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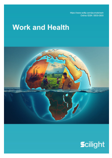

Article

Accuracy of Real-Time Dust Monitors in Quarry Settings: A Pilot Field and Laboratory Evaluation

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Abstract: Accurate real-time dust monitoring methods are essential in workplaces where exposure to respirable crystalline silica (RCS) presents serious health risks. While real-time monitors are increasingly adopted due to their ability to quickly detect dust-generating activities, concerns remain regarding their accuracy compared to conventional gravimetric methods. This pilot study evaluated the performance of three real-time personal dust monitors: the SidePak™ AM520, Trolex XD1+, and Nanozen DustCount 9000, against a gravimetric reference in both field settings (South Australian quarries) and controlled laboratory environments. Pairwise comparisons of respirable dust (RD) concentrations were conducted across full work shifts. Geometric means from the real-time monitors were regressed against corresponding gravimetric measurements to derive correction coefficients, which were then used to estimate RCS exposure. Agreement between estimated and measured RCS values was assessed using Lin's Concordance Correlation Coefficient (CCC). Field results revealed inconsistent accuracy for the SidePak™ and Nanozen monitors, with performance varying by task. For example, the SidePak™ overestimated RD by 51% for a truck driver but underestimated levels by up to 48% for other roles. The Trolex XD1+ consistently underestimated RD by 80–89%. All monitors underestimated dust levels under laboratory conditions. However, applying correction coefficients improved agreement with gravimetric data, yielding a high concordance for RCS estimates (Lin's CCC = 0.89; 95% CI: 0.66–0.97). These findings highlight both the utility and limitations of real-time monitors. Site-specific calibration is essential to enhance their reliability, and further studies with larger datasets are recommended to refine correction factors and improve accuracy of real-time dust monitors.

Keywords: real-time dust monitoring; respirable crystalline silica; occupational exposure assessment; gravimetric calibration

1. Introduction

The process of quarrying to generate resources for building roads, commercial and residential establishments involve tasks like extracting, crushing, and transporting rocks, which can result in significant dust production, including respirable crystalline silica (RCS). Occupational exposure to RCS can been directly linked to adverse respiratory health outcomes, including silicosis, asthma, and lung cancer [1]. Several international studies have reported a deterioration of lung function among quarry workers chronically exposed to silica dust [2,3], indicating quarrying as a high-risk dust-generating industry. In Australia, an unexpected diagnosis of accelerated silicosis on a quarry worker employed for 4 years was made in 2022 [4]. Importantly, occupational diseases due to exposure to RCS dust are preventable, underscoring the need for vigilant exposure monitoring and dust control in the workplace [5].

Under the model work health and safety (WHS) laws in Australia, a person conducting business or undertaking (PCBUs) must ensure that worker exposure to RCS is kept as low as reasonably practicable and under the workplace exposure standard (WES) of 0.05 mg/m^3 (eight-hour time weighted average) while processing crystalline silica substances [5]. If unsure whether the WES has been exceeded, the PCBU must measure worker's exposure to RCS by air monitoring in their breathing zone, using a cyclone sampler connected to a pump that draws air at a specified flow rate during their usual work activities [5,6]. The dust retained on the sampling filter is subsequently quantified gravimetrically for respirable dust (RD) and is analysed further in a laboratory for RCS quantification, often by analytical techniques such as X-ray powder diffraction (XRD) and/or Fourier Transform Infrared Spectroscopy (FTIR) [7].

While conventional gravimetric dust monitoring methods are validated and reliable, they do exhibit certain limitations. These methods provide averaged data encompassing an entire work-shift, which restricts their applicability for continuous compliance monitoring only, while risks from short-term exposure remain undetermined. Sampling for short-term task-based exposures using conventional techniques is unreliable due to the limit of detection for RCS when dust levels are low. According to a recent study by Rae [8], high-volume samplers could help overcome the issue, however, this approach requires further validation for wider application. Hence, the costs associated with sampling, analysis, and result interpretation remain a limiting factor within conventional dust monitoring methods.

To this effect, real-time dust monitoring techniques are being increasingly adopted to complement conventional sampling as they are relatively rapid, cost-effective, and user-friendly [9]. They are also useful for detecting and tracking hazardous conditions, evaluating and documenting effectiveness of control methods, and promptly triggering alarms in the event of extreme exposure conditions [10]. In recent times, a variety of real-time dust monitoring devices have been introduced to the Australian market [11,12], including a world-first web-based software 'Exposi' to assist real-time exposure monitoring and video [13].

Real-time dust monitoring technology relies on light scattering techniques which estimate the particle mass and size by a light source interacting with the dust particle in a sampled air, based on the principle of the Mie theory [14,15]. Light scattering techniques can be broadly classified as total light and single particle scattering. The former, e.g., photometers involve measuring the interaction between a light source and all the particles in the sampled air while, the single particle scattering instrument detects the interaction between a light source and each particle so it can count particles and estimate the size of each particle (e.g., optical particle counters, OPC). Factors like particle size, shape, refractive index, electric charge, wavelength of light and the sensitivity of the detector can influence the results with light scattering techniques [16,17], and are only corrected by calibrating with dust with the same optical properties [18]. The performance of most real-time monitoring technologies remains largely unassessed in the Australian context, in terms of their accuracy. That is the extent to which their measurements agree with measurements obtained from conventional (and validated) methods. Similarly, their value in complementing conventional and validated methods under real-world conditions, i.e., their utility remains underexplored. Statements relating to accuracy and utility are currently defined by manufacturers' claims, relying on proprietary and limited data held by the companies instead of a comprehensive assessment. There is a paucity of independent, open-access evidence on the performance of real-time devices for monitoring exposure in dust-generating industries.

While numerous previous studies have evaluated real-time dust monitors [7,18–24] often against reference gravimetric methods, most of these have primarily been conducted in controlled laboratory conditions or wind tunnels without worker involvement. This limits our understanding of these instruments and their performance under real-world field conditions. Furthermore, quarry sites and other industries seeking to utilise such technology need clearer insight on how to interpret the data effectively for estimating worker exposure to RD and RCS.

This study aimed to address these gaps, by evaluating the accuracy and utility of three commercial real-time dust monitors against a conventional and validated gravimetric dust sampler under both quarry (field) and controlled laboratory conditions.

2. Materials and Methods

2.1. Real-Time Dust Monitoring Instruments

Three commercially available real-time personal dust/aerosol monitoring instruments were used for the study, namely the Nanozen DustCount 9000 (Air-Met Scientific Pty Ltd., Victoria, Australia; hereinafter Nanozen), Trolex XD1+ (Trolex Ltd., Cheshire, UK; hereinafter Trolex) and the SidePak™ AM520 (TSI Incorporated, Minnesota, USA; hereinafter AM520). Further specifications are listed in Table 1. These were chosen based on discussion with a key stakeholder, the Mining and Quarrying Occupational Health and Safety Committee, Government of South Australia. One of the real-time monitors (Nanozen) also had a built-in 25-mm filter cassette for additional gravimetric RD and RCS analysis.

Table 1. Personal real-time dust monitoring equipment used in the study, with specifications.

