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Respirable dust concentration at workstations in a gold mine processing plant.

By

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A research project submitted in partial fulfilment of the requirements of a Bachelor of Science Honours Degree in Safety, Health and Environmental Management

MAY 2025

DECLARATION

To be complied by the student

Registration number B211690B

I, Ephraim Muchuweni, do hereby declare that this work is entirely the product of my own research and it was never used on any other academic work. All reference to previously published work has been clearly shown.

Student signature  Date 28 May 2025

To be complied by supervisor

This dissertation is suitable for submission to the faculty and have been checked for conformity with the faculty guidelines.

Supervisor’s signature:  Date: 30 May 2025

DEDICATION

I dedicate this research to my beloved parents, Mr. and Mrs. Muchuweni, whose unwavering love, sacrifices, and support have been the foundation of my academic journey. Your guidance and prayers have carried me through every step of this work. This achievement is as much yours as it is mine.

ABSTRACT

Background: Mining is one of the cornerstones of national economies, but is associated with serious environmental health risks, particularly from airborne dust in processing plants.

Objectives: Respirable dust concentrations were measured at selected dusty workstations within a gold mine processing plant to assess legislative compliance with the WHO 24-hour guideline of 0.015 mg/m³.

Methods: Area-based sampling was conducted using a Split II Haz-Dust Monitor over 8-hour shifts on 22 April 2025. Measured values were converted to 24-hour time-weighted averages using a standard extrapolation formula. Descriptive and inferential analyses were conducted using SPSS v27. Kruskal-Wallis test, post hoc pairwise comparisons using Dunn's test with Bonferroni correction, was used for data analysis in SPSS. Statistical significance was considered at $p < 0.05$.

Results: The 24-hour respirable dust concentrations ranged from 0.073 mg/m³ to 10.5 mg/m³ with a mean of 3.05±0.88SE mg/m³. The Shapiro-Wilk test indicated a non-normal distribution of the data ($p = 0.228$). A Kruskal-Wallis test revealed significant differences in respirable dust concentration across 13 workstations ($H = 37.687$, $p = 0.002$). Post-hoc Dunn's tests with Bonferroni correction grouped the workstations into six distinct groups. All converted measured concentration exceeded the WHO 24-hour guideline of 0.015 mg/m³, with the lowest value approximately 15 times higher than the recommended limit.

Conclusion: Findings highlight significantly high ambient dust levels in gold processing areas, reinforcing the urgent need for improved air quality control.

Keywords: $PM_{2.5}$, Respirable dust, Gold processing, WHO limit, ambient air, Dust control

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LIST OF ACRONYMS AND ABBREVIATIONS

LMICs	Low- and Middle-Income Countries
WHO	World Health Organisation
SHEQ	Safety, Health, Environment, and Quality
MTS	Mining Technical Service
PPE	Personal Protective Equipment
SPSS	Statistical Package for Social Science
PPM	Pickstone Peerless Mine
NIST	National Institute of Standards and Technology
PM	Particulate Matter
TWA	Time-Weighted Average

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CHAPTER 1: INTRODUCTION

1. Introduction

1.1 Background of the study

Respirable dust, particularly particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), has emerged as a significant environmental health concern in mineral processing plants (Duarte et al., 2022). In low- and middle-income countries (LMICs), ambient air within and around such plants often contains elevated dust levels due to inadequate engineering controls and outdated processing technologies (Quintero et al., 2024). Exposure to ambient $PM_{2.5}$ is associated with an increased risk of respiratory and cardiovascular diseases (Vlahovich & Sood, 2021). Global agencies, such as the World Health Organisation (WHO), recommend a 24-hour guideline limit of 0.015 mg/m^3 for ambient air (Hoffmann et al., 2021).

Environmental dust levels vary significantly between work areas within processing plants, influenced by ore type, ventilation, and proximity to crushing, milling, and material handling operations (Duarte et al., 2022). Studies from LMICs have reported localised $PM_{2.5}$ concentrations far exceeding the WHO threshold value, especially near milling stations and transfer points (Sepadi et al., 2020; Nabiwa et al., 2024). However, environmental exposure assessments in mining zones often rely on outdoor air monitoring, with limited attention to indoor ambient air within workstations where dust accumulates and circulates with minimal dispersion (Awokola et al., 2022).

There is limited literature assessing how respirable dust concentrations vary spatially across distinct workstations within gold processing plants. Most environmental assessments do not disaggregate data by workstations within a plant, making it difficult to identify high-risk zones or evaluate the effectiveness of local dust control systems (Hoffmann et al., 2021). This gap highlights the need for more spatially resolved studies using fixed workstations area monitors that can capture workstation-level variation and benchmark findings against international ambient air quality standards. Such research is essential for guiding plant-level air quality management in the LMIC context.

1.2 Problem statement

Indoor respirable dust exposure in gold processing plants in low- and middle-income countries (LMICs) is poorly quantified, despite alarming particulate matter ($PM_{2.5}$) levels in nearby mining zones. For instance, ambient $PM_{2.5}$ concentrations in Zambia's copper belt have recorded between (0.072 - 0.096 mg/m³), well above the WHO 24-hour guideline of 0.015 mg/m³ (WHO 2021; Sifanu et al., 2024). Existing studies in LMICs focus on outdoor air or underground shafts, neglecting indoor processing areas where workers face prolonged exposure (Matandirotya, 2021; McFarlane et al., 2021). The absence of workstation-specific $PM_{2.5}$ data benchmarked against environmental standards restricts regulation and worker protection. This study fills that gap by spatially assessing indoor $PM_{2.5}$ levels and comparing them with WHO 24-hour guideline to inform air quality controls in LMIC gold facilities.

