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Original article

Trends in Exposure to Respirable Dust and Respirable Crystalline Silica Among Lithium Mine Workers in Western Australia

David Gbondo *, Yun Zhao, Minh Pham, Krassi Rumchev

Curtin University of Technology, School of Population Health, Australia

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ABSTRACT

Background: Exposure to respirable dust (RES) and respirable crystalline silica (RCS) is common in mining operations and is associated with health effects such as pneumoconiosis, chronic obstructive pulmonary disease (COPD), interstitial pulmonary fibrosis, silicosis, lung cancer, and renal disease.
Methods: This study used industry occupational exposure data for respirable dust from two surface lithium mines in Western Australia for the period between 2017 and 2023. A total of 1122 samples were collected in workgroups across four departments - administration and support, mining, crushing and processing, and maintenance.
Results: The study found that the overall RES concentration did not exceed the exposure standard. However, Crusher Dry/Wet Plant Personnel (0.558 mg/m^3) and Workshop Boilermakers (0.842 mg/m^3) recorded elevated exposure to RES. The highest mean exposures for RCS over the seven-year study period were measured for Management Administration & Technical (0.068 mg/m^3), followed by Crusher Dry/Wet Plant Personnel (0.042 mg/m^3), exceeding the ES. Maximum results for both RES (15.00 mg/m^3) and RCS (2.50 mg/m^3) indicated exceedances.
Conclusion: The study demonstrated a decline in exposure to RES over the seven years of study from 0.472 mg/m^3 to 0.151 mg/m^3, with a slight increase in 2019 and 2022. A decline in the concentration of RCS was observed between 2019 -2021, followed by an increase after 2021. The mean concentration of RCS exceeded the exposure standard in 2023. Based on the study results and the established adverse health effects associated with exposure to silica, various control measuresto protect workers from RCS exposure should be considered.

1. Introduction

Lithium is a critical commodity used to produce batteries for electric vehicles, consumer electronics, and applications ranging from energy storage to air mobility. A continuous and rapid increase in the demand for lithium is expected in the coming years since different types of lithium batteries are the most promising candidates to power electric or hybrid vehicles [1,2]. The annual global growth of lithium batteries has been predicted at a compounding rate of approximately 30% per year with batteries anticipated to account for 95% of the lithium global demand [3]. This soaring demand has seen the production growth of 0.41 million metric tons of lithium carbonate equivalent in 2020, to a predicted 2.7 million metric tons of lithium supply in 2030 [3].

Australia is ranked second to Chile in hosting the largest reserves of lithium deposits in the world [3]. In fact, in 2020 Australia, Latin America, and China accounted for 98% of the global production of lithium [3]. The latest statistics review by the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) indicated that Lithium is Western Australia (WA)'s third most valuable mineral in Australia [4].

According to recent statistics provided by the Australian Bureau of Statistics (ABS), Australia is the world's biggest exporter of lithium [4]. In 2020, it was reported that 46% of the global supply of

David Gbondo: https://orcid.org/0000-0002-6563-2207; Yun Zhao: https://orcid.org/0000-0001-8445-8630; Minh Pham: https://orcid.org/0000-0002-4138-6427; Krassi Rumchev: https://orcid.org/0000-0002-2714-5723
* Corresponding author.
E-mail address: david.gbondo@student.curtin.edu.au (D. Gbondo).

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lithium came from Australia [4]. The Australian export of lithium has primarily been in the form of spodumene concentrate. However, the increasing global demand has seen several Lithium mining companies commence the production of lithium hydroxide [4].

Whilst lithium has unique properties useful to the storage of electricity, lithium mining is associated with exposure to airborne contaminants including respirable dust (RES) and respirable crystalline silica (RCS). An airborne contaminant is an atmospheric health hazard in the form of a fume, mist, gas, vapor, or dust and includes micro-organisms [5]. Occupational exposure assessment has also indicated that lithium mining is associated with exposure to dust, noise, heat stress, solar ultraviolet, whole-body and hand-arm vibration, and manual handling [6]. Potential health risks from these exposures include respiratory illnesses, noise-induced hearing loss and tinnitus, heat stroke, increased risk of melanoma, exacerbated preexisting spinal disorders, hand-arm vibration syndrome, and musculoskeletal injuries [7,6,8].

RES refers to dust with a particle size of less than 10 microns [9]. It constitutes very fine dust capable of reaching the secondary bronchioles and alveolar regions of the lungs after breathing it in [10]. The accumulation of RES in the secondary bronchioles and alveolar region over time may cause respiratory diseases such as pneumoconiosis, chronic obstructive pulmonary disease (COPD), and interstitial pulmonary fibrosis [10]. COPD is a lung disease characterized by a reduction in airflow related to increased resistance caused by the narrowing of the airway [11]. This occurrence of persistent airflow limitation is a defining attribute of COPD [12].

RCS, on the other hand, is a fibrogenic material found in nature, exposure to which causes interstitial pulmonary fibrosis known as silicosis [13]. RCS particles are respirable when they are less than 5 microns in diameter and when inhaled are capable of reaching the distal airways and alveoli and can scar the lungs [14,15]. Exposure to RCS has also been associated with COPD, lung cancer, airway obstruction, and renal disease [16].

Since the mid-1900s, the exposure standard (ES) for RCS had been introduced in most developed countries aimed to protect workers from potential adverse health effects due to exposure to RCS [17]; these standards were preceded by well-defined methodologies for exposure assessment.

In 1974 the United States National Institute of Occupational Safety and Health (NIOSH) recommended an ES of 0.05 mg/m^3 for RCS, while the American Conference of Governmental Industrial Hygienists (ACGIH) adopted a threshold limit value (TLV) of 0.025 mg/m^3 in 2006 [15]. In Alberta Canada, 0.025 mg/m^3 was adopted in 2009 as the ES for RCS [15].

In the 1970s, Australia introduced the ES for RCS at 0.2 mg/m^3 as an intervention to reduce the risk of exposure to silica. Later in 2005, the ES was reduced to 0.1 mg/m^3 [14]. According to an Australian study conducted in mineral mines, a reduction in RCS exposures was observed in Australia from 1986 to 2014 and attributed to the increased awareness of the health impact of silica dust, and the changing mining practices in dust controls [18].

