been appropriately acknowledged and referenced.



24 October 2023 in Johannesburg

ACKNOWLEDGEMENTS

Thanks to the following for the encouragement and support:

- Mrs Kelebogile Mongoma (Wife)
- Dr Vukosi Banyini
- Mr Vijay Nundlall
- Professor Gill Nelson
- Professor Derk Brouwer
- Dr Lindiwe Ndelu
- Mrs Bridget Novolo
- Mrs Constance Kekana

ABSTRACT

Background: Arising from the Mine Health and Safety Act 29 of 1996 (MHSA), one of the measures to protect mine workers is monitoring exposure to airborne pollutants. Mines are statutorily required to report airborne pollutant concentrations to the Department of Mineral Resources and Energy (DMRE) on a regular basis. Based on the DMRE's 2013 report, it was determined that 76% of workers were exposed to airborne pollutants at concentrations less than 10% of their respective occupational exposure limits (OELs). Using the same exposure data from the DMRE, the Chamber of Mines of South Africa reported a 14% improvement in the exposure to the airborne pollutants from 2005 to 2013. However, these reported reduced exposures to airborne pollutants are based on the summation of all airborne pollutant exposures by the DMRE. The annual reports refer to the percentage of employees exposed to the combined airborne pollutants, rather than to specific pollutants, such as silica dust – a hazard that is high on the occupational health agenda of the mining industry. From these reports, broad (and perhaps incorrect) conclusions are reached with regard to trends in silica dust and other exposures. The limitations of the SAMI include inaccurate data, self-regulation, incomplete employment and exposure records, and historical biases, which hinder its ability to effectively handle occupational health risks. This emphasizes the immediate need for clear and consistent regulations, accurate data collection, and impartial research approaches to protect the health of mine workers.

Objectives: The objectives of this study were to describe trends in combined airborne pollutant and silica dust concentrations from 2005 to 2016, and to evaluate the DMRE Mandatory Code of Practice (MCoP) and the EN 689 methods (for testing exposure levels in the workplace against the OEL of 0.1 mg/m^3) as published by the European Committee for Standardization (CEN), using reported silica dust concentrations from 2015 and 2016.

Methods: This was a cross-sectional study in which secondary airborne pollutants exposure data, reported to the DMRE by coal and gold mining members of the Minerals Council, were analysed. The 282 870 data points were pooled together to describe trends in airborne pollutant exposures as they comprised 69 airborne pollutants reported by different mines with various mining methods, activities, and occupations. The exposure data was categorized into coal and gold mines, and further into four three-yearly periods (i.e. period 1: 2005-2007, period 2: 2008-2010, period 3: 2011-2013, and period 4: 2014-2016). This was conducted in order to have a consistent metric to allow for uniform assessment across different pollutants with varying OELs. Dividing the exposure concentration by its OEL provided a ratio, similarly to the way that an Air Quality Index is

calculated. As a result, the data was normalized by dividing each pollutant exposure concentration by its occupational exposure limit (OEL) to obtain a ratio, termed Q. The arithmetic mean, standard deviation, geometric mean, and geometric standard deviation of the Qs were calculated for each of the three groups i.e. coal and gold mines combined, b) coal mines, and c) gold mines, for each period. Jeffreys's Amazing Statistics Program was used to analyse the Qs and silica dust concentrations. The Kruskal–Wallis test was used to identify statistically significant differences among the four time periods for each commodity group. Additionally, Scheffe's post-hoc test in JASP was conducted for further analysis and comparison of differences across all observed periods. Two methods, namely the EN 689 and the method required by the DMRE MCoP, were used to assess compliance. EXPOSTATS Tool 1 was used to calculate the arithmetic mean (AM), median, standard deviation (SD), geometric mean (GM), geometric standard deviation (GSD), and 90^{th} and 95^{th} percentiles of the exposure data derived from EN 689. Microsoft Excel was used to calculate the 90^{th} and 95^{th} percentiles of the exposure data based on MCoP method. A total of 127 014 silica dust data points from 2005 to 2016 out of the 282 870 were utilized to describe silica dust exposure trends, and 44 990 data points from the 127 014 were used to assess compliance for the years 2015 and 2016.

Results: A total of 282 870 personal airborne pollutant concentrations from 2005 to 2016, obtained from DMRE, were included the analysis. Analysis of the pooled airborne pollutant exposure concentrations indicated that there was a high variability (data points were far apart and also far from the GM) as the GSDs ranged from 6.37 to 7.53, 7.8 to 8.43, and 5.7 to 6.16 for the coal and gold mines combined, coal mines alone, and gold mines alone, respectively. The variabilities of the silica dust concentrations were less than that of the pooled airborne pollutant data. The GSDs of the silica dust concentrations were < 3.5 for all three groups compared to the GSDs calculated from the pooled airborne pollutants concentrations, where the lowest GSD was 5.7. The trends in the pooled airborne pollutant exposure concentrations over the 12-year period, for all three groups, showed that there was a reduction in reported exposures to combined airborne pollutants. The AMs of the ratios (Q) indicated that the reduction in exposures for coal and gold mines combined, gold mining alone and coal mining alone, were 57%, 55% and 26%, respectively. The corresponding GMs of the ratios (Q) for gold mining alone, coal and gold mines combined, and coal mining alone, reduced by 64%, 45% and 15%, respectively, from 2005 to 2016. The distribution of the airborne pollutant data was skewed, which affected AM more than GM, and resulted in differences between the two measures. This was evident in the gold mining data, where the AM decreased by 55% but the GM decreased by 64%. Data for the period 2005-2007 had the highest AM (1.54) and standard deviation (2.75),

suggesting that there were outliers. In this period, ratios (Q) ranged from 0.003 to 7.7, impacting the AM and creating a gap between median and AM values. From 2008 to 2010, the AM (1.26) and SD (2.04) decreased, showing reduced variability. A similar trend was observed from 2011 to 2013, with increased numbers of observations and further reduced variability. In 2014-2016, the AM decreased to 0.67 and SD to 1, indicating stability. The GMs for the coal and gold mines combined, coal mines alone and gold mines alone ranged from 0.17 to 0.31, from 0.22 to 0.28, and from 0.16 to 0.45, respectively.

The trends in reported silica dust concentrations in all three groups showed a reduction over the 12-year period. The AMs indicated that the reductions for coal and gold mines combined, gold mining alone and coal mining alone, were 61%, 38% and 34%, respectively. The GMs of the silica dust concentrations indicated that the reductions in exposures for coal and gold mines combined, coal mining alone, and gold mining alone, were 54%, 35% and 31%, respectively.

The AMs of the silica dust concentrations for coal and gold mines combined ranged from 0.17 to 0.44 mg/m^3, while the coal mines ranged from 0.67 to 1.02 mg/m^3 from 2005 to 2016. For gold mines, the AMs ranged from 0.13 to 0.23 mg/m^3. Similarly, the GMs of the silica dust concentrations for the coal and gold mines combined ranged from 0.11 to 0.24 mg/m^3, whereas coal mines ranged from 0.41 to 0.63 mg/m^3, and gold mines ranged from 0.09 to 0.13 mg/m^3. The 90th percentiles for the silica dust concentrations almost correlated with the AMs as they reduced by 67%, 40% and 34% for coal and gold mining combined, gold mining alone, and coal mining alone, respectively. The 90th percentiles for silica dust concentrations for the coal and gold mines ranged from 1.64 to 2.48 mg/m^3, and 0.29 to 0.51 mg/m^3, respectively. Although the trends indicated a reduction in exposure to silica dust concentrations, the AM, GM, 90th and 95th percentiles exceeded the OEL of 0.1 mg/m^3 for the entire study period for the three groups, except for the gold mines alone in 2016. In that year, the GM was 0.09 mg/m^3 (rounded to 0.1 mg/m^3). For coal mining only, the 90th percentiles ranged from 1.64 to 2.48 mg/m^3, whereas the 95th percentiles ranged from 2.16 to 3.16 mg/m^3. For gold mining only, the 90th percentiles ranged from 0.29 to 0.51 mg/m^3, and the 95th percentiles ranged from 0.35 - 0.63 mg/m^3.

A total of 44 990 silica dust concentrations were used from 2015 to 2016 to compare the 95th percentiles according to EN 689, and the 90th percentiles according to the MCoP. The DMRE MCoP method was shown to underestimate the exceedance of the occupational exposure limit by 5-26%, when compared with the EN 689 method.

Conclusion: Despite the variabilities and challenges associated with pooling the airborne pollutants concentrations in the coal and gold mining industries, exposures to the airborne pollutants in the three commodity groups decreased from 2005 to 2016. However, reporting employee exposure as pooled airborne pollutants concentrations is flawed and obscures exposures to individual pollutants such as silica dust. The three commodity groups showed a decrease in silica dust exposure measurements from 2005 to 2016. However, there was still overexposure to silica dust in the three groups (greater than the OEL of 0.1 mg/m^3). Inhalation of particles containing silica was higher in the coal than the gold mines, which is contradictory to what is known about the silica content of the ores in which the two commodities are found. The DMRE MCoP approach to compliance with silica dust levels underestimated the exceedance of the OEL in comparison to the EN 689's approach. The current DMRE reporting methodology, i.e. the pooling of all data, does not allow accurate reporting of silica dust exposures and as a result, it does not provide direction or support for carrying out measures to decrease exposure to silica dust. The MCoP method for compliance testing revealed higher 90th-percentiles for coal mining compared to the 90th-percentile estimated for the population (EN 689). For gold mining it was the opposite. The EN 689 method is a more precise means of estimating OEL compliance, which is crucial for managing silica dust and specific pollutant health hazards and should be used in favour of the method in the MCoP.

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ACRONYMS

ANOVA – Analysis of Variance

AQI – Air Quality Index

CIoM – Chief Inspector of Mines

DMRE – Department of Mineral Resources and Energy

HEG – Homogenous Exposure Group

JEM – Job Exposure Matrices

MCoP – Mandatory Code of Practice

MHSA – Mine Health and Safety Act No. 29 of 1996

MHSI – Mine Health and Safety Inspectorate

EN – Netherlands Norm-European Norm

NIOSH – U.S. National Institute of Occupational Safety and Health

OEL – Occupational Exposure Limit

PPM – Parts per million

SA – South African

SAMI – South African Mining Industry

SAMOHP – South African Mines Occupational Hygiene Program

SEG – Similar Exposure Group

TWA – Time Weighted Average

DEFINITIONS

Airborne pollutant – any substances that pose a risk to one's health consisting of various types such as dust, fumes, aerosols, gases, fibres, vapours, or mists.[1]

Air quality index – an index for reporting daily air quality.[2]

Exposure – a substance or element that can impact a person's physical condition, whether in a negative or positive manner, becomes a dosage upon entering their system. This dosage is described as a numeric approximation of the quantity of the substance that affects the individual or group in question during a specific exposure instance.[3,4]

HEG – a workforce consisting of individuals who encounter comparable levels of contaminants, to the point where inspecting the contaminant levels of any representative subset of the employees should produce findings that accurately reflect the entire group.[5]

OEL – the maximum quantity of hazardous material that laborers may come in contact with over their professional lives without causing detrimental health impacts to them or their offspring is referred to as an occupational exposure limit (OEL).[6]

EN 689 – method for testing exposure levels in the workplace against an occupational exposure limit.[7]

Sampling area – A region resulting from the fragmentation of a mine into one or more ventilation districts that share a common air inlet and outlet, but where the outlet is not utilized as an inlet for any other region.[1]

SEG – A group of employees with comparable exposure to a particular substance due to the similarity of the materials and techniques they handle, as well as their methods of task execution.[8]

Scope of the research and study report layout

This was a cross sectional study, comprising an analysis of secondary data from the gold and coal mining companies affiliated with the Minerals Council South Africa. Electronic personal airborne pollutant exposure concentrations from 2005 to 2016, from companies' reports, were accessed on the Department of Mineral Resources and Energy's (DMRE) information management system (Magic XPA system), and then exported into Microsoft Excel. The data were analysed using the Microsoft Excel, JASP (Jeffreys's Amazing Statistics Program, version 0.16.4) and Tool 1 of EXPOSTATS.

Chapter 1 describes how the mandatory code of practice (MCoP) requires the South African Mining Industry (SAMI) and the Department of Mineral Resources and Energy (DMRE) to report airborne pollutant exposures. It provides the background, problem statement, and the significance of the study, and states the research question, aim and objectives.

Chapter 2 comprises the literature review, which outlines the identified gap in research.

Chapter 3 describes the materials and methods used in the study: the study design, study setting, study population, data sources, study variables, and data management and analysis.

Chapter 4 presents the results of the analysis of personal airborne pollutant and silica dust concentrations from 2005 to 2016, as well as the results of the compliance assessment for the 2015 and 2016 silica dust concentrations, using the MCoP and EN 689 methods.

Chapter 5 covers the interpretation of the findings, discusses the strengths and limitations of the study, and provides some recommendations to improve the reporting of exposure to airborne pollutants.

Chapter 6 provides the conclusions reached from the analysis of the data.

CHAPTER 1: INTRODUCTION

This chapter describes how the Mine Health and Safety Act 29 of 1996 (MHSA) requires the South African Mining Industry (SAMI) to create and sustain a framework for monitoring occupational hygiene concentrations of airborne contaminants; and how the mandatory code of practice (MCoP) requires the SAMI and the Department of Mineral Resources and Energy (DMRE) to report airborne pollutant exposures. The nature and health effects of silica dust exposure are explained. The problem statement and significance of the study are provided, and the research question, aim and objectives are stated.

Background

Silica is the term used to describe the chemical compound silicon dioxide (SiO_2), which can exist as either a crystalline form known as quartz or a non-crystalline form known as amorphous.[9] In nature, alpha quartz (crystalline silica) is most commonly found in soil, rocks, and most mineral deposits,[9] and is released into the air during coal and gold mining activities.[10, 11] A study released in 2003 revealed that dust samples containing respirable airborne pollutants collected from 21 gold mines had silica levels ranging from 4.5% to 57%.[12] According to some reports, the amount of silica present in respirable coal dust is less than 5%.[12]

In the context of this research, exposure to silica dust pertains to the presence of respirable crystalline silica dust in the workplace. There is a causal link between silica dust exposure and silicosis,[13] which has the potential to advance to massive fibrosis, lead to an inability to breathe, and lead to death.[13] Silicosis has the potential to develop or worsen even after exposure to silica dust has stopped.[13] Between 1973 and 2013, it is estimated that no less than 1.2 million employees were employed in South Africa's gold mining sector, which involves significant exposure to silica dust.[14]

Being exposed to silica dust is linked to a higher likelihood of developing pulmonary tuberculosis (PTB), as reported by Hnizdo et al. (1998), Churchyard et al. (2004) and others.[15,16,17] Hnizdo et al. (1998) reported that silica dust that accumulates in the lungs poses a lifelong risk of PTB to miners, even if silicosis has not developed.[15] However, Ehrlich et al. (2021), in a recent meta-analysis, determined that miners with silicosis who are exposed to high levels of dust are more likely to contract tuberculosis than those without silicosis who are exposed to lower levels of dust.[14]

The inhalation of respirable dust puts all miners in danger.[12] Both coal and gold mining activities generate dust containing quartz, which places those who mine these commodities at risk of developing silicosis.[12,10] Silicosis is more likely to affect underground coal and gold miners due to the greater levels of dust present in their work environment. In contrast, surface miners are at a lower risk as the dust generated during their operations is dispersed by outdoor air.[10] The workers in gold mines who face the greatest danger of being exposed to silica dust are those in mining teams operating in stopes and development areas, as well as personnel such as team leaders, drill operators, scraper winch operators, tip operators, and locomotive drivers.[12] On the other hand, rock drillers in coal mines are the most vulnerable to silica exposure.[10]

To reduce the risk of silicosis in the mining industry, silica dust exposure concentrations need to be kept as low as possible. The Mine Health and Safety Act 29 of 1996 (MHSA) governs compliance regarding exposure to silica dust in mines in South Africa.[18] The Act states that an employer should comply with the occupational exposure limit (OEL) for silica dust of 0.1mg/m³, and also maintain a system for the regular measurement and recording of silica dust levels.[18]

For the mines to measure, record and report silica dust exposures, the 'Guideline for the Compilation of a Mandatory Code of Practice (MCoP) for an Occupational Health Programme on Personal Exposure to Airborne Pollutants' was issued under the MHSA in February 2002.[*5] The MCoP calls for each mine, where silica dust is a hazard, to monitor exposure. Personal exposure samples should be collected, and analysed by an accredited laboratory.[5] Both the personal silica dust exposure sampling methodology and laboratory analysis must comply with international best practices.[5] A mine must conduct personal exposure monitoring in an homogenous exposure group (HEG), which is defined as a set of workers who share comparable levels of exposure to pollutants, making it possible to obtain data representative of the entire group by monitoring a subset of these employees.[5] In 2002, the DMRE issued a Codebook for the South African Mines Occupational Hygiene Programme[1] (SAMOHP). For recording basic information that would assist the DMRE to ensure that the mines have established and maintained occupational hygiene systems for measuring and recording airborne pollutants and this included an airborne pollutant exposure DMRE reporting requirements (Appendix 2). Each specific pollutant (e.g. silica dust) is assigned a code and has its

[*] An updated guideline was issued on the 30th of April in 2018 (DMR 16/3/2/4-A1). Because the retrospective data under study was collected before this, the 2003 guideline is relevant for this report.

own OEL, which is regulated by the DMRE. Mines are required, by the MCoP, to sample pollutants to which employees within each HEG are exposed. Pollutant samples are collected at specified intervals. This sampling frequency is informed by the pollutant exposure concentrations (mg/m³ or ppm) determined from the year immediately preceding the assessment year. The mines must classify the HEGs into one of three categories, as described in Table 1. The 90th percentile personal exposure value of the specific pollutant concentrations determines whether a HEG is categorised as A (personal exposure level ≥ OEL), B (personal exposure level ≥ 50% of the OEL and < OEL), or C (personal exposure level ≥ 10% and < 50% of the OEL). A HEG is classified into a specific exposure category if both the arithmetic mean (AM) and the 90th percentile of the measurements taken for this group fall within that category.[19]

To begin with, exposure measurements for a given pollutant are arranged in ascending order, starting from the lowest concentration . (mg/m³ or ppm) and progressing to the highest. Each result (concentration) is assigned a number; a score of 1 is given to the least concentration observed, while the maximum concentration is assigned a score equivalent to the total number of samples gathered in the HEG. The total number of samples was multiplied by 0.9 to identify the sample that corresponds to the 90th percentile in a dataset, as indicated in the MCoP.[20] This 90th percentile measurement (concentration) is then assessed against the OEL of the specific pollutant to categorise the HEG as A, or B or C, with HEG A having the highest exposures.