Instruments	Sensor Technology	Gravimetric Measurement Function by Filter (Yes/No)	Particulate Measurement Size/s Available	Particulate Measurement Size/s Used	Flow rate (Default)	Sampling Interval (Logged)
Nanozen (Serial numbers: 706, 1026,1053)	Optical particle counter	Yes (built-in cassette with filter)	PM2.5, PM4 and PM10 with different attachments.	PM4	1.0 L/min	10 s
Trolex (Serial number: HH03700)	Light scattering photometer	No	PM1, PM2.5, PM4.25, PM10	PM4.25	0.1 L/min	10 s
AM520 (Serial number: 5202228004)	Light scattering photometer	No	Diesel Particulate Matter (DPM, at 0.8 μm), PM1, PM2.5, PM4, PM5 and PM10 with different attachments.	PM4	1.7 L/min	10 s

2.2. Conventional Dust Sampling Method

RD samples were collected using the Higgins-Dewell (Casella) respirable cyclone (Casella Solutions, MD, USA), fitted with pre-weighed 25-mm PVC membrane filters (GLA-5000, SKC Inc., EightyFour, PA, USA), and connected to a battery-operated pump (AirChek Touch Pump, SKC Inc., Eight Four, PA, USA) operating at a flow rate of 2.2 L/min [6]. Flow rates were calibrated before and after each sampling event using a dual ball rotameter (Precision 320 Series, SKC Inc., Eight Four, PA, USA). Samplers were worn for each whole shift.

2.3. Site Monitoring

Three quarry sites in South Australia, each extracting sandstone, limestone, and dolomite, were visited, with multiple dust monitoring events conducted at one of the sites. Typical quarry activities included loading the rock onto trucks at the face of the quarry, followed by transport to a crusher where the rock was processed and screened to collect the required size fractions ranging from rock to sand depending on the process and product requirements.

The quarry site was contacted by researchers to organize dates when it was mutually convenient to carry out the dust monitoring. The criteria for conducting dust monitoring were dry conditions, no rain for at least three days prior to monitoring and that the site was operating. These conditions would represent a 'typical' workday for potential dust exposure depending on the level of activity at the site. It meant most monitoring was conducted during summer.

Table 2 summarizes the field monitoring conducted at the quarry site. Four days of field monitoring were conducted involving 12 quarry workers. Personal monitoring for each worker included pairwise comparisons between a conventional gravimetric (Casella) sampler and at least one of three real-time dust monitors. On two occasions the gravimetric sampler was worn concurrently with two real-time dust monitors (Trolex and Nanozen), by excavator workers.

Table 2. Overview of quarry monitoring days and instruments compared.

Days	Worker	Gravimetric	AM520	Nanozen	Trolex
Day 1	Plant operator 1	✓	✓	NT	NT
	Maintenance supervisor	✓ *	NT	✓ *	NT
	Diesel mechanic	✓	NT	NT	✓

Table 2. *Cont.*

Days	Worker	Gravimetric	AM520	Nanozen	Trolex
Day 1	Plant operator 1	✓	✓	NT	NT
	Maintenance supervisor	✓ *	NT	✓ *	NT
	Diesel mechanic	✓	NT	NT	✓
Day 2	Truck driver 1	✓	✓	NT	NT
	Loader	✓	NT	✓	NT
	Excavator 2	✓	NT	✓	✓
Day 3	Truck driver 2	✓	✓ *	NT	NT
	Plant operator 2	✓	NT	✓	NT
	Quarry manager	✓	NT	NT	✓
Day 4	Excavator 1	✓	✓	NT	NT
	Watercart driver	✓	NT	✓ *	NT
	Excavator 3	✓	NT	✓	✓

NT: instruments not tested for the monitoring session; *: samples were deemed invalid.

2.4. Pairwise Monitoring Approach

Each real-time instrument was paired with a conventional gravimetric sampling device. Workers wore pumps fastened to them via hip belts, with cyclone attached to the lapel (breathing zone). The real-time dust monitors (AM520, or Nanozen,) were similarly fastened to the belt and lapel or collar on the opposite sides. The Trolex XD1+, which did not have any tubing, was securely clipped onto the chest strap of the backpack, maintaining its position within 30 cm of the breathing zone.

2.5. Gravimetric RD and RCS Analyses

Filters obtained from sampling with the conventional gravimetric samplers and also the Nanozen real-time monitor were analysed for RD and RCS. Gravimetric determination of RD was conducted using standard methods.The filter weights were determined gravimetrically for RD using an Automatic Electrobalance (CAHN 29). Replicate field and laboratory blank filters were recorded [6].

The RCS (quartz and cristobalite) analysis of filter samples was performed at an external NATA-accredited laboratory, using XRD, according to a modified thin film filter method based on the National Institute for Occupational Health and Safety and Health (NIOSH) analytical method 7500. The reported Practical Quantitation Limit (PQL) was 5 µg per sample for quartz and 10 µg per sample for cristobalite. Cristobalite contributed negligibly to total RCS: it was below the PQL in all field samples and accounted for only about 0.5% of total RCS in laboratory trials, even under high dust generation conditions.

2.6. Laboratory Controlled Dust Chamber Testing

Two materials sourced from South Australian quarries were included for this part of the study, namely limestone and dolomite. Samples were selected based on convenience sampling (a strategy based on accessibility and availability to the researcher) from participating quarries. A custom-built test chamber (60 cm × 80 cm × 80 cm) fitted with two glove compartments was used for simulating dust generation in a controlled environment, as described previously [25].

All real-time and conventional instruments were run concurrently to simultaneously sample dust generated within the chamber for a 30 min sampling period. The purpose was to compare all real-time samplers with a conventional sampler at the same time, in the same atmosphere. Field testing of all three real-time monitors plus conventional sampler at the same time, on the same worker, was not feasible due to worker discomfort.

There is little industry guidance available for the use of direct reading (real-time) monitoring equipment for particulate exposure assessment. The European Standard EN13205 Workplace Atmospheres—Assessment of Performance of Instruments for Measurement of Airborne Particle Concentrations (2014) [26] outlines experimental (laboratory-based) procedures to conduct gravimetric sampler comparison studies, however, there are currently no accepted standards for testing and validating real-time monitoring devices. The test method described in EN13205 was followed in principle, where possible, for this component of the study, whereby candidate real-time dust monitors were tested by comparison with a validated sampler, in an aerosol chamber, exposed to the same test aerosol. A total of 6 trials were carried out to evaluate the performance of the real-time dust monitors against the conventional gravimetric sampler under controlled conditions.

2.7. Data Analysis

All data from the real-time dust monitors were exported to Microsoft Excel spreadsheets using the specific software designed for each instrument. All data management, computation of dust concentrations, and descriptive statistics (geometric mean, arithmetic mean, frequencies) were determined in Excel. Given the right-skewed distribution commonly observed in real-time dust monitoring data, both arithmetic and geometric means were calculated from the real-time measurements to explore which better approximated the gravimetrically derived reference values. While the gravimetric measurement conceptually aligns with an arithmetic mean, the geometric mean was also included to account for the influence of data skewness on estimation accuracy. This dual presentation allows for a more nuanced comparison of the performance of real-time instruments in estimating respirable dust concentrations under varying distributional characteristics.

For gravimetric samples, RD data was transcribed from laboratory notebooks into Excel spreadsheets. Their RCS (quartz and cristobalite) contents, determined by XRD, were received from the external laboratory in Microsoft Excel format. Correction coefficients for each instrument were derived from the slopes of the regression lines plotted using the geometric means of the real-time monitor readings against corresponding gravimetric measurements. These correction coefficients, combined with the quarry product's RCS content (from its safety data sheet), were used to estimate potential RCS exposure levels for each worker. The degree of agreement between estimated and measured RCS levels was statistically tested using Lin's Concordance Correlation Coefficient (CCC).

3. Results

This study presents a side-by-side comparison of three real-time dust monitors against a conventional gravimetric RD sampler (Casella) under both field and laboratory-controlled conditions. In the field study, 12 quarry workers were monitored. Due to equipment failure, one of the gravimetric samples was excluded from further analysis, resulting in a total of 11 pairs of real-time versus gravimetric comparisons used for the final analysis. For the laboratory tests, six trials were conducted, with all three real-time instruments simultaneously tested against a gravimetric sampler in each trial, giving 18 pairwise comparisons.