In July 2020 a further reduction in the ES for RCS from 0.1 mg/m^3 to 0.05 mg/m^3 (eight-hour time-weighted average (TWA)) was introduced in Australia by the Federal Government, to be implemented through the state's Work Health and Safety Mines Regulations 2022. This reduction was informed by the emergence of silicosis in major capital cities in Australia in the engineered stone industry [19], and the national debate for the prohibition of its use. In 2019, the Commonwealth established the National Dust Disease Taskforce with the mandate to develop a national approach for the prevention, early detection, control, and management of occupational disease. The taskforce provided its final report in June 2021, which contained seven recommendations. Recommendation one addressed the need to strengthen work health and safety measures. It included the need to undertake a regulatory impact analysis for a licensing scheme to restrict access to engineered stone and strengthen health monitoring requirements [20]. Part of this recommendation was also to commence the process for the full ban on the importation of engineered stone by July 2024 [20]. Following the recommendation by the National Dust Disease Taskforce for a regulatory impact analysis, Safe Work Australia undertook an analysis of the regulatory impact of options to manage RCS to improve the protection of workers. Of the six options presented, option 6 provided consideration for the prohibition of engineered stone use [21].

On the 13th of December 2023 Commonwealth, State and Territory Workplace Relations and Work Health and Safety (WHS) Ministers met and unanimously agreed to prohibit the use, supply, and manufacture of engineered stone commencing 1 July 2024 [22]. In support of the ban, and the urgency for improvement in the management of silica exposures and the associated health risks, Safe Work Australia, in June 2024, released the *Engineered stone prohibition: Guidance for PCBUs* (Person conducting a business or undertaking) and the *Working with silica and silica containing products guidance material* [23,24].

On the other hand, the ES for RES remains to be 3 mg/m^3 [5]. Using the formula for the adjustment of ESs for working rosters and shift lengths of 12 hours outside of the TWA, the ESs for RES and RCS were adjusted to 2.1 mg/m^3 and 0.035 mg/m^3, respectively.

While there is currently no known literature on airborne contaminant exposures in lithium mining in Australia, recent studies on exposure to RES and RCS conducted in Western Australian mineral mines demonstrated a decline in exposure to RES among mine workers for the period 2001-2012 [25]. This study indicated that the RCS exposure of Western Australian mine workers was below the ES of 0.05 mg/m^3 [25]. Another study undertaken in Denmark also revealed a decline in RCS exposure in the past 50 years, with high concentrations emerging only in the foundries, stone and brick sector, and the construction industry [26].

While studies have indicated a decline in RCS exposures in Australia between 1986 and 2000 [18], RCS exposures in lithium mining have not been investigated.

This paper aims to investigate the exposure trend of RES and RCS between 2017 and 2023, and to compare the exposure to RES and RCS between mining occupations and departments among lithium mine workers in WA. The outcomes of this study will provide further insight into exposures to RES and RCS in lithium mines, contributing to the development of interventions aimed at mitigating these exposures. This will assist in preventing potential adverse health effects associated with RES and RCS exposures. To our knowledge, there is no previous study conducted in Australia to assess exposure to airborne contaminants among lithium mine workers.

2. Material and methods

2.1. Study population/data acquisition

This study used industry occupational exposure data for respirable dust from lithium mines for the period between 2017 and 2023. Lithium mining is undertaken using conventional open-pit mining methods. Drill and blast techniques are used to fragment the ore and waste material, while blasted rock is mined using hydraulic excavators to load the haulage trucks. The trucks then transport the ore to the Run of Mine (ROM) adjacent to the processing plant, ready for crushing prior to processing.

Ore is fed into the ROM bin where the ore passes a main feeder into the primary jaw crusher. The ore is then passed through a series of screens directing oversize through the secondary crushing unit. Screens and conveyors ensure that appropriate particle sizes are obtained. Where milling of the product is required for metallurgical processing, the crushed product is fed to parallel ball mills to produce a ground product. Following processing the final product is referred to as the spodumene concentrate, which is transported to port operations for shipping.

Lithium mining also includes a Maintenance Department responsible for the maintenance of mobile mining equipment and the crushing and processing plant. The Administration and Support services provide managerial and support services to operate the mines.

In WA, mining companies were required to conduct exposure assessments of certain occupational hazards, including RES and RCS, and report the findings to the DEMIRS. All mining companies are required to develop a health management plan (previously known as a health & hygiene management plan). The plan details the mining operations, processes, workgroups, hours of work, equipment, the associated health hazards, the anticipated level of exposure, controls and the mechanism to verify the effectiveness of the controls. The plan also details the quarterly monitoring requirements for health hazards through the legislatively appointed Mine Air Quality Officer. All monitoring results and the investigation of exceedances are communicated to DEMIRS through the online database known as the Safety Regulation System (SRS). The selection of workers from workgroups for the daily monitoring is through a random process. The Mine Air Quality Officer attends the prestart of the workgroups to be monitored on the day and requests management for random volunteers to wear the monitoring equipment for the shift. The demographics of the volunteers include males and females within the age range of 18- 65 years, mainly from WA. No worker was excluded from the exposure monitoring program.

The two lithium mines, where the study was conducted, are located in different geographical areas in WA. Although Mine A is located in the Southern region and Mine B is located in the Northern region of WA, they are similar in relation to mining and processing operations.

The available dataset used in this study consisted of exposure levels to RES and RCS among lithium mine workers who were involved in surface mining activities for the study period. For the purpose of this study, mine workers from four departments in lithium mining were randomly selected. The departments included administration and support, mining, crushing and processing, and maintenance. The study subjects provided their written informed consent to participate in this study including the survey and personal monitoring for RES and RCS. Lithium mine workers were grouped into eleven Similar Exposure Groups (SEGs) based on the similarity of their roles, activities, and work areas including Management Administration & Technical, Cleaning and Utilities Staff, Blast Crew, Geologists and Surveyor, Drill Operators, Mine Truck Operators, Earthmoving Equipment Operators, Crusher/Dry/Wet Plant Personnel, Laboratory Operations, Maintenance (Workshop and Infrastructure) and Workshop Boilermakers (Table 1).

2.2. Exposure assessment to respirable particles and respirable crystalline silica

Measurements of personal exposure to RES and RCS were conducted across both mines in WA. During each year mining companies are required to review the risk of exposures to health hazards across their operations and the effectiveness of control initiatives. This risk assessment is conducted in the form of a walk-through survey that examines tasks completed by the mine workers, including work processes, equipment used, emissions, environmental factors, shift length, roster patterns, health risks associated with activities, and the anticipated level of exposure, control measures, and their effectiveness. Other factors such as organizational structures and departments and the demographic of the workforce are also taken into account. This risk assessment leads to the development of a health risk assessment (HRA), documenting the qualitative risk profile of the mining operation, prior to the commencement of quantitative assessment of personal exposures.