1.3.1 Aim

- To determine and compare the concentration of respirable dust across selected workstations within a gold mine processing plant, following the WHO 24-hour ambient air quality guideline for $PM_{2.5}$

1.3.2 Objectives

- To determine the concentration of respirable dust at selected dusty workstations in a gold mine processing plant.
- To compare the mean 8-hour respirable dust concentrations at selected workstations in the gold processing plant with the WHO 24-hour ambient air quality guideline for $PM_{2.5}$ (0.015 mg/m^3).

1.4 Significance of the study

The study generates empirical evidence on respirable dust concentrations across specific dusty workstations in a gold processing plant, data that is currently lacking in Zimbabwe and other LMICs. Its findings may guide mine management, environmental health departments, and regulatory bodies in identifying high-risk zones and improving dust control practices at the workstation level. By applying fixed-point sampling, the study contributes to the broader knowledge base on environmental exposure monitoring in surface gold processing environments. The results also provide a scientific basis for future research and practical interventions aimed at improving air quality in mineral processing operations.

1.5 Hypotheses

- H_0: There is no significant variation in the concentrations of respirable dust across the selected dusty workstations at Pickstone Gold Mine.
- H_1: There is a significant variation in the concentrations of respirable dust across the selected dusty workstations at Pickstone Gold Mine.

- H_0: There is no significant difference between the mean respirable dust concentrations at each selected dusty workstations and the WHO 24-hour $PM_{2.5}$ air quality guideline of 0.015 mg/m³
- H_1: There is a significant difference between the mean respirable dust concentrations at each selected dusty workstations and the WHO 24-hour $PM_{2.5}$ air quality guideline of 0.015 mg/m³

1.6 Assumptions

- All dust monitoring equipment will function accurately and will be properly calibrated before use.
- Sampling will be conducted under normal operating conditions representative of typical work environments at the processing plant.

1.7 Limitations

- The results may not apply to other gold mines with different operating conditions or ventilation systems.

- Short-term sampling may not account for seasonal changes or long-term exposure patterns.

1.8 Delimitations

- The study focuses exclusively on respirable dust and excludes total dust and other airborne contaminants.
- Only the processing plant section of Pickstone Gold Mine is considered.
- Sampling is limited to dusty workstations directly involved in ore processing and material handling.

CHAPTER 2: REVIEW OF LITERATURE

2. Literature review

2.1 Introduction

This chapter reviews existing literature on respirable dust exposure in gold processing plants. It provides a summary, highlighting the origin and sources of dust, the environmental elements that influence its emission, and the differences in exposure levels between workstations. This provides a road map to assess compliance in various jurisdictions and addresses the environmental and health consequences of prolonged exposure. Dust monitoring and control approaches are also discussed, with a focus on those employed in low-and middle-income countries (LMICs). Finally, it provides a framework underpinning the study.

2.2 Sources and characteristics of respirable dust in gold processing

In gold processing environments, respirable dust mainly comes from crushing, grinding, and transferring of the ore materials. Mechanical operations such as these generate particles less than 10 µm that can reach deep into the alveolar regions of the lungs (Quintero et al., 2024). Dust generation is often increased by inadequate containment, high-speed equipment, and high ore throughput, particularly when engineering controls are not in place (Purohit et al., 2019). Primary crushers and feeders are major emission points for particulate release due to dry ore and mechanical abrasion (Wua et al., 2023).

The composition of the dust varies by ore body but typically contains silicates and quartz along with trace metals like Cd, Cu, Sb, and Zn (Hower et al., 2022; Maus et al., 2022).

Environmental conditions such as dry weather and low relative humidity are known to increase suspension time and airborne persistence of dust particles, while poor ventilation promotes accumulation in poorly ventilated areas, thus increasing exposure over time (Wua et al., 2023). Such physicochemical characteristics are crucial to understand, enabling the development of effective dust control specific to workstations or ore types (Huang et al., 2024).

2.3 Environmental influence on dust generation

Dust behaviour is greatly influenced by the environment, including temperature, humidity, and airflow patterns; low humidity and high ambient temperatures promote suspension, while poor ventilation promotes accumulation, with even small interruptions to ventilation causing increases in exposure due to recirculation of dust particles (Purohit et al., 2019). This implies that both operational design and environmental dynamics should be considered for effective dust control.

Recent empirical findings from gold and platinum mining sectors in sub-Saharan Africa suggest that processing plants located in arid or semi-arid zones report significantly elevated ambient respirable dust levels during dry seasons, when relative humidity drops below 30% (Sepadi et al., 2020; Nabiwa et al., 2024). Similarly, a study conducted in Ghana highlights that processing plants with open-sided structures and minimal cross-ventilation showed higher $PM_{2.5}$ concentrations compared to plants with enclosed systems and regulated airflow (Mensah et al., 2020). This supports the argument that unregulated workplace environmental conditions play a compounding role in worker exposure to dust, especially in low- and middle-income countries where engineering controls are inconsistently applied.

2.4 Exposure levels at workstations in gold mine processing plants

Table 2.1 shows earlier studies that were conducted in LMICs to assess respirable dust concentrations at workstations in gold mines. Literature indicates that even when respirable dust levels are below some occupational limits, they remain tens of times higher than the WHO 24-hour $PM_{2.5}$ guideline of 0.015 mg/m^3; underground operations, drilling, loading, and quality control tasks consistently report the highest exposures, while enclosed cabins and better controls are linked to reduced concentrations.

