Air and Particulates in Underground Oil Shale Mine

Subjects: Green & Sustainable Science & Technology
Contributor: Sergei Sabanov, Abdullah Rasheed Qureshi, Ruslana Korshunova, Gulim Kurmangazy

Particulate matter (PM) in the context of underground mining results from various operations such as rock drilling and blasting, ore loading, hauling, crushing, dumping, and from diesel exhaust gases as well. These operations result in the formation of fine particles that can accumulate in the lungs of mineworkers. The lung deposited surface area (LDSA) concentration is a variant solution to evaluate potential health impacts.

Keywords: particulate matter ; oil shale mining ; lung deposited surface area

1. Air Quality in Underground Mines

The origins of particle emissions in underground mines are mining activities, diesel engine vehicles, and blasting operations [1][2][3][4]. Dust concentrations depend on mining activities [5], and can contain crystalline silica that can cause silicosis, lung cancer, and other diseases of the respiratory system [6][7]. The issue of air quality has consistently been a matter of great concern because the dust generated during mining seriously affects the quality of underground air and worker health [8][9]. The authors state that most of the studies prefer to neglect the assessment of air quality in underground mines, confining themselves to the analysis and forecasting. However, the unique conditions of underground mines, with their increased concentration of gases and solid particles, make it urgent to apply the air quality index (AQI) for effective monitoring and maintenance of safe working conditions.

Significant emphasis should also be placed on the assessment of particulate matter (PM) concentration in underground mining operations [10]. A number of studies used various measurement tools and methodologies to determine the concentration of PM in underground mines. In a study conducted by Saarikoski et al. (2019) [11], an underground chrome mine revealed a significant influence of the location and time intervals of measurements on the number and mass concentration of particle matter. For measurements, an optical particle counter was used in various parts of the mine. It indicated that PM_{10} varied from 22 to 1100 μg/m^3, the total number of concentrations varied from 1.7×10^3 to 2.3×10^5 cm^{-3}, and the ore crushing process creates dust with particle sizes over 2.5 μm. At the same time, in the Saarikoski et al. (2018) [3] study, the average concentrations of particles in a chrome mine were measured, and this value was $2.3 \pm 1.4 \times 10^4$ cm^{-3}. The distribution of the number of particles by size varied in the range from 30 to 200 nm, but the most common sizes were less than 30 nm. As an alternative for assessment, the properties of solid particles and aerosols in underground mining environments could be assessed by scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDS) analysis [12][13][14].

2. Lung Deposited Surface Area

The combustion of diesel is the main source of the toxic gases and particles in underground mines. When underground miners, particularly truck drivers, continuously breathe contaminated air for a prolonged period of time, severe occupational disorders may develop. In addition to toxic gases, diesel engines also release ultrafine particles (UFPs) with a size of less than 0.1 μm. Their accumulation in the respiratory system is hazardous and can result in severe respiratory illnesses [15]. When evaluated in various environmental circumstances, the lung deposited surface area concentration (LDSA) approach was successful in recognizing UFP [16][17][18][19][20][21]. Salo et al. (2021) [22], using ELPI+ in a chrome underground mine, found that LDSA concentrations vary from 137 to 405 μm^2/cm^3. The optimal particle size to estimate the LDSA distribution was no more than 100 nm, except at the blasting site, where the particle sizes were closer to 700 nm. Jafarigo et al. (2023) [23] showed that the average concentration of LDSA was relatively high (4×10^3 μm^2/cm^3), while the majority of particles had a size of less than 100 nm. Afshar-Mohajer et al. (2020) [16] monitored the concentration of inhaled particles in the four main technological divisions of a taconite mine, crushing, dry and wet milling, and granulation, to measure particles smaller than 300 nm. The results showed that the average LDSA concentration was highest during the granulation process, at 199 ± 48 μm^2/cm^3. In other mining areas, the concentration ranged from 80 to 200 μm^2/cm^3. In addition, the taconite mine LDSAs in crushing and pelletizing operations were 142 ± 52 $\mu m^2/cm^3$ and 200 ± 48 $\mu m^2/cm^3$, respectively.

