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Real-Time Dust Monitoring in Occupational Environments: A Case Study on Using Low-Cost Dust Monitors for Enhanced Data Collection and Analysis

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Abstract
A worker's personal exposure to respirable dust in occupational environments has traditionally been monitored using established methodologies which entail the collection of an 8-h representative sample that is sent away for laboratory analysis. While these methods are very accurate, they only provide information on the average exposure during a specific time period, generally a worker's shift. The availability of relatively inexpensive aerosol sensors can allow researchers and practitioners to generate real-time data with unprecedented spatial and temporal granularity. Low-cost dust monitors (LCDM) were developed and marketed for air pollution monitoring and are mostly being used to help communities understand their local and even hyper-local air quality. Most of these integrated sensing packages cost less than $300 per unit, in contrast to wearable or area dust monitors specifically built for mining applications which have been around for decades but still average around $5000 each. At the National Institute for Occupational Safety and Health (NIOSH), we are leveraging the power of high-volume data collection from networks of LCDM to establish baseline respirable hazard levels and to monitor for changes on a seasonal basis as well as following any application of control technologies. We have seen the effective use and advantages of monitoring live data before, during, and after events like shift changes, operational changes, ventilation upgrades, adverse weather events, and machine maintenance. However, many factors have prevented a systematic adoption of LCDMs for exposure monitoring: concern for their analytical performance, the complexity of use, and lack of understanding of their value are some factors. This contribution outlines a 1-year case study at a mine in Wisconsin, USA, covering the installation, maintenance, data visualizations, and collaboration between NIOSH researchers and the industrial hygiene professionals at the mine.

Keywords Respirable dust · Low-cost dust monitors (LCDMs) · Aerosol sensors · Industrial hygiene · Crystalline silica · Real-time monitoring

1 Introduction

Exposure to respirable crystalline silica (RCS) poses a silent but potent threat to the health and well-being of workers across a wide range of industries. Silica, in its fine particulate form, can become airborne during various industrial processes, construction activities, and mining operations. The hazards of crystalline silica exposure are not to be underestimated, as they can lead to severe and often irreversible health consequences, including the development of debilitating lung diseases such as silicosis and an increased risk of lung cancer [1]. Silicosis is a fibrotic lung disease characterized by the chronic impairment of normal lung function due to the phagocytosis of crystalline silica within the lung, resulting in lysosomal damage [2]. Dust containing crystalline silica is invariably created through the mining process; blasting, drilling, crushing, screening, transferring, and processing into the final product all release dust into the air, which will have varying amounts of crystalline silica depending on the region and commodity being mined [3].

The National Institute for Occupational Safety and Health (NIOSH) has a recommended exposure limit for RCS of 50 μg/m^3 as a time-weighted average (TWA)

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concentration for an 8-h working shift. Additionally, the Mine Safety and Health Administration (MSHA) has an RCS permissible exposure limit that equates to 100 μg/ m^3, with a new proposed rule that would lower the exposure limit to 50 μg/m^3 as TWA as well. In the mining environment, the concentration of airborne RCS can be determined using time-integrated samples, collected with portable, wearable sampling instruments, and laboratory analysis or end-of-shift analysis with portable infrared spectrometers [4–7]. Both technologies, unfortunately, do not produce data in real time. In this context, it becomes imperative to delve deeper into the risks associated with silica exposure in respirable dust and the technologies available to monitor respirable dust in the working areas of those who labor in environments where exposure to silica is a prevalent threat.

Monitoring the workers' personal exposure to respirable dust or the respirable dust concentration level present in an occupational environment, such as a mine, is a fundamental step to understanding and characterizing the hazard and risk for overexposure conditions, to assess the compliance with company-based or regulatory exposure limits, and to select and verify a proper dust mitigation strategy. Traditional and established monitoring methodologies involve collecting time-weighted average representative samples, which are then sent for costly and lengthy laboratory analysis. The monitoring apparatus includes an aerosol sampler which must comply with the required respirable convention, generally the ISO/CEN/ACGIH [8], a medium for collecting the aerosol sample which is generally a filter, and a calibrated sampling pump set up at a proper volumetric flow rate which assures the proper functioning of the aerosol sampler and correct determination of the volume sampled. At the laboratory, the samples can be analyzed by a variety of analytical techniques; if the respirable dust mass concentration is the metric of interest, then a gravimetric analysis can be employed [8]. Thanks to the standardization of the monitoring apparatus and the analytical methods, filter-based monitoring methodologies for respirable dust provide operators with accurate data on average exposure or hazard concentration levels during a specific period of time.

Industrial hygienists or health and safety professionals at the mine site periodically collect data on respirable dust concentration and workers' exposure throughout the operation. The frequency and sampling strategies are different from company to company and are based on several factors such as the results of previous samples and the current priorities of the company. It is uncommon for an industrial hygienist to collect more than a handful of samples in a year from the same location in a mine or from the same similar exposure groups. These results ultimately provide a limited number of data points to the industrial hygienist professional who conducts all the activities such as understanding and characterizing the hazard and risk for overexposure conditions, assessing the compliance with company-based or regulatory exposure limits, and selecting and verifying the proper mitigation strategy. These methodologies cannot capture real-time variability in dust levels, such as fluctuations during work shifts or in response to operational changes.