The Air Quality Index (AQI) is used when different pollutants to which workers in a HEG are exposed, and such pollutant/s target and affect the same organ (e.g. the lungs).[21] The AQI is calculated by summing the dividends (exposure concentration divided by the relevant OEL) of the pollutant that is being reported.[19] Under the MCoP, the Air Quality Index (AQI) has been assigned an Occupational Exposure Limit (OEL) of 1 (unitless). To evaluate the combined effect of different pollutants acting on the same organ, the concentration of each pollutant is divided by its respective OEL, and the results are added to obtain a value that can be compared with an OEL of 1. Thereafter, a HEG can be categorised as A (value of mixture of exposures ≥ 1), or B (value of mixture of exposures ≥ 0.5 and <1), or C (value of mixture of exposures ≥ 0.1 and < 0.5).

Table 1. HEG categories based on exposure level, number of samples, frequency of sampling, and reporting for pollutants[1]

POLLUTANTS (EXCLUDING TOXIC GASES &VAPOURS)				
HEG CATEGORY	**PERSONAL EXPOSURE LEVEL (all airborne pollutants)**	**PERSONAL EXPOSURE LEVEL (silica dust (mg/m^3)**	**NUMBER OF SAMPLES TO BE TAKEN**	**FREQUENCY OF SAMPLING AND REPORTING TO THE DMRE**
A	Exposures ≥ the OEL or mixtures of exposures ≥1	≥ 0.1	†	Quarterly
B	Exposures ≥ 50% of the OEL and < OEL or mixtures of exposures ≥ 0.5 and <1	≥ 0.05 - < 0.1		Bi-annually
C	Exposures ≥ 10% of the OEL and < 50% of the OEL or mixtures of exposures ≥ 0.1 and < 0.5	≥ 0.01 < 0.05		Annually
TOXIC GASES & VAPOURS CATEGORIES				
A	Exposures ≥ the OEL or mixtures of exposures ≥1	NA	‡	Quarterly
B	Exposures ≥ 50% of the OEL and the OEL or mixtures of exposures ≥ 0.5 and 1	NA		Annually

The mines are required to submit hard copies of their signed exposure reports to the DMRE, with requirements as stated in Appendix 2 (DMRE reporting requirements), within a time frame of 60 days following the conclusion of the corresponding reporting period. The DMRE captures the exposure concentrations in a database: the Magic XPA information management system. Every year, the DMRE determines which airborne pollutant§ exposure concentrations within a HEG informs

† The number of samples to be taken is a minimum of 5% or 5 samples within each HEG per category.
‡ The number of samples to be taken is a minimum of 5% or 5 samples within each HEG per category.
§ e.g. crystalline silica quartz, particles not otherwise classified, coal dust, Picloram, lead, elemental, and inorganic compounds, arsenic & compounds, calcium carbonate respirable particulate, cychlohexane, iron oxide [dust & fume], acetaldehyde, manganese fume, n-Propyl acetate, chromium metal and inorganic compounds, welding fumes, carbon black.

whether a HEG fall into category A, B or C. Thereafter, the percentages of employees[**] (in all mines) that falls into categories A, B or C of the airborne pollutants by commodity, are calculated.

The percentage of employees exposed to a specific pollutant (e.g. silica dust) is not reported as the current method of reporting focuses on the percentage of employees exposed to all airborne pollutants combined (see Figure 1). It is therefore impossible to identify which individual pollutant, if any, is at a concentration above the OEL, which individual pollutant most workers are exposed to, and which contaminants present a danger to the well-being of employees.

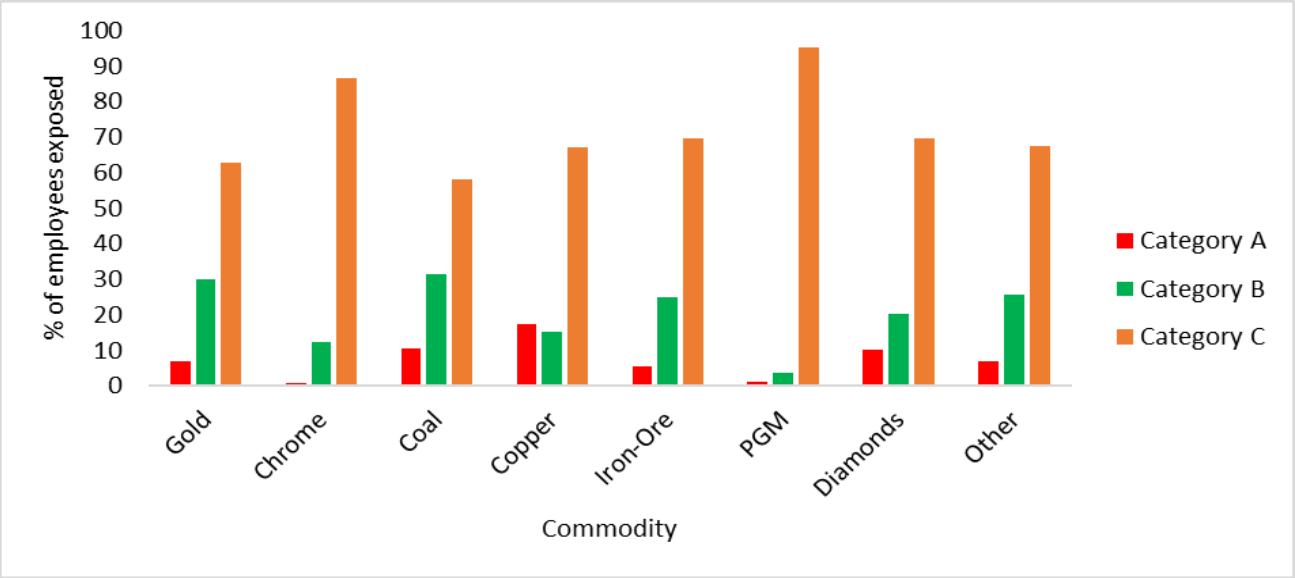


Figure 1. Percentage of employees within HEGs that the falls into category A, B and C, by commodity (2013)[22]

For the year 2013, an analysis of employee distribution, based on exposure concentrations across various commodities within the SAMI (as depicted in Figure 1) revealed that most employees were grouped into the HEG C category. This suggests that the concentrations of total airborne pollutants were lower than 10% of their respective OELs. However, Table 1 shows that categories for pollutants and those for toxic gases and vapours are separated for reporting purposes. The pollutants fall into three distinct groups, denoted as A, B, and C. The inclusion of toxic gases and vapours

[**] The percentage of employees is based on the total number of employees that is reported by the mines within HEG categories A, B and C. From the total number of employees exposed (A+B+C), the proportion of those falling into each category is calculated as a percentage of total employees exposed to airborne pollutants.

within category C is not in line with MCoP requirements, as gases and vapours are intended to be classified solely under Category A and B. This is an error on the part of the DMRE.

Up to 30% of the gold mining exposures fell into HEG B in 2013, and up to 20% of the coal mining exposures fell into HEG A. This manner of reporting exposures is unsatisfactory, as excessive exposures to specific pollutants, e.g. silica dust, cannot be identified.

In 2003, the Mine Health and Safety Council (MHSC) set a milestone for the elimination of silicosis: "By December 2008, 95% of all exposure measurement results will be below the OEL for silica dust of 0.1 mg/m^3 (these are individual, not average, measurements)".[23] It has been highlighted, in the national programme for the elimination of silicosis, that silica dust exposure is a significant challenge in the mining industry.[24] The Minerals Council South Africa (Minerals Council) intensified its endeavours to enhance engineering controls in 2009 by launching the Mining Industry Occupational Safety and Health (MOSH) initiative, aimed at adopting superior practices to tackle health and safety issues, and to fast-track the advancement towards accomplishing the MHSC objectives.[25] The milestones were revised in 2014, and the silica dust exposure milestone was halved to 0.05 mg/m^3, with the date for achieving the milestones being extended to 2024.[19]

Problem statement

Most epidemiological studies testing associations between exposure and occupational disease lack the occupational hygiene data necessary to accurately estimate exposure for occupations of interest, or over an extended period of study.[26] Similarly, in a workplace that has no exposure measurements, exposure concentrations can be estimated by using exposure concentrations from other similar workplaces, which is useful in retrospective exposure assessments, for example.[26]

In the 2013/2014 financial year, the Chamber of Mines (now the Minerals Council South Africa) used the exposure data from the DMRE to report that there was a 14% improvement in airborne pollutant exposure from 2005 to 2013.[27]

However, these assumptions of reduced exposure to airborne pollutants were based on the summation of all exposure concentrations to airborne pollutants, including gases and vapours, as reported by the DMRE. The annual reporting by the DMRE includes the percentage of employees exposed to the combined airborne pollutants within a HEG, rather than the percentage exposed to a

specific pollutant, such as silica dust. These assumptions do not assist in determining if silica dust exposures are decreasing, increasing, or remaining constant over time, or if the individual pollutants to which employees are exposed are below or the above their respective OELs.
The use of a 'HEG' is also misleading when reporting these exposures, as the clustering of information, i.e. different mining commodities, different activities, different occupations, and different exposures does not align with the definition of a HEG ("a group of employees that experiences pollutant exposures similar enough such that monitoring exposures of any representative sub-group of these employees should yield data representative of the whole group"[5]).

Silica dust is one of the pollutants included in the combined pollutant reports. Because the airborne pollutants exposures reported by the DMRE are not pollutant specific, the respirable crystalline silica dust exposure concentrations may not have improved (decreased) over this period. Specific exposure concentrations are obfuscated when reporting all airborne pollutants as a single unit. The practice of assessing health risks from mixed exposures (combined airborne pollutant exposures) is misleading as the actual risk is underestimated; this practice should be discouraged.[28] The conclusion that pollutant-specific exposures are decreasing in the SAMI may be incorrect and needs to be tested. Indications suggest that should the concentration of silica dust in South African mines surpass the present occupational exposure limit (OEL) of 0.1 mg/m^3, laborers in mines will persist in developing silicosis.[29]

The aggregation of airborne pollutant exposure data obscures silica dust exposure. This results in misinterpretation and invalid conclusions about exposure concentrations and hinders the implementation of interventions to reduce exposures in the SAMI. This emphasizes the necessity of interventions and controls that not only attenuate stressor intensity but also protect workers, aligned with the hierarchy of controls.

Significance of the study

Accurate and independent reporting of individual airborne pollutants (e.g. silica dust) to the SAMI by the DMRE, rather than combined pollutants, will assist in the selection and implementation of appropriate interventions to reduce exposure and thereby prevent disease. Reporting the silica dust exposure concentration results accurately will assist in developing and implementing appropriate controls that are designed to reduce exposure to silica dust.[30] The findings from this study can potentially assist the DMRE, together with the SAMI, to develop more specific and useful reporting

strategies, which, if implemented, may lead to appropriate monitoring and management of silica dust and other airborne pollutants, better categorisation of HEGs, and the execution of efficient measures to decrease exposure levels to below the OELs of the respective pollutants. Almost 20 years ago, Churchyard et al. (2004) reported that the current OEL is not protective against silicosis.[16] As early as 1974, the National Institute for Occupational Safety and Health (NIOSH-USA) recommended that the silica dust OEL be reduced to 0.05 mg/m^3 and this has been implemented by some countries, including the United States of America, Argentina, Australia, Belgium, and Canada.[31,32]

Research question

How can airborne pollutant concentrations be better reported for a more accurate assessment of individual pollutant exposure in gold and coal mines in South Africa?

Research aim

The aim of the study was to investigate whether the DMRE's current approach of reporting airborne pollutants provides an accurate estimate of silica dust concentrations in South African gold and coal mines.

Objectives

1. To describe trends in reported airborne pollutant personal exposure concentrations, from 2005 to 2016, using data from gold and coal mining companies affiliated to the Minerals Council South Africa, and data from the DMRE's information management system.
2. To describe trends in reported silica dust exposure concentrations, from 2005 to 2016, using data from gold and coal mining companies affiliated to the Minerals Council South Africa.
3. To assess compliance with the silica dust occupational exposure limit (OEL) of 0.1 mg/m^3 by comparing the findings from two methods: the mandatory code of practice (MCoP) and the EN 689, using data reported by gold and coal mining companies associated with the Minerals Council South Africa for 2015 and 2016.

CHAPTER 2: LITERATURE REVIEW

The literature review provides the framework of existing knowledge on mining-related silica dust exposure. There are limited studies that describe the reporting of silica dust exposure concentrations, especially in the South African mining industry. Studies have focused on different reporting approaches, different matrices, and job-exposure matrices for silica dust exposure,[16, 33, 34, 35] but have not investigated how the DMRE reports airborne pollutants exposures for the SAMI.

Airborne pollutants in the South African mining industry

Airborne pollutants are defined as substances that pose a risk to health, and comprise dust (e.g. respirable crystalline silica), fumes, aerosols, gases, fibres, vapours, and mists,[1] to which mine workers are exposed. Exposure to airborne pollutants is associated with the development of occupational lung diseases such as pneumoconiosis, lung cancer, asthma, allergic alveolitis, and irritation of the skin.[36]

Within the SAMI, the regulation of airborne pollutant exposures falls under the MHSA. This regulatory framework encompasses a comprehensive spectrum of 786 distinct airborne pollutants, each with its own OEL as defined in Schedule 22.9 of the MHSA.[36] Most (68.1%) of these pollutants affect the respiratory system. The eye is affected by 67.3%, the skin by 62.3%, and the central nervous system by 43.6% of these pollutants. Exposure to 78% of the substances listed in Schedule 22.9 results in adverse effects on at least five organs in the body.[36]

The focus on the respiratory and skin systems as primary targets aligns with the prevalence of occupational diseases within the SAMI.[36] In most instances, medical monitoring of employees focuses solely on a single organ, such as the lungs, but work-related illnesses also affect other organs or systems.[36]

As shown in Appendix 5, 69 discrete airborne pollutants, out of the total of 786, were reported to the DMRE by the gold and coal mining companies in the period 2005 - 2016. This further highlights the complexity and multifaceted nature of airborne pollutant management and reporting within the SAMI.

When exposure to many pollutants occurs simultaneously, the health effects might not equate to those resulting from exposure to each pollutant separately.[37] However, the National Academies of Science found that a strategy for regulating multiple pollutants together, considering how they interact, is probably better for safeguarding human health.[37,38]

Current methods for assessing health impacts from exposure to multiple pollutants are inadequate.[37] It is challenging to assess health effects when people are exposed, simultaneously, to several different pollutants, no matter what method is used.[37] This gap in our understanding needs attention.

The ability of decision-makers to create policies that consider exposure to multiple pollutants is currently restricted due to the scarcity of scientific knowledge about how mixtures of air pollutants affect health.[37]

Silica dust in gold mining

In 2015, it was reported that a the typical concentration of airborne crystalline silica in subterranean gold mining operations globally surpassed the threshold recommended by the U.S. National Institute of Occupational Safety and Health (NIOSH) by a factor of 337, while the exposure levels of miners working in above-ground settings were four times higher than the limit.[39] In South Africa, several studies have reported high levels of silica dust and silica dust exposure in gold mines (Hnizdo and Murray, 1998; Biffi and Belle, 2003; Kemsley, 2009; Kesilwe, 2012; Knight et al., 2020). In 2003, Biffi and Belle reported on the analysis of 21 respirable dust samples from gold mines in the Witwatersrand and Vaal Reefs areas. The silica content of the gold mine dust samples ranged from 4.5 to 57%, while gold mines' individual crushed rock samples had a silica content ranging from 9 to 39%.[40] Kemsley's study (2009) on silica dust exposure of 60 rock drill operators in two underground gold mines in the Free State province of South Africa confirmed that these mine workers were potentially exposed to high levels of harmful dust, including respirable silica, in their daily work.[41] In a later study, published in 2012, Kesilwe reported that, in an underground gold mine near Johannesburg, many exposures to silica dust were higher than the current OEL of 0.1 mg/m^3, ranging from 0.0 to 1.2 mg/m^3.[42]

Silica dust in coal mining

The increasing prevalence of pneumoconiosis in coal mine workers[43] provides evidence that they are exposed to levels of respirable crystalline silica above the OEL of 0.1 mg/m^3.[44,45,46,47] In numerous bituminous coal mines, the increased prevalence of CWP has also been associated with elevated levels of quartz content in inhalable dust.[48] Several studies have provided evidence for this (Mamuya et al., 2006; Doyle et al., 2009; Grové et al., 2014). Mamuya et al. (2006) that an examination of 134 respirable dust samples from coal miners working underground in Tanzania indicated that the underground maintenance group had the highest levels of silica content, followed by the development team, the mining team, and the drillers in the development area.[49] The International

Agency for Research on Cancer (IARC) Working Group on the Evaluation of Carcinogenic Risks to Humans (1997) study also highlighted that compositional data for airborne coal mine dust collected from mines in Britain showed that about a third of the dust samples contained non-coal material. On average, quartz made up about 4% of the dust, ranging from 0.8% to 6.9%.[50] Doyle et al. (2009) examined over 2 300 silica dust concentrations in 41 coal mines in Mpumalanga province, South Africa,[51] and did find that 8.1% of concentrations were higher than the 0.1 mg/m^3.

