Dust pollution hazard and harmful airborne dust exposure assessment for remote LHD operator in underground lead–zinc ore mine open stope

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Abstract
Underground mines embroil several occupational hazards, including airborne dust generation from various mining operations. Line-of-sight remote Load Haul Dumper (LHD) mucking is adopted to draw the blasted muck from unsupported open stopes in underground metalliferous mines. Assessment of particulate matter (PM) concentrations and remote LHD operator’s exposure is crucial for devising appropriate dust control measures. In this study, PM generated due to mucking in longhole open stope by line-of-sight remote LHD during downcast airflow was measured using real-time aerosol spectrometers. The particulate concentrations at upstream and downstream of dust source were analysed for various particle sizes as well as occupational dust types, such as alveolic and thoracic. The airborne dust concentration of \( \leq 10 \mu m \) (PM\(_{10}\)), \( \leq 5 \mu m \), and \( \leq 1 \mu m \) (PM\(_1\)) size at operator’s location in downstream was measured 71.3%, 28.5%, and 3.0%, respectively. The alveolic and thoracic dust types, respectively, were determined 25.1% and 74.2% in downstream and 48.9% and 84.6% in upstream total airborne dust concentration (311 ± 246 μg/m\(^3\)). Dilution of airborne dust generated due to muck sliding inside the stope was analysed with time. Moreover, dust concentrations under typical airflow scenarios encountered in open stope were simulated using Ventsim software to identify the potential dust exposure hazard for remote LHD operator. The simulation revealed that downcast airflow causes maximum exposure of harmful airborne dust for remote LHD operator. This study enhanced the understanding of exposure potential of airborne dust during remote LHD mucking. Moreover, it emphasised adoption of tele-remote-operated LHD and automated mucking operation in open stopes.

Keywords Dust pollution hazard · Airborne dust · Dust exposure · Remote LHD operator · Underground lead–zinc ore mine · Underground mine environment · Mines safety

Introduction
Underground mining is a process by which the naturally occurring mineral deposits are extracted from the earth’s crust by employing various mining methods (supported, unsupported, and caving methods) (Hamrin 2001). The mining processes involving drilling, blasting, mucking, hauling, crushing, etc., inherently produce particulate matter (PM) due to breaking down of rocks. The primary dust (generated due to mechanical forces), and secondary dust (airborne due to aerosolisation) are transported along with ventilating air current to other working and non-working areas in underground mines, and influence the downstream airborne dust concentration (Paluchamy et al. 2021). Exposure of the miners to various airborne contaminants in day-to-day mining operations in coal and metalliferous mines causes occupational respiratory diseases (Ambastha and Haritash 2022; Chen et al. 2022; Zilaout et al. 2017).
A significant amount of the dust generated due to production blasting is diluted by ventilating air, and a large quantity of dust is trapped under the blasted rock fragments in stopes (Chekan et al. 2004). If precautions, such as wetting of rock fragments before mucking, are not taken, the trapped dust poses airborne dust hazard. Nevertheless, wetting of muck pile in stopes is not an easy task and it has inherent difficulties, such as requirement of a safe location for the person to stand, water spray reachability, duration of spray, spray water penetration into the muck, etc., resulting abundance of dry dust in open stopes (Chekan et al. 2001). Studies have confirmed that the adverse health effects of airborne dust depend on the size (including nano size particles) and concentration of dust, toxic elements present in dust, and miners’ exposure to dust (NIOSH 2002; Patra et al. 2015; Zheng et al. 2013). Moreover, the physico-chemical properties of dust greatly vary with the minerals mined and mining activities.

Earlier studies on dust issues in metalliferous mines focussed on reduction of the miners’ exposure to harmful dusts (Biffi and Belle 2003; Gautam et al. 2022, 2015; Saarikoski et al. 2018). However, they did not assess the particles size distribution for individual mining operations in underground metalliferous mines, which is very crucial for devising effective dust control measures specific to the mining operations. Moreover, studies on generation and dispersion of airborne dust in open stopes are not available. Some recent studies addressing the dust issues in mechanised metalliferous mines are summarised in Table 1.

Identification of hazards is crucial in the risk assessment process, as the new mining operations could bring unidentified hazards in the workplace. In view of the above, this research mainly focuses on the measurement of airborne dust and identification of dust pollution hazard during remote Load Haul Dumper (LHD) mucking in underground metalliferous mine open stopes. The outcome of this study can aid in development of sensor-based low-cost dust monitoring and control system for stope areas in mechanised underground metalliferous mines.