3.1. Field Test Results

3.1.1. Pairwise Comparison of AM520 and Gravimetric RD measurements

Pairwise comparison tests between the AM520 and the gravimetric sampler were conducted in a quarry site with three workers: a plant operator, a truck driver, and an excavator. Table 3 summarises the RD concentrations recorded by both methods. The results indicate that the AM520 real-time monitor both overestimated and underestimated gravimetric RD exposure levels, depending on the work/worker. For Truck Driver 1, the AM520 overestimated dust levels by 51%, while for Excavator 1 and Plant Operator 1, it underestimated concentrations by 31% and 48%, respectively compared to the gravimetric RD measurements.

Table 3. Pairwise comparison of gravimetric and AM520 real-time RD concentrations.

Worker	Gravimetric (μg/m^3)	Trolex Real-Time Readings (μg/m^3)			
		Arithmetic Mean	Geometric Mean	% Mean Difference	Range
Truck driver 1	4.1	17	6.2	51	0–4840
Excavator 1	42	254	28.8	−31	3–25,900
Plant operator 1	101	147.7	52.8	−48	6–41,700

3.1.2. Pairwise Comparison of Trolex and Conventional Gravimetric

The Trolex monitor was evaluated against the conventional gravimetric sampler in four quarry monitoring sessions with a diesel mechanic, a quarry manager, and two excavators. The Trolex monitor consistently underestimated gravimetric concentrations by 80% to 87%. Table 4 provides a summary of RD concentrations for each worker, comparing Trolex measurements with (Casella) gravimetric results.

3.1.3. Pairwise Comparison of Nanozen and Gravimetric RD Measurements

The Nanozen monitor was evaluated against the conventional gravimetric sampler in four quarry monitoring sessions. In addition to real-time RD measurement, the Nanozen was the only real time monitor to feature a filter cassette for post-sampling gravimetric as well as RCS analyses. Table 5 compares RD concentrations from the

Nanozen real-time and conventional gravimetric methods. The comparison between the Nanozen and gravimetric sampler showed inconsistencies, with the Nanozen alternately underestimating and overestimating dust concentrations depending on the work/worker. For example, real-time Nanozen readings showed mixed performance—overestimating RD for Plant operator 2 (42.5%) and Excavator 3 (123%) but underestimating for the Loader (−19%) and Excavator 2 (−30%).

Table 4. Pairwise Comparison of Gravimetric and Trolex Real-Time RD Concentrations.

Worker	Gravimetric (μg/m³)	Trolex Real-Time Readings (μg/m³)			
		Arithmetic Mean	Geometric Mean	% Mean Difference	Range
Excavator 2	51	40	10	−80	1.6–1489
Excavator 3	21	4.4	2.7	−87	0.3–56
Diesel Mechanic	34.5	17	5.6	−83	1.2–3307
Quarry manager	83	19	13	−84	0.6–146

Table 5. Pairwise comparison of gravimetric and Nanozen real-time RD concentrations.

Worker	Gravimetric (μg/m³)	Nanozen Real-Time Readings (μg/m³)			
		Arithmetic Mean	Geometric Mean	% Mean Difference	Range
Plant operator 2	80	196	114	42.5	9–9241
Loader	139	241	112	−19.4	2–10,305
Excavator 2	51	57	35.7	−30	5–1010
Excavator 3	21	85	47	123	2–1401

Gravimetric analysis showed that RD levels from the Nanozen closely matched those from the conventional gravimetric sampler for Plant Operator 2. However, for the Loader, Nanozen underestimated RD by 19.4%, and for both Excavators, it overestimated RD by more than 100%. Interestingly, these discrepancies in RD measurements were not mirrored in the RCS results. For the Loader, despite a lower RD concentration, Nanozen reported RCS levels approximately 24% higher than the conventional gravimetric sampler. In contrast, for both Excavators, no RCS was detected on the Nanozen filter, even though it recorded higher dust concentrations (Figure 1).

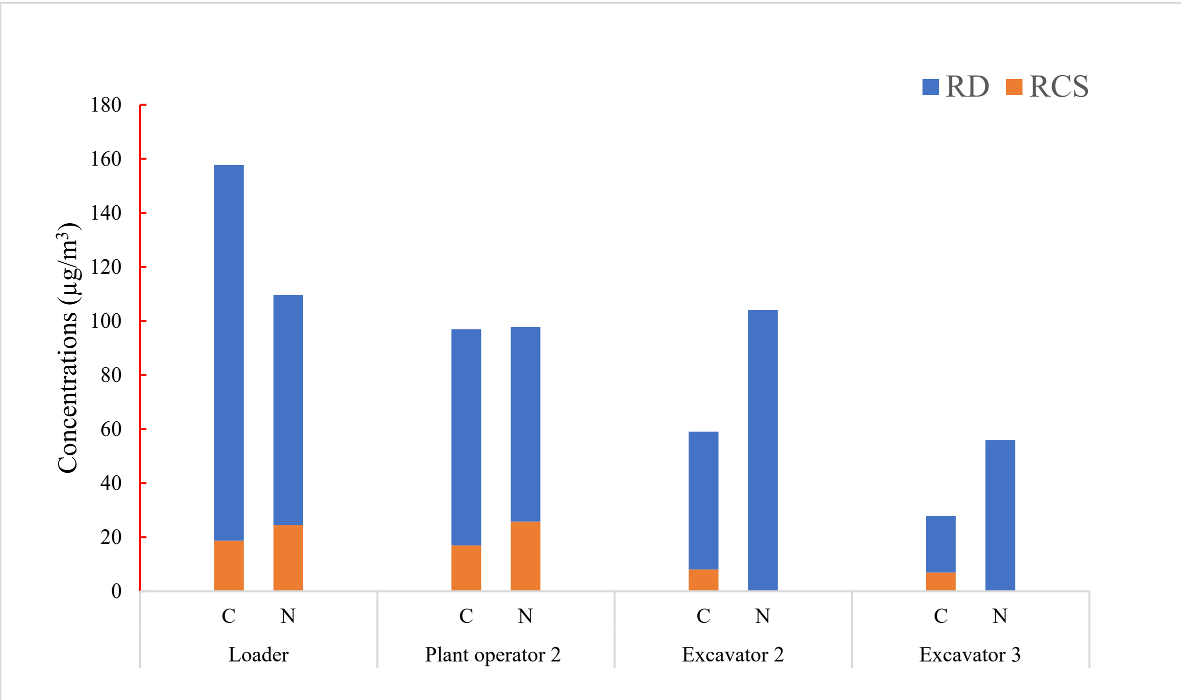


Figure 1. Comparison of gravimetric measurements (RD) and RCS Levels Measured by conventional gravimetric sampler (Casella) (C) and Nanozen (N) Sampler Across Different Work Roles.

3.1.4. Correction Coefficients and Estimation of RCS Levels

Figure 2 presents the geometric mean of full-shift concentrations from each real-time monitor plotted against gravimetrically determined concentrations, along with the corresponding R^2 values, slopes, and y-intercepts of the regression equations. Given that real-time instrument data was highly skewed, with a few peaks and many low concentration readings, using geometric mean values resulted in a better linearity (higher R^2) than using arithmetic mean values. The slope of each regression line serves as a correction coefficient, providing a multiplier to adjust real-time instrument readings for more accurate gravimetric concentration estimates.