Other monitoring technologies based on aerosol sensors have been available for health and safety practitioners in the mining industry for several years. These technologies, such as area monitors or personal monitors, can provide time-series data throughout the sampling event, and they can assist industrial hygienists in a variety of activities. Many publications report their potential added value [9–12]. These technologies require substantial work from the professional in terms of set-up, data download, data manipulation, and interpretation. Recent technological advancements have introduced an additional option—relatively inexpensive aerosol sensors, referred to here as low-cost dust monitors (LCDMs). These sensors might enable researchers and industrial hygienist practitioners to generate time-series area hazard monitoring data with unprecedented spatial and temporal granularity and the opportunity for targeted and timely intervention, opening new possibilities in hazard monitoring [13, 14]. This article documents how NIOSH has been able to harness the potential of LCDMs in establishing baseline respirable hazard levels and monitoring changes following remediation interventions on both seasonal and real-time bases. To obtain an extended evaluation of sensor utility, NIOSH researchers have conducted a 12-month study at a sand mine in Wisconsin, USA, and present the findings here as a general framework when using LCDMs in occupational environments.

The advent of LCDMs has brought about significant advantages for occupational hazard monitoring, and these types of sensors offer compelling benefits that make them an appealing way to augment traditional methods, including the following: 1. Cost-effectiveness and accessibility, 2. Real-time data generation, 3. Increased spatial and temporal granularity, and 4. Continuous monitoring. Despite these significant advantages, the adoption of LCDMs for hazard monitoring faces some challenges, including the following: 1. Analytical performance concerns, 2. The complexity of use, and 3. Lack of understanding about the value of the data. Concerns regarding analytical performance and the perceived complexity of usage have, at times, distracted the professionals from exploring the possible value. This case study showcases the installation, maintenance, and data visualization techniques employed, along with the fruitful collaboration between NIOSH researchers and the mine's management, employees, and industrial hygienist professionals. By delving into the case study findings, this article aims to shed light on the benefits of real-time respirable dust monitoring using LCDMs. Additionally, it emphasizes the significance of such advancements in enhancing workplace safety, informed decision-making, and paving the way for future advancements in hazard monitoring technologies.

LCDMs offer significant potential advantages for real-time data generation, and their implementation in occupational settings can enhance hazard monitoring capabilities and strengthen the pre-existing workplace safety protocols. Additionally, we will underscore the value proposition of LCDMs to stakeholders, making a case for their widespread adoption. Through presenting this case study, we aim to establish LCDMs as a practical tool in the tool belt of industrial hygienist professionals for enhancing workplace safety, informed decision-making, and advancing hazard monitoring technologies in the realm of occupational health and safety.

2 Methods

For this study, NIOSH researchers established a collaboration with an industrial mineral sand mine in Wisconsin. The company actively mines and crushes ore into screened final size-selected sand products. The processing of the ore involves a multi-story screen house where all the size-selective screening occurs and two dry houses that remove the excess moisture from the products. These three buildings were identified by the industrial hygienist on site as having the highest likelihood for high respirable dust concentration, and the company was interested in monitoring and identifying sources of high concentrations of dust so that remediation strategies could be implemented.

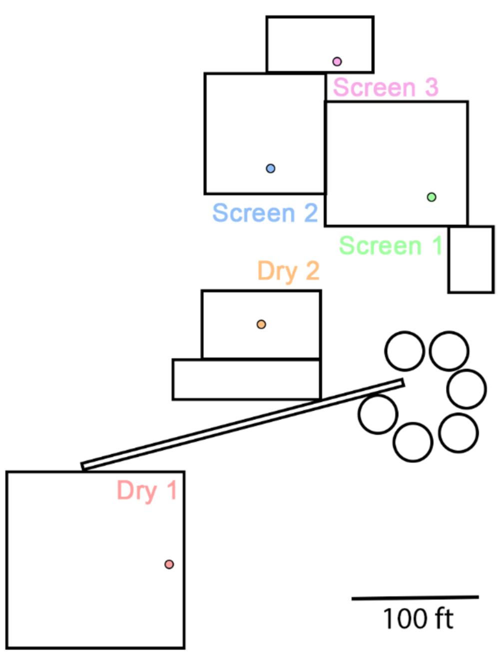

Fig. 1 Schematic layout of the locations of the sensors and the buildings

Table 1 Sensor specifications

Communication	WiFi 802.11 b/g/n 2.4 GHz
PM sensor concentration range	0–1000 µg/m
PM sensor size range	0.3–10 µm
Temperature sensor range	0–65
Humidity sensor range	0–100%
Pressure sensor range	300–1100 hPa
Measurement time	15 s
Current	< 1000 mA
Dimension	5.12″ × 3.92″ × 2.75″
Weight	11.2 oz