Grové et al. (2014) reported that silica dust exposure generated in an underground environment is influenced by different tasks performed in underground coal mining, and some tasks expose workers to higher levels of respirable silica dust compared to others.[35] The South African coal mine where the study was conducted was identified, by the DMRE, as one of 10 mines with the highest personal respirable silica dust exposures in 2006.

It is clear that workers in coal and gold mines are still at a significant risk of developing silicosis. Nevertheless, in 2014, the SA Chief Inspector of Mines (CIoM) reported that the proportion of mines with silica dust concentrations below the OEL increased by 2.6% in 2012/13 to 2013/14; 94.6% of the exposure concentrations were below the 0.1 mg/m^3 OEL in 2013/14, compared to 92% in 2012/13.[22]

Prevalence of silicosis in the SAMI

The prevalence of silicosis remains a global health issue due to its widespread occurrence.[52] In 2017, the Global Burden of Disease (GBD) study reported 23 695 new cases of silicosis, accounting for 39% of the total 60 055 incident cases of pneumoconiosis.[53] Although there is a global plan to eliminate silicosis, with several countries having similar national plans (including South Africa), the more than 20 000 new cases that emerge each year are evidence that the disease has not been eliminated.[52]

Silicosis poses a significant health problem on a global scale, affecting a large number of gold miners in South Africa.[54] The number of reported new cases is decreasing, probably because the mining industry is shrinking.[19] For years, silicosis and other diseases linked to exposure to respirable crystalline silica have contributed significantly to both morbidity and mortality in South Africa.[19]

Churchyard et al. (2004) found that more cases of silicosis occurred as workers spent more time on the job. For example, among miners who worked for less than 15 years, only 1.6% had silicosis; this rose to 47.6% for those who worked for more than 30 years.[16]

In the past few decades, very high prevalences of silicosis have been recorded in former gold mine workers in both South Africa and neighbouring countries (Steen et al., 1997; Park et al., 2009; Knight et al., 2015; Maboso et al., 2020).

Silicosis is frequently linked to the coal mining sector.[10] Naidoo et al. (2002) reported that, during postmortem investigations, the occurrence of coal workers' pneumoconiosis (CWP) and silicosis among individuals who had been solely exposed to coal dust were 6.9% and 10.2%, respectively.[55] The rates of silicosis in coal mine workers are increasing in countries such as the USA Cohen et al. (2022).[56]

How to sample silica dust exposure

Sampling of respirable dust (particles that settle deep within the lungs and cannot be expelled by exhaling, coughing, or mucus[57]) is important for assessing the amount of dust to which workers are exposed, and for assessing risks of respiratory diseases in epidemiological studies.[57] The main aim of collecting personal respirable dust (including silica dust) samples is to assess the quality of the air in a workplace in terms of the amount and size of dust particles, which helps to estimate exposure concentrations.[57]

In the SAMI, in addition to the requirements stipulated in the MCoP, respirable dust levels are typically assessed using different gravimetric sampling instruments. One common instrument is a cyclone, which is placed on the upper chest near the collarbone in the area where a person breathes.[58] Gravimetric dust monitoring includes taking a known volume of air from an employee's breathing zone through a cyclone and passing it through a filter.[57] The SAMI has adopted a flow rate of 2.2 L/min to mimic the International Organization for Standardization (1995) standard curve for respirable dust particles.[57]

The filters are weighed before and after the sampling procedure to measure the weight of the dust collected, and to calculate the concentration.[57] Thereafter, filters are sent to an analytical laboratory to determine the respirable dust composition.[57]

Reporting silica dust exposure

Brouwer and Rees (2020) highlighted that that the monitoring and reporting of silica dust in the South African Mining Industry (SAMI) needs improvement, as the current approach is inadequate to monitor progress towards achieving the milestones of the Mine Health and Safety Council

(MHSC).[19] According to the EN 689 method, assessing whether sampled concentrations fall below the legislated OELs is based on the 95th percentile of the estimated distribution of the concentrations.[7] The 95th percentile is a useful estimate of the upper bound of a distribution of exposures throughout a shift, and it is appropriate that exposure management decisions are based on a statistic that includes almost all (95%) of employees.[59] However, in South Africa, to assess whether the sampled concentrations are below the legislated OELs, the 90th percentile of the sampled concentrations is calculated and compared to the airborne pollutant's OEL. For airborne pollutants with a mixture, an AQI is calculated by summing the dividends (exposure concentration divided by the relevant OEL) and comparing the result to a value of 1.[60] Brouwer and Rees (2020) recommended that Bayesian statistics, integrated in tools such as Expostats, should be introduced in the MCoP for analyses of exposure concentrations.[19]

Epidemiological studies have typically identified an individual's job title as the main determinant of workplace exposure, leading to the development of job exposure matrices (JEMs) to characterise specific workplace exposures - in contrast to the HEG approach.[61] JEMs can be developed to calculate workers' lifetime exposures. Missing exposure data must be sourced and, if there are any historical dust exposure concentrations that were measured using outdated devices, such concentrations should be converted in accordance with current standards.[33] Furthermore, to provide pertinent exposure information, a JEM related to silica should incorporate the levels of respirable dust and other commonly found agents present in the workplace.[33]

In a study of gold miners in South Africa, Churchyard et al. (2004)[16] used five different exposure standards to determine exposure response relationships: (i) length of service, (ii) cumulative exposure to respirable dust, (iii) cumulative exposure to respirable quartz, (iv) average intensity of exposure to respirable dust, and (v) average intensity of exposure to respirable quartz.[16] These are some exposure standards that the DMRE MCoP can incorporate in reports on silica dust exposure. The use of the 90th percentile by the DMRE might be underestimating employees' exposures in the SAMI. Even though there are reports of a decrease in silica exposure levels in South Africa, there are doubts about the reliability of these reports.[19]

Employment statistics with regard to pollutant exposure

Much information has arisen from the reporting of *combined* pollutant exposure data. While many pollutants pose a risk of disease, it is important to understand the exposure and effect of individual

specific airborne pollutants. Daily, mine workers are exposed to silica dust, among other pollutants. In 2021, it was reported that mines employed just less than half a million people.[62] However, the accuracy of these employment figures is unclear. In 2022, Statistics South Africa acknowledged that their "Master sample that was used to draw the sample for the Quarterly Labour Force Survey (QLFS) did not have a mining stratum", and that the Quarterly Employment Statistics might give a clearer picture of the data than the QLFS.[63] Statistics South Africa also noted that, in 2019, employment increased, but not for mine employees.[64] There has been a decline in the number of workers employed directly by mines, and an increase in the number employed through labour brokers and as subcontractors.[64]

The SAMI's deficiency in maintaining precise and accurate records of silica dust concentrations in gold mines is a notable flaw.[65] Rather than conducting precise measurements, approximations are often relied upon, which affects the reliability of the reported data.[65]

The practice of self-regulation of mines (providing their own dust measurements) raises concerns. Measurements are used for risk assessment purposes and to the calculate levies paid to the MHSC as well as to the Compensation Commissioner for Occupational Diseases in Mines and Works in South Africa.[65,66] Self-regulation undermines the credibility of data used to evaluate health risks.

The obfuscation of employment data further affects the interpretation of pollutant exposure data. The absence of comprehensive employment histories and exposure records in the SAMI[65] affects the accurate assessment of workers' exposures to hazardous substances. Historically, studies excluded black workers, which further undermined the accuracy of health risks assessments among black mineworkers.[65] An analysis of the prevalence of silicosis among gold, diamond, and platinum workers over the course of 30 years brought to attention the inadequacies of the SAMI in regulating and addressing occupational diseases.[65]

Collectively, these inadequacies weaken the SAMI's ability to ensure workers' health and safety. Inaccurate data, self-regulation, lack of comprehensive employment and exposure histories, and historical biases prevent the SAMI from effectively addressing and managing occupational health risks. This scenario underscores the urgency for transparent and uniform regulations, precise data collection, and unbiased research methodologies to safeguard the health and well-being of all mine workers.

Clearer and more transparent processes of reporting silica dust exposures, and open data, coupled with effective and methodical monitoring of pollutant exposures, could positively impact the lives of employees, and potentially improve productivity.

CHAPTER 3: METHODS

This chapter describes the study design, study setting, study population, data sources, study variables, and data management and analysis methods.

Study design

This was a cross-sectional study, using secondary airborne pollutant exposure data that were reported by the Minerals Council members to the DMRE, as part of statutory requirements under the MHSA.

Study setting

The Minerals Council is made up of 105 mines of varying sizes, as well as four associations, and together they account for roughly 90% of the value of mineral production in South Africa.[67,68] This study was conducted, using data from the seven gold and 14 coal mining companies in South Africa that are affiliated with the Minerals Council.

Data sources

A request was made to Minerals Council members to provide their airborne pollutant exposure data. Some mines stated that these data could be obtained from the DMRE, while other mines ignored the request entirely. Eventually, the exposure data from seven gold and 14 coal mines were accessed from the DMRE database. It is important to note that, while mines are required to submit their pollutant exposure data to the DMRE, it is not explicitly stated that mines must enable public access to their data.

The airborne pollutant exposure data for the period 2005 to 2018 were requested from the DMRE's System Application Developer. These data are captured on the DMRE's information management system (Magic XPA system). There were some problems with the Magic XPA system, and the only airborne pollutant exposure data available were for the period 2005 to 2016. The data contained information regarding the year in which airborne pollutants were measured, the mine code, the main commodity code, the commodity description, the pollutant code, the pollutant description, and airborne pollutant concentrations (measurements). The airborne pollutant concentrations were not assigned to specific occupations or HEGs.

Data management

Airborne pollutant exposure data were accessed (as secondary data) from reports submitted by mining companies to the DMRE. After the DMRE receives the signed hard copies of reports, personnel manually input the information into the Magic XPA system.

Although data from 2005 to 2018 were requested from the DMRE's System Application Developer, only data up to and including 2016 were available. The dataset comprised 673 924 data points (a time-weighted average (TWA) concentration of 0.25 mg/m³ for silica dust represents one data point, while a TWA concentration of 2 mg/m³ for particulates not otherwise classified (PNOC) respirable dust denotes another data point) for various mining commodities, reported as 8-hour TWAs. The data were exported into a Microsoft Excel worksheet. Variables included year of measurement, mine code, main commodity code, commodity description, pollutant code, pollutant description, and pollutant concentration.

The study focus was narrowed down to coal and gold mining companies affiliated with the Minerals Council South Africa. The member's information was sourced from the Minerals Council's website and integrated into the dataset. Respective OELs, regulated by the DMRE, were assigned to each airborne pollutant. Concentrations were not linked to specific occupations or HEGs.

A dataset, representing 21 mining companies affiliated with the Minerals Council, and comprising seven gold and 14 coal mining companies, was created using Microsoft Excel's filtering feature. The final dataset comprised 314 300 airborne pollutant concentrations. The dataset was cleaned to remove records with incomplete/inaccurate information such as the recording of the pollutant code instead of the pollutant concentration.

The airborne pollutant concentration data were arranged in ascending order. Some concentrations, both at the lower and upper sides of the distribution appeared to be inaccurate, e.g. they exceeded their respective OELs by 200%. The mines were requested to utilize below detectable limits (BDL) if a pollutant was analysed and not detected, only from 2019. However, the DMRE database does not distinguish BDL data points from others. Therefore the data were trimmed to exclude the lowest and highest valued (outliers), which made the dataset robust and reduced the influence of extreme values on the estimates of central tendency.[69]

Thus, 282 870 data points for 69 different airborne pollutants (see Appendix 5) remained in the dataset (from the initial 314 300). These data points were divided into three groups: a) coal and gold mines combined, b) coal mines alone (90 125 data points), and c) gold mines alone (192 745 data points). Each of the three groups was further divided into four periods of three-yearly intervals:

period 1 (2005 to 2007), period 2 (2008 to 2010), period 3 (2011 to 2013), and period 4 (2014 to 2016). The use of three-year intervals aided in the management of the data, making analysis, interpretation, and comparison achievable, and allowed identification of changes in exposure levels. This process resulted in the creation of 12 Excel spreadsheets with each group corresponding to the four time periods with its own commodity-specific dataset. This process was done to mirror the reporting approach used by the DMRE for both combined and commodity-specific pollutants.

Silica dust concentration data from 2005 to 2016 were extracted from the dataset, resulting in 127 014 data points (44.9% of 282 870). The silica dust concentrations data were also split into the same three commodity groups and four time periods: a) coal and gold mines combined, b) coal mines alone (24 230 data points), and c) gold mines alone (102 784 data points). This process also resulted in the creation of an additional 12 Excel spreadsheets.

For objective 2, the 12-silica dust concentration Excel data spreadsheets created for coal and gold mines combined, coal mines only, and gold mines only, aligned to the four time periods were used. The 2015 and 2016 silica dust concentrations were used to achieve objective 3.

Data management and analysis

This analysis endeavoured to replicate the DMRE's reporting method, as illustrated in Figure 1, which highlights the percentage of employees exposed to the combined airborne pollutants in different commodities without considering each pollutant's specific OEL. To accomplish this, two objectives were formulated. The first, similar to the DMRE's approach (pooling data), involved analysing the combined exposure to airborne pollutants across different commodities. The second objective focused on silica dust. This study aimed to replicate the DMRE's reporting approach while also shedding light on what the findings might have been if the DMRE analysed and reported individual pollutants separately.

For simplicity and alignment with the DMRE's reporting method, the data spanning from 2005 to 2016 normalized, to establish a consistent metric, which enabled a uniform assessment across various pollutants with different OELs. Each pollutant's concentration was divided by its corresponding OEL, generating a ratio termed as "Q." This ratio provided a uniform and standardised representation of the data in line with the prescribed reporting methodology. This method aligns with the calculation of an Air Quality Index (AQI), where the pollutant concentration is divided by the relevant OEL. This approach eliminated the necessity to assess each pollutant against its specific OEL and was aligned with the current DMRE reporting practice. Thus, normalization allowed for a

simplified assessment of relative exposure levels across pollutants, using Equation 1: $Q_i = \frac{\text{Pollutant concentration}_i}{OEL_i}$.

The AM, median, SD, GM, and GSD were computed for each of the three commodity groups and each of the four time periods, using Tool 1 of the EXPOSTATS toolkit. Expostats is an innovative and accessible toolkit that harnesses the adaptability of Bayesian analysis for conducting a comprehensive array of calculations, aligning with the directives outlined in various globally recognized protocols pertaining to occupational hygiene practices.[60] This approach was used to evaluate both the variability and distribution of the data. The disparity between the 90th and 95th percentiles of silica dust concentrations within each three-year period was quantified and converted into a percentage, using Equation 2: % difference = $\frac{change}{original\ number * 100}$.

To analyse the ratios (Q) and the silica dust concentrations of each group for each period, Jeffreys's Amazing Statistics Program (JASP), version 0.16.4. was used.[70] JASP is an open-source graphical software tool used for fundamental statistical analyses.[70] With the use of JASP, the non-parametric Kruskal–Wallis (one-way ANOVA on ranks) test was applied to the untransformed data to determine if the differences between the four time periods for each commodity group were statistically significant. The JASP Scheffe's post-hoc test was conducted to further analyse and compare differences between all the observed periods.

For objective 3, the 2015 and 2016 silica dust exposures concentrations were used to compare the different approaches of the MCoP and EN 689, regarding compliance testing. The EN 689 approach, i.e. using the 90th and 95th percentile, were assessed using Tool 1 of EXPOSTATS. Microsoft Excel was used to calculate the 90th and 95th percentile of the data as per the MCoP.

Data entry

In order to analyse the data, the Excel file was imported into JASP. The EXPOSTATS interpretation tools were accessed from the website (https://www.expostats.ca/site/en/tools.html) and the simplified version of Tool 1 (Mirror) was selected to analyse the data.

Ethics and permissions

The University of the Witwatersrand Human Research Ethics Committee (Medical) approved the study (clearance certificate M210460, Appendix 3). In June 2021, Dr Lindiwe Ndelu - Chief Director of Occupational Health under the DMRE - granted permission to conduct this study (Appendix 4).

CHAPTER 4: RESULTS

This chapter presents the results of the analysis of personal airborne pollutant and silica dust concentrations from 2005 to 2016, as well as the compliance assessment of the 2015 and 2016 silica dust concentrations, using the MCoP and EN 689 methods.

1. Trends in airborne pollutant exposures

Table 2 shows the measures of central tendency and variation of the 63 combined airborne pollutant ratios for the pooled data from the 21 mines.