This activity precedes the personal exposure monitoring of RES and RCS. The method used to assess personal concentrations of RES and RCS followed the Australian Standard for sampling and gravimetric determination of respirable dust in workplace atmospheres (AS2985-2009), which is adapted from the International Standard ISO 7708:1995, Air quality—Particle size fraction definitions for health-related sampling. According to the standard, cyclones are used for the monitoring using the 25mm, 5μm PVC pre-weighed filters placed into the blank cassettes. The inlet sections are removed prior to mounting them onto the cyclones. The assembled filter, cassette, and cyclone were installed in the filter cassette holders which were clipped in the workers' breathing zone. During the monitoring, which was undertaken for a minimum of four hours according to the Australian standard, respirable dust particles were collected on the filter, while larger particles fell into the grit pot (the bottom of the cyclone). Emissions of airborne contaminants are monitored in active mining areas, within the cabin of mining mobile equipment, at discharge points of fixed processing plants, in maintenance workshops, and within-laboratory sampling preparation facilities. The lithium mine workers were monitored during their normal shift work and asked to keep a diary to record their daily activities.

Independent analyses of the personal monitoring samples were undertaken through the National Association of Testing Authorities (NATA)-accredited laboratory. Gravimetric analyses were used for the determination of RES, while the Fourier *Transform Infrared Spectroscopy* was used to determine the content of RCS following the NHMRC standard method (AS 2985-2009 define the analytical methods, which are adopted by the NATA-accredited laboratory). The NATA-accredited laboratory holds an accreditation number and a compliance reference to ISO/IEC 17025. Quality controls were in place for blanks, surrogate spikes, laboratory control samples (LCS), matrix spikes, and duplicates; and all samples were tested in batches of 20. Following the analyses, PDF laboratory reports were generated, approved, and communicated to the Mine Air Quality Officer.

2.3. Statistical analysis

Data was analyzed by IBM SPSS Statistics Version 26 [27]. Descriptive statistics were obtained for summarizing the sample population (mean $\pm$ standard deviation or median (IQR) for continuous variables; frequency (%) for categorical variables). Exposure data has been presented according to the type of airborne contaminants (RES and RCS), department of lithium mining (Administration & Support, Mining, Crushing & Processing, and Maintenance), and workgroups within the departments. The exposure data were examined to identify patterns, changes, or trends that occurred over consecutive 7 annual periods from 2017 to 2023.

Both outcome variables (RES and RCS) were assessed for normality prior to conducting statistical parametric tests for comparisons of the contaminant concentrations between different groups, and non-parametric tests were applied when the assumption of normality was violated. Specifically, parametric two (independent) samples t-test or analysis of variance (ANOVA) was used to compare RES and RCS concentrations between two groups or multiple ($>$3) groups, respectively. If normality assumption was not assumed, analogous non-parametric Mann—Whitney U test for

Table 1
Department occupations and activities

Department	Workgroups/Occupations	Activities
Administration & Support Services	Management Administration & Technical	Safe and efficient operation of surface and process plant operations. Ensuring compliance with mining regulations. Overseeing scheduling, planning, and budgeting. Management of health and safety, and environment.
	Cleaning and Utilities Staff	Cleaning of mine site crib rooms. Running of village services. Cleaning operational areas Cleaning out fridges and wiping down surfaces. Wiping down sinks and benchtops. Cleaning toilets and showers.
Mining	Blast Crew	Following and amending tie-in plans. Following explosive loading plans, reporting faults or discrepancies. Erecting bunting and signage before loading of blast patterns. Tie-in and preparation for shots and igniting shot. Inventory controls at OP magazines. Compliance with the Dangerous Goods License and Explosive management plans. Loading shots in compliance with all Safe Working Procedures. Transport and storage of explosives.
	Geologists and Surveyor	Setting out drill patterns. Collecting samples. Geochemical sample preparation. Database entry.
	Drill Operators	Carrying out prestart checks on drill rig before commencing and reporting any faults. Doing edge holes, collaring holes, and marking out patterns properly. Use of modular mining and GPS navigation. Operation of drill rig for drilling blast holes as detailed on blast pattern. Recording drill hole depths and voids.
	Mine Truck Operators	Carrying out prestart checks on truck and reporting any faults. Safe operation of plant and maintaining a safe work area. Write up logs during and at the end of the shift.
	Earthmoving Equipment Operators	Safe operation of plant and maintaining a safe work area. Conducting vehicle prestarts. Clearing, bench preparation, dump preparation, road construction, empty floors, push-up ore stockpiles, and feed.
Crushing and Processing	Crusher/Dry/Wet Plant Personnel	Monitoring and adjusting the day-to-day operation of the plant. Undertaking inspections of the plant and carrying out breakdown maintenance. Clearing blockages from the crushing circuit. Conducting continuous monitoring of conveyors. Completing daily shift log. Completing general housekeeping duties.
	Laboratory Operations	Preparing samples. Weighing samples in balance room. Operation of jaw crusher, pulverizers, shakers, and riffle splitters. Sampling, reagent preparation, and analysis. Quality control of data and reporting.
Maintenance	Maintenance (Workshop and Infrastructure)	Maintenance of functional assets to meet operational targets. Identifying and following up opportunities to continuously improve technical business performance. Safe operation of handheld, fixed-mounted, and plant machinery. Maintaining documentation and service/repair history of plant and equipment.
	Workshop Boilermakers	Maintenance of functional assets to meet operational targets. Welding including arc, metal inert gas, oxy acetylene, and tungsten inert gas. Safe operation of handheld, fixed-mounted, and plant machinery. Maintaining documentation and service/repair history of plant and equipment.

comparing two groups or Kruskal–Wallis test for multiple (>3) groups was used All tests were two-sided and a p value < 0.05 was considered statistically significant.

RES and RCS concentration levels were presented as minimum, maximum, arithmetic mean (AM), geometric mean (GM), geometric standard deviation (GSD), and 95% percentile. The AM was used to evaluate the exposures, and to determine regulatory compliance to the ES. The ES represents the airborne concentration of a particular substance or mixture, exposure to which, according to current knowledge, should not cause adverse health effects or undue discomfort to nearly all workers. TWA ES for RES and RCS are 3 mg/m^3 and 0.05 mg/m^3. Using the formula in the legislation the ES for RES and RCS were adjusted to 2.1 mg/m^3 and 0.035 mg/m^3 for work shifts and rosters outside of the 8-hour working shift for 40 hours a week.