Following discussions with the mine, five units were distributed across two buildings (screen house and dry house) (Fig. 1). The specifications for the sensors used in this study can be seen in Table 1. Three units were placed in various locations in the screen house, and two units were placed in the dry house (Table 2). The particulate matter (PM) sensors used in this study were purchased as off-the-shelf standalone units. The sensors record PM1, PM2.5, PM10, pressure, temperature, and humidity data at a 15-s resolution. The sensors use a light-scattering methodology to monitor dust particles. Additional thought regarding the expected humidity levels and type of aerosol needs to be considered for proper calibration [16]. When installing the sensors, the location of each unit was driven by the needs of the mine and the availability of both 120 V power and Wi-Fi at each location. The sensors have a small internal battery to maintain stability through intermittent power interruptions, but they need to be plugged in and thus cannot be located too far from a power supply. Additionally, each sensor needs to have access to Wi-Fi or a hardwired ethernet connection to transmit the collected data, which also may limit sensor placement based on availability. For this application, we attached four high-strength magnets to the back of each unit to allow for easy installation while also being able to withstand the vibrations typically seen in a screen house.

Table 2 Sensor metrics

Sensor name	Location	Data points (Sept'22–Sept'23)	Spike events	Uptime
Dry 1	Dry house	1,978,164	732	99.963%
Dry 2	Dry house	1,412,776	976	99.931%
Screen 1	Screen house	1,978,204	0	100.000%
Screen 2	Screen house	1,978,196	305	99.985%
Screen 3	Screen house	1,978,204	0	100.000%

After the installation of the dust monitors, respirable dust samples were collected for two days at each sensor location using three 37-mm, 5-μm pore PVC filters (SKC Inc., Eighty Four, PA, USA) with 10-mm nylon Dorr Oliver cyclones at a flowrate of 1.7 lpm [15]. This series of triplicated gravimetric samples was used to determine a correction factor for respirable dust that could be applied to the monitors if needed. After 3 months of continuous use, we noticed "spike events" where the sensor would immediately go up to a PM10 reading above 1 million μg/m^3, persist for a short period (less than 10 min), and then immediately fall back to pre-spike levels. We documented these events, removed them from downstream analysis, and displayed the total number of spike-related timestamps for each monitor in Table 2. After removing the spike events, all monitors retained a greater than 99.9% sensor uptime, and we believe these spikes are a hardware issue on the sensor side and not related to true dust levels.

Once the sensors were all set up and transmitting data, the next task was data management and delivery of processed data to the mine. Two data management approaches were followed. The first approach relied on the online dashboard through the manufacturer, like most LCDMs. The dashboard could be manually refreshed to bring in new data every 15 s, which is a level of live feed generally not possible for other sensors. Both the mine operators (management, industrial hygienist, foreman) and the researchers had access to the live data and could monitor and download the data at any time. A second approach was explored by NIOSH to streamline the process and to explore valuable information for the mine operators. We wrote a series of scripts in R that generated weekly automated emails and PDF visuals of the dust levels that week.

The weekly reports were generated through a custom R script that calls the monitors through an application programming interface (API), downloads the data, appends it to a locally maintained master file each night, creates the visuals, and sends a weekly email directly to the mine industrial hygienist, foreman, and management as well as to the NIOSH researchers. Because the data is transmitted at such a high frequency, the script outputs three. csv files; the first averages the data by minute, the next averages by hour, and the final calculates a time-weighted average (TWA) for an 8-h shift from 8 a.m. to 4 p.m. The TWA value for each day is then multiplied by the average percent crystalline silica content seen at this mine in the last 3 years to approximate the silica concentration at that specific location. This provided an estimation of what a worker's exposure to quartz would have been if they had been standing next to that specific monitor for a whole shift.

3 Results

Correcting the data coming from any type of LCDM can be important given the known limitation of the sensors in these devices, the fact that these types of devices are not traditionally used in industrial settings, and the internal calibration may not be set for the specific environment in which it is currently being used. For this specific mine and application, we saw no need to correct the PM10 data that we were receiving from the monitors after comparing it to the gravimetric data for respirable dust that was collected while were on-site setting up the system. For that reason, we considered the PM10 data to be an acceptable representation of respirable dust concentration data. It should be mentioned that there may be a need to periodically collect gravimetric samples throughout the use of the LCDMs to ensure there is no drift in the instruments, although, for this early pilot study, we were unable to collect such data.

One of the main questions that the mining company was hoping to answer was whether the size of the screens used to size-select the product impacted the airborne dust levels. The screen house is a seven-story structure where the sand is lifted to the top via a bucket lift and moves to the bottom through a series of screens on each level. With that in mind, three of the sensors were placed in the screen house at the mine, all at ground level. This was primarily driven by a poor Wi-Fi signal as we moved up through the various floors; although had this not been a limitation, having monitors on multiple floors may have led to more informative data analysis. For the other two sensors, the mine wanted to better understand the dust levels when the product was transitioning in and out of the dry houses, so on the ground floor of each drying building, we placed one sensor. These buildings had relatively open interiors and were again located on the ground floor due to the availability of Wi-Fi. We were not given any production data from the mine and thus were unable to make any correlations between screen size and dust levels in the screen house. However, through working closely with the mining company and explaining how to read and understand the data, the on-site industrial hygienist found that there was a correlation between screening size and dust levels (data not shown).