Table 2.1 Earlier studies assessing respirable dust concentrations at workstations in gold mines in LMICs

Country/ Mine	Sampling method (Respirable Dust)	Mean ± SE (mg/m^3)	Key findings	Reference
Tanzania (Geita)	Area gravimetric (cyclone + pump, NIOSH 0600)	• Crushing: 0.36±0.05	• Crushing and milling areas exceeded the WHO $PM_{2.5}$ guideline by 20–30 times • Frequent resuspension of dust in dry months	Rusibamayila et al (2018)
Ghana (Tarkwa Mine)	Area gravimetric (cyclone + pump)	• Crushing: 0.42±0.04 • Milling: 0.55±0.05	• Dust is highest near the crushers • Poor enclosure in the processing plant • Recommended upgrading of ventilation and dust capture	Mensah et al (2020)
Burkina Faso (Essakane Mine)	Area gravimetric (cyclone + pump)	• Crushing: 0.44±0.07 • QC zone: 0.60 ± 0.08	• Crushing and sampling points showed consistently high respirable dust • Minimal wet suppression • Workers used inadequate PPE	Awokola et al (2022)

Philippines (Didipio Mine)	Gravimetric + DustTrak (TSI, real-time)	• 0.60 ± 0.09 (average for crushers/mills)	• Dust spikes during ball mill loading • Engineering controls reduced exposures by 30%	Halterman et al (2018)
Côte d'Ivoire (Tongon Mine)	Ambient MiniVol sampler ($PM_{2.5}$, PM_{10})	• Ambient $PM_{2.5}$: 0.078 ± 0.012	• $PM_{2.5}$ levels around the gold plant exceeded the WHO 24-hr limit	Awokola et al (2022); McFarlane et al (2021)
Peru (Yanacocha Mine)	Area gravimetric (cyclone + pump, NIOSH 0600)	• Crushing: 0.91±0.13	• Respirable dust is highest at conveyor-drop points • Water sprays reduced airborne dust by 38%	Vetter & Carcedo (2021)
South Africa (Witwatersrand Basin)	Stationary gravimetric (cyclone + pump)	• 0.47±0.06 (processing plant average)	• Surface crushers produced 2 times the dust levels of underground units • Aging ventilation compromised capture • Workers near the crushers showed respiratory complaints	Sepadi et al (2020)

Mongolia (Boroo Mine)	Area gravimetric (cyclone + pump)	• 0.52 ± 0.07 (processing plant average)	• Milling and ore transfer zones are most contaminated • Enclosed operator cabins lowered dust exposure significantly	Quintero Santofimio et al (2024)

2.5 Time-weighted conversion of short-term $PM_{2.5}$ measurements

Time-weighted conversion is widely used to estimate 24-hour $PM_{2.5}$ concentrations from shorter sampling periods in industrial settings where continuous monitoring is not feasible WHO (2021) . This is particularly useful in gold mine processing plants, where logistical and safety constraints make 24-hour sampling impractical. The World Health Organisation (WHO) recommends a 24-hour $PM_{2.5}$ limit of 0.015 mg/m³ to protect against cardiopulmonary and respiratory risk (Hoffmann et al., 2021). An 8-hour sample can be extrapolated to a 24-hour estimate using a formula: TWA (24h) = ($C_8 \times 8$) / 24, where C_8 represents the 8-hour average concentration, and this method assumes either a constant dust level or zero exposure during unsampled hours WHO (2021)

A study conducted in Zambia has validated this approach in both ambient and occupational settings. Partial day measurements $PM_{2.5}$ were shown to closely reflect full-day averages under stable conditions (Sifanu et al., 2024) . Similar applications in LMIC industrial zones demonstrated the method's reliability in dust-prone areas (Raza & Ali, 2021). These findings support time-weighted extrapolation as a scientifically sound tool for environmental exposure assessment.

2.6 Ambient $PM_{2.5}$ monitoring techniques in gold processing environments

Several recent studies rely on short-term ambient sampling (6 - 10 hours) with time-weighted conversion to 24-hour averages, as discussed in Section 2.5. However, some large-scale gold processing operations have adopted a 24-hour ambient monitoring system. Agnico Eagle's Fosterville Gold Mine in Australia has continuous beta attenuation monitors and high-volume $PM_{2.5}$ samplers installed around its processing to record dust levels over a full day (Wilson & Vetten, 2019). This setup captures real-time fluctuations in particulate levels and removes the need to assume stable conditions during unsampled hours. It also enables direct comparison with daily air quality guidelines.

In recent community-based studies near gold mining areas, continuous ambient particulate monitoring has been used to characterise exposure. For instance, Atakorra et al. (2021) conducted 24-hour PM 2.5 and PM 10 monitoring in communities surrounding the Obuasi gold mine in Ghana using gravimetric samplers, while other studies in Sub-Saharan Africa have deployed real-time monitors to capture temporal dust variability near mine sites (Awokola et al., 2022; Sifanu et al., 2024). Although these data were collected outside the plant, they represent true 24-hour ambient monitoring. Despite such advancements, most processing plant assessments still rely on short-term sampling followed by extrapolation to estimate daily exposures

2.7 Area-based respirable dust sampling at processing workstations

Fig. 2.1 shows a sampling personnel recording particulate matter (PM) from a fixed area dust sampler installed in a dusty section of the processing plant. In this study, sampling monitors were placed near typical breathing zones at 13 identified dusty workstations in the gold processing plant using a Splitt 2 particulate monitor. The goal was to assess environmental exposure levels relative to the WHO 24-hour PM2.5 guideline (0.015 mg/m^3). A similar method was applied in a Tanzanian gold processing facility, where respirable dust concentrations were measured at fixed locations in milling areas to inform environmental control measures (Rusibamayila et al., 2018).