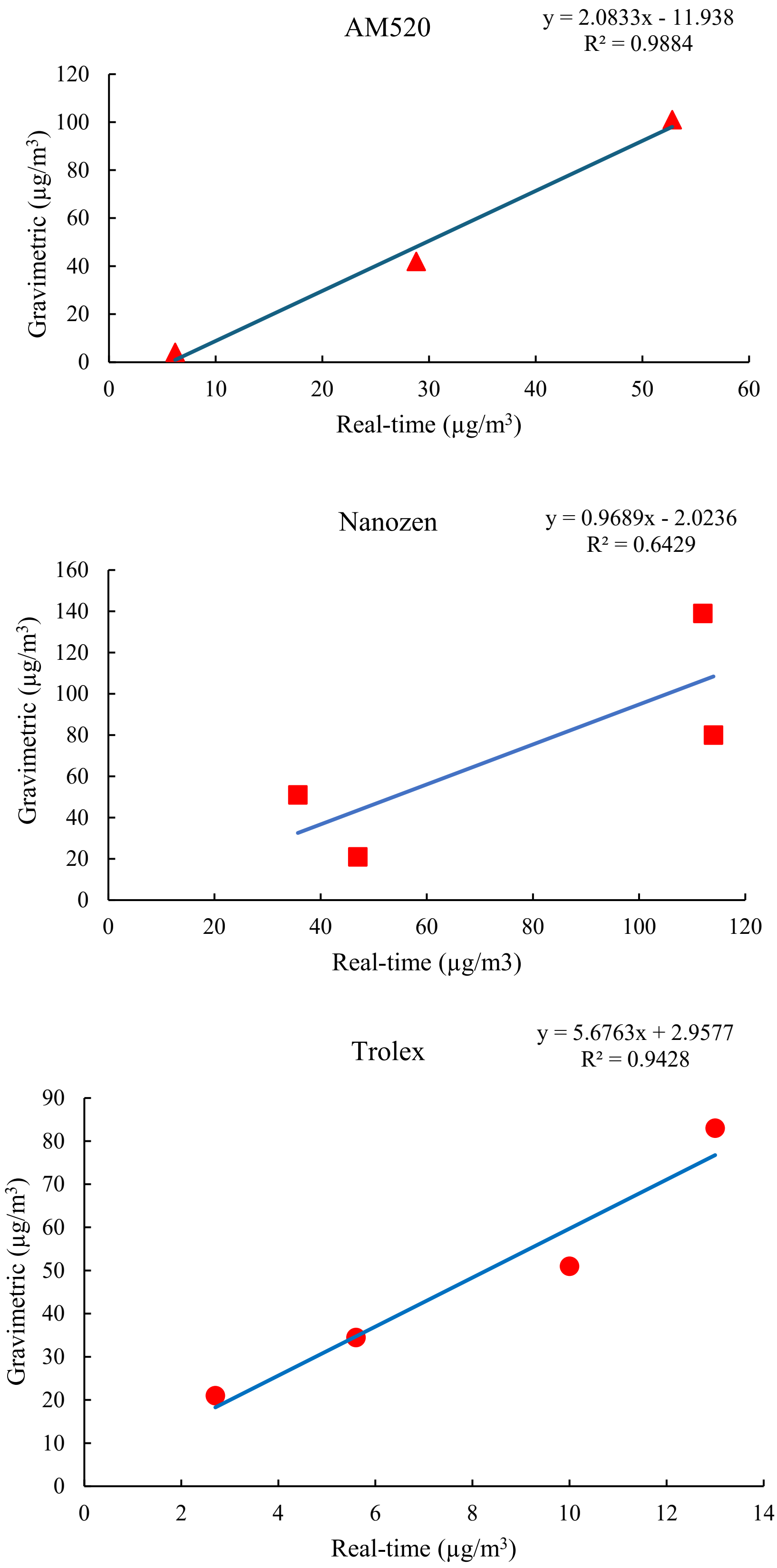


Figure 2. Regression Plots of Geometric Mean Real-Time vs. Gravimetric Measurements.

The correction factors for the AM520, Nanozen, and Trolex were found to be 2, 0.97, and 5.7 respectively. These were used to estimate likely RCS exposure levels for each worker, as discussed below.

We estimated the likely RCS exposure for each worker by applying correction coefficients to the recorded RD levels and incorporating the rock material's 20% RCS content (as specified in its safety data sheet) (Table 6). The estimated RCS exposure levels were then compared to the measured RCS exposure levels for each worker using concordance analysis. Figure 3 presents the concordance correlation analysis between the measured and estimated RCS levels. The solid blue line represents the concordance line, which depicts a theoretical 1:1 perfect agreement. The red dotted line represents the best-fit regression line. The CCC is a measure of two components: (1) accuracy—the degree to which the red dotted regression line deviates from the concordance line, and (2) precision—the extent to which each data point (red circles) aligns with the fitted regression line [21]. The CCC was calculated as 0.89 (95% CI: 0.66–0.97), indicating a strong level of agreement between measured and estimated silica exposure levels.

Table 6. Comparison between estimated RCS exposure levels with measured levels.

Worker Role/Task	RTM	Corrected RD (μg/m^3)	Estimated RCS (μg/m^3) *	Measured RCS XRD (μg/m^3)
Plant operator 1	AM520	110	22	21.2
Truck Driver	AM520	12.9	2.6	0
Excavator 1	AM520	60	12	7
Loader	Nanozen	108.5	21.7	18.7
Excavator 2	Nanozen	34.6	6.9	8.1
Plant Operator 2	Nanozen	110	22.1	16.9
Excavator 3	Nanozen	45.5	9.1	6.9
Diesel Mechanic	Trolex	31.8	6.3	6.2
Excavator 2	Trolex	56.8	11.2	8.1
Quarry Manager	Trolex	73.8	14.8	18
Excavator 3	Trolex	15.3	3.1	6.9

* 20% of the corrected RD concentration, as specified in the material safety data sheet from the quarry site.

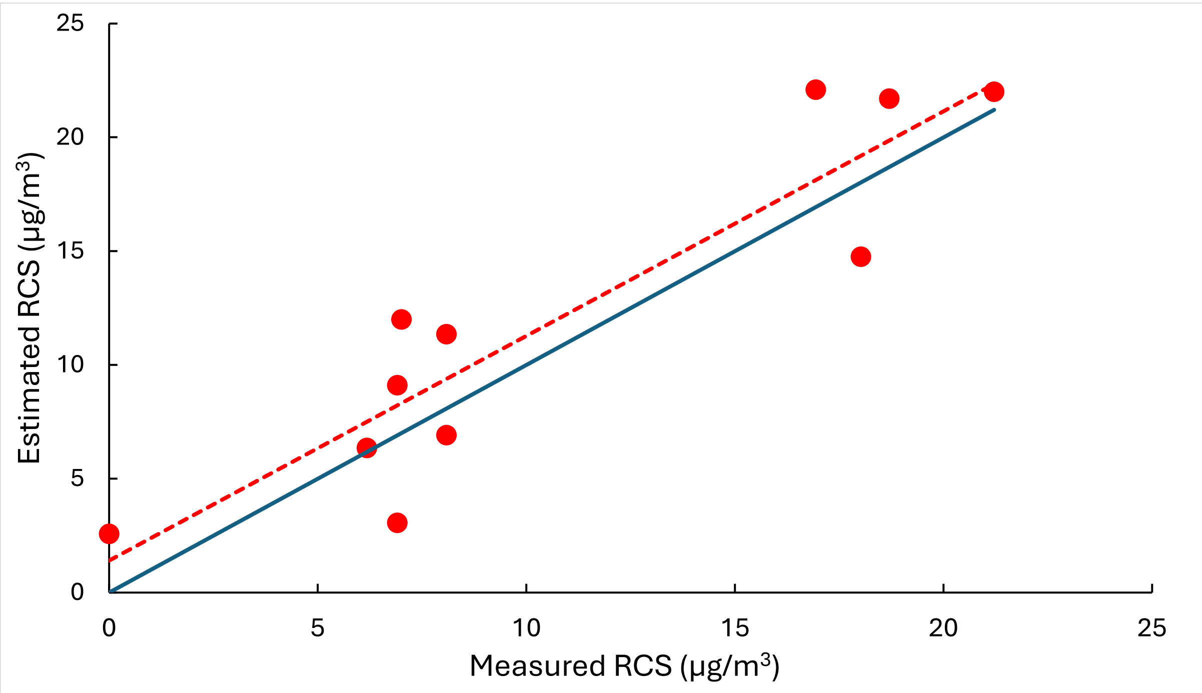


Figure 3. The Degree of Agreement Between Measured and Estimated RCS Exposure Levels for Quarry Workers.