One of the most important outcomes of the interactions with the mine is the creation of an automated script that sends weekly reports to both the mine and the researchers. We found that relying only on the live feed of the data was overly time-consuming and did not allow for a good enough way to see a representative snapshot of the overall dust levels across all monitors. Additionally, with the provided dashboard from the sensor manufacturer, there was some ability to search through the data, but you had to know what you were looking for to find it, and it was

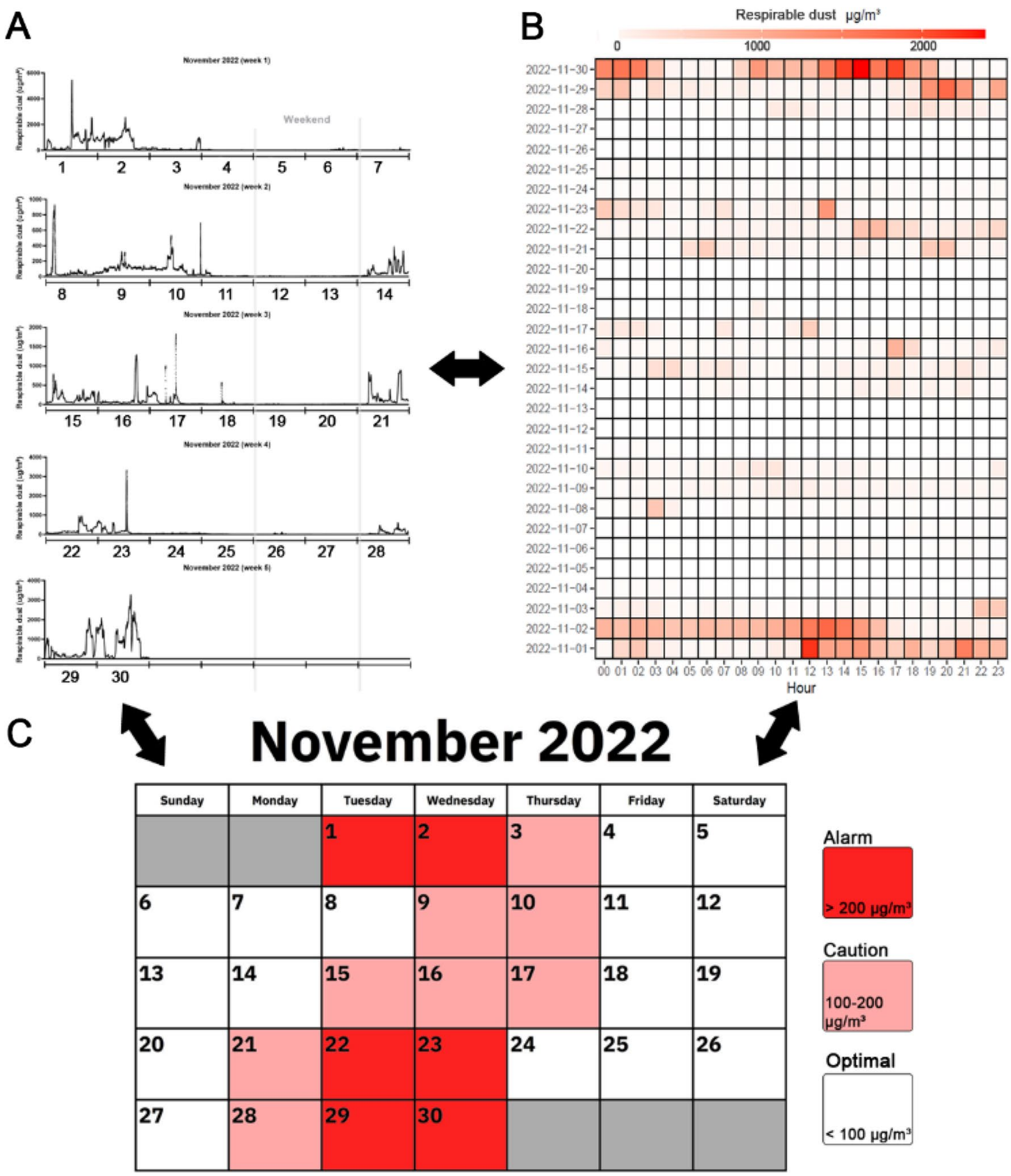

Fig. 2 Progression of data visualizations. Analysis of the data progressed from line charts (**A**) to heatmaps (**B**), and finally calendar view heatmaps (**C**)

not very useful to observe overall trends. As an example, Fig. 2 is generated using 1 month of data from the screen 1 sensor. The first step taken to clean up the data was to take the raw data from the sensor and average it by minute and display it as a line chart (Fig. 2A). This is the fundamental building block of the data, and this type of visualization is routinely accessed when looking for a specific time of an event (startup, shutdown, or shift change). While very useful, line charts alone make it hard to observe longer term trends, and so through communications with the mine we began to add heatmaps to the weekly reports (Fig. 2B). The heatmap data is averaged by hour, making the data much less dense and easier to understand. Each panel in Fig. 2 represents the same data, and it is more intuitive to understand that in panel B there is more red, indicating higher dust levels, on November 1, 2, 29, and 30 than on the other days. While possible to discern that same information from panel A, it is easier and faster to find that same information on panel B.