3. Results

3.1. Sample population characteristics

A total of 1122 samples were collected for RES and RCS over the study period (Table 2). The initial monitoring protocol was the collection of samples to establish baseline exposures. The number of samples for baseline assessment was informed by the National Institute for Occupational Safety and Health (NIOSH) 1977 Sampling Strategy Manual [28]. The number of workers in the workgroups was used to determine the number of samples to be collected from the workgroup, ensuring that at least one worker from the workgroup would be in the top 20% of the exposures, with a confidence limit of 95% [28]. Following the baseline monitoring, maintenance monitoring programs were developed

Table 2
Sample population characteristics by years

	Total	2017	2018	2019	2020	2021	2022	2023
	$n = 1,122$	$n = 234$	$n = 200$	$n = 92$	$n = 92$	$n = 138$	$n = 186$	$n = 180$
Age, year, mean (SD)	39.0 (12.0)	37.7 (10.7)	40.7 (10.9)	40.3 (12.6)	40.6 (12.4)	37.9 (14.7)	38.9 (11.5)	38.4 (12.0)
Gender								
Female	178 (15.9)	20 (8.5)	22 (11.0)	8 (8.7)	14 (15.2)	36 (26.1)	34 (18.3)	44 (24.4)
Male	944 (84.1%)	214 (91.5%)	178 (89.0)	84 (91.3)	78 (84.8)	102 (73.9)	152 (81.7)	136 (75.6)
Department								
Administration & support	172 (15.3)	40 (17.1)	34 (17.0)	6 (6.5)	16 (17.4)	18 (13.0)	30 (16.1)	28 (15.6)
Mining	462 (41.2)	108 (46.2)	98 (49.0)	44 (47.8)	42 (45.7)	56 (40.6)	56 (30.1)	58 (32.2)
Crushing & processing	310 (27.6)	56 (23.9)	50 (25.0)	20 (21.7)	18 (19.6)	42 (30.4)	70 (37.6)	54 (30.0)
Maintenance	178 (15.9)	30 (12.8)	18 (9.0)	22 (23.9)	16 (17.4)	22 (15.9)	30 (16.1)	40 (22.2)
Respiratory protection wearing								
No	338 (45.7)	2 (2.0)	0 (0.0)*	0 (0.0)[2]	30 (48.4)	138 (100.0)	78 (46.4)	90 (50.6)
Yes	402 (54.3)	98 (98.0)	58 (100.0)	36 (100.0)	32 (51.6)	0 (0.0)	90 (53.6)	88 (49.4)
Shift length								
Day	1,086 (96.8)	226 (96.6)	176 (88.0)	88 (95.7)	92 (100.0)	138 (100.0)	186 (100.0)	180 (100.0)
Night	36 (3.2)	8 (3.4)	24 (12.0)	4 (4.3)	0 (0.0)†	0 (0.0)†	0 (0.0)†	0 (0.0)†

Data are presented as frequency (percentage); otherwise, specified; n, number of measurements. SD, standard deviation.
* The use of respiratory protection was not reported by personnel.
† Exposure monitoring was only undertaken on day shift.

Table 3
Comparison of contaminant concentrations of RES and RCS (mg/m^3) according to selected personal characteristics

	Respirable dust (RES)			Silica, crystalline, quartz (RCS)		
	n	Mean (SD)	Median (IQR)	*n*	Mean (SD)	Median (IQR)
Overall	560	0.295 (0.871)	0.100 (0.100)	560	0.019 (0.117)	0.005 (0.004)
Age group (year)						
<40	304	0.308 (0.96)	0.100 (0.100)	304	0.015 (0.051)	0.005 (0.004)
≥40	256	0.28 (0.754)	0.100 (0.100)	256	0.023 (0.163)	0.005 (0.004)
p		0.71	0.83		0.38	0.52
Gender						
Female	89	0.148 (0.135)	0.100 (0.030)	89	0.034 (0.264)	0.004 (0.002)
Male	471	0.323 (0.946)	0.100 (0.100)	471	0.016 (0.055)	0.005 (0.005)
p		<0.001	0.40		0.509	0.44
Department						
Administration & support	80	0.140 (0.070)	0.100 (0.100)	80	0.037 (0.279)	0.005 (0.003)
Mining	217	0.182 (0.422)	0.100 (0.100)	217	0.006 (0.005)	0.005 (0.002)
Crushing & processing	154	0.439 (1.313)	0.125 (0.300)	154	0.033 (0.092)	0.006 (0.020)
Maintenance	109	0.434 (1.025)	0.200 (0.200)	109	0.011 (0.019)	0.004 (0.007)
p		0.004	0.001		0.06	0.0001
Respiratory protection wearing						
No	169	0.161 (0.189)	0.100 (0.050)	169	0.006 (0.011)	0.004 (0.002)
Yes	200	0.457 (1.315)	0.100 (0.200)	200	0.039 (0.193)	0.005 (0.015)
p		0.002	0.40		0.016	0.42
Shift						
Day	542	0.300 (0.885)	0.100 (0.100)	542	0.019 (0.118)	0.005 (0.004)
Night	18	0.144 (0.070)	0.100 (0.100)	18	0.009 (0.011)	0.005 (0.002)
p		0.46	0.52		0.71	0.43

IQR, interquartile range; n, number of measurements; SD, standard deviation.
p-values are based on the two-sample t-test, ANOVA, Mann–Whitney U test or Kruskal–Wallis test.

and executed to verify controls and track potential changes in exposures.

The average age of lithium workers monitored in this study was 39 years of age (with a standard deviation of 12 years). The majority of the lithium workers were males ($n = 944$, 84.1%) although the percentage of female lithium workers increased over the years representing 24.4% ($n = 44$) in 2023 compared to 8.5% ($n = 20$) in 2017. Irrespective of the gender and the composition of males and females within the workforce, mining activities did not change over the seven-year study period, and hence it was not expected for gender to impact the exposure results.

Overall, most of the lithium workers were involved in mining related activities ($n = 462$, 41.2%) followed by crushing and processing ($n = 310$, 27.6%). This present study found that a higher percentage of lithium workers ($n = 402$, 54.3%) reported wearing respiratory protection equipment (RPE) and this trend was observed over the study years except in 2023. A large proportion of the exposure monitoring was undertaken during the day shift, with only 3.2% ($n = 36$) of the monitoring conducted on the night shift.

Some data was collected on smoking status of the lithium workers, but due to large proportion of missing values, this variable was not analyzed and reported. This study limitation has been acknowledged in the paper.

3.2. RES and RCS exposure among lithium mine workers according to departments and workgroups

A significant difference in mean exposures to RES was identified among departments and regarding respiratory protection use (Table 3). There was an observable decrease in the number of observations among different departments from 2017 to 2013, except for the Maintenance Department. The highest decline in the observations was recorded in the Mining Department, which went from a total of 108 observations in 2017 to 58 observations in 2023.