3.2. Controlled Dust Chamber Test Results

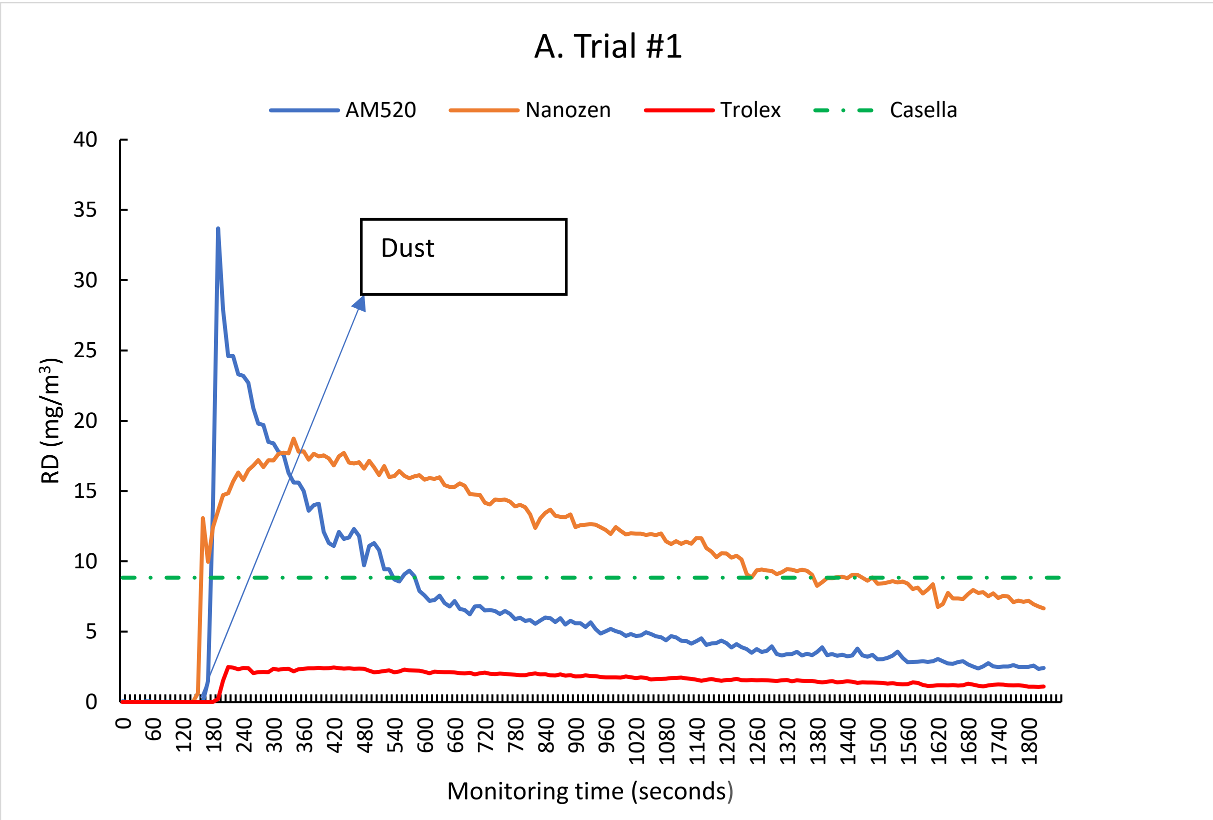
Table 7 shows the comparison of gravimetric concentrations (TWA, mg/m³) and real-time readings (GM, mg/m³) for two quarry materials across six controlled trials. The pairwise comparison shows that, on average, under very high dust conditions, all real-time monitors tend to underestimate the gravimetric dust concentrations recorded by the conventional sampler (Casella), with AM520 underestimating by approximately 56%, Nanozen by 21%, and Trolex by 86%. The Nanozen gravimetric result also underestimated the concentration by 42% when compared to the conventional (Casella) measurements.

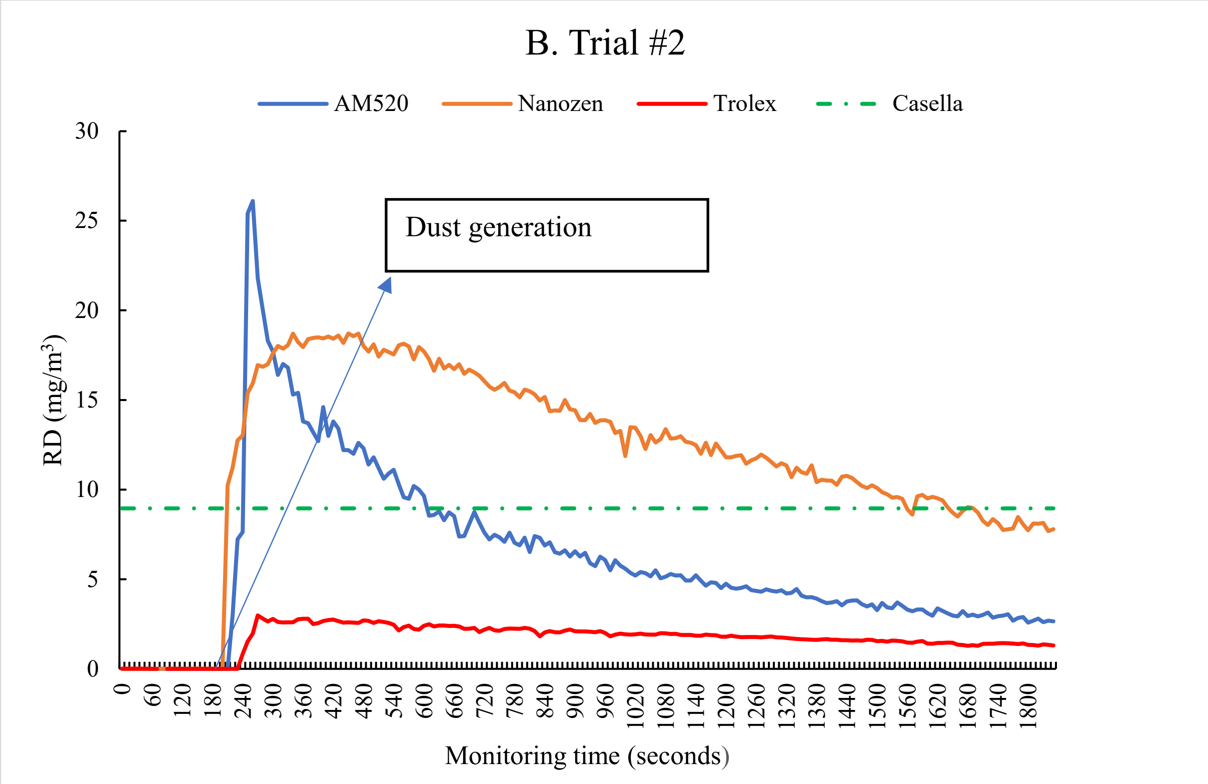
Across six trials, the three real-time monitors were tested simultaneously in the dust chamber, recording time-series data over a 30-min period. This data, aligned across instruments and presented in Figure 4A–D, shows a consistent response pattern across repeated trials. All monitors simultaneously detected an immediate rise in dust levels following quarry material cutting. Following the peak levels, the AM520 readings showed the fastest decline, while the Nanozen was the slowest to return to baseline, eventually approaching gravimetric dust concentrations toward the end of the 30 min trial period. In contrast, the Trolex consistently underestimated dust levels, with most of its peak readings reaching only about 30% or less of the concentrations recorded by conventional gravimetric sampler.