After using the combination of the heatmaps and the line charts for a few months, the mine felt they had a better understanding of the sensors and wanted an even more simplified weekly report. To accomplish this, we decided it best to create a "calendar view" heatmap (Fig. 2C) which ran some simple calculations and displayed the average dust level for that day as one of three options: optimal, caution, or alarm. The dust level for that day is generated using the raw data from the sensor and averaged from 8 a.m. to 4 p.m., which is indicative of that mine's normal time of operation and a standard 8-h shift. Working closely with the mine, we began to discuss the key factors and assumptions that need to be answered to simplify a whole day's data down into one number and its colored risk classification (red for alarm, pink for caution, or white for optimal), including the following: How many hours does any single worker spend in the microenvironment around the sensor? How many alarm levels are needed? Are there already established regulatory limits? What will the actions be for an "alarm" day? Once we had the necessary conversations and found, with the mine industrial hygienist, a comfortable status with the necessary assumptions, we began placing the calendar view heatmaps on the first page of the weekly report for each sensor. If there was no red on the weekly report, then they could simply move on to the next sensor and know that the first sensor was good last week. When a day gets flagged as red, then the mine would be able to work backward to the hourly heatmap to try and isolate the event to see if it was high levels for a long time or a spike event that caused the day to be red. Then, when finally using the line charts, the mine personnel could go through the data minute by minute and see how the dust data correlated with the production data or other factors to determine why that day may have failed.

When a high dust day was identified, we found that working backward from the calendar view, to the hourly heatmap, and then to the line charts was not overly cumbersome and overall, less effort than trying to constantly monitor the live feed data for the same information. The result of these interactions with the mine resulted in weekly reports for the last 7 days being automatically emailed out to everyone on Friday mornings so that the industrial hygienist at the mine had time to see the data before the end of the week and make any necessary changes. Additionally, at the end of each month, a monthly report like Fig. 2B and C would be sent out to view the month, which is good for keeping records as well as comparing to previous months' reports.

Well before we had an established system to display the data and aggregate the information in the weekly reports, we saw the first practical "data-to-action" application for using the deployed sensors. Within the first few weeks, the foreman on site had identified a pattern of high dust concentration when one of the conveyor belts that fed a specific screen would start up, and upon investigation, substantial spillage was found from the backside of the belt, and it was replaced with an auger lift system. Figure 3A depicts the

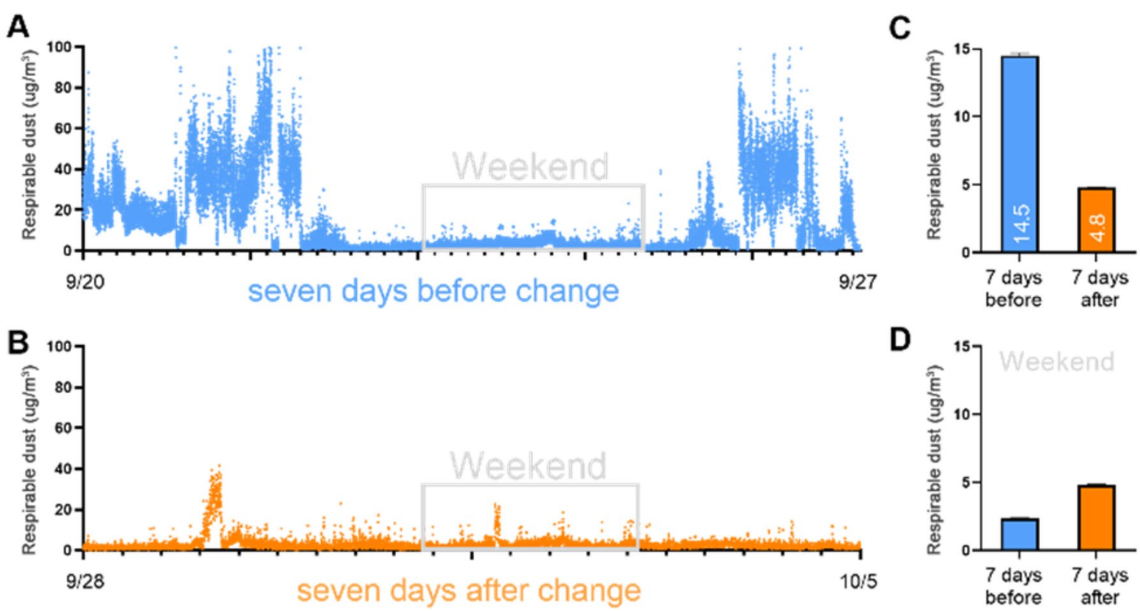

Fig. 3 Respirable dust concentrations following the change from a belt-fed to an auger-fed size-selective screen on 9/27. **A** Scatter plot representing the respirable dust levels for 7 days before the change in blue and **B** the 7 days following the change in orange. **C** Bar graph representing the average respirable dust concentration before and after the change. **D** Depicts the same data but over a weekend showing minimal difference