However, these changes did not impact the exposures as work activities and processes remained unchanged over the years. Two departments (Administration & support and Mining) recorded a mean concentration of RES 0.140 (s.d: 0.070) and 0.182 (s.d: 0.422) mg/m^3, respectively, which were well below the ES of 2.1 mg/m^3. Although still below the ES, crushing and processing, and the maintenance working groups recorded the highest mean exposures of 0.439 mg/m^3 and 0.434 mg/^{3}, respectively. Mine workers who reported to have used respiratory protection had higher mean exposures to RES (0.457 mg/m^3) and RCS (0.039 mg/m^3) compared to those who reported to have not used respiratory protection (0.161mg/m^3 and 0.006 mg/m^3, respectively). The study findings showed that the Administration & Support Department, and mine workers who reported using respiratory protection were exposed to RCS levels that exceeded the ES of 0.035 mg/m^3.

There was no observable significant difference in mean exposures of RES and RCS between age and gender groups, nor between day and night work shifts.

When the contaminant concentrations (mg/m^3) were compared between workgroups within each department, higher mean exposure for RES was identified in Crusher/Dry/Wet Plant Personnel (0.558 mg/m^3) followed by Workshop Boilermakers (0.842 mg/m^3). Both workgroups and Drill Operators recorded the maximum concentrations for the seven-year study period, Crusher/Dry/Wet Plant Personnel (15.00 mg/m^3), Workshop Boilermakers (8.800 mg/m^3) and Drill Operators (5.70 mg/m^3). When compared with the ES, all the mean exposures to RES were below the ES of 2.1 mg/m^3, while the maximum concentrations exceeded the ES (Table 4). Six RES and two RCS outliers were noted through a box and whisker as well as spike plots. Those extreme values may in part be due to practical work participants were frequently engaged in (e.g., crushing and processing personnel and workshop boilermakers). Technical issues regarding the assessment of exposure to pollutants cannot be ruled out.

The study established that the Management Administration & Technical personnel (0.068 mg/m^3) and Crusher/Dry/Wet Plant workers (0.042 mg/m^3) were exposed to higher mean concentrations and exceeding the ES of 0.035 mg/m^3 compared to other workgroups. The maximum silica exposures (Table 4) were identified among Management Administration & Technical (2.5 mg/m^3), followed by Crusher/Dry/Wet Plant Personnel (0.710 mg/m^3), Workshop Boilermakers (0.130 mg/m3), Laboratory Operations and Maintenance (0.120 mg/m^3), Maintenance (Workshop and Infrastructure) (0.053 mg/m^3), Blast Crew (0.050 mg/m^3), and Earthmoving Equipment Operators (0.042 mg/m^3). All these maximum exposures were above the ES.

The elevated mean RCS exposures among Crusher/Dry/Wet Plant personnel can be explained by crushing and processing activities which generate more dust than any other operation on site. Tasks such as monitoring and adjusting the day-to-day operation of the plant, undertaking inspections, carrying out breakdown maintenance, and clearing blockages are all undertaken in dusty environments. The Health & Safety personnel are part of the Management Administration & Technical workgroup. A review of the results indicated that the maximum exposure of 2.5 mg/m^3 was recorded from this workgroup. They are responsible for implementing health and safety initiatives to prevent injuries and exposures in the workplace across all the departments. Upon review of the maximum result recorded from the Health & Safety personnel, it was revealed that the worker had spent most of their shift in the sample preparation shed reviewing pulverizing activities and at the processing plant.

Workshop Boilermakers also carry out maintenance activities at the crushing and processing plant, hence they were exposed to slightly elevated exposures to RES. Other occupations have lower exposures partly due to the less dusty environments within which they work such as those who work in enclosed cabins and maintenance infrastructure.

3.3. Exposure trend for RCS and RES for the period 2017-2023

In Fig. 1 we present the trend of exposure for RES and RCS for the period between 2017 and 2023. Although a decline in the AM exposures was observed from 2017 to 2021, there has been a change in the exposure trend for RCS during the last two years of the study when an increased exposure to RCS was observed. After mid-2022, slightly elevated RCS levels exceeding the ES of 0.035 mg/m^3 were recorded [5].

Mine B went into care and maintenance in December 2019, during which there were no mining, crushing, processing and maintenance activities on site. This would have contributed to the reduction in the mean RES and RCS concentrations from 2019 to

Table 4
Comparison of contaminant concentrations of RES and RCS (mg/m^3) according to occupations within each department

	Respirable dust (RES)								Respirable crystalline silica (RCS)							
	n	No. below LOD	Min	Max	AM	GM	GSD	95th	*n*	No. below LOD	Min	Max	AM	GM	GSD	95th
Administration & Support Services																
Management Administration & Technical	40	16	0.040	0.400	0.142	0.128	1.562	0.320	40	35	0.003	2.500	0.068	0.006	2.868	0.013
Cleaning and Utilities Staff	40	24	0.100	0.300	0.137	0.126	1.472	0.300	40	37	0.001	0.025	0.005	0.004	1.779	0.015
p					0.750	0.880							0.322	0.130		
Mining																
Blast Crew	37	8	0.100	1.000	0.212	0.163	1.918	0.900	37	31	0.001	0.050	0.007	0.005	2.107	0.031
Geologists and Surveyor	35	16	0.040	0.900	0.140	0.118	1.629	0.300	35	30	0.003	0.019	0.005	0.005	1.521	0.014
Drill Operators	48	25	0.040	5.700	0.249	0.127	2.043	0.300	48	42	0.002	0.028	0.005	0.005	1.643	0.012
Mine Truck Operators	51	29	0.050	0.400	0.117	0.109	1.377	0.200	51	48	0.001	0.009	0.004	0.004	1.499	0.007
Earthmoving Equipment Operators	46	17	0.100	1.400	0.190	0.139	1.887	0.570	46	41	0.002	0.042	0.006	0.005	1.795	0.018
p					0.536	0.020							0.251	0.483		
Crushing and Processing																
Crusher/Dry/Wet Plant Personnel	103	35	0.040	15.000	0.558	0.238	2.860	1.700	103	52	0.002	0.710	0.042	0.011	4.162	0.250
Laboratory Operations and Maintenance	51	24	0.100	0.960	0.199	0.152	1.939	0.600	51	28	0.001	0.120	0.015	0.008	2.986	0.064
p					0.111	0.006							0.021	0.142		
Maintenance																
Maintenance (Workshop and Infrastructure)	68	19	0.070	1.000	0.187	0.154	1.767	0.400	68	50	0.003	0.053	0.008	0.006	1.968	0.024
Workshop Boilermakers	41	5	0.100	8.800	0.842	0.371	3.208	2.100	41	24	0.002	0.130	0.017	0.008	2.972	0.066
p					$<$0.001	$<$0.001							0.040	0.029		

AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation; LOD, limit of detection; n, number of measurements.
p-values are based on two samples t-test or ANOVA (or Mann−Whitney U test or Kruskal−Wallis test when normality assumption was not met).