UFPs can carry a high concentration of toxic substances, and therefore, they can cause inflammation through oxidative stress responses, atherosclerosis, an increase in blood pressure, and even myocardial infraction [24]. The LDSA is a different method of describing particle toxicity. The challenge with current mass-based exposure limits is that they fail to account for ultrafine particles (less than 100 nm), which have negligible contributions to particle mass, but can penetrate deep into human airways, lodge in lung alveoli, and have high toxicity contributions. This is especially concerning because most diesel engine particle emissions (measured by number) fall into the ultrafine range [17]. In distinct metropolitan contexts, LDSA concentrations, size distributions, and height profiles have been measured in ambient conditions [18][19][21]. LDSA concentrations have been connected to emissions from combustion sources. Afshar-Mohajer et al. (2020) [16] used a variety of measures, including LDSA, to investigate the variability of aerosol concentrations in different processing zones of a taconite mine. Huynh et al. (2018) [17] used numerous particle concentration measures, including LDSA, to investigate fine particle concentrations in six taconite mines. LDSA concentrations in their investigation ranged from 50 to 300 $\mu m^2/cm^3$ depending on the processing region. Although LDSA levels varied from station to station, Afshar-Mohajer et al. (2020) [18] also noticed the remarkable repeatability of concentration each day. The aim of this experimental sampling was to determine the exposure of the cabin operator to diesel exhaust nanoparticles.

Benedetto et al., in their study, were the first to characterize and determine the behavior of UFPs in synthetic lung fluids. The authors found a large variability in the hydrodynamic diameter, with values less than 1 nm and greater than 5 µm, and recognized aggregation and disaggregation processes in Gamble solution and artificial lysosomal fluid using dynamic light scattering. The results of their study proposed an interaction between nanoparticles and lung fluids, particularly within the alveolar macrophage region. [25]. Kalaiarasan at al. concluded that respiratory deposition doses and particle number concentrations can be applicable to investigate relationships between particle diameter and deposition in the different regions of the lungs, considering the impact of the UFP deposition in the deeper region of the lungs [26].

A notable Issue arises from the observation that a majority of the particles generated in coal and oil shale mines have a finely dispersed nature, enabling their infiltration into the respiratory system [27][28]. Thus, the LDSA indicator can be used to determine the potential places of deposition of particles in the lungs and to study the impact of inhaled particles on humans [29]. A number of researchers measured the LDSA in underground mines using a variety of measuring instruments in their research. Salo et al. (2021, 2023) [22][30] studied the distribution and concentration of LDSA in various places of a chrome underground mine using an electrical low-pressure impactor (ELPI+), and evaluated the possibility of using sensors to measure this indicator. The author stated that the environment around the sensors was complex because the particle sizes often exceeded the optimal range (20–300 nm), and dust accumulated inside the devices. Studies conducted in different underground mines confirm the high concentration of fine particles. These results highlight the need for enhanced monitoring of mine air quality to protect workers' health and ensure safe working conditions.

3. Oil Shale Particulates

According to Wang, Liu, and Gratt (1985) [27][28][31][32], coal and oil shale mines are significant sources of dust particles in the mining environment, and their detailed study in the context of composition, size, and monitoring methods is of particular interest. In underground coal mines, dust includes the smallest particles, and this dust consists mainly of particles containing carbon, heavy metals (arsenic, mercury, lead, etc.), and other pollutants that can lead to serious diseases of the respiratory tract of mine workers [32]. Chang and Xu (2017) [33] and Widodo et al. (2023) [34] claimed that in coal mines, especially with improper ventilation, the formation of explosive mixtures of dust and gas is possible, which increases the risk to workers. A study on the measurement of dust concentration in a coal underground mine was conducted by Jin et al. (2023) [35] and showed that it ranges from 3.4 to 106.2 mg/m^3.

In comparison with coal mines, oil shale mines produce dust with a different composition [27][28]. According to the authors' study, oil shale dust contains minerals such as quartz, gypsum, and mica, as well as various chemical compounds associated with oil and gas production processes (kerogen, lead, cadmium, etc.). Typical oil shale mineral parts chemical composition consists of SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, SO_3, K_2O, Na_2O, P_2O_5, and kerogen oil with an elemental composition H, C, S, N, and O [36][37]. As an unconventional resource, oil shale is widely distributed around the world and has a very high potential; however, industrial mining produces it only in China, Estonia, and Brazil [36][37]. For this reason, there are only a few studies related to oil shale dust compounds, and none about particulate matter or aerosol concentration and distribution in oil shale underground mines. Wang et al. (2019) [27], in their study about the explosibility of oil shale dust, argued that dust particles in oil shale have an extremely small size and fine dispersion. In the study of kinetic analysis on the deflagration characteristics of oil shale dust conducted by Meng et al. (2022) [38], the distribution of particles of oil shale dust was determined using a laser particle size analyzer called ‘Mastersizer 2000’. The average particle size of two different oil shales was 15 μm and 60 μm, respectively. In studies conducted by Yu et al. (2017) [39], the particle sizes in the oil shale dust were measured using a laser diffraction analyzer with particle sizes 68–80 μm. Teinemaa et al. (2002) [40] investigated oil shale combustion fly-ash aerosols and stated the bimodal composition first maximum at 0.1 μm (fine particles) and the second maximum around 3.5 μm (coarse particles).