Fig.2.1: Sampling personnel recording particulate matter

2.8 Dust exposure monitoring

Table 2.2 highlights recent findings from LMICs on dust control in gold processing plants. Engineering solutions like misting systems, ventilation, and enclosed cabins consistently reduce dust more effectively than administrative measures or PPE, which often suffer from low worker compliance. Despite these efforts, respirable dust levels frequently exceed WHO guidelines. In contrast, developed countries use real-time monitoring tools, such as beta attenuation monitors (BAMs), to track $PM_{2.5}$ levels continuously. These systems support early detection and prompt corrective action, helping maintain exposure within safe limits (Shukla & Aggarwal, 2022).

Table 2.2 Recent findings from LMICs on dust control in gold mines

Country (Mine)	Controls	Post-control key findings	Reference
Nigeria (Zamfara ASM Milling)	Wet-spray misting; community training	Silica was reduced by 80% and airborne lead was reduced by 95%	McFarlane et al (2021)
Tanzania (Buhemba ASM Site)	Wet milling only	Respirable dust 0.4–2.0 mg/m^3, above WHO 24-h limit	Rusibamayila et al (2018)
Tanzania (Large-Scale Mine)	AC cabins, job role separation, and PPE masks	Cabin levels 0.17 mg/m^3 vs. open areas 0.41 mg/m^3	Rusibamayila et al (2018)
Ghana (Chirano Underground Mine)	Ventilation, health screening, reusable respirators	>40% of SEGs, >0.05 mg/m^3 silica, and low respirator comfort noted	Mensah et al (2020)
Burkina Faso (Kalsaka Gold Mine)	Enclosed conveyors, fog sprays, and PPE reinforcement	Dust exposure was reduced by 70% and PPE use increased among process operators	Awokola et al (2022)

2.9 Ambient air quality standards and regulatory compliance

Ambient air quality standards for $PM_{2.5}$ vary significantly between countries, often influenced by local economic factors and regulatory capabilities. Many LMICs have standards that are much less stringent than international health recommendations. For instance, India's 24-hour limit is set at 0.060 mg/m^3, and South Africa's is at 0.040 mg/m^3 (Matandirotya, 2021; Purohit et al., 2019). By comparison, the WHO updated its $PM_{2.5}$ guideline in 2021 to a much lower level of 0.015 mg/m^3 over 24 hours, based on extensive studies linking $PM_{2.5}$ exposure to serious cardiovascular, respiratory, and developmental health risks (Hoffmann et al., 2021).

In the absence of enforceable or protective national standards, many peer-reviewed studies conducted in LMIC gold mining contexts explicitly adopt the WHO guideline to evaluate ambient respirable dust concentrations in processing areas (Matandirotya, 2021). Recent studies from Uganda and the Democratic Republic of Congo have compared their 8-hour ambient $PM_{2.5}$ measurements to the 2021 WHO 24-hour guideline, recognizing its strong health basis and value for comparing results across different countries (McFarlane et al., 2021). The widespread use of the WHO standard shows local regulations often fall short and underscores the need for a reliable, science-based exposure benchmark.

2.10 Theoretical framework

This study is guided by the Source-Pathway-Receptor (SPR) Model (Jose & Srimuruganandam, 2021), which conceptualizes the generation, transport, and measurement of pollutants such as respirable dust ($PM_{2.5}$) in environmental contexts. In this framework, operational factors at workstations, including material movement and machinery type, serve as independent variables, while ambient $PM_{2.5}$ concentrations measured through area-based monitoring represent the dependent variable. The model facilitates understanding of how dust generated during gold processing travels through the air (pathway) to the sampling location (receptor), thereby explaining spatial variations in air quality within the processing plant.