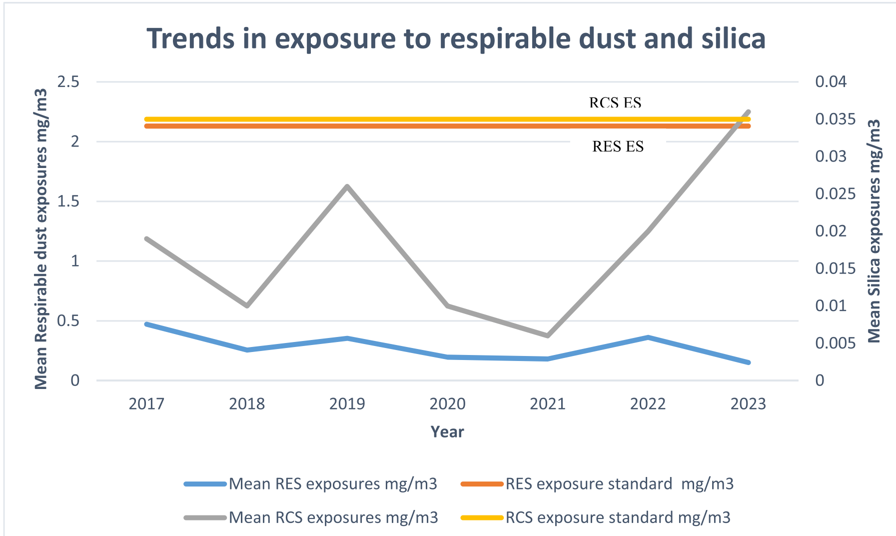

Fig. 1. Trends in exposure to respirable dust and silica (2017-2023).

2021. In January 2022, mining operations resumed at Mine B, which was associated with the increase in RES and RCS mean concentrations. In 2022, a tunnel linking the crusher and the processing plant was commissioned in Mine B in 2022, for conveying crushed ore to the processing plant. The records from personal exposures to RCS showed elevated RCS concentrations that exceeded the established ES in Australia. This was addressed through dust suppression in the form of water spray bars, and the mandatory use of powered air purifying respirators (PAPR) for access to the tunnel.

The study results demonstrated that the male observations increased from 73.9% to 81.7% from 2021 to 2022, which was consistent with the increase in RCS exposure levels. This highlights the risk of potential health effects for the increased male population.

4. Discussion

The current study used a large population data set of 1122 observations of exposure to respirable dust and RCS from Western Australian lithium mine workers over the seven-year period, between 2017 and 2023. Robust representative exposure data was collected over the seven-year period to establish the exposure risk profile, and document the exposure levels to both RES and RCS for all workgroups in the lithium mines. The established risk profile informed the requirement for continuing risk management and health monitoring. A portion of the monitoring was independently undertaken by external occupational hygiene consultants, which removed a level of bias in the monitoring process. Due to the historical use of data, it was difficult to retrospectively define the physical environmental and operational conditions within which the monitoring was undertaken which is acknowledged as a study limitation. Although this can be viewed as a weakness for 2017 to 2018, it was rectified with inhouse monitoring from 2019 to 2023, during which infield observations were undertaken by Mine Air Quality Officers.

4.1. Exposure to RES and RCS among lithium mine workers by workgroups and departments

The study demonstrated a decline in exposure levels to RES over the seven years (2017-2023) from 0.472 mg/m^3 to 0.151 mg/m^3, with a slight increase in 2019 and 2022. The decrease is attributable to control interventions in the form of dust suppression in crushing and in mining and haul roads through water carts, the introduction of automatic batch machine technology in laboratories for sample preparations, the use of potable extraction ventilation in workshops, and the provision of training for the use and maintenance of the control. However, the overall RES concentration did not exceed the ES of 2.1 mg/m^3 [5]. A decline in the concentration of RCS was observed between 2019 and 2021, followed by an increase after 2021. The mean concentration of RCS exceeded the ES in 2023.

The majority of the study population consisted of males (84.1%) which is consistent with previous studies [25]. A higher percentage of lithium workers was engaged in activities related to mining (41.2%), followed by crushing and processing (27.6%). Job characteristics in Mining included drilling, blasting, sample collection, sample preparation, and sampling logging; all of which are undertaken in outdoor environments. Other mining activities included the operation of mining mobile equipment for the extraction and transport of ore and waste to stockpiles and crushing and processing plants. Personnel operating mobile equipment work in air-conditioned cabins with positive pressure to prevent the ingress of dust. On the other hand, workers in Crushing and Processing and Maintenance (Workshop Maintenance) work in dusty environments undertaking activities such as inspection, maintenance, and general housekeeping. These workers are exposed to elevated levels of RES and RCS.

Fifty-four percent of the study population reported wearing respiratory protective masks compared to 45.7% who did not. Elevated mean exposure to RES was recorded for Crusher Dry/Wet Plant Personnel (0.558 mg/m^3), and Workshop Boilermakers (0.842 mg/m^3), compared to other workgroups. This can be explained by the fact that both Crusher Dry/Wet Plant Personnel and Workshop Boilermakers undertake activities on the fixed plants where dust is generated by crushing of ore.

Among the occupations, the highest mean exposures for RCS over the seven-year study period were measured for Management Administration & Technical (0.068 mg/m^3), followed by Crusher/Dry/Wet Plant Personnel (0.042 mg/m^3), exceeding the ES of 0.035mg/m^3. Health & Safety personnel have exposure to all work areas, highlighting the need for them to adhere to controls for themselves while engaging work areas and personnel for injury and exposure prevention.