However, all of these studies on oil shale were limited to measurements, monitoring, and analysis of PM and LDSA in underground oil shale mines, and therefore focused on the air quality problems in operational faces. The aim of this research is to analyse PM and LDSA concentrations in the operational workings of the oil shale underground mine. Producing relationships between currently used PM indicators and more descriptive and innovative indicators (LDSA and PNC) determines the need to study these components. The investigation of the correlation between LDSA and PM_1 and $PM_{2.5}$ is an important part of this research because these indicators have more diverse sources, including diesel exhaust emissions and secondary aerosol formation, which might be anthropogenic or biogenic in origin [41]. Kuula et al. (2020) and Luoma et al. (2021) stated in their studies that $PM_{2.5}$ has been shown to highly correlate with BC and LDSA [18][42]. PM_{10} concentrations are dominated by noncombustion sources, e.g., dust.

References

1. McDonald, J.D.; Zielinska, B.; Sagebiel, J.C.; McDaniel, M.R.; Mousset-Jones, P. Source apportionment of airborne fine particulate matter in an underground mine. J. Air Waste Manag. Assoc. 2003, 53, 386–395.
2. Ghose, M.K. Generation and quantification of hazardous dusts from coal mining in the indian context. Environ. Monit. Assess. 2007, 130, 35–45.
3. Saarikoski, S.; Teinilä, K.; Timonen, H.; Aurela, M.; Laaksovirta, T.; Reyes, F.; Hillamo, R. Particulate matter characteristics, dynamics, and sources in an underground mine. Aerosol Sci. Technol. 2018, 52, 114–122.
4. Timonen, H.; Teinilä, K.; Aurela, M.; Reyes, F.; Vásquez, Y.; Bloss, M.; Oyola, P.; Hillamo, R.; Asmi, E.; Saarikoski, S. Sources and composition of particulate matter in boreal arctic environment next to an active mining area. Boreal Environ. Res. 2018, 23, 105–125.
5. McDonald, J.D.; Zielinska, B.; Sagebiel, J.C.; McDaniel, M.R. Characterization of fine particle material in ambient air and personal samples from an underground mine. Aerosol Sci. Technol. 2002, 36, 1033–1044.
6. Straif, K.; Benbrahim-Tallaa, L.; Baan, R.; Grosse, Y.; Secretan, B.; El Ghissassi, F.; Bouvard, V.; Guha, N.; Freeman, C.; Galichet, L.; et al. A review of human carcinogens-Part C: Metals, arsenic, dusts, and fibres. Lancet Oncol. 2009, 10, 453–454.
7. Leung, C.C.; Yu IT, S.; Chen, W. Silicosis. Lancet 2012, 379, 2008–2018.
8. Li, S.; Chen, X.; Peng, G.; Han, M.; Guo, Q.; Hou, J.; Gao, B. Research on the Evaluation of Air Quality in Underground Coal Mines Based on a Generalized Contrastive Weighted Comprehensive Scale Index Method. Atmosphere 2023, 14, 1021.
9. Liu, W.; Zhou, Y. Study of comprehensive evaluation on air quality in mine based on matter element model. Miner. Resour. Dev. 2015, 35, 61–63. (In Chinese)
10. Patra, A.K.; Gautam, S.; Kumar, P. Emissions and human health impact of particulate matter from surface mining operation—A review. Environ. Technol. Innov. 2016, 5, 233–249.
11. Saarikoski, S.; Salo, L.; Bloss, M.; Alanen, J.; Teinilä, K.; Reyes, F.; Timonen, H. Sources and characteristics of particulate matter at five locations in an underground mine. Aerosol Air Qual. Res. 2019, 19, 2613–2624.
12. Roy, D.; Singh, G.; Gosai, N. Identification of possible sources of atmospheric PM 10 using particle size, SEM-EDS and XRD analysis, Jharia Coalfield Dhanbad, India. Environ. Monit. Assess. 2015, 187, 680.
13. Puławska, A.; Manecki, M.; Flasza, M.; Styszko, K. Origin, distribution, and perspective health benefits of particulate matter in the air of underground salt mine: A case study from Bochnia, Poland. Environ. Geochem. Health 2021, 43, 3533–3556.
14. Akinyemi, S.A.; Oliveira, M.L.; Nyakuma, B.B.; Dotto, G.L. Geochemical and morphological evaluations of organic and mineral aerosols in coal mining areas: A case study of Santa Catarina, Brazil. Sustainability 2022, 14, 3847.
15. Diesel Particulate Matter Exposure of Underground Coal Miners. (2001, January 19). Federal Register. Available online: https://www.federalregister.gov/documents/2001/01/19/01-995/diesel-particulate-matter-exposure-of-underground-coal-miners (accessed on 17 December 2023).