week leading up to the change, where evident days of production can be seen in the dust levels, as well as low levels over the weekends. Figure 3B shows the 7 days following the change where the dust levels rarely exceed weekend dust levels. With this simple change, using parts the mine personnel already had on-site, mine personnel were able to reduce the dust level around that monitor threefold (Fig. 3C). It can also be seen that the weekend dust levels were similar before and after the change (Fig. 3D), indicating that the observed change is explicitly linked to a reduction in airborne dust during production. This type of confirmation has great utility in ensuring that the engineering control is performing in the way expected, not only after initial installation but also after continued use.

One of the major benefits of an LCDM system like the one described here is access to high-resolution historical data. Using the full year of data, we were able to discern seasonal, weekly, and hourly trends in the respirable dust levels within the plant. Figure 4A depicts a *Z*-score heatmap of daily TWA respirable dust data from all sensors for 365 days. A *Z*-score is a numerical value that represents how far a given data point is from the mean of that sensor, measured in terms of standard deviations. It is a way to standardize data for comparison across different sensors. Functionally, blue days represent lower than average, and red days represent higher than average for that sensor. From this panel of the figure, it can be seen that there is a clear pattern of overall dust level increase for all sensors starting in early November 2022 compared to September and October. Additionally, weekends, not surprisingly, can be seen as prominently blue vertical stripes down the right side of each heatmap which are more apparent in the screen house than in the dry house. Dry 2 has a gray portion of the data from September to December where the original sensor installed had failed and a new one had yet to be installed resulting in a loss of around 500,000 timestamps (Table 2). Because each heatmap is normalized to its yearly average, these types of visualizations allow for a more comprehensive perspective on the day-to-day changes that go on throughout both buildings where the sensors are deployed.

Using the same TWA information, we next sought to parse the data by day of the week to determine if the day of the week had any impact on overall dust levels (Fig. 4B). In general, the highest days in terms of concentration levels tended to be earlier in the week with Friday, Saturday, and Sunday, exhibiting the lowest dust levels. When observing the hourly respirable dust data and organizing by hour in the day, an additional pattern of elevated levels from 6 a.m. to 6 p.m. can be seen, which follows along with the standard work shifts as reported by the mine (Fig. 4C). From panels B and C, the overall dust levels can be discerned as Dry 2 having the highest overall dust levels while Dry 1 had the lowest, and additionally, Dry 1 was not as impacted by day of the week or hour of the day as much as other sensors.

After using the LCDM system for 1 year, we met with the mine to get their feedback on the pros and cons of the system and how the data could better serve their needs. We have synthesized our interactions with this mine into three major takeaways from this case study:

(1) The live feed of the data is very helpful, but often too much information to be monitored continually. After a period of around 2–3 months, the industrial hygienist at the mine felt that there was a high enough level of understanding of the data live stream that they would prefer to get weekly summary reports of the dust levels on site. From that point on, the weekly reports were monitored, and when a high dust level day occurred, they felt that looking back seven days to identify a potential source of the dust was not too large of a burden. Monthly reports were also implemented but were too infrequent and hard to identify the source of dust when looking 20–30 days into the past. A combination of the weekly reports to monitor overall trends and the live feed to monitor specific short-term dust levels was ultimately used by the on-site industrial hygienist.

(2) The first hour of startup is always the highest dust levels. This pattern was first identified by the industrial hygienist on-site through the observation of the early morning cyclical high concentration events that only occurred on production days. Once the mine figured out this pattern, they began to alter their start-up routines to purposely avoid overlapping with times when workers will be near the machines. This was fully identified, assessed, and put into operation by the industrial hygienist on-site with no suggestions or interventions from the NIOSH researchers and is a perfect example of empowering industrial hygienist professionals to make "best practice" decisions for their workers by using data generated from these sensors.

(3) Mobility of the system is important. At this specific site, there were both power and Wi-Fi limitations as to the potential location of the sensors which limited the functionality of the system. The mine has expressed interest in purchasing more sensors and running power and ethernet ports to new locations to install more. The industrial hygienist on-site wanted to be able to use the sensors to identify problematic dust areas, create mitigation strategies, confirm the efficacy of the intervention, and move the sensors to a new location to repeat the process but were unable to fully carry out the full scope of this plan due to sensor location restrictions.