Although the mean RCS concentrations for other workgroups are below the ES, high RCS concentrations were measured for Crusher/

Dry/Wet Plant Personnel (0.710 mg/m^3), Workshop Boilermakers (0.130 mg/m3), Laboratory Operations and Maintenance (0.120 mg/m^3), Maintenance (Workshop and Infrastructure) (0.053 mg/m^3), Blast Crew (0.050 mg/m^3), and Earthmoving Equipment Operators (0.042 mg/m^3). This data indicates that workers in these workgroups are exposed to RCS levels above the ES during their work. Mining, crushing, maintenance, earthmoving, and laboratory processes are associated with emissions of dust. Boilermakers, on the other hand, are responsible for the repair of machinery from mining activities. They are also required to undertake welding activities at the crushing plant and potentially become exposed to high levels of dust. Personal monitoring results revealed that the elevated exposures among these workgroups are due to crushing and processing activities, maintenance activities undertaken by boilermakers on fixed plants, sample preparation activities in laboratory operations, maintenance of mobile mining equipment and infrastructure, drilling and blasting operations, and earthmoving work. Dust suppression through spray bars and the use of water carts, location exhaust ventilation, and a robust respiratory protection program were implemented as controls for the protection of these workers.

This study has revealed that Crusher/Dry/Wet Plant Personnel and Management Administration & Technical personnel are exposed to silica levels above the ES. Based on the maximum exposure results, this study has highlighted that Blast Crew, Earthmoving Equipment Operators, Crusher/Dry/Wet Plant Personnel, Laboratory Operations and Maintenance, Maintenance (Workshop and Infrastructure), and Workshop Boilermakers are exposed to silica levels above the Australian ES. It has also indicated that while the mean RES concentrations are below the Australian ES for all workgroups, the maximum exposure results reveal that Drill Operators, Crusher/Dry/Wet Plant Personnel, and Workshop Boilermakers are exposed to levels above the RES ES, requiring a revision of the effectiveness of controls.

Across the four departments, the exposures to RES concentrations were statistically different, with Crushing & Processing recording the highest mean exposures (0.439 mg/m^3), followed by Maintenance (0.434 mg/m^3). This was not consistent with the findings for exposures to RCS. The highest mean concentration of RCS was measured in the Administration & Support Department (0.037 mg/m^3), followed by Crushing & Processing (0.033 mg/m^3). The more in-depth analyses showed that Crusher/Dry/Wet Plant Personnel were exposed to the highest mean concentration of RES (0.558 mg/m^3), followed by Workshop Boilermakers (0.842 mg/m^3). With regard to RCS, the statistical analyses established the highest mean concentration for Management Administration & Technical (0.068 mg/m^3), followed by Crusher/Dry/Wet Plant Personnel (0.042 mg/m^3).

Administration & Support recorded the highest mean silica exposures (0.037 mg/m^3) for the four departments. Workgroups within this department include management and administration, cleaners and utilities staff, and Health, Safety & Environment personnel. Managers, cleaners, and Health, Safety & Environment personnel have exposure to all work areas across the mine, and this could be a contributing factor. Hence emphases should be on these workgroups adhering to airborne contaminants controls specific to work areas, for the prevention of potential occupational illnesses associated with exposures to RCS. Cleaners are responsible for cleaning work areas across the entire mine and accommodation village. Cleaning processes are associated with contact with dust generated by mining operations in and around offices, and crib rooms which can explain their likely exposure to higher dust concentrations. Cleaners are also required to work around the crushing and processing plant, for the removal of generated waste from rubbish bins. This study reveals that when considering exposure control and exposure reduction for the occupations in lithium mining operations, those within crushing and processing, administration & support, and maintenance are potentially at high risk for the occurrence of occupational illnesses due to the higher dust exposure.

The findings of this study are consistent with a cross-sectional survey study undertaken in Australia in 2012 which confirmed that compared to other occupations, miners and construction workers are more likely to be exposed to high levels of RCS, with over 60% of them deemed to have these high exposures [17], compared to 12.9% of lithium mine workers. While the current study reveals a lower exceedance percentage for lithium mine workers mainly due to the population of the workgroups, it must be noted that the health impacts are not minimized for these workers with elevated exposures to RCS. Tasks associated with these exposures were cutting, grinding, sanding, or mixing concrete in construction, and crushing in mining [17]. This study conducted in lithium mining confirmed that crushing activities are associated with dust emissions and elevated RCS exposures.

Another study conducted in WA between 2001 and 2012 revealed that exposure to RCS declined steadily over the study period [25], and was consistent with previous studies undertaken in the USA, Europe, China, and Canada [29–32]. Similar to these studies, a study from Denmark in 2018 among eleven occupations in mining, construction, and manufacturing indicated low exposures to RES and RCS among these occupations [26].

There were no observable significant differences in mean exposure to respirable dust and silica due to age, gender, and work shift (day and night). However, it was identified that exposures were significantly different within the departments. In 2021, Mine B was in care and maintenance, during which all mining, processing, and maintenance activities were suspended. Respiratory protection use was not recorded for Mine A in 2021, which can be explained by the implementation of the monitoring plan.

4.2. Trend of exposure to RES and RCS in lithium mines during a seven-year study period (2017-2023)

The study demonstrated a decline in exposure to RES over the seven years (2017-2023) from 0.472 mg/m^3 to 0.151 mg/m^3, with a slight increase in 2019 and 2022. With regard to RCS exposures, although a decline in concentration was observed between 2019 and 2021, a rapid increase in exposure was recorded after 2021. This can be explained by the increased mining activity at the operations and the commissioning of the tunnel at Mine B, highlighting the anticipated elevated exposures in confined spaces and underground. The difference in the decline of RES and elevation of RCS over the seven-year period can also be attributed to higher silica content in the orebody. Data analyses also indicated that workers who wore respiratory protection had significantly higher AM exposures to RES than those who did not wear respiratory protection.

Although a decrease in RES exposure was observed in the seven-year study period, the findings of this study are inconsistent with previous studies undertaken in Australia, USA, Europe, China, and Canada as it revealed an increase in RCS exposure in the past two years of this study. It must be noted that the studies undertaken in other parts of the world were not conducted in lithium mining and did not indicate the presence of tunnels and other confined spaces. The elevated RCS exposures can be attributed to the tunnel commissioned in Mine B, which indicated elevated atmospheric RCS concentrations.

4.3. Preventive measures to protect lithium mine workers from silica dust

The findings of this study reveal the urgency for silica management plans and regulatory audits in lithium mining, addressing

HRAs, the monitoring requirements, the implementation of controls, the verification of control effectiveness, silica awareness training, health monitoring and reporting of exposure and health monitoring data to stakeholders. Control interventions to reduce exposures in crushing and processing, maintenance processes in fixed plants, and sample preparation in laboratory settings are also required. Most of these controls should be aimed at engineering the risk out of the operations, thereby reducing the impact of human factors for effectiveness. Further research is also encouraged for the impact of real-time RES and RCS monitoring, to inform corrective actions to reduce workplace airborne contaminant concentrations. There is also a gap in knowledge on the effectiveness of dust suppression chemical binding agents in reducing dust generation from human and machinery activity.