Mucking and hauling of un-wetted blasted rock fragments with load haul dumpers (LHDs) in underground metalliferous mine development headings and stopes liberate large amounts of particulates. LHD is a rubber-tired, low-profile front-end loader used in underground mines or tunnels to load the fragmented/blasted rocks in its scoop, haul them to an unloading point, and dump the muck. LHDs have environmentally protected cabins for protecting the operator from dust and heat. However, the environment inside the cabin depends on many parameters that include design and operational factors (Cecala et al. 2019). Line-of-sight remote control (i.e., the operator operates the machine under his direct eyesight using remote) LHDs are commonly operated in unsupported areas in underground metalliferous mines to enhance the operator safety, and ore recovery (Schunnesson et al. 2001). The line-of-sight remote LHD operation has several advantages, which include reliable operation, no network delay, and low investment. However, the operation range of line-of-sight remote controlled LHD is limited

| Study area/mine                        | Pollutant types                        | Studies                                                                 | Technique applied                      | Author (year)            |
|----------------------------------------|----------------------------------------|------------------------------------------------------------------------|----------------------------------------|--------------------------|
| Underground gold and platinum mines    | Respirable airborne dust               | Respirable dust generation characteristics based on different mining activities | Gravimetric method                    | Biffi and Belle (2003)   |
| Surface iron ore mine                  | Respirable airborne particulates (PM₁, PM₂.₅, PM₁₀) | Dispersion study of different size dust particles inside the mine        | Real-time monitoring                   | Gautam et al. (2015)    |
| Opencast copper mine                   | Particulate matter (concentration in seven size ranges) | Concentration prediction using artificial neural network model          | Real-time monitoring                   | Patra et al. (2015)     |
| Underground uranium mine               | Airborne dust (from 0.39 to 10.2 µm)   | Aerosol particle size distributions of uranium and its daughter products | Used 6-stage Cascade Impactor          | Mala et al. (2016)      |
| Underground gold mine                  | Respirable dust                        | Physico-chemical characterization of different size dusts               | Gravimetric method: aerosolized dust in laboratory | Chubb and Cauda (2017)  |
| Underground chromite mine              | Airborne dust (from 2.5 nm to 10 µm)   | Physico-chemical characterization of different size dusts               | Aerosol mass spectrometry             | Saarikoski et al. (2018) |
| Opencast copper mine                   | Particulate matter (15 different size ranges) | Estimation of spatiotemporal concentration of dust in mines through deep learning approaches | Real-time monitoring                   | Gautam et al. (2022)    |
within the operator’s visual range and cannot be as fast as an on-board operator. The LHD operator usually stands and operates the LHD remotely from a safe distance of 10 to 40 m in line-of-sight of stope corner (Swart et al. 2002).

During line-of-sight remote LHD mucking, the LHD operator stays inside the LHD cabin until he reaches near the stope brow, which is a safe place where he can come out of the cabin with a remote and send the LHD inside the stope to draw the muck (WSN 2012). The major steps involved in line-of-sight remote LHD mucking operation are specified in Fig. 1.

The LHD cabin door is required to be opened and closed. This allows the outside dusty air to enter the cabin two times in a regular cycle. Hence, there is a possibility that the remote LHD operator can directly be exposed to harmful mineral dust, heat, diesel engine exhaust fumes, and DPM (Du et al. 2020; Ping et al. 2019). Figure 1 a illustrates the top view of a typical open stope while the LHD drawing blasted muck inside the stope. Figure 1 b shows the typical remote operator location (e.g., safe sides in the mucking drive, specified size x-cut for operator to stand and operate the LHD), with the visual range of LHD. In the mucking drive, the loaded LHD is manually operated to reach the unloading point (Fig. 1c).