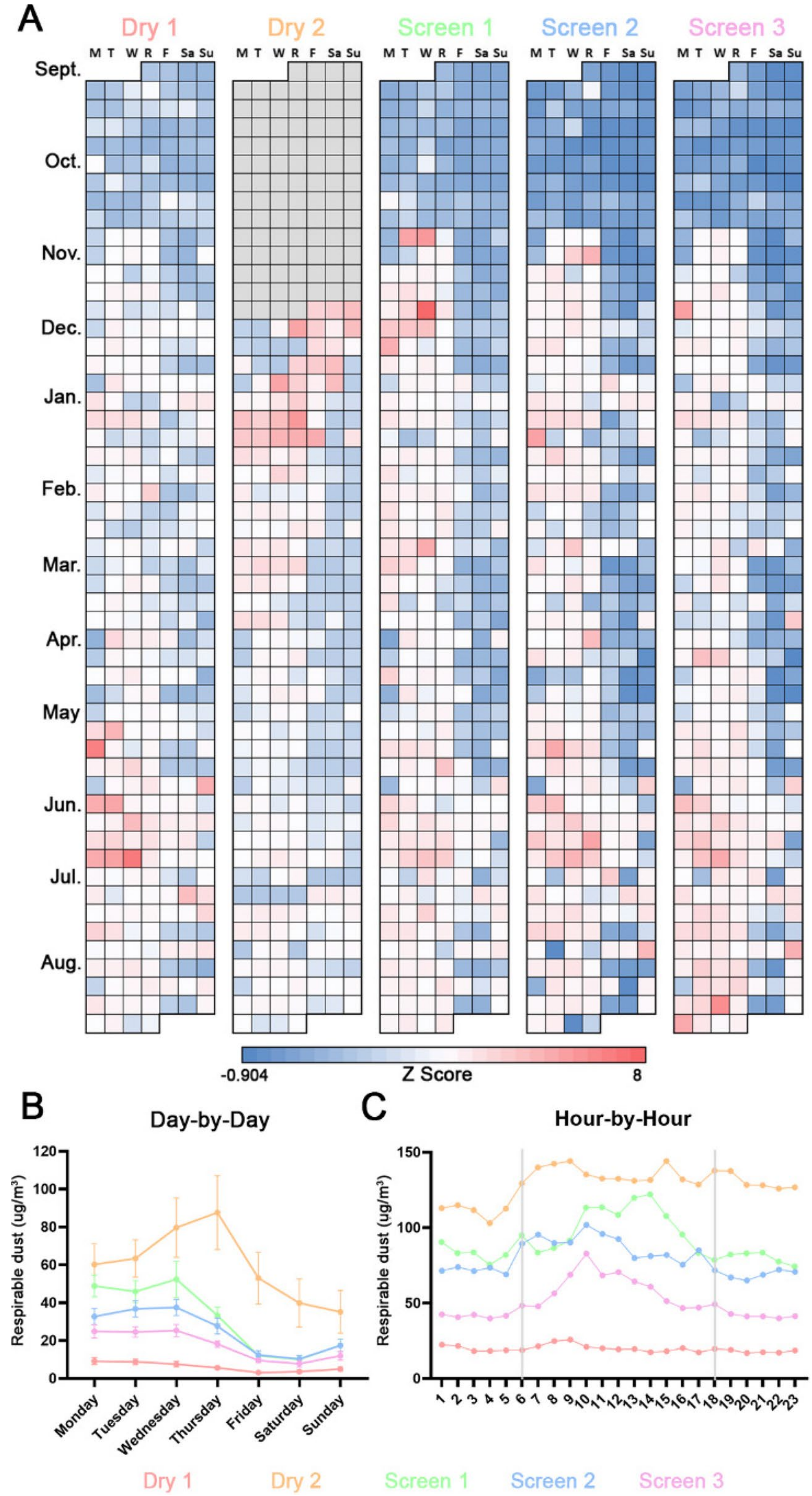

Fig. 4 Observing year-long trends in respirable dust data. **A** *Z*-score heatmap showing the relative change in daily TWA value for each of the five sensors in order by day of the week. **B** Line chart showing the daily TWA value for each sensor organized by day of the week. **C** Line chart showing the respirable dust data for each sensor organized by hour

4 Discussion and Conclusion

This case study depicting the interactions between a sand mine in Wisconsin and the researchers at NIOSH lays the groundwork for the future use and implementation of low-cost dust monitors in the mining environment. Through this publication, we have discussed what is needed to set up a system of LCDMs, what the expected outcomes could be, and how the data can be used. At NIOSH, we see the need for wider adoption of sensors and more data collection but believe that the value added should be on pace with the increased burden on the industrial hygienist professionals who will be responsible for carrying out the actions. These types of data and in general data of the future is only growing more and more complex, so having effective ways to convey the meaning of complex data to the right people at the correct time is extremely important. Through this collaboration, we at NIOSH have been able to answer many questions about the viability of using LCDMs in an operational environment, but it also brought up many questions that remain to be answered.