Occupational hygienists understand the work environment and the associated health hazards and the adverse health effects. They are trained in exposure assessment, control, and reporting for the protection of workers' health but possess little knowledge and experience in health monitoring. This gap in knowledge presents an improvement opportunity for the medical industry to consider a stringent pathway to train certified occupational hygienists into occupational physicians.

Workplace inspections and qualitative risk assessments are used to anticipate exposures in the workplace to inform exposure controls. Where exposures are predicted to be high, workers are informed to use respiratory protection. However, there is no information on the effective use of respiratory protection including respiratory protection fit testing, being clean-shaven and worker behavior. This can explain the mean high concentration of RES exposure among those workers.

Workers need to be aware that the RPE provided and worn will protect them from dust exposure which can be associated with adverse health effects. The seal of any RPE is crucial therefore training is crucial. However, the care of the respirators is the responsibility of the individual. A respiratory protection program was in place for the selection, use and maintenance of RPE. The atmospheric airborne contaminants and the exposure level, the work environment, and personal comfort were considered for the selection of RPE. This was followed by training, fit testing where required, and the necessity to be clean-shaven. Management was also trained on the respiratory protection program. However, infield verification by Management for compliance to respiratory protection use was identified as an improvement opportunity.

In addition to RPE, a range of other control measures to protect workers from exposure to RCS should be considered which includes increasing ventilation to sweep away dust; making sure water sprays are working properly; and slowing down mining machines to diminish dust.

Research conducted on RCS dust suppression among workers fabricating countertops indicated a significant reduction of exposures when dust suppression was applied on stone saws in combination with local exhaust ventilation. The study compared RCS dust exposures during simulated stone countertop cutting with a handheld circular saw under three conditions—wetted blade only, wetted blade and supplementary water curtain, and wetted blade and local exhaust ventilation. It was revealed that wetting the blade alone resulted in a 10-fold reduction in RES exposures, compared to dry cutting, while the supplementary application of a location exhaust ventilation provided a further 10-fold reduction [33]. This study demonstrated that ventilation and dust suppression through water sprays are effective in reducing workplace exposures to airborne contaminants. Location exhaust ventilation and water sprays should be considered in boilermaker workshops and within crushing and processing plants.

4.4. Study limitations

The use of historical data in the current study was associated with limitations due to the lack of involvement by the investigators in the field data collection. This is acknowledged by the authors. In 2021 respiratory protection use was missed during data collection for Mine A, which might have impacted the respiratory protection use results. Some workers did not report the use of respiratory protection, and as a limitation of this study, analyses were not conducted for respiratory protection use compliance for the departments. Across Processing, Maintenance and Laboratory Operations, P2 disposable dust masks were provided for protection against airborne dust exposures with the potential to exceed the ES. Some workers did not wear the P2 masks although training and instructions were provided.

Although some data was collected on smoking, analyses were not conducted on this variable due to missing values. The authors also acknowledged that this is also a limitation of this study.

5. Conclusion

The most common form of silicosis is chronic silicosis, which occurs after a low to moderate level of exposure to RCS for over 10 years [15]. The exposures observed in lithium mining fall within this range, which are capable of causing chronic silicosis without effective exposure control and exposure reduction interventions. These exposures also have the potential to impact the other known health conditions associated with silica exposures—COPD, lung cancer, airway obstruction, and renal disease. It must also be noted that RCS is classified as a Group 1 carcinogen by the International Agency for Research on Cancer in 1997 [15]. A Group 1 carcinogen is a known cancer-causing agent in humans. Without adequate control measures to protect the health of workers, the RCS exposures in lithium mining are at levels capable of causing lung cancer, a well-known health effect associated with RCS exposure.

Even with the current ES of 0.05 mg/m^3 (the equivalence of 0.035 mg/m^3 for this study), the lifetime exposure presents an estimated risk of 20 to 40% for developing chronic silicosis [13]. This implies that adherence to the current ES does not guarantee the prevention of chronic silicosis. As such the focus should be on the implementation of hard controls to eliminate or reduce exposures to as low as reasonably practicable. It is also known that due to biological variations and individual susceptibilities, a small proportion of people may experience adverse health effects below the ES; hence the urgency for the elimination or reduction of exposures to protect the health of lithium mine workers.

Based on the findings of the exposure trends in this paper, it is the position of the authors to present that the RES exposures of personnel in lithium mining are within limits which should not cause adverse health effects. The authors maintain that the RES exposure trends from this study are well below the ES for respirable dust, as opposed to the RCS exposure trends. According to the literature, without adequate exposure control and exposure reduction interventions, the RCS exposures of Management Administration & Technical personnel, and Crusher/Dry/Wet Plant Personnel may fall within the concentration range capable of causing potential chronic adverse health effects such as silicosis [13]. It is recommended that additional control measures be considered. These measures include implementing dust suppression techniques (using chemical binders where necessary), local exhaust ventilation for dry crushing, tunnels, and pulverizing in sample preparation sheds and welding workshops. In addition, automation of sample preparation using the Autobatch technology – the ABM3000 Milling Machine 380-415V 50-60HZ can be considered to eliminate the manual milling of samples which is associated with elevated exposure to dust. To ensure the effectiveness of respiratory protection, it is advised to verify its suitability based on factors like exposure, comfort, and the work environment. This involves regular training, fit testing, proper storage and usage of procedures, and infield verification by Management.

In combination with the Australian Standard for sampling and gravimetric determination of respirable dust in workplace atmospheres (AS2985-2009), and the International Standard ISO 7708:1995, proactive methods for real-time RCS monitoring across lithium mining should be explored. There is an emerging technology for real-time monitoring of respirable dust and silica, providing an indication of airborne concentrations, and the requirement for controls and the verification of control effectiveness in the workplace.

Ethics statement

The study was reviewed and approved by the Human Ethics Research Committee, Curtin University with approval number: HRE2023-0408. All procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the appropriate institutional committees. The study subjects provided their written informed consent to participate in this study including the survey and personal monitoring.

CRediT authorship contribution statement

David Gbondo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Yun Zhao:** Supervision, Formal analysis, Conceptualization. **Minh Pham:** Supervision, Formal analysis. **Krassi Rumchev:** Validation, Supervision, Conceptualization.

Conflicts of interest

There has been no conflict of interest considering the below.

Exposure assessment followed a scientific methodology and all samples collected were independently analyzed in the National Association of Testing Authorities laboratory. The results of the laboratory analyses were used to determine exposure risks.

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