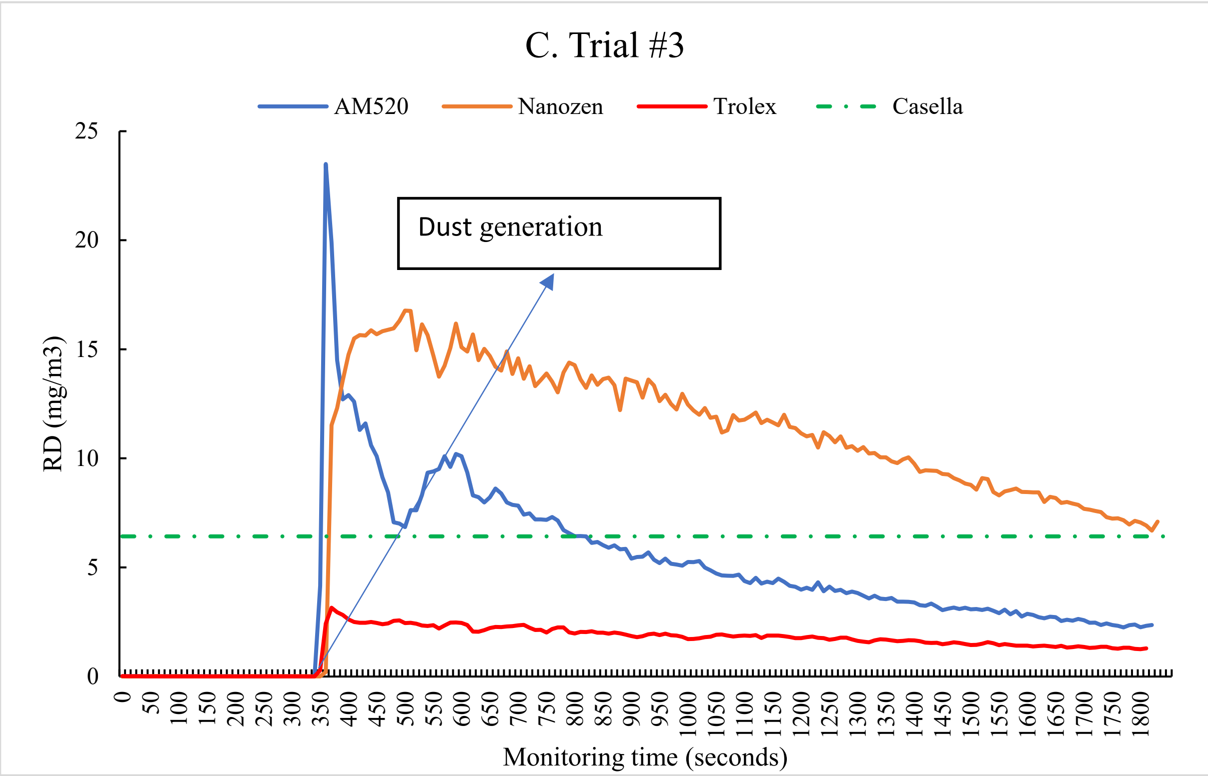
Table 7. Comparison between gravimetric results and the three real-time monitors in laboratory trials.

Trial #	Quarry Material	Gravimetric Concentration (TWA, mg/m³)		Real-Time Readings (GM, mg/m³)		
		Conventional Sampler (Casella)	Nanozen	Am520	Nanozen*	Trolex
1	Limestone	8.8	6.0	4.0	5.9	1.2
2	Limestone	9.0	5.1	3.2	4.9	1.0
3	Dolomite	6.4	2.6	1.9	3.6	0.7
4	Dolomite	7.4	4.3	3.2	9.2	1.2
5	Dolomite	8.3	5.3	5.0	--	1.6
6	Limestone	11.9	7.1	5.9	11.1	1.4

* Nanozen stopped recording real-time data during trial #5.




B. Trial #2
AM520
Nanozen
Trolex
Casella
Dust generation
RD (mg/m3)
Monitoring time (seconds)


C. Trial #3
AM520
Nanozen
Trolex
Casella
Dust generation
RD (mg/m3)
Monitoring time (seconds)

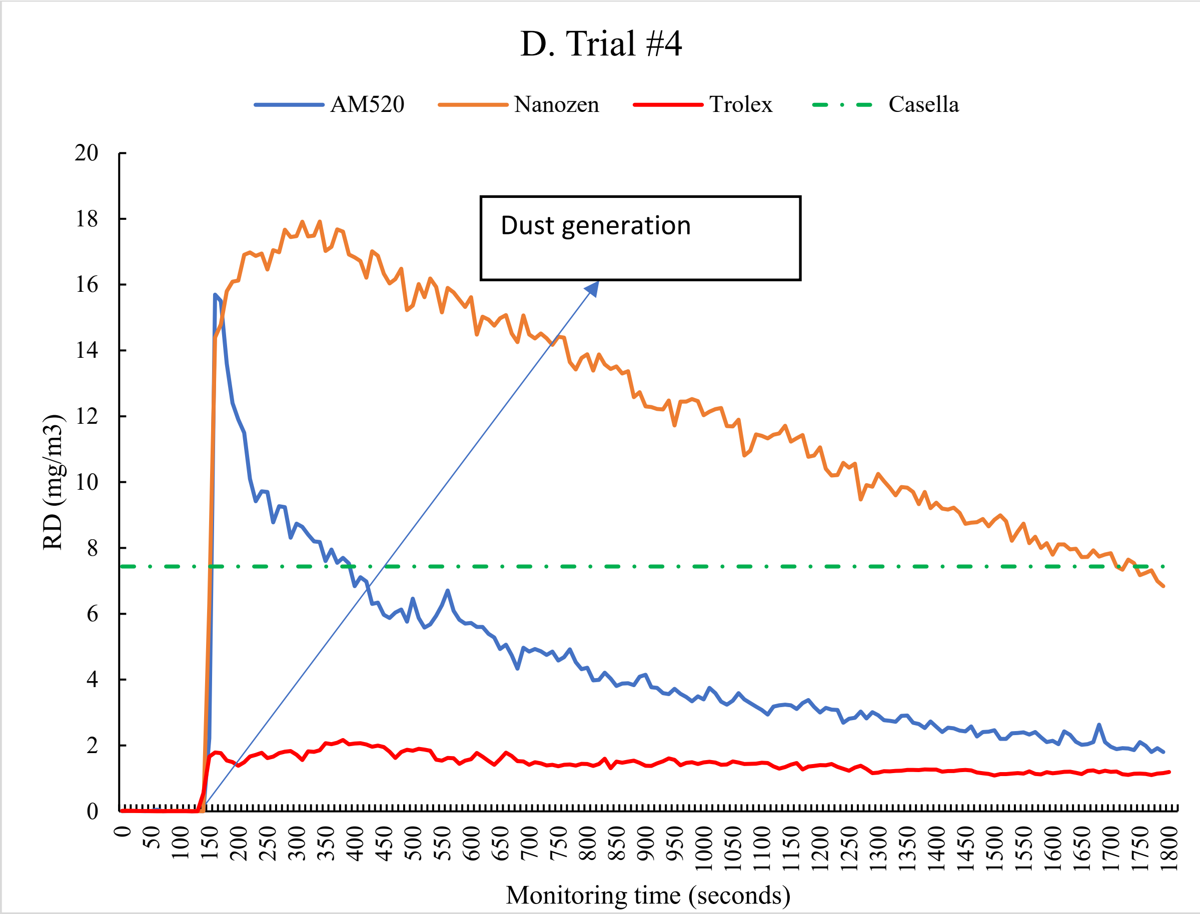


Figure 4. Generated Dust Concentration Readings from Three Real-Time Monitors Across Six Lab-based Trials.