Few researches have been conducted on dilution of exhaust fumes generated during LHD mucking in stopes (Nakaryakov and Grishin 2021). Besides, most studies did not assess the generation and dispersion profiles of dust based on particle size, which is very important from the occupational health hazard point of view and for devising appropriate dust control strategies in underground metaliferous mines. Use of electric LHDs though eliminates diesel exhaust fumes and DPM hazard in underground working environment, the mineral dusts generated owing to their use could pose health hazard. Keeping this in mind, this study focused on the measurement of airborne dust generated due to line-of-sight remote LHD (17 tonne capacity) mucking in an underground lead–zinc ore mine open stope under downcast airflow. It compared the airborne dust concentrations in upstream (baseline) and downstream sides of the stope. Moreover, this research identified the dust pollution hazard for remote LHD operator under typical airflow scenarios in open stope through numerical simulation. The outcomes of the field measurement and simulation studies will guide the mine management in taking necessary measures to minimize the miners’ exposure in underground metaliferous mines. Overall, this study can benefit the mining industry in preventing and eliminating silicosis worldwide by 2030 as targeted by the World Health Organisation (WHO) and International Labour Organisation (ILO) (DGMS 2010; WHO 1999).

Fig. 1 A typical line-of-sight remote LHD mucking operation in open stope. a Top view through open stope. b LHD is remotely operated. c LHD is manually operated

(a) Top view through open stope

(b) LHD is remotely operated

(c) LHD is manually operated

- Safety checklist.
- LHD is operated manually till it reaches near the stope.
- Operator comes out of his cabin and operates LHD remotely from a safe place to draw the blasted muck from open stope.
- Once LHD returned from inside the stope to near the operator location, LHD switched to on-board manual operation.
- LHD moves to unloading point.
- Next cycle of operation begins.

Picture courtesy: L. Sharma, Youtube
Materials and methods

Approach

In this study, the airborne dust concentrations were measured under downcast airflow scenario in an open stope using real-time aerosol spectrometers (Grimm 1.108) to assess the harmful airborne dusts. The airborne dust concentrations were analysed for particle size distribution considering different dust types including alveolar dust. Subsequently, the dust pollution hazard for remote LHD operator engaged in mucking in open stope was identified by simulating different airflow scenarios using Ventsim software. Among the different scenarios simulated, the downcast airflow in open stope has the greater potential for high dust exposure for the LHD operator. In order to achieve the study objectives, the important factors, such as site selection, field monitoring, and procedures, followed during the field study, data analysis, and empirical relation development are outlined. Furthermore, relevant ventilation parameters, such as dry-bulb temperature (DBT), wet-bulb temperature (WBT), relative humidity (RH), equipment movement, and drive dimensions, were measured to examine the behaviour and relative size distribution of dusts.

Site selection

The study site was selected based on the level of mechanisation implemented in various mining operations, accessibility, and safe installation of dust monitoring equipment. Kayad lead–zinc ore mine (KLZM) of Hindustan Zinc Limited (HZL), a fully mechanised underground lead–zinc ore mine in India, was selected for the field study. The KLZM is located in Kayad village, Ajmer city of Rajasthan state as shown in Fig. 2. The mine is relatively of shallow depth. The main access to the mine is through the main decline. The surface level of the mine is 487 mRL. The mine decline is of 5.50 m × 5.00 m (W × H) cross-section with arched roof and gradient 1 in 7. The main decline splits into North decline and south decline at 412 mRL (Fig. 2). The study was conducted at 375 mRL in the North section of KLZM. A working longhole open stope was identified in 375–400 mRL for subsequent field monitoring.

Boundary and exhaust ventilation system is implemented to meet the ventilation requirement of the mine. The speed of ventilation fans in the mine is regulated by variable frequency drive (VFD).

Field measurement and data analysis

An open stope under downcast airflow in North section of the mine was considered for assessment of harmful airborne dust at remote LHD operator’s location (Fig. 3). Figure 3 illustrates the airflow network in the working stope with North decline, intake air shaft, stope top level drive, stope mucking level drive, and monitoring locations.

The LHD operator maintains a distance of 20 to 50 m between the mucking point (i.e., remote LHD in stope) and his location depending upon the visibility and safety during...
the line-of-site remote LHD operation. The dust monitors were placed near the breathing zone at about 1.6 m height beside the mucking drive wall to prevent their damage from moving LHD. Engineering sampling (Belle 2018) was adopted for measuring the dust generation and dispersion due to line-of-sight remote LHD mucking in the open stope. Here, engineering sampling represents the monitoring of airborne dust to characterise the dust emission source when the particular engineering activity (e.g., LHD mucking in this case) is taking place.