One of the major questions that remains unanswered is how many sensors are needed to accurately capture the variability within a given location. The answer to this question is probably a balance between increasing the resolution of the data by adding more monitors which could help and more data to be analyzed and comprehended which may not be needed. These types of sensors were purchased as off-the-shelf units which were designed as pollution monitors and were not specifically built for use in the more rugged mining environment. There could be problems with sensor drift due to vibrations, high dust levels, wear and tear, or other types of reliability issues when using these sensors outside their intended environments. The mine industrial hygienist brought up the idea of using the sensors as a mobile hot spot identification tool, wherein the monitors would have a default location they are normally in but could be removed and easily moved to other locations. The mobility of that type of system would allow the on-site industrial hygienist to set up all sensors near a site of future dust mitigation work to collect baseline data, then repairs or modifications are made, and the sensors continue to collect post-mitigation data, and verify how effective those changes were at actually reducing the dust levels. Then, the monitors could be put back in the long-term locations or in another location. The last of the possible uses for a system like this is to use the baseline data collected as part of a predictive model that can use the previous dust data generated to predict/forecast future conditions which can help determine specific times and locations that are predicted to be hazardous.

Additionally, the distinction between area monitors and personal monitors needs to be kept in mind when establishing a system like this. Wearable monitors, typically worn by individual miners, estimate personal exposure data. These types of devices are compact, lightweight, and portable, enabling miners to move freely throughout the worksite while collecting data on their personal exposure level. On the other hand, area dust monitors are stationary devices strategically placed in different zones within the mining environment to continuously monitor dust levels over a larger area, as done in this study. These monitors, especially if used in a network, can offer a broader perspective of dust dispersion and concentration trends across the site, which can aid in identifying high-risk areas and informing dust control measures. While wearable monitors prioritize individual safety and awareness, area monitors focus on overall site monitoring and management, ensuring comprehensive dust control and compliance with safety regulations.

A major takeaway from this case study is that through continuous monitoring over extended periods, LCDMs allow for the establishment of baseline respirable hazard levels. This baseline serves as a reference point, offering insights into typical dust levels during routine operations. Comparing subsequent data to the baseline enables the identification of abnormal trends or hazardous deviations that may require further investigation or remediation. Along the same vein, LCDMs excel in tracking dust levels over time, making it possible to monitor changes on a seasonal basis. Different weather conditions, temperature variations, and operational changes can impact dust concentrations. With the data generated from LCDMs, researchers and professionals can observe these fluctuations at a higher resolution and better understand the dynamics influencing the hazard levels at their workplace. Furthermore, LCDMs can play a crucial role in monitoring the effectiveness of mitigation interventions. When changes are made to ventilation systems, work processes, or other factors affecting dust levels, LCDMs can detect if these interventions have the desired impact. This ability to assess intervention effectiveness in real-time facilitates evidence-based decision-making and continuous improvement. By leveraging the data from multiple monitors, establishing baselines, and tracking changes over time, researchers and industry professionals gain valuable insights into exposure patterns and the efficacy of interventions. This data-driven approach fosters a proactive and informed strategy toward maintaining safer occupational environments and minimizing the risks associated with respirable dust exposure.

This contribution outlines an effort to use LCDMs in above-ground screening and drying facilities, but there are many uses for deploying LCDMs in other challenging environments such as underground mines. There is still much research needed to be done to establish the efficacy of these systems underground, but some factors to consider when looking to deploy an LCDM system effectively are 1. selecting the right equipment, 2. monitor placement, 3. calibration and maintenance, 4. data transmission and monitoring, and 5. integration with existing safety systems. In the underground setting, the major limiting factor is the data transmission aspect which could necessitate using wired connections when wireless technologies such as Wi-Fi or Bluetooth are unavailable. By implementing these strategies, low-cost dust monitors can be effectively deployed in both above and underground mines to monitor dust levels and protect the health and safety of miners.

LCDMs offer an affordable and accessible means to continuously measure and track dust levels, enabling employers and workers to identify and therefore mitigate potential health hazards. By providing real-time data on airborne particulate matter, these monitors enhance workplace safety measures, allowing for timely interventions to reduce exposure and prevent occupational respiratory diseases. This technology empowers industries to prioritize employee well-being and create healthier work environments through informed decision-making based on accurate and up-to-date data. Collaboration between researchers and industry professionals is essential as it bridges the gap between theoretical advancements and real-world applications. By combining the expertise of researchers who delve into cutting-edge concepts with the practical insights of industry professionals who understand market needs, innovation is accelerated and refined. This type of synergy not only drives the development of the technologies and solutions investigated, but also ensures their viability, scalability, and successful integration into the market.

4.1 Limitations

While this study has provided valuable insights into the use of LCDMs, several limitations should be acknowledged. First, the data presented in this study was generated from a single mine site and does not account for differences in geology, mining processes, or site infrastructure at other locations which could lead to different results. Second, the LCDMs used in the study have been adapted to a new application that is outside what they were originally designed for, and further validation is needed on the long-term impacts of operating in the harsh conditions of a mining operation. Third, the application of the silica concentration to the dust data must be done with caution and only after thoroughly understanding the implications and limits of making the necessary assumptions. Fourth, the study does not provide a direct comparison with traditional monitoring methods over time to validate the accuracy and reliability of the LCDM data. Fifth, the lack of correlation with production data limits the understanding of site-specific operational factors influencing dust levels.

Declarations

Competing Interests The authors declare no competing interests.

Disclaimer. The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, or the Centers for Disease Control and Prevention. Mention of any company or product does not constitute an endorsement by NIOSH or CDC.

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