Table 2. Measures of central tendency and variation of ratios (Q[††]) for the three groups, over four time periods

Group	Time period	No. of data points	Range		Geometric mean (GM)	Geometric standard deviation (GSD)
			Min	Max		
Coal and gold mines combined	2005-2007	29 224	0.004	16.50	0.31	7.53
	2008-2010	13 067	0.00891	11.40	0.29	6.69
	2011-2013	86 128	0.00795	8.58	0.33	6.33
	2014-2016	154 451	0.00433	5.27	0.17	6.37
Coal mines	2005-2007	19 592	0.00455	22.1	0.26	8.43
	2008-2010	6 194	0.00591	18.8	0.28	8.18
	2011-2013	27 097	0.005	27.7	0.23	8.11
	2014-2016	37 242	0.00414	15	0.22	7.80
Gold mines	2005-2007	9 632	0.003	7.7	0.45	5.91
	2008-2010	6 873	0.0113	7.8	0.31	5.75
	2011-2013	59 035	0.0127	6.6	0.39	5.70
	2014-2016	117 205	0.004	3.91	0.16	6.16

[††] Q (unitless), where $Q_i = \frac{\text{Pollutant concentration}_i}{OEL_i}$

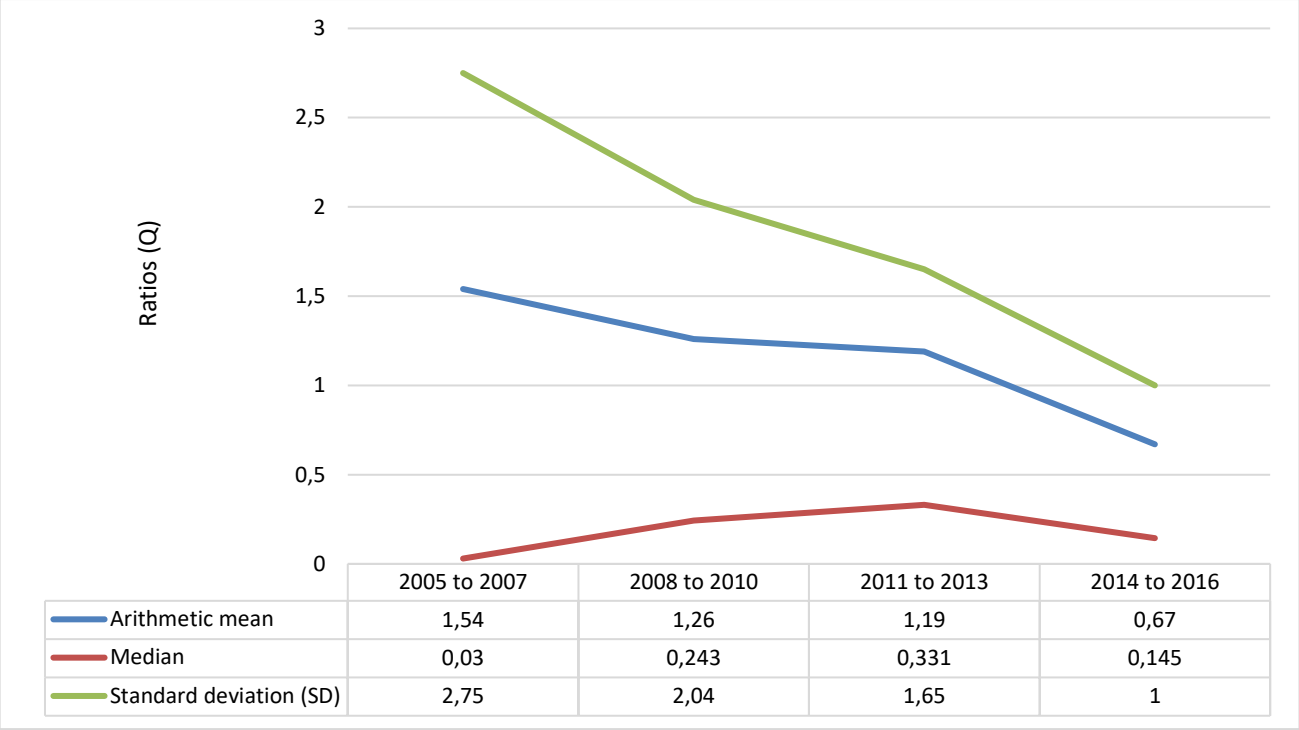
Measures of central tendency and variation of ratios (Q) for the pooled data for coal and gold mines combined

Table 2 shows the trends in the distribution of ratios (Q) for combined coal and gold mines for the years 2005 to 2016. The mean pollutant concentrations for the period 2005 to 2007 was 1.54 (± 2.75), indicating considerable variability. In this period, the ratios (Q) ranged from 0.003 to 7.7. The highest Q value increased the mean, leading to a discrepancy between the median and the mean.

In the period 2008 to 2010, the mean decreased to 1.26 (±2.04) from the previous period, indicating reduced variability (Figure 2). From 2011 to 2013, there was a substantial increase in the number of observations. Here, there was a further decrease in the mean and SD (Figure 2), suggesting even less variability than in the previous period. The median aligned more closely with the mean when compared to earlier periods. From 2014 to 2016, the mean significantly decreased to 0.67, and the SD was the lowest among all periods, signalling minimal variability. The median closely approximated the mean in this interval.

The average means of the ratios (Q) showed that there was a 57% reduction in exposure to airborne pollutants from 2005 to 2016. Specifically, reductions of 18%, 6%, and 44% were observed from period 1 (2005 to 2007) to 2 (2008 to 2010), from period 2 (2008 to 2010) to 3 (2011 to 2013), and from period 3 to 4 (2014 to 2016), respectively. The ratios (Q) for combined coal and gold mines showed substantial variability from 2005 to 2016, as indicated by the large geometric standard deviations (GSDs), which ranged from 6.33 to 7.53 (Table 2).

Table 2 shows a general downward trend in the geometric mean (GM). The GMs for the ratios (Q) fluctuated, with an overall decrease of 45% from 2005 to 2016. Changes in the different time periods were a 7% reduction from period 1 to period 2, a 14% increase from period 2 to period 3, and a 49% reduction from period 3 to period 4.



	2005 to 2007	2008 to 2010	2011 to 2013	2014 to 2016
Arithmetic mean	1,54	1,26	1,19	0,67
Median	0,03	0,243	0,331	0,145
Standard deviation (SD)	2,75	2,04	1,65	1

Figure 2. AM, Median and SD for coal and gold mines combined.‡‡

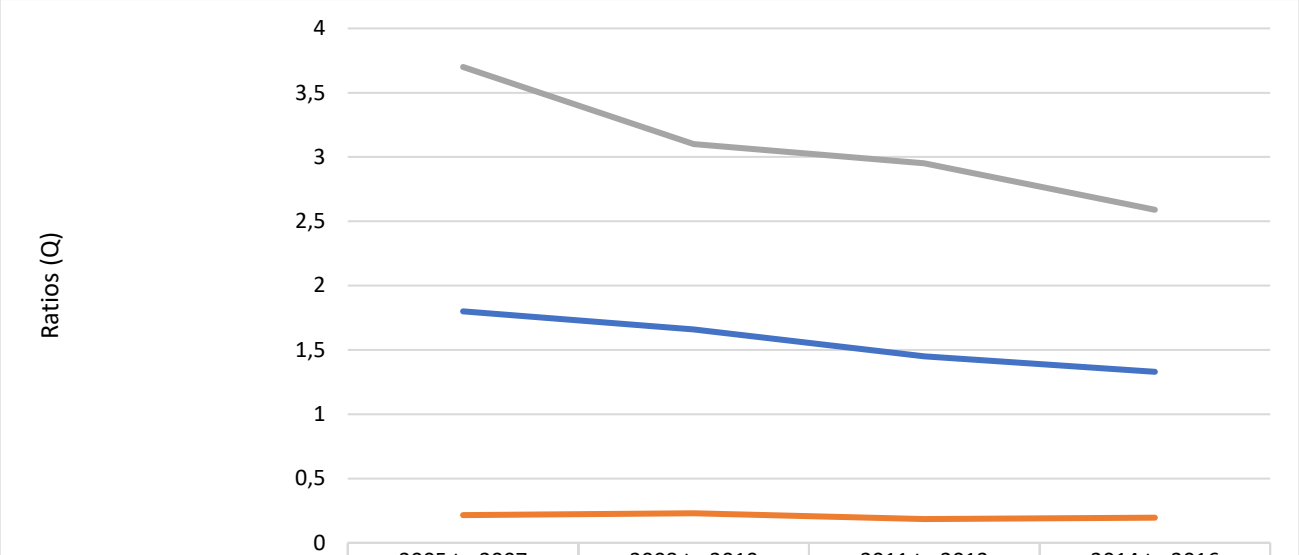
Measures of central tendency and variability of ratios (Q) for the pooled data for coal mines

Table 2 and Figure 3 shows the results of the data analysis for the 14 coal mines. The AM exposure levels for the coal mines consistently decreased over time, indicating a decline in overall airborne pollutant exposure. The median values fluctuated but remained lower than the AM, suggesting that the distribution of the exposure ratios was skewed.

In terms of the variability, both the SD and GSD consistently decreased over time. This means that data points were moving closer to the AM, indicating more consistent pollutant concentrations.

The GM also decreased over time, showing that the airborne pollutants concentrations reduced. The GMs for the ratios (Q) fluctuated. There was an increase of 8% from period 1 to period 2, a decrease of 18% from period 2 to period 3, and a decrease of 4% from period 3 to period 4, with an overall reduction of 15% in the airborne pollutant concentrations from 2005 to 2016.

‡‡ The left Y-axis shows the ratios (Q), whereas the X-axis shows the different periods



	2005 to 2007	2008 to 2010	2011 to 2013	2014 to 2016
Arithmetic mean	1,8	1,66	1,45	1,33
Median	0,215	0,23	0,185	0,195
Standard deviation (SD)	3,7	3,1	2,95	2,59

Figure 3. AM, Median and SD for coal mines.[§§]

Measures of central tendency and variability of ratios (Q) for the pooled data for gold mines

Table 2 and Figure 4 shows the results for the 7 gold mines. The AM and median, as measures of central tendency, demonstrated a consistent decrease over time, suggesting an overall decline in exposure to the airborne pollutants. The highest variability was in 2005-2007(SD = 1.58 and GSD = 5.91). In subsequent periods, the pooled pollutant concentrations showed less variability (more stability).

The GM reflected the downward trend in variability that was indicated by the AM. This aligned with the overall reductions in all the central tendency measures. The GMs for the ratios (Q) fluctuated, with an overall decrease of 64% from 2005 to 2016. There was a decrease of 31% from period 1 to period 2, an increase of 26% from period 2 to period 3, and a decrease of 59% from period 3 to period 4. The minimum ratio was 0.003 and maximum was 7.8, highlighting a considerable range of exposure values.

[§§] The left Y-axis shows the ratios (Q), whereas the X-axis shows the different periods

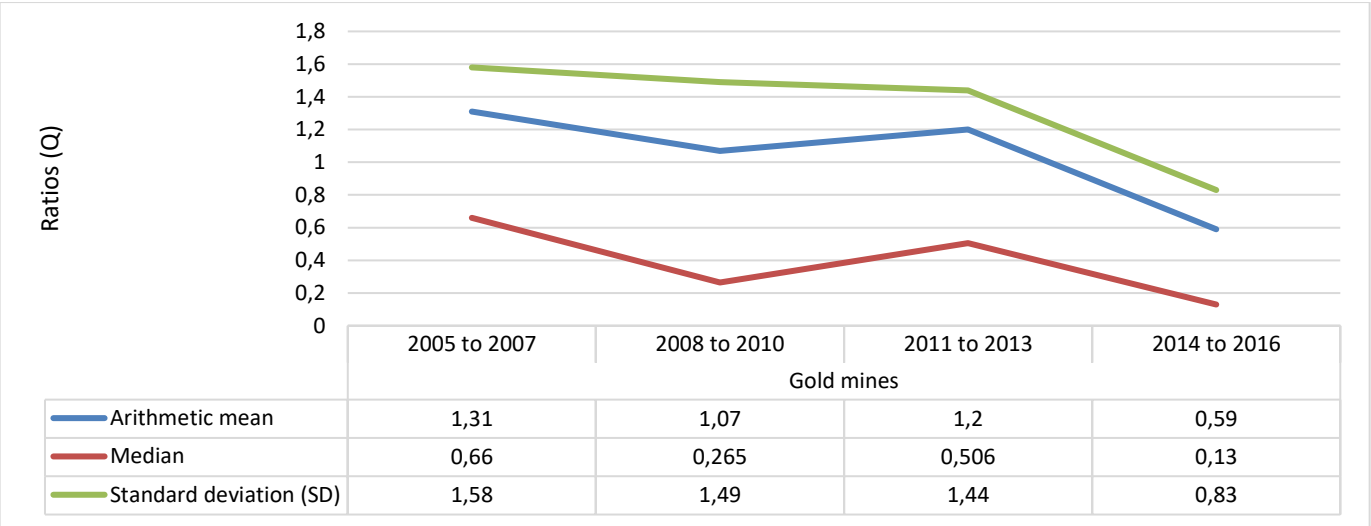


Figure 4. AM, Median and SD for gold mines alone.[***]

Table 3. Results of the *H* statistic, Degrees of freedom and the *P* values

Group	**Factor**	***H* Statistic**	**Degrees of Freedom (df)**	***P***
Coal and gold mines combined	Period	7680.09	3	< 0.001
Coal mines	Period	99.69	3	< 0.001
Gold mines	Period	11347.35	3	< 0.001

Due to varying sample sizes within the four time periods for the three groups, Scheffes' post hoc test was applied. This showed that there were large variations in the average means (AMs) of the ratios (Q) across the three groups, as indicated in Table 4. However, there was no significant difference when comparing data from the coal mines between the periods of 2005-2007 and 2008-2010.

[***] The left Y-axis shows the ratios (Q), whereas the X-axis shows the different periods

Table 4. Differences in AMs of the ratios (Q): results of Scheffe's Post Hoc Comparisons test

	Post Hoc Comparisons – Period					
Group	**Periods compared**		**Mean difference**	**SE**	**T**	**$p_{scheffe}$**
Coal and gold mines combined	2005-2007	2008-2010	0.27	0.02	16.86	< 0.001
		2011-2013	0.34	0.01	32.36	< 0.001
		2014-2016	0.87	0.01	88.51	< 0.001
	2008-2010	2011-2013	0.06	0.01	4.44	< 0.001
		2014-2016	0.59	0.01	42.51	< 0.001
	2011-2013	2014-2016	0.53	0.01	81.26	< 0.001
Coal mines	2005-2007	2008-2010	0.14	0.04	3.21	0.016
		2011-2013	0.36	0.03	12.66	< 0.001
		2014-2016	0.48	0.03	18.06	< 0.001
	2008-2010	2011-2013	0.22	0.04	5.09	< .001
		2014-2016	0.34	0.04	8.20	< .001
	2011-2013	2014-2016	0.12	0.02	5.09	< .001
Gold mines	2005-2007	2008-2010	0.24	0.02	13.64	< .001
		2011-2013	0.11	0.01	8.60	< .001
		2014-2016	0.72	0.01	60.39	< .001
	2008-2010	2011-2013	-0.14	0.01	-9.48	< .001
		2014-2016	0.48	0.01	34.23	< .001
	2011-2013	2014-2016	0.61	0.01	108.11	< .001

2. Trends in silica dust exposures

Measures of central tendency and distribution for silica dust concentrations for three groups

A total of 127 014 silica dust concentrations from the 12-year span were analysed (45% % of the entire pooled data). Table 5 shows the measures of central tendency for the respirable silica dust concentrations, and the 90th and 95th percentiles. The percentage differences between the 95th and 90th percentiles for each of the three groups in the four exposure periods are also shown.

The GSDs related to the silica dust concentrations were < 3.5 for the three groups (coal and gold mines combined, coal mines alone, and gold mines alone). These were lower than the GSDs for the pooled airborne pollutants concentrations (the minimum GSD for the airborne pollutants concentrations was 5.7).

The AMs for the coal and gold combined group indicate that the exposures to silica dust decreased from 2005 to 2016. The AMs for the silica dust concentrations for coal mining were higher than those for coal and gold mines combined, and gold mines alone from 2005 to 2016. However, Figures

5 and 7 indicate that there was a decrease in exposures to silica dust over time for both coal and gold mines combined and gold mines alone; the decrease was greater in the gold mines. Even though the silica dust concentrations fluctuated over time (Figure 6) for coal mines, they were higher than those for the gold mines (Figure 7).