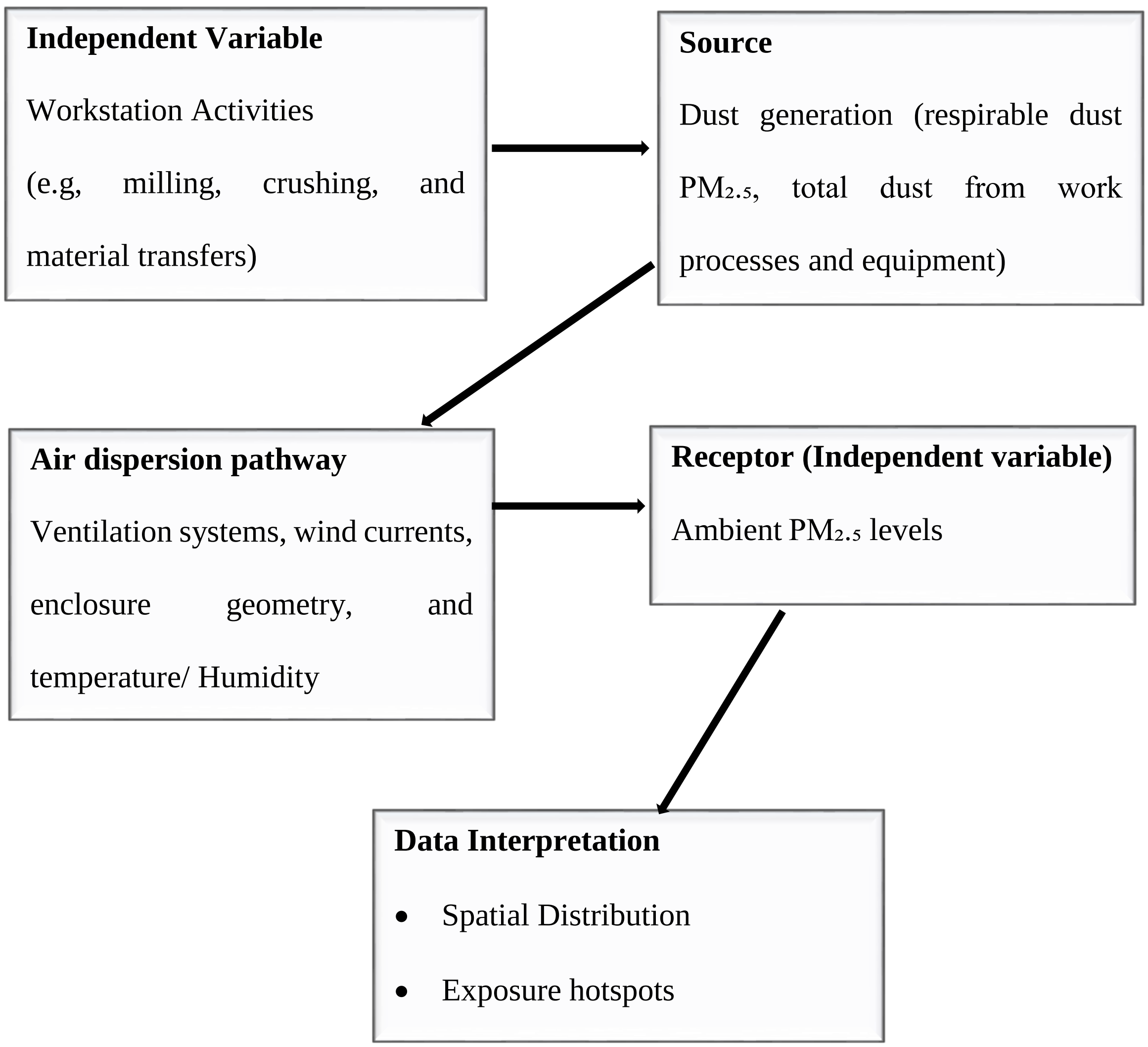

Fig. 2.2: Conceptual model based on source-pathway-receptor framework (Jose & Srimuruganandam, 2021)

2.11 Summary

The literature shows that most research on dust exposure in mining focuses on underground work and personal sampling, mainly in high-income countries. There is little focus on gold processing plants, especially in LMICs, and even less on area-based exposure at specific workstations. Recent studies highlight that engineering controls reduce dust more effectively than PPE alone. However, many sites still exceed safe dust limits, showing weak enforcement. Few studies use the WHO 24-hour PM guideline in processing plants. This reveals a gap in monitoring ambient respirable dust at fixed workstations. This gap directly shapes the aim of the study.

CHAPTER 3: METHODS AND MATERIALS

3. Methods and materials

3.1 Description of the study

Pickstone Peerless Mine (PPM) is an underground gold mine located approximately 120 km southwest of Harare (18°17.5′S; 23°30.13′E; 1.200 m a.s.l) and 20 km southeast of Chegutu, Zimbabwe (Fig 3.1). The mine operates in a semi-arid region characterised by average annual precipitation between 650 and 800 mm, with most rainfall occurring between November and March. The average temperatures range from 15°C to 30°C, exhibiting significant seasonal variations. The mine was commissioned in 2015 following its acquisition and refurbishment by Dallaglio Investments.