16. Afshar-Mohajer, N.; Foos, R.; Volckens, J.; Ramachandran, G. Variability of aerosol mass and number concentrations during taconite mining operations. J. Occup. Environ. Hyg. 2020, 17, 1–14.

17. Braakhuis, H.M.; Park, M.V.; Gosens, I.; De Jong, W.H.; Cassee, F.R. Physicochemical characteristics of nanomaterials that affect pulmonary inflammation. Part. Fibre Toxicol. 2014, 11, 18.

18. Kuula, J.; Kuuluvainen, H.; Niemi, J.V.; Saukko, E.; Portin, H.; Kousa, A.; Aurela, M.; Rönkkö, T.; Timonen, H. Long-term sensor measurements of lung deposited surface area of particulate matter emitted from local vehicular and residential wood combustion sources. Aerosol Sci. Technol. 2020, 54, 190–202.

19. Kuuluvainen, H.; Rönkkö, T.; Järvinen, A.; Saari, S.; Karjalainen, P.; Lähde, T.; Pirjola, L.; Niemi, J.V.; Hillamo, R.; Keskinen, J. Lung deposited surface area size distributions of particulate matter in different urban areas. Atmos. Environ. 2016, 136, 105–113.

20. Huynh, T.; Ramachandran, G.; Quick, H.; Hwang, J.; Raynor, P.C.; Alexander, B.H.; Mandel, J.H. Ambient fine aerosol concentrations in multiple metrics in taconite mining operations. Ann. Work. Expo. Health 2018, 63, 77–90.

21. Tran, P.T.M.; Ngoh, J.R.; Balasubramanian, R. Assessment of the integrated personal exposure to particulate emissions in urban micro-environments: A pilot study. Aerosol Air Qual. Res. 2020, 20, 341–357.

22. Salo, L.; Rönkkö, T.; Saarikoski, S.; Teinilä, K.; Kuula, J.; Alanen, J.; Keskinen, J. Concentrations and size distributions of particle lung-deposited surface area (LDSA) in an underground mine. Aerosol Air Qual. Res. 2021, 21, 200660.

23. Jafarigol, F.; Sabanov, S.; Magauiya, N.; Dauitbay, Z.; Qureshi, A.R.; Adotey, E.; Salmanimojaveri, M.; Torkmahalleh, M.A. Particle number, mass, and surface area concentrations inside an underground metalliferous mine in Kazakhstan. Atmos. Pollut. Res. 2023, 14, 101871.

24. Delfino, R.J.; Sioutas, C.; Malik, S. Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health. Environ. Health Perspect. 2005, 113, 934–946.

25. Schiavo, B.; Morton-Bermea, O.; Meza-Figueroa, D.; Acosta-Elías, M.; González-Grijalva, B.; Armienta-Hernández, M.A.; Claudio Inguaggiato, C.; Valera-Fernández, D. Characterization and Polydispersity of Volcanic Ash Nanoparticles in Synthetic Lung Fluid. Toxics 2023, 11, 624.

26. Kalaiarasan, G.; Kumar, P.; Tomson, M.; Zavala-Reyes, J.C.; Porter, A.E.; Young, G.; Sephton, M.A.; Abubakar-Waziri, H.; Pain, C.C.; Adcock, I.M.; et al. Particle Number Size Distribution in Three Different Microenvironments of London. Atmosphere 2024, 15, 45.