Table 5. Summary statistics of silica dust concentrations for the three groups, over four time periods

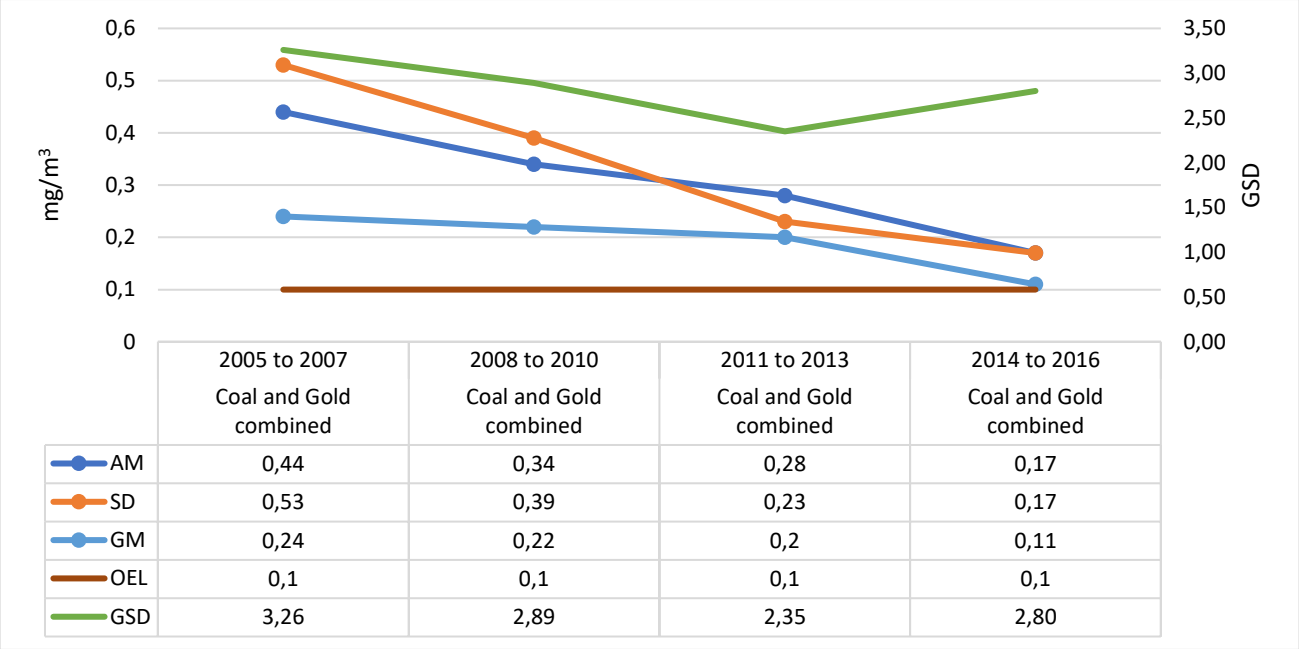
Group	Time period	No. observations (n) Data points	90th percentile (mg/m^3)	95th percentile (mg/m^3)	Difference between 95th and 90th percentiles (%)
Coal and gold mines combined	2005-2007	10 213	1.17	1.67	29.9
	2008-2010	5 459	0.92	1.26	27.0
	2011-2013	41 573	0.59	0.77	23.4
	2014-2016	69 769	0.39	0.53	26.4
Coal mines	2005-2007	3 765	2.48	3.16	21.5
	2008-2010	2 016	1.72	2.27	24.2
	2011-2013	7 930	1.79	2.41	25.7
	2014-2016	10 519	1.64	2.16	24.1
Gold mines	2005-2007	6 448	0.48	0.62	22.6
	2008-2010	3 445	0.51	0.63	19.0
	2011-2013	33 643	0.46	0.55	16.4
	2014-2016	59 248	0.29	0.35	17.1

Measures of central tendency and distribution for silica dust concentrations for coal and gold mines combined

In Table 5 and Figure 5, the silica dust concentrations data for coal and gold mines combined from 2005 to 2016 show a moderate level of variability with GSDs, ranging from 2.35 to 3.26, with 2005 to 2007 being the highest by 3.26. The standard deviation over time ranged from 0.17 to 0.53 mg/m^3.

The overall AMs indicated that exposure to silica dust concentrations decreased by 51% from 2005 to 2016 (Table 5 and Figure 5). There was a reduction of 23% from period 1 to period 2, 18% from period 2 to period 3, and 39% from period 3 to period 4 .

The overall GMs for silica dust concentrations reduced by 54% from 2005 to 2016. The GMs for the for-silica dust concentrations fluctuated. From period 1 to period 2, there was a decrease of 8%, from period 2 to period 3, there was an increase of 9%, and period 3 to period 4, there was again a reduction of 45%.



	2005 to 2007 Coal and Gold combined	2008 to 2010 Coal and Gold combined	2011 to 2013 Coal and Gold combined	2014 to 2016 Coal and Gold combined
AM	0,44	0,34	0,28	0,17
SD	0,53	0,39	0,23	0,17
GM	0,24	0,22	0,2	0,11
OEL	0,1	0,1	0,1	0,1
GSD	3,26	2,89	2,35	2,80

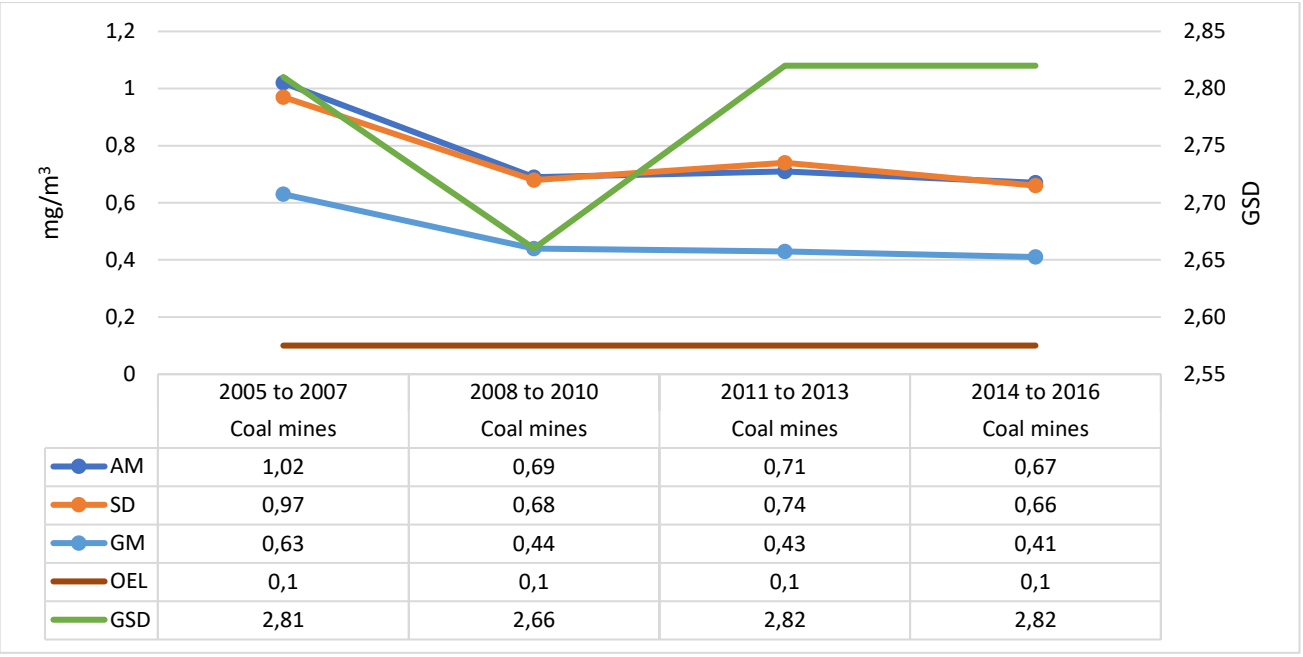
Figure 5. AM, SD, GM, and GSD of silica concentrations for coal and gold mines combined.[†††]

The overall 90th percentiles indicated that exposure to silica dust concentrations decreased by 67% from 2005 to 2016 (Table 5). There was a reduction of 21% from period 1 to period 2, 36% from period 2 to period 3, and 34% from period 3 to period 4.

The overall 95th percentiles indicated that exposure to silica dust concentrations decreased by 68% from 2005 to 2016 (Table 5). There was a reduction of 25% from period 1 to period 2, 39% from period 2 to period 3, and 31% from period 3 to period 4.

The AMs, GMs, 90th and 95th for the silica dust concentrations data for coal and gold mines combined exceeded the OEL of 0.1 mg/m^3 from 2005 to 2016, the silica dust concentrations fell into MCoP exposure category A over the entire study period. The percentage (%) differences between 95th and 90th percentiles are also plotted in Figure 6 and show a range from 23.4% to 29.9%, indicating the long tail of the lognormal distribution.

[†††] The left Y-axis shows the silica dust concentrations in mg/m^3, whereas the right Y-axis shows the value of the GSD



	2005 to 2007 Coal mines	2008 to 2010 Coal mines	2011 to 2013 Coal mines	2014 to 2016 Coal mines
AM	1,02	0,69	0,71	0,67
SD	0,97	0,68	0,74	0,66
GM	0,63	0,44	0,43	0,41
OEL	0,1	0,1	0,1	0,1
GSD	2,81	2,66	2,82	2,82

Figure 6. AM, SD, GM, and GSD of silica dust concentrations for coal mines alone.‡‡‡

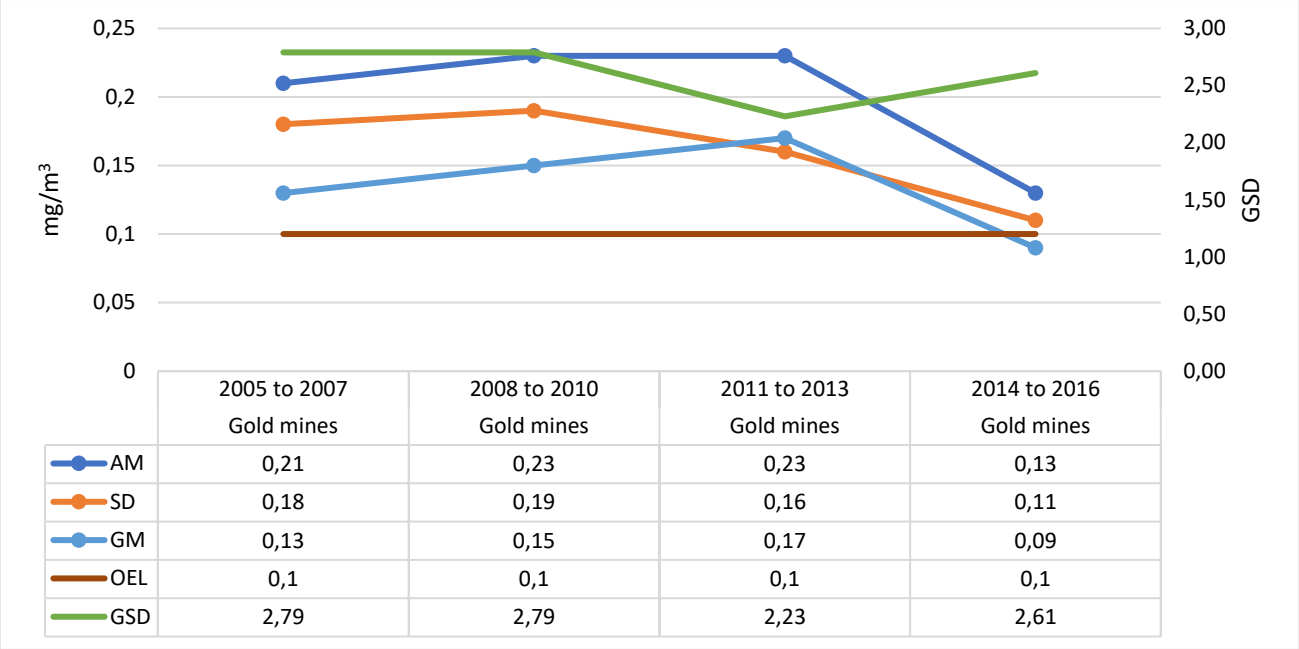
Measures of central tendency and distribution for silica dust concentrations for coal mines

The results in Table 5 and Figure 7 represent the silica dust data of 14 different coal mines, with the GSDs showing a relative stable variability over time, ranging from 2.66 to 2.82 in 2005 to 2016, with the highest in period 3 to period 4. The standard deviation ranged from 0.66 to 0.97 mg/m^3.

The overall AMs indicated that exposure to silica dust concentrations decreased by 34% from 2005 to 2016 (Table 5 and Figure 7). The AMs of the silica dust concentrations for coal mines alone show that exposure to silica dust fluctuated from 0.67 to 1.02 mg/m^3. There was a reduction of 32% from period 1 to period 2, then an increase of 3% from period 2 to period 3, and a reduction of 7% from period 3 to period 4.

The overall GMs for silica dust concentrations reduced by 35% from 2005 to 2016. There was a reduction of 30% from period 1 to period 2, 2% from period 2 to period 3, and 5% from period 3 to period 4.

‡‡‡ The left Y-axis shows the silica dust concentrations in mg/m^3, whereas the right Y-axis shows the value of the GSD



	2005 to 2007 Gold mines	2008 to 2010 Gold mines	2011 to 2013 Gold mines	2014 to 2016 Gold mines
AM	0,21	0,23	0,23	0,13
SD	0,18	0,19	0,16	0,11
GM	0,13	0,15	0,17	0,09
OEL	0,1	0,1	0,1	0,1
GSD	2,79	2,79	2,23	2,61

Figure 7. AM, SD, GM, and GSD of silica dust concentrations for gold mines alone.[§§§]

The overall 90th percentiles indicated that exposure to silica dust concentrations decreased by 34% from 2005 to 2016 (Table 5). There was a reduction of 31% from period 1 to period 2, there was an increase of 4% from period 2 to period 3, and there was again a decrease of 8% from period 3 to period 4.

The overall 95th percentiles indicated that exposure to silica dust concentrations decreased by 32% from 2005 to 2016 (Table 5). There was a reduction of 28% from period 1 to period 2, there was an increase of 6% from period 2 to period 3, and a decrease of 10% from period 3 to period 4.

The percentage (%) difference between 95th and 90th percentile ranged from 21.5 to 25.7% for the coal mines alone indicating the long tail of the lognormal distribution.

Measures of central tendency and distribution for silica dust concentrations for gold mines

The results in Table 5 represents seven different gold mines. The GSDs indicate a rather stable variability of the silica dust concentrations ranging from 2.23 to 2.79 in 2005 to 2016, with the highest in period 1 to period 2. The standard deviation ranged from 0.11 to 0.19 mg/m^3 for period 4.

[§§§] The left Y-axis shows the silica dust concentrations in mg/m^3, whereas the right Y-axis shows the value of the GSD

The overall AMs indicated that exposure to silica dust concentrations decreased by 38% from 2005 to 2016 (Table 5 and Figure 7). The AMs of the silica dust concentrations for gold mines alone show that exposure to silica dust has been fluctuating between 0.13 and 0.23 mg/m^3. There was an increase of 9% from period 1 to period 2, then there was percentage change from period 2 to period 3, and a reduction of 44% from period 3 to period 4.

The overall GMs for silica dust concentrations reduced by 31% from 2005 to 2016. The GMs for the for-silica dust concentrations fluctuated. From period 1 to period 2, there was an increase of 15%, 13% from period 2 to period 3, and period 3 to period 4, there was a decrease of 47%.

The overall 90th percentiles indicated that exposure to silica dust concentrations decreased by 40% from 2005 to 2016 (Table 5). There was an increase of 6% from period 1 to period 2, then a decrease of 10% from period 2 to period 3, and a decrease of 37% from period 3 to period 4.

The overall 95th percentiles indicated that exposure to silica dust concentrations decreased by 44% from 2005 to 2016 (Table 5). There was an increase of 2% from period 1 to period 2, then a decrease of 13% from period 2 to period 3, and a further decrease of 36% from period to period 4. The percentage (%) difference between 95th and 90th percentile ranged from 16.4 to 22.6% for the gold mines alone, indicating a lognormal distribution. The results suggest a lognormal distribution for silica dust concentrations in gold mines. From 2005 to 2016, there was a decreasing trend in the 95th percentiles, with specific changes between periods. The percentage differences of more than 5% between the 95th and 90th percentiles suggest an uneven pattern emphasise the skewness of the data.

Differences in the AMs of silica dust concentrations between the three groups

The AMs of the silica dust concentrations over the 12-year period for the three groups were also significantly different for the four time periods ($p < 0.001$), as shown by the results of the Kruskal-Wallis test (Table 6).

Table 6. Results of the *H* statistic, Degrees of freedom and the *P* values

Group	Factor	*H* Statistic	Degrees of Freedom (df)	*P*
Silica dust exposures for both coal and gold mines combined	Period	10683.15	3	< 0.001

Silica dust exposures for coal mines	Period	446.12	3	< 0.001
Silica dust exposures for gold mines	Period	9670.13	3	< 0.001

Because the sample sizes in the four periods were different for the three groups, Scheffes' post hoc test was deployed, which showed that there were significant differences in the AMs of the silica dust concentrations between the three groups in the four time periods (Table 7). However, there were no significant differences in coal mines alone when comparing period 2 to periods 3 and 4. There were no significant differences observed between period 2 and period 3 for the gold mines alone.

Table 7. Differences in AMs of silica dust concentrations: results of Scheffe's Post Hoc Comparisons test

Group	Post Hoc Comparisons – Period					
	Periods compared		Mean Difference	SE	T	$p_{scheffe}$
Coal and gold mines combined	2005-2007	2008-2010	0.07	0.004	17.73	<0 .001
		2011-2013	0.16	0.003	59.78	< 0.001
		2014-2016	0.27	0.003	102.05	< 0.001
	2008-2010	2011-2013	0.09	0.004	25.19	< 0.001
		2014-2016	0.19	0.003	55.77	< 0.001
	2011-2013	2014-2016	0.11	0.002	67.96	< 0.001
Coal mines	2005-2007	2008-2010	0.32	0.02	15.60	< 0.001
		2011-2013	0.31	0.02	20.97	< 0.001
		2014-2016	0.35	0.01	24.59	< 0.001
	2008-2010	2011-2013	-0.01	0.02	-0.63	0.942
		2014-2016	0.03	0.02	1.49	0.526
	2011-2013	2014-2016	0.04	0.01	3.49	0.007
Gold mines	2005-2007	2008-2010	-0.02	0.003	-6.88	< 0.001
		2011-2013	-0.02	0.002	-10.49	< 0.001
		2014-2016	0.08	0.002	43.21	< 0.001
	2008-2010	2011-2013	< 0.01	0.002	0.14	0.999
		2014-2016	0.09	0.002	40.67	< 0.001
	2011-2013	2014-2016	0.09	< 0.001	103.89	< 0.001

3. Comparison between MCoP and EN 689 methodologies for testing compliance with silica dust concentrations reported for 2015 and 2016

There were 44 990 silica concentrations data that were used for analysis under this section. From these data 52% represented the data collected in 2015, and 48% represented the 2016 data.