The concentration and size distribution of airborne dust were measured using Grimm aerosol spectrometers (model 1.108) with necessary field measurement accessories. The percentage of respirable dust is a function of dust particle size. Recent studies showed that finer dust particles have more impact on human lungs in a typical mining environment (Gautam et al. 2015; Patra et al. 2016). Therefore, the aerosol spectrometers which can classify up to 15 size ranges starting from 0.23 to 20 μm were used in this study. The aerosol spectrometers also classify the airborne dusts in terms of respirable, thoracic, and inhalable dust types (Grimm 2010). ‘Mass distribution’ option was selected in operational mode, and the rest of the values kept default in this study.

The average airflow velocity in the study area was measured using a vane anemometer (Micon-2 dial). The temperature and relative humidity were measured using a humidity meter (Lutron: PHB-318) during the LHD movement in the study area. Moreover, LHD entry and exit times in the monitoring area were recorded. The airflow velocity at monitoring location in the drive was measured in the range of 0.6–1.1 m/s. The drive was of 5 m × 4.5 m cross-section with arched roof, over break due to earlier down-level stopes, and wetted rock surfaces (sides and floor). The dust monitor was placed at a distance of 45 m from the LHD mucking location (Fig. 3). Moreover, the required distance was set aside for the generated dust in the stope to mix with mine air before reaching the dust monitor location. The DBT, RH, O₂, and CO concentrations in the dust monitoring location during mucking were measured in the range of 28.5–30.5 °C, 82–77%, 20.6–20.9%, and 5–10 ppm, respectively.

### Simulation method

Commonly, LHDs are involved in mucking of blasted muck or rock fragments from the working face and haulage to unloading points, such as truck or dump stockpile (DSP), and loading and hauling material for backfilling in KLZM. The shift in-charges and LHD operators provide the preliminary information about the dust flow patterns (e.g., downcast and upcast airflow) in production stopes. In order to assess the variations of airborne dust concentrations at remote operator location under typical airflow scenarios in open stope, a stope adopting longhole open stoping method with relevant drives (e.g., mucking level and top level drives, declines) was created using Ventsim software (Fig. 9). Ventsim software is widely used for airflow simulation in tunnels and underground mines. Moreover, this software has the capability of modelling heat, fire, dust, radon, and other contaminants in underground mine environment (Stewart et al. 2015; Ventsim 2015).

The simulations were performed under downcast airflow, upcast airflow, and partial recirculation scenarios, as shown in Fig. 9 a, b, and c, respectively, to comprehend the dust dispersion at LHD operator’s location in mucking drives well as other drives in the ventilation network under different airflow scenarios. A point dust source (1 mg/m³) was considered at the mucking location (i.e., bottom of the stope) in addition to the background dust concentration in decline (0.1 mg/m³). The main geometrical and simulation parameters used are summarised in Table 2. The transparent drives shown in Fig. 9 were not included in the simulation.
Assessment of airborne dust

The average concentration of total airborne dust (TAD) in upstream (i.e., baseline) and downstream side at the remote LHD operator’s location are estimated $311 \pm 246 \mu g/m^3$ and $6210 \pm 2690 \mu g/m^3$, respectively (number of readings, $N = 10$ trips). During the field study, the blasted muck was in dry condition. Normal operating procedures at mines necessitate wetting of muck piles prior to loading. However, sometimes it is difficult to wet the blasted muck in stopes adopting longhole-open stoping method of mining (Chekan et al. 2001). Figure 4 presents the cumulative dust concentrations and percent proportions of $\leq 20 \mu m$, $\leq 15 \mu m$, $\leq 10 \mu m$, $\leq 5 \mu m$, and $\leq 1 \mu m$ dusts in TAD.

From Fig. 4, it is evident that the dust particles greater than $10 \mu m$ size, which are irrespirable (DGMS 2010), constitute $29.7\%$ and remaining $\leq 10 \mu m$ (i.e., PM$_{10}$) dusts share $71.3\%$ in the downstream TAD. Moreover, the percent proportion of $\leq 5 \mu m$ and $\leq 1 \mu m$ dust in the downstream TAD are estimated $28.5\%$ and $3.0\%$, respectively. The results are aligned with the study conducted in open-cast mine workings, which reported the sub-micron particle (PM$_{1}$) concentration in the range of $7–15\%$ (Gautam et al. 2015). A past study conducted by the authors in a decline of the same mine estimated the percent proportions of $6\%$ and $0.5\%$ for $\leq 5 \mu m$ and $\leq 1 \mu m$, respectively, in downstream TAD generated due to loaded LPDT travelling, which is much lower than in stope mucking areas (Paluchamy and Mishra 2021). Nevertheless, the air velocity in the decline was higher (3 m/s) than the stope mucking drive. Moreover, the air velocity inside the stope is lower than the mucking drive due to larger void space in the stope. The low air velocity in the mucking drive might have facilitated quick settling of the coarser particles before reaching the aerosol monitor.