4. Discussion

In this pilot study, we assessed the performance of three real-time dust monitoring instruments, the AM520, Nanozen, and Trolex, by comparing them against a reference method, i.e., a conventional gravimetric RD sampler. The evaluation was conducted in both field conditions involving quarry workers, and in a controlled laboratory environment using a custom-built dust chamber. This study adds to the increasing body of knowledge on real-time dust monitor performance [18–20,22], with a particular emphasis on their effectiveness in real-world settings. The findings and discussion presented in this study offer valuable insights toward informing the selection, deployment, operation, and interpretation of data from these instruments.

4.1. Key Findings

The field monitoring results indicate that both the AM520 and Nanozen monitors underestimated and/or overestimated exposure, depending on the worker role/tasks. This variability suggests the potential influence of task-related or environmental factors that were not controlled for in this study. In contrast, the Trolex monitor consistently underestimated gravimetric concentrations by 80% to 87% across different work contexts. Controlled laboratory tests further supported these findings, showing a similar range of underestimation (80%–89%) for theTrolex. This underestimation was expected due to the instrument's passive sampling function, especially in the controlled laboratory chamber with limited air movement. However, the similar degree of underestimation under field conditions with natural air movement was unexpected.

Comparison of gravimetric measurements (RD) and corresponding RCS concentrations between Nanozen and the conventional gravimetric sampler (Casella) showed that discrepancies in RD measurements did not follow similar trends in RCS. Nanozen reported higher RCS for the Loader despite lower RD, while no RCS was detected for the Excavators despite higher dust concentrations. This indicates that higher RD levels measured by Nanozen did not necessarily correspond to higher detected RCSlevels by XRD analysis. However, these inconsistencies observed under field conditions were not present in controlled laboratory tests, where Nanozen consistently underestimated both RD and RCS compared to conventional gravimetric sampler (Casella). The discrepancies in field measurements may be influenced by factors such as work tasks, tools used, or environmental conditions (e.g., weather), none of which were monitored in this study. Additionally, uncertainty in XRD silica detection at very low silica levels in field conditions could have contributed to these inconsistencies, unlike the controlled laboratory tests conducted under high atmospheric dust concentrations.

Existing studies have primarily evaluated the performance of real-time dust monitors against reference methods, but these assessments were typically conducted in controlled laboratory aerosol chambers [18,24] or dust tunnels [23], often using standardised reference dust such as Arizona road dust. The key contribution of this pilot study was therefore to evaluate the performance and accuracy of real-time dust monitors in real-world quarry environments involving workers and real-world materials. Even the controlled laboratory tests in this study used rock materials sourced from quarry sites, enhancing their practical relevance, as the dust type and consequently its optical properties can influence the performance of light-scattering instruments [18]. Additionally, this study provides new data on the performance of Trolex and Nanozen, for which no previous published studies were found. While one study examined the Nanozen in a controlled laboratory setting [27], this study represented the first to independently assess its in-field performance. Among the three instruments, the AM520 has been the most extensively studied in workplace conditions [18–20]. Similar to our findings, Patts, Tuchman [18] reported that the AM520 alternately underestimated and overestimated dust concentrations when compared to a reference gravimetric sampler, depending on the work contexts.

Overall, these findings suggested that field-based correction coefficients are required to accurately estimate RD. Noting the pilot nature of the study, we provided case study examples of how pairwise comparison data may be used to determine correction coefficients and in turn estimate the likely RCS exposure levels for workers.Correction coefficients are typically derived by averaging the pairwise ratios of real-time readings to reference gravimetric results or by using the slope of a regression line [18]. Correction coefficients were derived using regression analysis of real-time dust monitor readings against conventional gravimetric results. The geometric mean was preferred over the arithmetic mean for better linearity due to the skewed nature of the data, highlighting the importance of data distribution in determining correction factors. The estimated correction coefficients suggest that AM520, Nanozen, and Trolex readings might apply a multiplier to approximate RD concentrations. However, these values are for demonstration purposes only and should be interpreted with caution given the limited number of samples used in calculating these values.

When working with silica-producing materials such as in quarries, engineered stone, or other construction materials, there is increasing interest in understanding what real-time dust monitors can reveal about workers' exposure to silica dust. Since real-time monitors cannot directly measure RCS exposure, RCS levels were estimated by applying correction coefficients to real-time RD readings and factoring in the material's silica content, specified as 20% in the safety data sheet. This study applied Lin's Concordance analysis [21] in a novel way to statistically assess the agreement between estimated and measured RCS levels. The estimated RCS levels showed a strong correlation with the measured RCS levels, achieving a CCC of 0.89, indicating a high degree of agreement.

This approach could potentially be used in the field but has limitations due to the fixed 20% silica content assumption. In practice, this assumption may not be entirely accurate due to (1) potential variability in silica levels within bulk materials, especially in a dynamic quarry context and (2) the likelihood that not all the silica in the bulk material becomes airborne when processed. In this study, actual RCS proportions were consistently below 20% (see Figure 1), indicating that the SDS-based figure may serve as a conservative estimate when site-specific data are unavailable. For more accurate field estimation using real-time monitors, a better alternative, where available, is to utilize historical paired data of gravimetric RD and RCS measurements specific to the site. By analysing multiple RD-to-RCS ratios, a site-specific average can be derived to improve estimation accuracy. For a more protective approach, the 95th percentile of the RD-to-RCS ratio could be used instead of the mean. In addition, incorporating an analysis of existing Casella sampling data to examine how the RCS/RD ratio varies by job title could further strengthen this approach. This would support the development of job-specific correction factors that, when applied to real-time monitor readings, could more accurately alert workers to potential overexposures to RCS.

4.2. Strengths and Limitations of the Study

The study strength lies in its dual evaluation of real-time dust monitors, incorporating both controlled laboratory tests and real-world quarry conditions to ensure a thorough assessment. Field monitoring involving workers provided valuable insights into the practical application of these devices in occupational settings. However, as a pilot study, the small sample size (four days of field monitoring and 12 workers) limited the robustness of statistical analyses and the generalizability of findings. Data completeness was occasionally affected by instrument failures, and the absence of weather data is a notable limitation, as environmental conditions are likely to influence airborne dust levels. The small sample size and potential site-specific variations in environmental conditions may affect the accuracy of the instruments coefficients [18]. While weather data was collected on two of the four field monitoring days, the dataset was insufficient to establish a meaningful relationship between weather conditions and instrument accuracy and thus not included in the discussion. Additionally, the lack of detailed task information due to restricted site access meant researchers relied on workers' verbal accounts, limiting the ability to discuss task exposure relationships. Equipment configuration (i.e., any open windows in an excavator cabin) may be a determinant of exposure and this information was not captured by researchers due to restricted access for observation. Similarly, the placement of two instruments on opposite shoulders could also impact results, being a source of potential data variability, even though they remained within the breathing zone. Despite these limitations, the study and the data presented here contribute to the growing body of literature on accuracy of real-time dust monitors particularly their performance under actual field conditions which has only rarely been tested.

5. Conclusions

The performance of three real-time dust monitors, AM520, Nanozen, and Trolex, was evaluated under both field (quarry) and laboratory conditions, with the conventional gravimetric RD sampler serving as the reference method. Significant discrepancies were observed between real-time and gravimetric measurements. The AM520 and Nanozen monitors showed varying degrees of overestimation and underestimation dependent on the work/task, while the Trolex consistently underestimated RD concentrations by more than 80%. The high data variability between and within instruments highlights the need for additional data to establish reliable correction coefficients, which could refine the accuracy of real-time monitors in estimating RD and RCS exposure levels. While real-time dust monitors exhibit inaccuracies and inconsistencies compared with conventional methods, they hold significant potential for informing exposure control by providing immediate, task-based insights and identifying peak exposure levels, to enable rapid intervention much like the canaries in coal mines once served as early indicators of hazardous conditions. The outcomes of this study will assist workplaces, Work Health and Safety (WHS) managers, occupational hygienists, and regulators to better understand the capabilities and limitations of real-time dust monitoring technologies, which in turn will empower them to make informed decisions about their optimal utilisation for hazard management purposes within a quarry context.