Table 8 shows that the for the 2015 data for coal mines alone and the coal and gold mines combined data, the 90th and 95th percentile of measured concentrations and the estimate of the 90th and 95th percentile of the population distribution based on Bayesian statistics, were never below the OEL of 0.1 mg/m^3. Thus, according to both the MCoP and EN 689 approaches, compliance was poor.

Table 8. 90th and 95th percentile silica dust exposure concentrations for three groups (2015 and 2016)

Approach	Combined coal and gold mines (mg/m^3)	Coal Mines (mg/m^3)	Gold Mines (mg/m^3)
2015 – 90th percentile			
MCoP	0.41	1.73	0.30
EN 689	0.50	1.64	0.32
2015 – 95th percentile			
MCoP	0.80	2.28	0.37
EN 689	0.80	2.39	0.46
2016 – 90th percentile			
MCoP	0.32	2.14	0.23
EN 689	0.39	1.59	0.25
2016 – 95th percentile			
MCoP	0.60	2.18	0.28
EN	0.60	2.28	0.35

MCoP approach – 90th percentile of measured concentrations

EN 689 approach - estimate of 90th percentile of the population distribution

The data captured in Table 8 are graphically expressed in Figure 8. Table 9 presents the differences in percentages between the results from the MCoP and EN 689 methodologies, for the three groups.

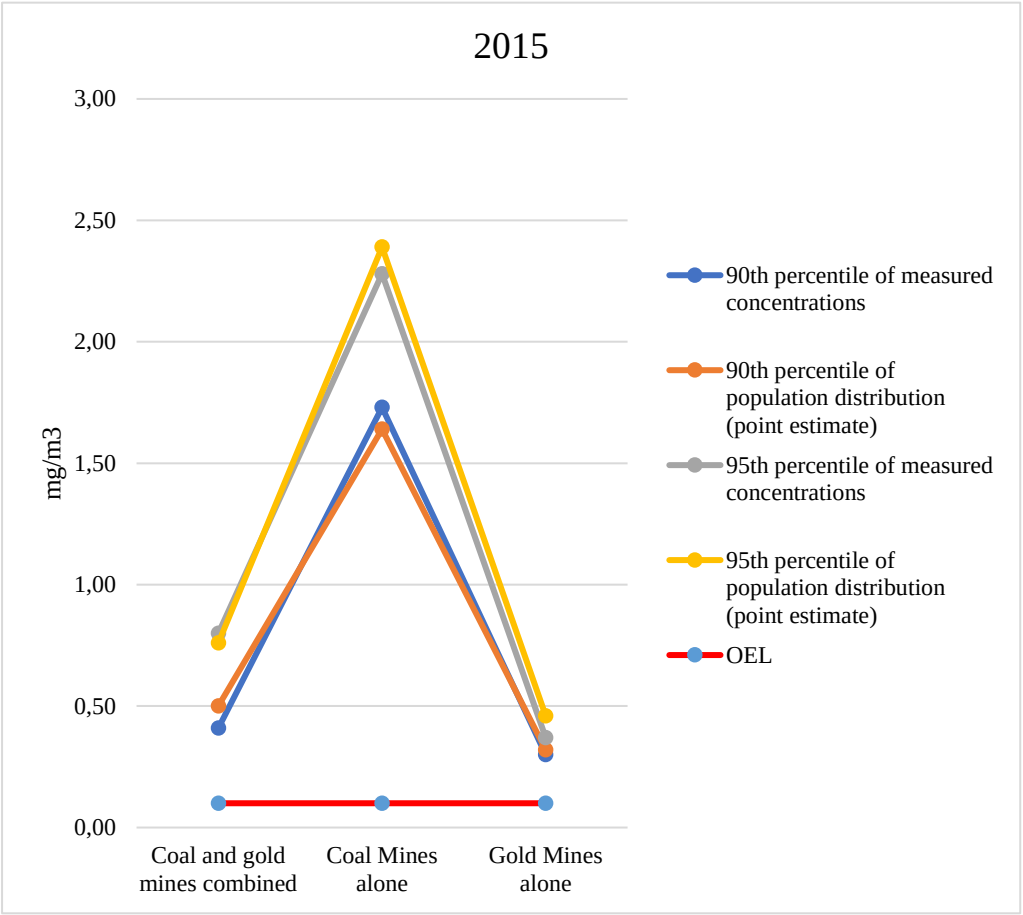
Table 9. Percentage difference of the three groups when comparing MCoP and EN 689 methodologies

Approach	Combined coal and gold mines (mg/m^3)	Coal Mines (mg/m^3)	Gold Mines (mg/m^3)
2015 – 90th percentile			
MCoP		5 % higher than EN 689	
EN 689	18% higher than MCoP		6 % higher than MCoP
2015 – 95th percentile			
MCoP	no difference		
EN 689		5% higher than MCoP	20% higher than MCoP
2016 – 90th percentile			
MCoP		26% higher than EN 689	
EN 689	18% higher than MCoP		8% higher than MCoP
2016 – 95th percentile			
MCoP	no difference		
EN		4% higher than MCoP	20% higher than MCoP

The data shows that in 2015 and 2016, for combined coal and gold mines, the 90th percentile of the population distribution (EN 689) was consistently 18% higher than the 90th percentile of measured concentrations using the MCoP approach.

For coal mines alone, the 90th percentile of measured concentrations using the MCoP approach was 5% higher than the 90th percentile of the population distribution (EN 689) in 2015 and 26% higher in 2016. For gold mines alone, the estimate of the 90th percentile of the population distribution (EN 689) was 6% higher in 2015 and 8% higher in 2016 than the 90th percentile of measured concentrations using the MCoP approach.

Similarly, in 2015 and 2016, for combined coal and gold mines, the 95th percentile of the population distribution (EN 689) was the same as the 95th percentile of measured concentrations using the MCoP approach. For coal mines alone, the 95th percentile of measured concentrations using the MCoP approach was 5% lesser in 2015 and 4% lesser in 2016 than the 95th percentile of the population distribution (EN 689). For gold mines alone, the estimate of the 95th percentile of the population distribution (EN 689) was 20% higher in both 2015 and 2016 than the 95th percentile of measured concentrations using the MCoP approach.



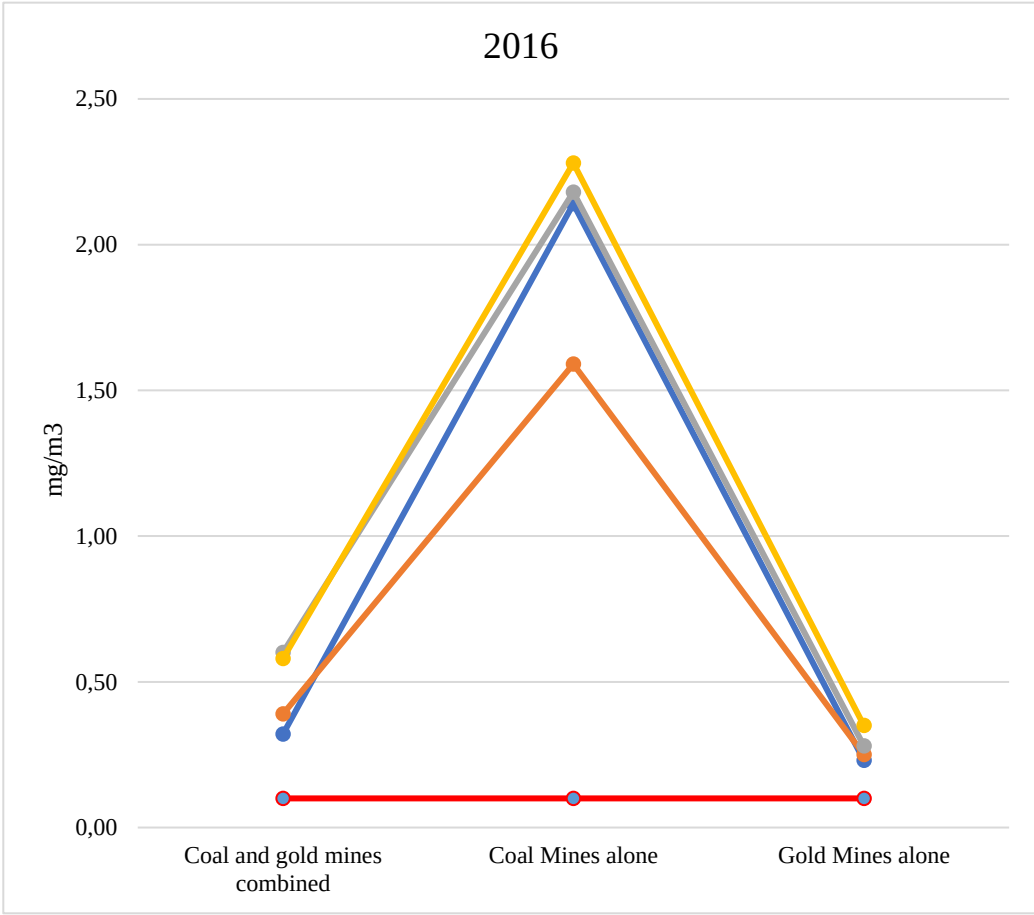


Figure 8. 2015 and 2016 90th and 95th percentiles for coal and gold mines

CHAPTER 5: DISCUSSION

In this chapter, the outcomes of the three study objectives, derived from the analysis of the data, are discussed. The study objectives were to describe the trends in the reported airborne pollutant concentrations and silica dust concentrations, and to compare MCoP and EN 689 methodologies for testing compliance with silica dust concentrations. To achieve these objectives, exposure data, representing seven gold mines and 14 coal mines, were analysed.

Introduction

Monitoring and reporting occupational hygiene data are crucial for safeguarding the well-being of workers and for informed decision-making by regulatory bodies and industry stakeholders.

The uneven distribution of 282 890 airborne pollutant data points across four time periods reveals an interesting pattern. Period 4 of the combined coal and gold mines emerges as the most significant contributor, comprising 54.61% of the data. Additionally, coal mine only and gold mines only show non-proportional contributions, with coal mines experiencing a noteworthy decrease in period 2 (68%), followed by increases in periods 3 (10%) and 4 (13%). Similarly, gold mines had a decrease in period 2 (29%), followed by increases in periods 3 (21%) and 4 (42%). This pattern deviates from MCoP requirements, which requires that a greater number of samples should be collected from a HEG classified as category "A." However, Figure 1 did show that a higher percentage of employees in category "A" were in coal mining, despite that, gold mines reported more data points.

A comparable pattern was also observed when assessing the silica dust data points from 2005 to 2016. The combined data from coal and gold mines indicated a 47% decrease in period 2, followed by a 33% increase in period 3, and a further 55% increase in period 4. Coal mines consistently contributed moderately, with percentages ranging from 2.96% in period 1 to 8.28% in period 4. Gold mines experienced a 47% decrease in period 2, then increased to 27% in period 3, and further increased to 47% in period 4. Another important finding in the analysis was the uneven distribution of silica data across time periods, with 8% in period 1, 4% in period 2, 33% in period 3, and a significant 55% in period 4. Within period 4, 35% of the silica data points were recorded in 2015 and 2016.This also highlights that most of the silica data points in 2015 and 2016 were reported by the gold mines.

There was also a noticeable increase in the number of mines that submitted statutory reports to the DMRE from the 2012/14 to the 2014/15 period, as observed from the DMRE annual reports. These

reports play a pivotal role in capturing and documenting essential data related to workplace exposures, facilitating the effective implementation of measures to mitigate health risks. The increase in the number of mines might be attributed, in part, to the 2014 biennial tripartite summit, where the silicosis milestones were revised.[19] The anticipation of reporting on progress against these revised milestones might have motivated mines to improve their statutory report submissions. These factors may have impacted the 2015 and 2016 data, leading to the representation of 35% of the total silica dust data points in this period.

Pooled airborne pollutant exposure concentrations

The findings from this study suggest that the reported concentrations of certain airborne pollutants exceeded their respective OELs by over 200%. This concerns about the accuracy of the data - reported or measured. This study was, however, not designed to assess the quality of airborne pollutant concentrations. Nevertheless, normalizing the pollutant concentrations allowed for a more accurate assessment of the data.

Pooling the airborne pollutant concentrations from coal and gold mines (combined) resulted in a high degree of variability in the concentrations of pollutants. Pooling the airborne pollutants from coal and gold mines together resulted in variability. The primary source of this variability was the data from the coal mines, which was apparent when the data from the coal and gold mines were analysed separately. The differences in the minimum and maximum ratio (Q) values between coal mines and gold mines might have contributed to the variability. For example, the ranges of Q for coal mines were 0.004 to 27.7, whereas these were for gold mines 0.003 to 7.8. Thus, reporting the combined measurement results for all commodities masks differences in exposures between the commodities.

Combining data from 69 different airborne pollutants (see Appendix 5), which differ over time, can obscure specific pollutant exposures. This approach complicates the interpretation of reported pollutant exposures as each pollutant has its own OEL. The combined impact of pollutants may not be a simple sum of their individual effects - it could be greater or less, depending on their interactions of the different pollutants. This also hinders the identification of pollutant-specific health impacts

Reporting combined exposures also obscures the identification of individual pollutants' sources and pathways, undermining strategies, control measures to mitigate workplace exposure, and risk management programmes. Consequently, policy decisions driven by these reported combined data may compromise the effectiveness of regulations.

Despite these serious limitations, there was a reduction in the reported pooled airborne pollutant concentrations from 2005 to 2016 in all three groups (gold, coal and gold and coal mines combined). The decrease was smaller in the coal mines.

This decrease could have been due to a reduction in exposure to all 69 pollutants, or to a few. The way that the data are reported (pooled) makes it impossible to draw any conclusions about which pollutants drove the reduction in exposure measurements over the 12-year period.

The aim of this analysis was to examine whether the method used by the DMRE to report levels of airborne pollutants accurately represents silica dust concentrations in gold and coal mines in South Africa. It was not to focus on the trends of individual pollutants as reported by the mines. Consequently, inferences regarding the specific pollutants responsible for the observed reduction in exposure measurements over the 12-year period could not be made. The reported decrease in exposure might have been attributed by all 69 pollutants, a combination of some of the pollutants, or even a single pollutant.

Silica dust exposure concentrations

The analysis of the silica dust concentrations from the coal and gold mines combined showed less variability than that for the pooled airborne pollutant concentrations. Similarly, the variability of silica dust measurements from the coal mines was higher than of the gold mines, despite the fact that only 19% of the silica dust measurements data came from coal mines.

The variability in silica dust exposure measurements from surface coal mines have also been reported by Joy et al.[71] The variability in the silica dust measurements might have been a result of the information being obtained from different geographical areas, etc., as for the pooled data.

During the 2003 Mine Health and Safety Summit, stakeholders reached a consensus that, by the year 2008, 95% of all recorded respirable crystalline silica exposures should be below the OEL of 0.1 mg/m^3.[12] It is important to note that these are individual measurements, not averages. This prompted an evaluation of progress towards this target at biennial tripartite summits. An informative booklet on best practices for preventing silicosis was developed in 2006,[12] which aimed to enhance the existing dust control initiatives in the SAMI. Its purpose was to lend substance to the MHSC's milestones concerning the eradication of silicosis.[12] These initiatives and interventions likely contributed to the observed decline in silica dust concentrations across all three commodity groups, with a notably greater reduction in gold than coal mines.

While there was a decrease in silica dust concentrations in all three groups, the decrease was steeper in the gold mines than the coal mines. The AM revealed a considerable discrepancy in silica dust exposure measurements between coal mines and gold mines across the four time periods. For example, for the period 2014 to 2016, the exposure levels were 0.67 mg/m^3 for coal mines and 0.13 mg/m^3 for gold mines. The silica dust exposure measurements from the coal mines were higher than those from the gold mines, despite previous research suggesting that gold mines typically have higher levels of silica dust exposure.[12, 15,40] Higher levels of silica exposure may happen when miners remove overburden or drill through rock to reach the coal for mining,[12] as indicated by the AM in this study. Moreover, disparities in mining methodologies, ventilation systems, and dust control practices might contribute to the observed variance in exposure levels. The exposure levels for all three groups were not below the silica dust OEL of 0.1 mg/m^3 in any year throughout the study period.

Using both the 90th and 95th percentiles (DMRE and EN approaches, respectively) to assess compliance with silica dust concentrations in the coal and gold mines combined, there was a significant decrease in silica dust exposure from 2005 to 2016, suggesting that efforts to reduce exposure to silica dust in this time period were effective. There was a decrease in exposure to silica dust from 2005 to 2016 in the coal mines and the gold mines, although the exposures levels fluctuated over time. The reductions in silica dust exposure did not vary much when using the AM, the 90th percentile and the 95th percentile as indicators for both coal mines and gold mines. However, the 95th percentile demonstrated higher exposures to silica dust concentrations than did the AM, GM, and 90th percentile, for both commodities.