The airborne dust was also analysed in terms of occupational dust types, such as alveolic and thoracic (CEN 1993). The percent proportions of alveolic and thoracic dusts in respective inhalable dust concentrations of upstream and downstream sides are shown in Fig. 5.

The downstream concentration of inhalable dust (i.e., TAD) at remote operator location in the mucking drive is measured in the range of $2192–10,433 \mu g/m^3$. From Fig. 5, it may be observed that the proportions of alveolic (48.9\%) and thoracic (84.6\%) dusts in the upstream side are higher than the respective dust types (i.e., 25.1\% alveolic, and 74.2\%...
In downstream side. However, upstream inhalable dust concentration is found in the range of 93–759 μg/m$^3$, which is due to dust concentration in declines as the North decline air serves as one of the primary intakes of the stope (Fig. 3). Occupational exposure studies conducted in open-cast mines’ working areas measured the alveolar dust in the range of 17–29% (Gautam et al. 2016). It is well known that alveolar dust is most hazardous as they penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs (WHO 1999). Though ventilation is one of the effective means of diluting respirable dust in stopes, wetting of blasted muck is of paramount importance to prevent the dust becoming airborne (Chekan et al. 2001). Further analysis of downstream airborne dust concentration (Fig. 6) led to the establishment of following linear empirical relationships between the alveolar, thoracic, and inhalable dust concentrations:

$$\begin{align*}
y_1 &= 0.2039x + 290.53 \\
y_2 &= 0.7417x + 2.7998
\end{align*}$$

where $y_1$ and $y_2$ are concentrations of alveolar and thoracic dust types in inhalable dust, and $x$ is inhalable dust concentration in downstream. These relationships will be useful for assessing the alveolar dust concentration from the known total airborne dust in similar working areas.

Recent studies are focused on the assessment of airborne dust exposure of miners in opencast metalliferous mines based on particle size ranges (Gautam et al. 2022; Patra...
et al. 2015). The differential dust concentrations of various size ranges plotted against the TAD in Fig. 7 depict that the concentrations of dust sizes 15.0–20.0 μm, 10.0–15.0 μm, 5.0–10.0 μm, and 0.23–5.0 μm linearly increase with increase in the TAD concentration in downstream air. Differential concentration of downstream airborne dust (DS) for the size ranges of 15.0–20.0 μm, 10.0–15.0 μm, 5.0–10.0 μm, and 0.23–5.0 μm is analysed in the range of 0–707 μg/m³, 315–2205 μg/m³, 786–4577 μg/m³, and 862–2756 μg/m³, respectively. The large variation in concentration (i.e., 862–2756 μg/m³) of 0.23–5.0 μm dust in the downstream air may be attributed to the variation in LHD bucket filling and muck sliding in different mucking cycle. Moreover, the analysis revealed better correlations for the 10.0–15.0 μm and 5.0–10.0 μm (R² = 0.95 and 0.98) size ranges than the coarser sizes (i.e., 15.0–20.0 μm) (R² = 0.76) with TAD. Empirical correlations established for different particle size ranges are given below.

\[ y_3 = 0.0689x - 82.374 \]  \hspace{1cm} (3)

\[ y_4 = 0.2387x - 299.76 \]  \hspace{1cm} (4)

\[ y_5 = 0.4664x - 237.74 \]  \hspace{1cm} (5)

\[ y_6 = 0.2352x + 310.38 \]  \hspace{1cm} (6)

where \( y_3, y_4, y_5, \) and \( y_6 \) are dust concentrations of the size ranges 15.0–20.0 μm, 10.0–15.0 μm, 5.0–10.0 μm, and 0.23.0–5.0 μm, respectively. ‘x’ is the concentration of TAD in downstream.