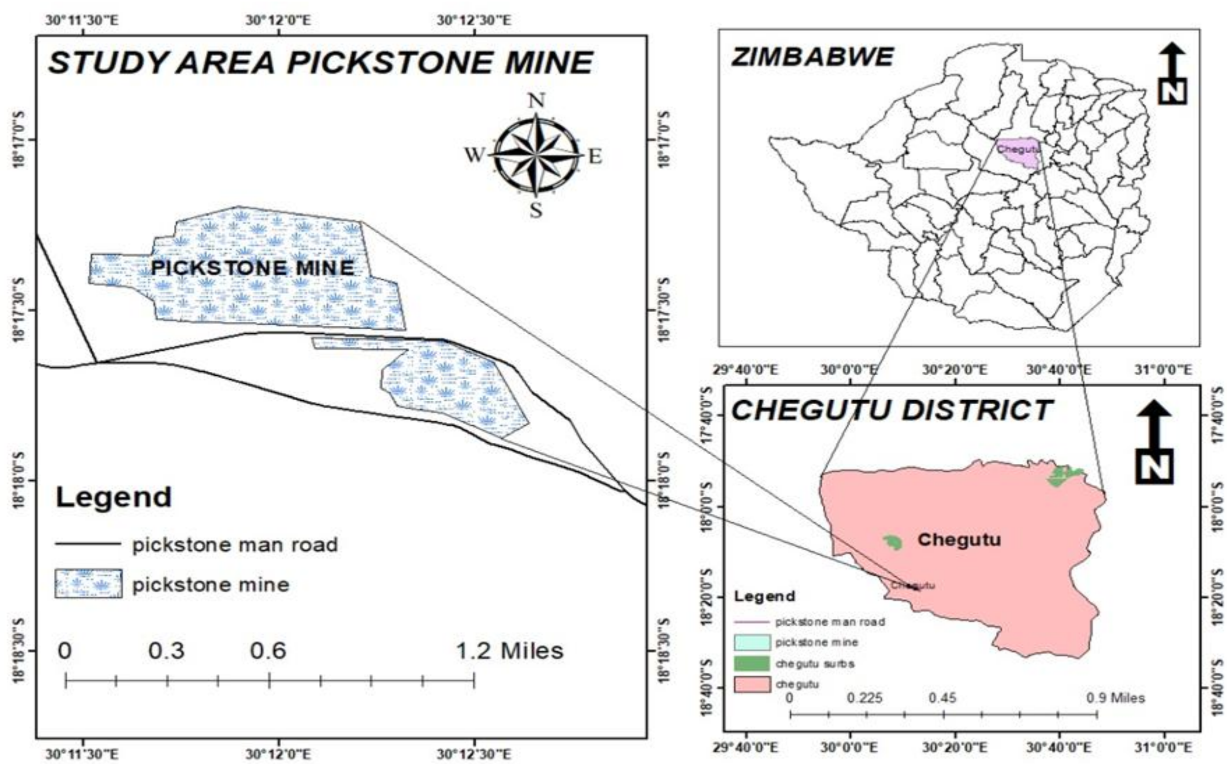

Fig. 3.1: Map of Zimbabwe showing the location of Pickstone Peerless Mine

As of 2025, PPM employs approximately 1,400 individuals across various departments, including Processing, Maintenance, Mining Technical Services (MTS), Underground Operations, Shared Services, and Safety, Health, Environment, and Quality (SHEQ).

3.2 Research design

This study adopted a quantitative cross-sectional research design, suitable for assessing respirable dust concentrations at multiple workstations during a single point in time. The design involved the use of primary data collected through gravimetric air sampling using the Split II HAZ-Dust monitor, a validated and calibrated instrument. Cross-sectional studies are widely used in environmental exposure assessment due to their cost-effectiveness and time efficiency (Wolfe et al., 2024). Although causality cannot be established, the study minimised this limitation through triangulation with calibration records and site documentation. A similar design has been applied in a cement factory in Chilanga, Zambia (Nkhama et al., 2017).

3.3 Determination of sample size

Purposive sampling was used to identify 13 dusty workstations within the processing plant, based on their high potential for dust exposure. The selection criteria included the nature of tasks performed such as crushing, milling, and bin loading, proximity to dust emitting machinery, lack of effective ventilation systems, and prior site-specific assessments indicating elevated dust levels. This non-probability sampling technique was appropriate given the study's focus on specific high-risk locations rather than generalisability (Noi et al., 2024). Since the aim was not to estimate population parameters but to assess environmental risk levels, no statistical sample size formula was applied (Duarte et al., 2022). The selected sites included areas such as the crushing chamber, milling station, and conveyor points.

3.4 Ethical considerations

Permission to conduct research was granted by the Safety, Health, Environmental, and Quality (SHEQ) manager for the collection of indoor air quality data, including $PM_{2.5}$ measurements, across gold processing plant workstations (Appendix 1). No personal identifiers were recorded, and all data were anonymised. The study adhered to the ethical guidelines outlined by the American Psychological Association APA (2017).

3.5 Data collection

To assess respirable particulate matter levels in the processing plant, this study employed the Split II Haz-Dust Particulate Monitor (Serial No. 10123897), a direct-reading, real-time aerosol monitor designed for environmental dust assessment. The instrument was calibrated according to the manufacturer's guidelines, which recommend performing zero and span calibrations before each measurement session. Zero calibration involves using a HEPA filter to ensure the monitor reads zero in clean air, eliminating baseline offsets. Span calibration was conducted using the NIST-traceable aerosol standards and alignment with ISO 12103-1 A2 Fine Test Dust to verify the instrument's response accuracy. (Appendix 2)

Sampling was conducted using a fixed area-based monitoring approach, targeting 13 designated dusty workstations across the processing section of the mine. At each location, the monitor was mounted on a tripod at approximately 1.5 metres above ground level, corresponding to the average breathing zone height, but without being directly attached to individual employees. This setup allowed the study to capture ambient dust concentrations reflective of the general working environment rather than individual exposure.

Data collection was conducted over a continuous 8-hour daytime shift per workstation, consistent with normal mine operations. At each site, sampling was conducted on 22 April 2025, using the SPLITT II particulate monitor, which recorded minute-by-minute concentrations of $PM_{2.5}$ and PM_{10}, which were internally stored and later downloaded using proprietary SPLITT II software. The environmental conditions during sampling, ambient temperature (22°C), relative humidity (30%), and atmospheric pressure (760 mmHg) were maintained within the calibration envelope, and these variables were also recorded for each sampling session using a handheld weather meter to contextualize the particulate data.

Since this study was not based on personal exposure sampling, the measured values were assessed against general ambient guidelines. Notably, WHO (2021) recommends a 24-hour mean $PM_{2.5}$ concentration limit of 0.015 mg/m³ to minimise adverse health effects, especially in vulnerable populations and high-exposure industrial areas (Hoffmann et al., 2021). To estimate 24-hour average concentrations from 8-hour monitoring data, a time-weighted average (TWA) extrapolation method was applied using the formula:

$$TWA(24hr) = \frac{Cmeasured \times Tmeasured}{24} \ldots\ldots Equation\ 1$$

Where:

- $Cmeasured$ = average concentration recorded during the 8-hour sampling (mg/m³),
- $Tmeasured$ = duration of sampling (8 hours),
- 24 = total hours in a day.

This extrapolation assumes consistent conditions across the full 24-hour period and is widely accepted in ambient air quality studies when full-day data are unavailable.

All datasets were subjected to initial screening for anomalies, including signal dropouts, environmental interferences, and instrument drift. After validation, data were exported to SPSS Version 27 for statistical analysis. This included computation of means, standard errors, and inter-location comparisons to identify high-dust accumulation zones. The findings provided a basis for recommending targeted engineering and administrative control measures within the processing plant.