From the AM, the silica dust exposure measurements from the coal mines were substantially higher than the gold mines in all four time periods, e.g. 0.67 mg/m^3 and 0.13, respectively, in the period 2014 - 2016.

Contributing factors to the airborne pollutant and silica dust exposure concentrations

Number of samples taken, and reporting of employees exposed to assess compliance

The number of data points (measurements) is affected by the minimum sample size as required by the DMRE MCoP, whereby the mine must sample a minimum of 5% or five samples per HEG. The number is further influenced by the professional judgement of the appointed occupational hygienist or mine environmental engineer. In this way, the MCoP provides guidelines on the minimum

number of dust samples to be taken for assessment of compliance. From 2005 to 2016, there were more than twice the number of airborne pollutant concentration measurements for the gold (192 745) than for the coal mines (90 125), and more than four times the number of silica dust concentration measurements for the gold mines (102 784) than for the coal mines (24 230). This might have been influenced by the fact that gold mining is a higher risk environment for silica dust exposure than coal mining industry but was surprising as employment in the coal mines increased over the study period (Figure 13) while that in the gold mines decreased (Figure 12).

In the South African mining context, the way samples are gathered, especially under MCoP guideline, places emphasis on obtaining more samples from areas classified as category "A". This increased sampling frequency in any HEG that has been categorised as "A", which then influences the outcomes. Focusing on high-exposure areas, like the category A, suggests a bias in data collection. This bias can impact how we view and manage job-related exposures in South African mines. If many samples come from high-exposure areas, it might exaggerate the prevalence of high exposures in mining. If decisions are based on these results, there is a risk of overstating the dangers of high exposures. In the SAMI context, it is crucial to question the representativeness of the samples and whether they truly reflect exposure across different work areas. Nevertheless, despite the substantial difference in the number of silica dust samples collected by coal mines (24 230) compared to gold mines (102 784), the coal mines still exhibited higher levels of silica dust exposure than the gold mines.

Variations in measurement frequencies could be reflective of a mine's commitment to safety, resource availability, past experiences, and, in some cases, resource limitations. Differences in measurements between the mines could have been attributed to some factors beyond regulatory requirements. Mines with more financial resources might allocate funds for additional measurements, potentially driven by a commitment to improving their health and safety standards. Similarly, mines with better resource management may be able to allocate more time for sampling, enabling them to exceed the minimum stipulated samples per HEG. A reduction in the number of samples, and thus potentially incomplete exposure measurements, might result in challenges in meeting regulatory standards.

Mines with a greater emphasis on safety and health considerations might take extra measurements to ensure a comprehensive understanding of exposure risks, particularly if they have the means to do so. Mines with more complex operations might naturally require more measurements to adequately assess potential hazards, while those with a history of health issues or occupational illnesses might opt for a more robust measurement approach.

Having more data can improve the quality of analysis and accuracy of conclusions, assuming that the data is of good quality. A larger dataset helps to identify patterns and trends and to detect outliers, which reduces the impact of random variation or measurement error. In exposure analysis, having more data points can provide a complete picture of the exposure profile of a population or environment and account for individual variability.

The percentage of employees sampled, as well as the frequency of sampling, can be affected by incorrect categorization of the HEGs, e.g. by the lack of a statistically sound analysis to assign the correct exposure category to a HEG (i.e. the AM and the 90th-percentile of the measurement results should fall in the same HEG exposure category), use of incorrect OELs, or incorrect interpretation of results from the analytical laboratory.[72]

Impact of gold and coal production on exposures

The number of employees in the mining industry in South Africa changed over the study period.[64] The variability of exposure to airborne pollutants in the coal and gold mines could be due a decrease in production and employment in the gold mining industry (Figure 9) and the increase in production and employment in the coal mining industry (Figure 10).

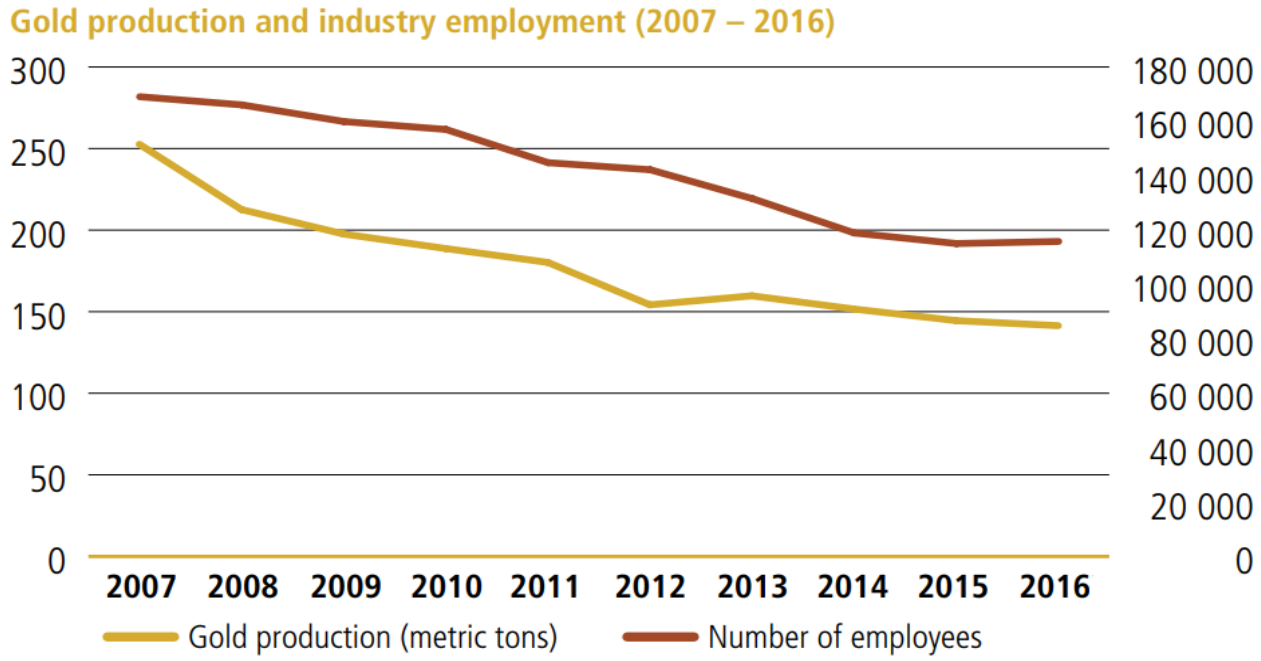


Figure 9. Gold production and industry employment from 2007 to 2016[73]

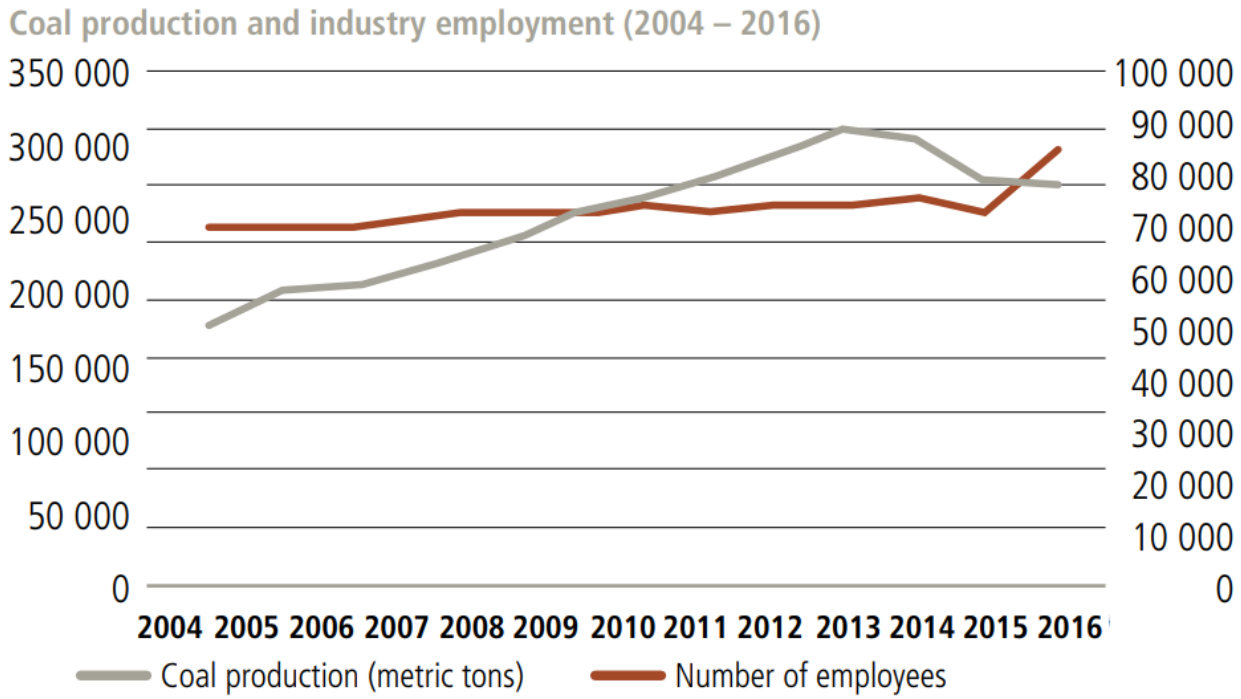


Figure 10. Coal production and industry employment from 2004 to 2016[73]

Worldwide, the gold mining sector is experiencing growth, contrasting with diminishing gold production in South Africa.[19,74] The decrease in exposure levels in the gold mining industry may have been caused by a reduction in gold production and the resulting decrease in employment. This theory is supported by the direct relationship between gold production and the number of workers employed in the industry.[19] As gold production decreases, fewer workers may be exposed to hazardous conditions, and work practices may change to become safer. However, this theory requires further investigation to establish the relationship between gold production, employment, and exposure levels, and to explore other factors that may have contributed to the observed decrease in exposure.

The possibility exists that exposure levels may decrease with a reduction in production. This is because mining activities typically lead to a decrease in the number of employees. In South Africa, there is a specific focus on obtaining more samples from areas classified as category "A." Therefore, if there are fewer employees in Category A, it follows that fewer samples will be taken, indicating a reduction in exposure.

A reduction in the number of samples or frequency of sampling can indicate a reduction in exposure, because it suggests a decreased need for extensive monitoring.

When exposure levels are consistently low or within acceptable limits, there may be less urgency to collect a large number of samples. This reduction in sampling frequency could signify that the workplace environment has improved, or that control measures are effective. However, it is crucial to ensure that, even if fewer samples are taken, they accurately reflect exposure levels, to maintain a comprehensive understanding of potential risks.

Comparison of silica dust exposure in the coal and gold mines

If coal miners are exposed to more dust than gold miners, they could also be exposed to more silica dust. Coal miners are not exposed to silica dust from only the rock in which coal is found. There is also silica in the surrounding ore. Airborne dust typically contains higher levels of crystalline silica (quartz) than the host material.[75] Stanton et al. (2006) reported that during the 1970s, the coal mines in Scotland generated a remarkably elevated level of respirable quartz, reaching up to 60%, and this was caused by the mechanical cutting of sandstone layers above and below a coal seam.[12] Biffi et al. (2000) reported that, the thinner coal seams in South Africa tend to contain high-quality coal, which means that to reach the coal seam more efficiently, more host rock with higher silica content needs to be mined. According to Doyle's (2009) report, individuals who worked in high-risk areas on 41 coal mines between 2002 and 2006 were in danger of developing silicosis and other diseases associated with quartz due to excessive exposure to respirable quartz.[51] The report indicated that these high-risk areas were primarily found in the longwall and continuous miner activity sections.[51]

In terms of the coal mines, the International Agency for Research on Cancer (IARC) Working Group on the Evaluation of Carcinogenic Risks to Humans (1997) highlighted that production and the mining method play major roles in dust levels. The longwall mining technique is commonly used in underground coal mining due to its ability to achieve high productivity in limited spaces.[50,76] However, longwall mining usually results in higher concentrations of dust than other mining methods.[50] As dust forms during the mining of coal, it fills the mining environment and travels through the ventilation system, where high velocities can carry particles of dust that previously settled on the floor, side walls and mining devices, and thereby increasing dust exposure.[77-79]

It is estimated that the dust generated accounts for up to approximately 3% of the mass of all coal excavation.[80] Brodny and Tutak (2018) estimated that, if the daily average mining output is 10 000 kg, then the dust generated may amount to 300 kg/day.[81] The decrease in dust exposures, despite an increase in coal production, could have been attributed to several factors, e.g. the implementation of more effective dust control measures, technological advancements, regulatory compliance, increased

awareness of health risks, and changes in mining practices. Additionally, the commitment to achieving the MHSC health milestones likely incentivized the reduction in dust exposure.
Joy et al. (2014) reported that the percentage of silica present in the respirable dust samples that were gathered from coal mines from 1997 to 2011 varied significantly between underground and surface locations, as the difference in variability was particularly noticeable for samples taken from surface locations.[71]

Joy et al. (2014) also highlighted that surface mine operators may have to cut through a significant amount of rock material to recover sufficient coal and, through this process, dust with varying percentages of silica can be generated. This dust contains a significant percentage of silica, which is much more common in surface coal mines or in surface locations of underground coal mines than in an underground coal mines.[71]

Measures undertaken to decrease exposures to airborne pollutant and silica dust concentrations in the coal and gold mines

In response to studies that reported high levels of silica dust exposure in gold mines, and high prevalence of silicosis in gold mining employees, the gold miner have taken efforts to reduce exposure to respirable dust, by reducing silica dust concentrations.[82] In 2015, du Plessis and van der Bank reported that the average reduction in the TWA quartz concentration across all occupations in a gold mine was calculated to be 79.2% due to implementation of the in-stope water-blast.[83] Senekal (2017) also reported that there were significant improvements in respirable dust and respirable quartz concentrations after the introduction of the high pressure water spray system.[82]

As production increased in the coal mines, exposure to dust increased and high prevalence of silicosis in gold mining employees, the coal and gold mines adopted practices such as fogger dust suppression systems, footwall and side wall wetting, multi-stage filtration systems, winch covers and the continuous personal dust monitors to decrease the silica dust concentrations. However, the extent of the roll-out of these practices in the mining sector in South Africa is not clear.[19]

Coal mining has played a crucial role in the global economy for several years and, despite the growing emphasis on renewable energy sources, demand for coal persists. The production and employment linked with coal remain vital, but the industry is also known for being highly hazardous by exposing employees to dust. As a result, measures have been taken to enhance safety, including

the implementation of innovative technologies such as remote monitoring systems and improved ventilation systems to minimize workers' exposure to airborne pollutants.

Comparison between MCoP and EN 689 methodologies for testing compliance with silica dust concentrations

In this study, two methods for compliance testing were compared, viz. the MCoP and the EN 689 methods. Using different percentiles when assessing compliance – the 90th percentile used in the MCoP method based on empirical data, and the 95th percentile used in the EN 689 method from an estimated population distribution - highlights a distinct and significant difference in these methods. In deciding which method to use when assessing compliance, one should attempt to strike a balance between the MCoP and EN 689 methods. The EN 689 requires that there must be at least 70% confidence that the 95th percentile of the exposure concentrations distribution is below the OEL, while the DMRE calculates the 90th percentile value of the exposure concentrations to assess whether such percentile value falls into HEG categories A, B or C and no indication of the uncertainty is required.[19]

Use of the 95th percentile as an exposure reduction benchmark is well-founded due to its sensitivity to extreme values.[76, 77] This sensitivity is important because silica dust levels can spike during intense mining tasks. The AM is influenced by extreme values, and the 90th percentile might not effectively capture these high concentrations. Using the 95th percentile allows the identification of these spikes, which might indicate the necessity for a comprehensive reduction strategy that targets the upper range of exposures. Therefore, choosing the EN 689 method for assessing silica dust exposure is well-founded as it facilitates the identification of priorities for action.

In analysing the DMRE data, the two methods resulted in the calculation of different estimates of silica dust concentrations. The MCoP method generally estimated higher concentrations at both the 90th and 95th percentiles during specific years. The MCoP method also generally estimated higher concentrations, especially in coal mines, while the EN 689 method estimated higher levels in gold mines. The differences in estimated silica dust concentrations from the two methods emphasizes the importance of choosing an appropriate method for assessing compliance with OELs in mining contexts in an effort to implement effective control measures and ensure accurate and effective protection of workers' health.

The analysis of the data using both the MCoP and EN 689 methods highlighted that the silica dust OEL of 0.1 mg/m^3 was consistently exceeded. The DMRE MCoP method was shown to underestimate the exceedance of the occupational exposure limit by 5-26%, when compared with the

EN 689 method. The EN 689 method, which estimates the 95th percentile of the population distribution and not of the sample, was found to be more conservative in estimating compliance with the silica dust OEL than the MCoP method, which considers the 90th percentile of the sample. The 90th percentile of measured concentrations, assessed in accordance with the MCoP method might be sensitive to the extreme values. Nevertheless, both methods indicated that the silica dust exposures in all three groups exceeded the OEL from 2015 to 2016.

For the data from the combined coal and gold mines, the 90th percentile estimated silica concentrations calculated using the EN 689 method exceeded those estimated using the MCoP method by 18%. The 95th percentile calculated for combined coal and gold mines using both methods did not indicate any differences.