The analysis of finer and coarser particles in TAD will facilitate the assessment of particles deposition in human respiratory tract (Patra et al. 2016). Moreover, the aforementioned relationships established through this research will aid environmental monitoring and smart dust control through wireless sensor network (WSN) in mechanised underground mines (Muduli et al. 2018). Apart from airborne dust exposure risk during downcast airflow scenario in open stope, the remote LHD operator may be exposed to harmful exhaust gases and other sub-micron particulates, such as diesel particulate matter (DPM) emitted by LHD.

**Airborne dust dilution**

The generation and dispersion of dust due to muck sliding and loose rock falling inside an open stope have the potential to generate dust cloud, which in turn influence the line-of-sight LHD operation (Miner 2022). Therefore, the particulates aerosolised due to muck sliding and loose rock falling inside the stope have been considered in this research. The airborne dust concentration was measured at remote LHD operator location in the mucking drive. The high-resolution concentration data obtained during 10 s muck sliding and loose rock falling inside the stope was analysed subsequently. The analysis of results presented in Fig. 8 revealed the peak concentration of alveolic, thoracic, and inhalable airborne dust in the order 1439 μg/m³, 4961 μg/m³, and 8700 μg/m³, respectively. Moreover, Fig. 8 shows the dilution of alveolic, thoracic and inhalable dust clouds with time from peak concentration to baseline concentration by ventilation air (air velocity in the mucking drive: 0.7 m/s) at the remote operator’s location in the mucking drive. Though the concentration of finer dust (alveolic) is found to be low, the coarser (thoracic and inhalable) dusts can affect the visibility in the mucking...
drive and stope till they are cleared away by the airflow. The frequent sliding of blasted muck or falling of loose rocks inside the open stope may also increase the operation cycle time as the remote LHD operator has to wait for better visibility before sending the LHD inside the stope for line of sight mucking operation. From Fig. 8, it may also be observed that the airborne dusts are diluted exponentially by the ventilation air. The empirical relations relating the clearance of airborne dust generated due to muck sliding and loose rock falling inside the open stope at operator’s location with time are given below. These equations may be useful for predicting the dilution time for dusts of different sizes in open stope mucking drive.

\[ y_7 = 1852.3e^{-0.023x} \]  
\[ y_8 = 5818.6e^{-0.024x} \]  
\[ y_9 = 9616.9e^{-0.027x} \]
where $y_7$, $y_8$, and $y_9$ are concentration ($\mu g/m^3$) of alveolar, thoracic, and inhalable dust, respectively. ‘$x$’ is the time (s).

**Dust pollution hazard identification for remote LHD operator in open stopes**

The variations of dust concentrations under typical airflow scenarios simulated, viz., upcast airflow, downcast airflow, and partial recirculation, in an open stope for line-of-sight remote LHD mucking are illustrated in Fig. 9. A well-planned ventilation network will have the airflow direction as marked in the stope top level drive (a-b-c-g) and mucking level (d-e–f) drive (Fig. 9a). As depicted in Fig. 9a, the remote LHD operator location in the mucking level drive is ventilated by intake air from decline, and the stope return air is directed towards return drive in the stope top level. However, the other two scenarios, viz., downcast airflow and partial recirculation illustrate that the remote LHD operator’s location is contaminated by the stope exhaust air, which contains the harmful diesel exhaust and airborne mineral dust due to downcast airflow (Fig. 9b) and recirculation (Fig. 9c) of air in the working stope, respectively. The undesired airflow direction a-b-c-f-e-d and d-e–f-c-b-a depicted in Fig. 9b and c, respectively, may be caused by unplanned obstructions in the airways, opening or closing of ventilation doors, connecting development drives in different working levels, opening or backfilling of stopes, and unexpected stoppage of main fans in mechanised underground metalliferous mines (McPherson 2009).

The simulated layout indicates the background dust concentration of 0.1 mg/m$^3$ (blue colour) at remote LHD operator location under upcast airflow scenario (Fig. 9a). However, the simulation performed under downcast-airflow (Fig. 9b) and partial recirculation (Fig. 9c) scenarios revealed the dust concentration of 1.1 mg/m$^3$ and 0.5 mg/m$^3$, respectively, at the remote LHD operator location in mucking drive. From the simulation results, it can also be inferred that downcast airflow and partial recirculation can increase the downstream dust concentration in the decline (green colour in Fig. 9b, c). Hence, it is evident that the undesired downcast airflow in open stopes may lead to the maximum exposure of remote LHD operator to harmful airborne contaminants, such as airborne mineral dust, diesel engine exhaust gases, and diesel particulate matter (DPM) during line-of-sight remote LHD mucking. Past studies conducted in opencast mines also showed that the airflow direction plays a significant role in dust particle transportation from source to other working areas (Gautam et al. 2015).