3.6 Data management

Data were captured using SPLITT II HAZ-Dust monitor and downloaded proprietary SPLITT II software. Raw datasets were screened for anomalies such as signal dropouts and environmental interferences. Validated dated were converted to 24-hour time weighted averages using the formula: TWA (24hr) = (C × t) / 24. The Shapiro-Wilk test assessed normality. Due to non-normal distribution non-parametric tests were applied. The Kruskal-Wallis test compared PM 2.5 levels across workstations, and where significant differences were observed, Dunn's Post Hoc test with Bonferroni correction was applied to identify specific pairs with statistically significant differences. Analysis was conducted in SPSS version 27. Statistical significance was considered at $p < 0.05$.

CHAPTER 4: PRESENTATION OF RESULTS

4. Results

4.1 Test of normality

The Shapiro-Wilk test was used to assess the normality of the respirable dust concentration data. Results showed that data were not normally distributed (Sig. p-value = 0.228; $p < 0.05$).

4.2 Variation of respirable dust concentration across workstations

Table 4.2 shows the mean respirable dust concentrations (± standard error) measured across 13 processing plant workstations. A Kruskal-Wallis H test revealed a statistically significant difference in respirable dust concentration between workstations (H = [37.687], p = 0.002). Post-hoc pairwise comparisons using Dunn's test with Bonferroni correction identified five statistically distinct groups as denoted by superscripts (a-f).

4.3 Comparison of workstation respiratory dust concentration against international threshold value (0.015 mg/m3)

The lowest 24-hour equivalent concentration recorded was approximately 15 times higher than the WHO 24-hour guideline value of 0.015 mg/m^3. All observed concentrations exhibited substantial magnitude differences relative to the threshold value, highlighting consistently elevated exposure levels across assessed workstations.

Table 4.2: Variation of respirable dust concentration at selected workstations

Workstation	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Mean dust concentrations (mg/m^3)	1.36 ± 0.05^{a}	1.99 ± 0.06^{a}	0.49 ± 0.02^{a}	1.47 ± 0.07^{a}	3.95 ± 0.14^{b}	1.18 ± 0.05^{a}	0.23 ± 0.01^{a}	14.25 ± 0.34^{c}	11.55 ± 0.46^{d}	31.78 ± 0.98^{e}	21.38 ± 0.66^{f}	19.10 ± 0.52^{f}	12.81 ± 0.36^{cd}

Note: Superscripts (a-f) denote statistically significant groupings ($p < 0.05$) based on post hoc pairwise comparisons using Dunn's test with Bonferroni correction. Workstations sharing the same superscript are not significantly different from each other, while those with different superscripts belong to distinct groups.

CHAPTER 5: DISCUSSION

5. Discussion

5.1: Introduction

This chapter provides a comprehensive interpretation of the study's findings on respirable dust exposure across 13 workstations within a gold mine processing plant in Zimbabwe. The discussion draws comparisons with similar studies from gold processing plants in low- and middle-income countries (LMICs) to explain the observed spatial patterns. It explores possible reasons for high or low dust levels, considers influencing operational factors, and reflects on the statistical findings. Particular attention is given to how these findings relate to international ambient particulate matter guidelines

5.2 Normality of data

The Shapiro-Wilk test indicated that the data were not normally distributed. This non-normality may arise from the presence of extreme values observed at workstation 10. Skewed data are common in area-based monitoring studies, especially when sampling across workstations. A study conducted in Chinese cement factories also reported non-normal distributions, attributed to varying work practices and environmental controls (Huang et al., 2024). In such contexts, non-parametric tests are appropriate for hypothesis testing, as they do not assume normality.

5.3 Variation of respirable dust concentration across workstations

The significant inter-workstation differences in respirable dust concentrations underscore the spatial variability inherent in gold ore processing plants. Variations are often linked to task type, proximity to dust-emitting machinery, and the extent of containment or suppression systems (Wua et al., 2023). Elevated concentrations in crushing and milling zones suggest persistent emission sources and limited extraction ventilation (Duarte et al., 2022). Literature indicates that bin loading and grinding activities consistently produce peak exposures due to their mechanical disruption of fine ore particles (Otieno et al., 2022).

The observed groupings (a - f) from Dunn's test reflect functionally distinct exposure clusters influenced by ventilation, task frequency, and equipment layout. Workstations under group 'a' likely benefit from structural protection or operational isolation, lowering dust exposure WHO (2021). Conversely, those in groups 'd' and 'f' may reflect inadequate controls and high task intensity. Rusibamayila et al. (2018) report a similar trend in Tanzanian mines, where exposure was significantly higher in stations with poor dust abatement. These findings underscore the need for targeted interventions, rather than generalized controls.

5.4 Comparison of workstation respiratory dust concentrations against international threshold value

The extremely high respirable dust concentrations observed, up to 70 times above the WHO 24-hour guideline, are likely due to intensive dry mechanical operations such as crushing, grinding, and screening, which release fine particulates into enclosed spaces. Inadequate engineering controls, poor dust suppression systems, and lack of local exhaust ventilation further exacerbate dust accumulation. Similar conditions were reported in Burkina Faso by (Awokola et al., 2022), where respirable dust levels reached 0.900 mg/m^3 in gold processing areas with minimal dust control.

These findings align with studies from Zambia, where Sifanu et al. (2024) recorded $PM_{2.5}$ levels exceeding 0.070 mg/m³ in poorly ventilated processing plants. Conversely, lower concentrations were reported in Tanzania by Rusibamayila et al. (2018), where active water-based dust suppression was employed, highlighting the role of mitigation strategies. The consistency in elevated exposure across many LMICs suggests shared infrastructural and regulatory challenges contributing to excessive respirable dust levels in gold processing facilities.