In coal mines, the MCoP method consistently estimated higher silica dust concentrations for both percentiles (90th and 95th percentiles) than did the EN 689 method. This suggests that the MCoP method may provide a more conservative estimate of exposure in coal mining environments. Figure 8 shows that both methods estimated exposures above the OEL in 2015 and 2016.

Additional compliance assessment was carried out using the two methods, utilizing silica dust concentration data points from 2005 to 2016 (refer to Annexure 7 for the comparison). The purpose of this analysis was to determine if the outcomes using the entire 2005-2016 dataset differed from that using the two years, 2015 and 2016.

The findings still revealed notable discrepancies in the coal mine data, where the 90th percentile of the empirical data consistently estimated higher values than the 90th percentile value derived from the distribution of the entire population (after inference). For gold mine data, characterized by lower variances, it was consistently observed that the population distribution estimate showed higher values for the 90th percentile. This, however, does not provide conclusive evidence about the reliability of the methods. Instead, it underscores that the pooling of data, resulting in such high variances, does not represent a sample from one population but rather from multiple populations.

The differences in estimated silica dust concentrations from the two methods emphasizes the importance of choosing an appropriate method for assessing compliance with OELs in mining contexts. The differences in the results from the MCoP and EN 689 methods can be ascribed to a several factors, including differences in measurement approaches, equipment calibration, techniques for analysing data, and disparities in the workplace conditions such as differences in temperature and humidity levels, distance of workplaces from pollution sources, and implementation of control measures such as personal protective equipment.

Recommendations

1. Monitoring and reporting exposure to airborne pollutants by the DMRE should be based on pollutant-specific approaches, rather than pooling all airborne pollutants.
2. Monitoring and reporting the exposure to airborne pollutants by the DMRE should be commodity-specific, separating surface operations and underground operations, using associated activities of exposure, and considering related occupations that are at risk, to determine which occupations have been impacted by overexposures.
3. Future research should be conducted to describe the factors that affect the decrease in exposures and how the SAMI should reduce exposures.
4. The DMRE should consider using the 95^{th} percentile to evaluate and report compliance, as the 90^{th} percentile underestimates the probability of exceeding a limit value, such as the OEL.

Study limitations

Considering the findings of this study, it is important to consider the following limitations:

- As the personal airborne pollutant concentration data were obtained from a third party which, in turn, receives data from different parties, it is not clear how the samples were collected. This is related to both validity and reliability of the measurements. It is possible that mines use different methods and that the samples are analysed at different laboratories.
- The personal airborne pollutant concentrations were collected for regulatory purposes, not for research. The problems with the Magic XPA indicate limitations associated with administrative data.
- Quality assurance, regarding the data, is a potential limitation. Several factors could impact the accuracy of the study's results, including the use of appropriate sampling methodology, competent personnel for data analysis, correct equipment preparation and storage, recording of relevant information that could affect sampling results, calibration and maintenance of sampling instruments, and accurate recording and transfer of data into the DMRE's information management system.
- The exposure data that could be accessed from DMRE covered the period2005 to 2016, although the intended study period was 2005 to 2018.
- It was not possible to investigate reasons for changes in exposures
- Exposures measurements were not available for different mining activities, job categories, or HEGs.

CHAPTER 6: CONCLUSIONS

The aim of this study was to investigate whether the DMRE's current approaches to reporting airborne pollutants allows for the accurate assessment of silica dust exposure in South African coal and gold mines.

Despite the variabilities and challenges associated with pooling the airborne pollutants concentrations in the coal and gold mining industries, exposures to the airborne pollutants in the three commodity groups decreased from 2005 to 2016. However, the results of this analysis showed that there were excessive airborne pollutant exposures in coal and gold mines from 2005 to 2016. Reporting employee exposure as pooled airborne pollutants concentrations is flawed and obscures exposures to individual pollutants such as silica dust.

Reporting pooled airborne pollutants exposure data does not provide any indication of trends in exposures to specific hazards, such as respirable silica dust. Reporting on pooled airborne pollutants masks the exposure of individual pollutants. It is important to know to which specific pollutants exposures are changing in the various subsectors of the mining industry. Using the concept of a ratio (Q) of the airborne pollutant exposure concentrations, there was an overexposure to airborne pollutants in coal and gold mines from 2005 to 2016.

The three commodity groups showed a decrease in silica dust exposure measurements from 2005 to 2016. However, there was still overexposure to silica dust in the three groups (higher than the OEL of 0.1 mg/m^3). Exposure to silica dust was higher in the coal than the gold mines.

The current DMRE reporting methodology, i.e. the pooling of all data, does not allow accurate reporting of individual pollutant exposures and therefore does not guide or facilitate the implementation of actions to reduce exposures to airborne pollutants. To accurately assess exposures in the South African mining industry, pollutant-specific measurements should be reported. If the DMRE does not modify its approach, compliance testing against the OELs for airborne pollutant concentrations (pooling airborne pollutant concentrations) and individual pollutant concentrations will continue to underestimate employee exposure levels. Drawing from the findings of this study, the current reporting approach adopted by the DMRE, which combines or aggregates airborne pollutant exposure data, presents challenges for accurately assessing and managing exposure. To

ensure effective exposure management, individual pollutants should be measured, assessed, and reported separately.

The DMRE MCoP approach to compliance with silica dust levels underestimated the exceedance of the OEL in comparison to the EN 689's approach. This performance of the MCoP and EN 689 methods in evaluating compliance with the silica dust OEL was compared. There were notable differences between the two methods, with regard to the outcomes, emphasizing the need for both the DMRE and the mines to select an appropriate method for assessing compliance.

The EN 689 method, particularly when utilizing the 95th percentile, provided a more accurate estimate of OEL compliance than the MCoP method, although both methods indicated exceedances of the OEL in both coal and gold mines. As such, it is important to note that pooling data from different mines will increase variability. Using the EN 689 method and the estimate of the 95th percentile of the population will reveal higher values than if the 95th percentile of all the data points was calculated (without inference). The pollutant data submitted to the DMRE should be analysed separately, and the information provided by DMRE should consist of statistically sound analysed data or a summarized version thereof.

In conclusion, to achieve a more accurate assessment of individual pollutant exposure in South African gold and coal mines, it is important to adopt the EN 689 method, with a focus on the 95^{th} percentile and population estimates. Regarding the compliance testing, the use of EN 689 (5% exceedance) and the population estimates rather than the sample estimates should be considered. Additionally, data from different mines should not be pooled to avoid increased variability. These measures will contribute to a more accurate and comprehensive assessment of individual pollutant exposure in South African mines.

The findings from this research suggests the need for further investigation into the relationship between exposure reduction, production decrease, labour workforce reduction, and other factors contributing to the observed decreases in exposures to both combined pollutants and silica dust.

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Appendix 1 – Plagiarism Declaration

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

I **BRIAN TSHEPO MONGOMA** (Student number: **330338**) am a student

registered for the degree of **MASTERS IN PUBLIC HEALTH** 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.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature:  Date: 24 October 2023

Appendix 2 – DMRE Reporting Requirements

The mines are required to provide detailed information as summarised below when reporting silica dust exposure to the DMRE.

Table 10. DMRE Airborne Pollutant Reporting Variables

	Stipulated Reporting elements[1]
1.	Mining commodity
2.	Year of report
3.	Occupations exposed within a HEG
4.	Occupation code/s as listed in the South African Mines Occupational Hygiene Program (SAMOHP)
5.	Number of Persons per Occupation
6.	Pollutant Code
7.	Sample Concentration per Occupation (TWA-8hr) mg/m^3
8.	Pollutant analysis %
9.	90^{th} percentile HEG Classification
10.	The range of pollutant concentrations in terms of minimum and maximum
11.	A pollutant Index
12.	An Air Quality Index

Appendix 3 – Ethics Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG

R49 Mr B Mongoma

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
CLEARANCE CERTIFICATE NO. M210460

NAME: (Principal Investigator)	Mr B Mongoma
DEPARTMENT:	School of Public Health Department of Occupational Health Medical School University
PROJECT TITLE:	*Reporting silica dust exposure measurements in South African gold and coal mines: 2005 to 2018*
DATE CONSIDERED:	2021/04/30
DECISION:	Approved unconditionally
CONDITIONS:	
NOTE:	If contact information regarding student study participants is required, please contact the Registrar's office - <Nicoleen.Potgieter@wits.ac.za>
SUPERVISOR:	Professors G Nelson and D Brouwer
APPROVED BY:	CB Penny Dr CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL:	2021/11/08

This Clearance Certificate is valid for 5 years from the date of approval. An extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office secretariat on the 3rd floor, Phillip Tobias Building, Parktown, University of the Witwatersrand, Johannesburg.

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 submit details to the Committee. **I agree to submit a yearly progress report**. When a funder requires annual re-certification, the application date will be one year after the date when the study was initially reviewed. In this case, the study was initially reviewed in April and therefore reports and re-certification will be due in the month of **April** each year. Unreported changes to the study may invalidate the clearance given by the HREC (Medical).

Signature of Principal Investigator

03 January 2022
Date

Appendix 4 – Permission to Perform Research

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF HEALTH SCIENCES

Chief Director – Occupational Health
Department of Mineral Resources and Energy
Cnr 173 Visagie St, Bosman,
Pretoria,
0001

To: Dr Lindiwe Ndelu

A PERMISSION TO PERFORM RESEARCH PROJECT ON AIRBORNE POLLUTANT EXPOSURE MEASUREMENTS REPORTED TO THE DEPARTMENT OF MINERAL RESOURCES AND ENERGY

In fulfilment of Master's in Public Health – Occupational Hygiene, the students are required to perform a research on Occupational Hygiene. Brian Tshepo Mongoma, a 3rd year University of Witwatersrand student, is hereby requesting a permission to undertake the research project utilizing airborne pollutants exposure data reported by the Minerals Council's gold and coal mining members from 2005 to 2018 to the Department of Mineral Resources and Energy.

My research project is titled **"Reporting silica dust exposure measurements in South African gold and coal mines, from 2005 to 2018"** with the following specific objectives:

- To describe trends in airborne pollutant personal exposure measurements, from 2005 to 2018, using data from gold and coal mining companies affiliated to the Minerals Council and using data from DMRE MHSI annual published reports.
- To describe trends in silica dust exposure measurements, from 2005 to 2018, using data from gold and coal mining companies affiliated to the Minerals Council.
- To compare the SAMI's and CEN's approaches to silica dust exposure measurements with regard to the OEL (compliance testing), using data collected in 2017 and 2018 by gold and coal mining companies affiliated to the Minerals Council.

South African Mining Industry will benefit from this proposed study by reporting silica dust exposure measurements appropriately.

The high level of confidentiality, anonymity and respect to all the members participating will be maintained always. Please advise if my request has been accepted.

Yours sincerely
Brian Mongoma
Occupational Hygienist - Southern African Institute for Occupational Hygiene (SAIOH)

Signature for approval
Date: 11/06/21

Signature for not approval
Date:_____

Appendix 5 – Different airborne pollutants reported per period

Table 11. Different airborne pollutants reported per period from 2015 to 2016 for coal and gold mines

	2005 - 2007	2008 - 2010	2011 - 2013	2014 - 2016
Coal	Acetaldehyde	Acetonitrile	Aluminium oxides (inhalable particulate)	2-Aminoethanol
Coal	Calcium carbonate respirable particulate	Coal tar pitch volatiles [as cyclohexane soluble]	Benzene-1,2,4,-tricarboxylic acid 1,2-anhydride	Aluminium oxides (inhalable particulate)
Coal	Chlordane	Cresols, all isomers	Bis(chloromethyl) ether [BCME]	Benzene-1,2,4,-tricarboxylic acid 1,2-anhydride
Coal	Cresols, all isomers	Molybdenum compounds soluble compounds	Calcium oxide	Biphenyl
Coal	Particles not otherwise classified	Particles not otherwise classified	Carbon monoxide	Bis(chloromethyl) ether [BCME]
Coal	Propoxur	Pentaerythritol respirable particulate	Cement (inhalable particulate)	Calcium carbonate inhalable particulate
Coal	Respirable crystalline silica	Respirable crystalline silica	Chromium, metal and inorganic compounds [as Cr]	Chromium, metal and inorganic compounds [as Cr]
Coal	Respirable coal dust	Respirable coal dust	Coal tar pitch volatiles [as cyclohexane soluble]	Copper fume
Coal	Welding fumes		Copper Dusts & mists [as Cu]	Cresols, all isomers
Coal			Cresols, all isomers	Cyanogen
Coal			Iron oxide, dust & fume [as Fe]	Diphenyl
Coal			Magnesium oxide [as Mg] inhalable particulate	Iron oxide, dust & fume [as Fe]
Coal			Manganese, fume [as Mn]	Lead, elemental, and inorganic compounds [as Pb]
Coal			Naphthalene	Magnesium oxide [as Mg] inhalable particulate
Coal			Oil mist, mineral	Manganese, fume [as Mn]
Coal			Particles not otherwise classified	Nickel, inorganic compounds [as Ni] insoluble
Coal			Phenol	Oil mist, mineral
Coal			Plaster of Paris respirable particulate	Oxalonitrile
Coal			Respirable crystalline silica	Particles not otherwise classified
Coal			Respirable coal dust	Respirable crystalline silica
Coal			Terphenyls, all isomers	Respirable coal dust
Coal			Tin compounds, inorganic except SnH4 [as Sn]	Rhodium [as Rh] soluble salts
Coal			Zinc oxide, fume	Silica, fused [respirable particulate]
Coal				Titanium dioxide inhalable particulate
Coal				Welding fumes
Coal				Zinc oxide, fume
Gold	Acetaldehyde	Aluminium alkyl compounds	Acetic acid	2-Aminoethanol
Gold	Ammonia	Arsenic & compounds, except arsine [as As]	Acrylic acid	Acetaldehyde

Gold	Carbon dioxide	Carbon black	Arsenic & compounds, except arsine [as As]	Arsenic & compounds, except arsine [as As]
Gold	Carbon monoxide	Chromium, metal, and inorganic compounds [as Cr]	Benzene-1,2,4,-tricarboxylic acid 1,2-anhydride	Bis(chloromethyl) ether [BCME]
Gold	Cresols, all isomers	Cresols, all isomers	Bis(chloromethyl) ether [BCME]	Copper Dusts & mists [as Cu]
Gold	Cychlohexane	Hydrogen cyanide and cyanide salts [as CN] *Hyd	Calcium carbonate inhalable particulate	Cresols, all isomers
Gold	Lead tetra-methyl [as Pb]	Lead, elemental, and inorganic compounds [as Pb]	Cresols, all isomers	Manganese, fume [as Mn]
Gold	Nitrogen dioxide	n-Amyl acetate	Lead, elemental, and inorganic compounds [as Pb]	Molybdenum compounds soluble compounds
Gold	Particles not otherwise classified	Particles not otherwise classified	Particles not otherwise classified	n-Propyl acetate
Gold	Picloram	Pentaerythritol inhalable particulate	Plaster of Paris respirable particulate	Paraquate dichloride respirable particulate
Gold	Respirable crystalline silica	Pentyl acetate	Respirable crystalline silica	Particles not otherwise classified
Gold	Respirable coal dust	Respirable crystalline silica	Respirable coal dust	Phthalic anhydride
Gold	Silica, amorphous respirable particulate	Respirable coal dust	Welding fumes	Respirable crystalline silica
Gold	Sodium fluoroacetate	Silica, amorphous respirable particulate	Zinc stearate respirable particulate	Respirable coal dust
Gold		Trichloroacetic acid	Zinc stearate inhalable particulate	Sulphur hexafluoride
Gold				TEPP
Gold				Tetraethyl pyrophosphate
Gold				Welding fumes

Appendix 6 – Turnitin report signed by supervisor



Checked and approved 24 Oct 2023
Gill Nelson

Brian Mongoma - revised research report 24 Oct 2023 changes highligted Final.docx

ORIGINALITY REPORT

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Appendix 7 – 2015 and 2016 silica dust concentrations compared with 2005 to 2016 silica dust concentrations

2015 and 2016

Approach	Combined coal and gold mines (mg/m^3)	Coal Mines (mg/m^3)	Gold Mines (mg/m^3)
2015 – 90th percentile			
MCoP	0.41	1.73	0.3
EN 689	0.5	1.64	0.32
2015 – 95th percentile			
MCoP	0.8	2.28	0.37
EN 689	0.8	2.39	0.46
2016 – 90th percentile			
MCoP	0.32	2.14	0.23
EN 689	0.39	1.59	0.25
2016 – 95th percentile			
MCoP	0.6	2.18	0.28
EN	0.6	2.28	0.35

2005 to 2016

Commodity	Time period	90th percentile (mg/m3)		95th percentile (mg/m3)	
		MCOP approach	EN 689 approach	MCOP approach	EN 689 approach
Coal and gold mines combined	2005-2007	1.17	1.07	1.67	1.64
	2008-2010	0.92	0.86	1.26	1.27
	2011-2013	0.59	0.6	0.77	0.81
	2014-2016	0.39	0.41	0.53	0.59
Coal mines	2005-2007	2.48	2.37	3.16	3.45
	2008-2010	1.72	1.55	2.27	2.21
	2011-2013	1.79	1.61	2.41	2.34
	2014-2016	1.64	1.56	2.16	2.27
Gold mines	2005-2007	0.48	0.5	0.62	0.72
	2008-2010	0.51	0.55	0.63	0.79
	2011-2013	0.46	0.48	0.55	0.64
	2014-2016	0.29	0.31	0.35	0.43