Author Contributions

Y.T.: conceptualization, methodology, data curation and analysis, project administration, visualization, writing—original draft preparation, writing—reviewing and editing; C.R.: conceptualization, methodology, writing—reviewing and editing; R.J.: data curation, visualization, project administration, writing—reviewing and editing; S.R.: writing—reviewing and editing; H.A: writing—reviewing and editing; S.G.: conceptualization, methodology, project administration, writing—reviewing and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Low-Risk Human Research Ethics Committee (Faculty of Health and Medical Sciences, The University of Adelaide). Ethics Approval No. H-2023-302.

Informed Consent Statement

Informed consent was obtained from all study participants.

Data Availability Statement

The raw data supporting the findings of this study remains inaccessible to protect the privacy of participants.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Nemer, M.; Giacaman, R.; Husseini, A. Lung function and respiratory health of populations living close to quarry sites in Palestine: A cross-sectional study. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6068. https://doi.org/10.3390/ijerph17176068.
2. Nwibo, A.N.; Ugwuja, E.I.; Nwambeke, N.O.; et al. Pulmonary problems among quarry workers of stone crushing industrial site at Umuoghara, Ebonyi State, Nigeria. *Indian J. Occup. Environ.* **2012**, *3*, 178–185.
3. Bahrami, A.R.; Mahjub, H. Comparative study of lung function in Iranian factory workers exposed to silica dust. *East. Mediterr. Health J.* **2003**, *9*, 390–398. https://doi.org/10.26719/2003.9.3.390.
4. Leong, T.L.; Wimaleswaran, H.; Williams, D.S.; et al. Unexpected case of accelerated silicosis in a female quarry worker. *Occup. Med.* **2022**, *72*, 420–423. https://doi.org/10.1093/occmed/kqac016.
5. Safe Work Australia. *Working with Silica and Silica Containing Products*; Safe Work Australia (SWA): Canberra, Australia, 2022.
6. *AS 2985-2009*; Workplace Atmospheres—Method for Sampling and Gravimetric Determination of Respirable Dust. Standards Australia: Sydney, NSW, Australia, 2009.
7. Ichikawa, A.; Volpato, J.; O'Donnell, G.; et al. Comparison of the analysis of respirable crystalline silica in workplace air by direct-on-filter methods using X-ray Diffraction and Fourier Transform Infrared Spectroscopy. *Ann. Work Expo. Health* **2022**, *66*, 632–643.
8. Rae, H. A case study of pairwise sampling using a high flow rate respirable cyclone to overcome potential LOD issues. In Proceedings of the 39th AIOH Annual Scientific Conference & Exhibition, Brisbane, QLD, Australia, 3–7 December 2022; p. 11.
9. Cauda, E.; Dolan, E.; Cecala, A.B.; et al. Benefits and limitations of field-based monitoring approaches for respirable dust and crystalline silica applied in a sandstone quarry. *J. Occup. Environ. Hyg.* **2022**, *19*, 730–741. https://doi.org/10.1080/15459624.2022.2132257.
10. Trolex. AIR XS Silica Monitor. Available online: https://trolex.com/product/air-xs/ (accessed on 3 February 2024.
11. Zhou, V. Real-Time Dust Monitoring Arrives in Australia. Available online: https://www.australianmining.com.au/real-time-dust-monitoring-arrives-in-australia/ (accessed on 3 February 2024).
12. Air-Met Scientific Pty Ltd. Introducing the Nanozen DustCount 9000 Real-Time Personal Dust Monitor. Available online: https://www.airmet.com.au/events/news/introducing-the-nanozen-dustcount-9000-real-time-personal-dust-monitor (accessed on 3 January 2024).
13. GCG. Exposi Intelligent Exposure Control. Available online: https://www.gcg.net.au/technology/exposi-real-time-exposure-monitoring/ (accessed on 5 September 2024).
14. Chu, B. *Laser Light Scattering: Basic Principles and Practice*, 2nd ed.; Academic Press Inc.: Cambridge, MA, USA, 1991.
15. Mishchenko, M.I.; Hovenier, J.W.; Travis, L.D. Light scattering by nonspherical particles: Theory, measurements, and applications. *Meas. Sci. Technol.* **2000**, *11*, 1827. https://doi.org/10.1088/0957-0233/11/12/705.
16. Williams, K.L.; Timko, R.J. *Performance Evaluation of a Real-Time Aerosol Monitor*; U.S. Dept. of the Interior, Bureau of Mines: Avondale, MD, USA, 1984.
17. Page, S.J.; Jankowski, R.A. Correlations between measurements with RAM-land gravimetric samplers on longwall shearer faces. *Am. Ind. Hyg. Assoc. J.* **1984**, *45*, 610–616. https://doi.org/10.1080/15298668491400340.
18. Patts, J.R.; Tuchman, D.P.; Rubinstein, E.N.; et al. Performance comparison of real-time light scattering dust monitors across dust types and humidity levels. *Min. Metall. Explor.* **2019**, *36*, 741–749. https://doi.org/10.1007/s42461-019-0080-8.
19. Ben Walsh, S.V.; Cattani, M.. Real time versus conventional sampler comparison study. In Proceedings of the AIOH Annual Conference 2023, Southbank, VIC, Australia, 4–6 December 2023.
20. Dix, C. Real-time dust monitoring to prioritise and assess control effectiveness in processing plants. In Proceedings of the AIOH Annual Conference 2018, Melbourne, VIC, Australia, 1–5 December 2018.
21. Hawley Blackley, B.; Gibbs, J.L.; Cummings, K.J.; et al. A field evaluation of a single sampler for respirable and inhalable indium and dust measurements at an indium-tin oxide manufacturing facility. *J. Occup. Environ. Hyg.* **2019**, *16*, 66–77. https://doi.org/10.1080/15459624.2018.1536826.

22. Mehadi, A.; Moosmüller, H.; Campbell, D.E.; et al. Laboratory and field evaluation of real-time and near real-time PM2.5 smoke monitors. *J. Air Waste Manag. Assoc.* **2020**, *70*, 158–179. https://doi.org/10.1080/10962247.2019.1654036.
23. Thorpe, A. Assessment of personal direct-reading dust monitors for the measurement of airborne inhalable dust. *Ann. Occup. Hyg.* **2007**, *51*, 97–112. https://doi.org/10.1093/annhyg/mel032.
24. Thorpe, A.; Walsh, P.T. Comparison of portable, real-time dust monitors sampling actively, with size-selective adaptors, and passively. *Ann. Occup. Hyg.* **2007**, *51*, 679–691. https://doi.org/10.1093/annhyg/mem047.
25. Ramkissoon, C.; Gaskin, S.; Thredgold, L.; et al. Characterisation of dust emissions from machined engineered stones to understand the hazard for accelerated silicosis. *Sci. Rep.* **2022**, *12*, 4351. https://doi.org/10.1038/s41598-022-08378-8.
26. *EN 13205-4:2014*; Workplace Exposure—Assessment of Sampler Performance for Measurement of Airborne Particle Concentrations—Part 4: Laboratory Performance Test Based on Comparison of Concentrations. European Standard: Plzen, Czech Republic, 2014.
27. Rasmussen, P.E.; Levesque, C.; Niu, J.; et al. Characterization of Airborne Particles Emitted During Application of Cosmetic Talc Products. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3830. https://doi.org/10.3390/ijerph16203830.