**Limitations and scope of further studies**

This study investigated the concentration and dispersion of the airborne dust, and identified the potential dust pollution hazard for remote LHD operator during mucking in an open stope. The dust dispersion is assumed to be homogenous in the dust monitoring locations. As the analysis is based on engineering sampling, the measured dust concentrations should not be construed as regular miners’/operators’ exposure values. However, the outcomes of this study may aid in assessing and controlling the dust in similar mining operations and environment.

There is lots of scope for furthering this study. Automation in mucking and loading operations can help in enhancing safety and productivity under difficult situations (Swart et al. 2002). It is well known that the operation of tele-remote LHD can be controlled from the surface control room, which would facilitate the operator to run the LHD immediately after shift allocation till the end of 8-h shift (Hwang et al. 1999). In future, full automation of LHD operation may be considered in mines or sections of mines to eliminate the physical presence of remote operators in mucking areas (Tampier et al. 2021). Besides, mine ventilation is an integral part of dust control strategies to dilute the respirable dust in working areas in mechanised underground metalliferous mines (Cecala et al. 2005). The primary airflow direction in longhole open stopes plays an important role in diluting and dispersing the airborne dust. Use of battery-operated LHDs may create better working environment by achieving zero-emission of DPM and exhaust gases in mines. Nevertheless, generation and dispersion of mineral dust due to mining operations is a menace, hence future studies should focus on airborne mineral dust in metalliferous mines (Jang and Topal 2020). Idea about the average size of dust particles propagated in underground mine workplace will be vital in selecting and implementing appropriate dust control strategy and creating awareness among the miners about life threatening airborne dust hazards.

**Conclusions**

This study measured and analysed the airborne dust concentrations at remote LHD operator’s location in underground lead–zinc ore mine stope under downcast airflow scenario. Moreover, it simulated for variations of dust concentrations under typical airflow scenarios in open stope, viz., upcast airflow, downcast airflow, and partial recirculation, using Ventsim software to identify the dust hazard for line-of-sight remote LHD operators during mucking in mechanised underground metalliferous mine. The conclusions drawn from the study are outlined as follows:

(a) The particulates above 10 $\mu$m size, which are irrespirable, share 25–32%, and the submicron particles (i.e., $\leq 1$ $\mu$m) occupy 3.0% in the downstream TAD at the remote operator’s location in the mucking drive.
(b) The percent proportions of occupational dust types, such as alveolic and thoracic dusts, in downstream airborne dust at the remote operator’s location are determined 25.1% and 74.2%, respectively. Empirical relations have also been developed to predict the proportions of alveolic and thoracic particulates in the downstream TAD.

(c) Differential concentrations of downstream dusts for the size ranges of 15.0–20.0 µm, 10.0–15.0 µm, 5.0–10.0 µm, and 0.23–5.0 µm are analysed, and their correlations with total airborne dust have been developed. Tele-operated LHD is recommended to avoid LHD operator’s exposure to respirable dust in mucking areas.

(d) Airborne dust generated due to rock fragments sliding and loose rock falling inside the open stope is estimated. Moreover, dilution of alveolic, thoracic, and inhalable dusts at the remote operator location in mucking drive is analysed. Continuous wearing of dust mask is recommended for the remote LHD operators to reduce their dust inhalation exposure during mucking.

(e) Simulation of dust concentrations under typical airflow scenarios revealed that downstream airflow causes maximum exposure to harmful airborne dust for the remote LHD operator during line-of-site remote LHD mucking in open stope.

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Author contribution B. Paluchamy: investigation, methodology, software, data curation, formal analysis, writing — original draft. Devi Prasad Mishra: conceptualization, visualization, methodology, supervision, writing — review and editing.

Data availability All relevant data generated during the study are included in the article.

Declarations

Ethical approval Not applicable. This research does not involve the use of any animal or human data or tissue.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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