27. Wang, J.; Meng, X.; Ma, X.; Xiao, Q.; Liu, B.; Zhang, G. Experimental study on whether and how particle size affects the flame propagation and explosibility of oil shale dust. Process Saf. Prog. 2019, 38, e12075.

28. Wang, Z.; Li, S.; Ren, T.; Wu, J.; Lin, H.; Shuang, H. Respirable dust pollution characteristics within an underground heading face driven with continuous miner–A CFD modelling approach. J. Clean. Prod. 2019, 217, 267–283.

29. Lepistö, T.; Kuuluvainen, H.; Lintusaari, H.; Kuittinen, N.; Salo, L.; Helin, A.; Niemi, J.V.; Manninen, H.E.; Timonen, H.; Jalava, P.; et al. Connection between lung deposited surface area (LDSA) and black carbon (BC) concentrations in road traffic and harbour environments. Atmos. Environ. 2022, 272, 118931.

30. Salo, L. Characterization and Development of Electrical Methods for Aerosol Measurement. 2023. Available online: http://urn.fi/URN:ISBN:978-952-03-2930-3 (accessed on 16 June 2023).

31. Gratt, L.B. Risk analysis of hazardous materials in oil shale. J. Hazard. Mater. 1985, 10, 317–350.

32. Liu, T.; Liu, S. The impacts of coal dust on miners' health: A review. Environ. Res. 2020, 190, 109849.

33. Chang, P.; Xu, G. A review of the health effects and exposure-responsible relationship of diesel particulate matter for underground mines. Int. J. Min. Sci. Technol. 2017, 27, 831–838.

34. Widodo, N.P.; Putra, S.H.; Ihsan, A.; Gautama, R.S.; Cheng, J.; Waly, F.Z.; Permadi, D.A. The study of coal dust minimum explosion concentration of subbituminous coal. Process Saf. Environ. Prot. 2023, 177, 1387–1392.

35. Jin, H.; Li, S.; Yu, H.; Yuan, L.; Zhou, F.; Tan, Z. Filtration of dust particles in underground coal mines. Powder Technol. 2023, 423, 118506.

36. Dyni, J.R. Geology and Resources of Some World Oil-Shale Deposits. Scientific Investigations Report 2005–5294, USGS. 2003. Available online: https://pubs.usgs.gov/sir/2005/5294/ (accessed on 1 June 2006).

37. Sabanov, S.; Qureshi, A.R.; Dauitbay, Z.; Kurmangazy, G. A Method for the Modified Estimation of Oil Shale Mineable Reserves for Shale Oil Projects: A Case Study. Energies 2023, 16, 5853.

38. Meng, X.; Liu, Y.; Wang, J.; Wang, Z.; Yan, K. Experimental study and kinetic analysis on the deflagration characteristics of oil shale dust. Process Saf. Environ. Prot. 2022, 159, 830–841.

39. Yu, L.; Li, G.; Liu, W.; Yu, J.; Yuan, C. Experimental investigations on ignition sensitivity of hybrid mixtures of oil shale dust and syngas. Fuel 2017, 210, 1–7.
40. Teinemaa, E.; Kirso, U.; Strommen, M.; Kamens, R. Atmospheric behaviour of oil-shale combustion fly ash in a chamber study. Atmos. Environ. 2002, 36, 813–824.
41. Sillanpää, S.; Fung, P.L.; Niemi, J.V.; Kousa, A.; Kangas, L.; Zaidan, M.A.; Timonen, H.; Petäjä, T.; Kulmala, M.; Hussein, T. Long-term air quality trends of regulated pollutants in Helsinki metropolitan area in 1994–2019 and implications to air quality index. Boreal Environ. Res. 2022, 27, 61–79. Available online: http://hdl.handle.net/10138/343590 (accessed on 17 December 2023).
42. Luoma, K.; Niemi, J.V.; Aurela, M.; Fung, P.L.; Helin, A.; Hussein, T.; Kangas, L.; Kousa, A.; Rönkkö, T.; Timonen, H.; et al. Spatiotemporal variation and trends in equivalent black carbon in the Helsinki metropolitan area in Finland. Atmos. Chem. Phys. 2021, 21, 1173–1189.