5.5 Limitations

Several limitations may affect the interpretation and generalisation of the study's findings. The data were collected over a single 8-hour shift per workstation, potentially overlooking temporal fluctuations due to varying operational intensities or climatic conditions. Additionally, the study's focus on one processing plant constrains the applicability of the results to other mining contexts that differ in scale, processing technologies, or regulatory environments. Instrument calibration errors or environmental interferences may also have introduced minor measurement biases.

5.6 Summary

This chapter provided a critical interpretation of the study's findings, revealing that respirable dust concentrations at the gold processing plant are alarmingly high compared to the WHO guidelines. The discussion linked these findings to operational characteristics, such as equipment use and control systems, supported by literature from comparable mining settings. The non-normal distribution of the data justified non-parametric testing, which confirmed both the lack of significant variation across workstations and the consistent exceedance of exposure limits. Finally, while the results offer valuable insights, methodological constraints necessitate cautious extrapolation beyond the study site.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6. Conclusion and recommendations

6.1 Conclusion

This study revealed significant differences in respirable dust exposure across workstations, with employees at ore crushing and screening stations facing the highest risks. Exposure patterns were strongly influenced by the nature of operational processes and proximity to dust-generating activities. The key message is that respirable dust exposure is unevenly distributed within gold processing plants, demanding targeted, workstation-specific interventions. In contrast to most existing studies that prioritise underground mining or ambient community exposures, this research centres on fixed indoor processing areas, an often-overlooked setting in low-resource contexts. This study advances current understanding by generating context specific evidence on respirable dust within indoor gold processing plants, offering critical evidence for advancing worker protection. Future research should examine the effectiveness of engineering controls and explore the cumulative health impacts of long-term respirable dust exposure in processing environments.

6.2 Recommendations

- Implement localised dust suppression technologies, across all workstations to reduce respirable dust concentrations to below international thresholds.

- Adopt continuous area-based environmental monitoring, including 24-hour dust sampling, to improve understanding of full-shift and ambient exposure profiles beyond the 8-hour occupational frame.

- Strengthen engineering controls and ventilation systems within the processing plant, informed by workstation-specific exposure data, to address chronic dust accumulation in poorly ventilated zones.

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APPENDICES

Appendix 1: Data collection approval letter

Pickstone Peerless Mine

P.O Box 274

Chegutu

10 April 2025

Dear Dr. Kanda

We are pleased to grant permission for Ephraim Muchuweni, a BSc SHEM student at Bindura University of Science Education, to conduct his research at Pickstone Peerless Mine. We appreciate the opportunity to support academic pursuits and believe his study on occupational exposure to silica dust will be beneficial.

The student can communicate the data collection plan and ensure adherence to our organization's requirements and protocols which he is familiar with. We look forward to receiving the research findings and potentially implementing recommendations. We are glad to assist him; he was our student during his attachment which he is a well-behaved young man with potential.

Thank you for your collaboration.

Best regards,

Mr. Clifton Nyamukachi

SHEQ Manager, Pickstone Peerless Mine

0772764538

Appendix 2: Calibration certificate for the Splitt II Haz-Dust Monitor

Certificate of Calibration

Certificate Procedure Number: EDCQP200-4.11.5

Environmental Devices Corporation certifies the Haz-Dust Particulate Monitors are calibrated gravimetrically against the specifications and protocols set forth in NIOSH method 0600 and/or 0500. Calibration is NIST traceable and conforms to original published specifications of +/- 10%.

Calibration Dust Specifications are determined with a NIST traceable Coulter Mutisizer, ISO12103 –1 A2 Fine Test Dust and primary Flow Standard: LFE774300.

Our quality system standard meets the requirements of ANSI/NCSLZ540.1 and ASQC standard ISO 9001, MIL-STD 45662A, and customer's specifications if requested.

Calibration Test Dust Particulate Micron Size	**Cumulative Volume Numeric Data** % Less Than
1	2.9
2	11
3	19.6
4	27.7
5	34.6
7	43.6
10	52.1
20	70.7
40	89.2
80	99.8
120	100

Temperature = 22°C
Relative Humidity = 30%
Atmospheric Pressure = 760 mmHg
Measurement Uncertainty Estimated @ 95% Confidence Level (k=2)

Model	Serial Number	Calibration Date	Next Calibration Due Date
Split II	10123897	April 2023	April 2025

Calibration Span Accessory if purchased	K=	Model:

Technician	Supervisor
Matt Gosslin	Mark Sullivan

Environmental Devices Corporation
4 Wilder Drive Building #15
Plaistow, NH 03865
ISO-9001 Certified

Appendix 3: Supervisor acceptance letter

Research supervision acceptance letter

The Chairperson
Department of Environmental Science
Bindura University of Science Education

9th November, 2024

Dear Sir

RE: BSc RESEARCH SUPERVISION ACCEPTANCE LETTER FOR Mr. E. MUCHUWENI (B211690B)

The above matter refers.

I wish to inform you that I am accepting *Ephraim Muchuweni* as my student to guide his research work leading to attainment of a BSc. SHEM degree with Bindura University Science and Education. I will supervise him throughout the research process.

Proposed title (can be amended slightly):

Occupational exposure to silica dust and associated toxic trace elements in respirable dust and health risk assessment for underground gold mine employees: case of a gold mine in Zimbabwe

Sincerely,

A. Kanda (PhD PH, MSc WREM, BSc Hons Chem, PostGrad Dip WSS, Dip Sci. Ed)