Responsible Mining in The Arctic: Management, Monitoring and Mitigation of Dust Emissions

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Significant reserves of base metals and critical minerals such as rare earth elements vital for renewable energy, electronics and defense are present across the Arctic. As global demand rises, the region has become strategically important, exemplified by U.S. interest in Greenland. However, mining in the Arctic poses serious environmental risks, including erosion, biodiversity loss and contamination of soil and water. Emissions of mineral dust from open-pit mining is one of the major concerns as they have adverse effects on local communities and surrounding environments. Despite the potential impacts, dust emissions from Arctic mines remain poorly quantified and effective international guidelines for dust monitoring and dust mitigation are currently lacking. Addressing these shortcomings will be essential for responsible expansion of mining in the Arctic to minimize impacts on the environment. This paper reviews mining dust sources, potential adverse environmental effects, as well as relevant legislation and dust management practicesin Arctic mines and highlights key issues for future research to further improve the mitigation of negative environmental impacts by mineral dust caused by mining in the Arctic.

Introduction

The Arctic holds vast resources of critical minerals including rare earth elements, base metals, uranium and many other elements which are essential for renewable energy systems, electronics and military equipment. As global demand for these raw materials surges, the Arctic has become a strategic battleground for major powers. This was recently illustrated when the U.S. administration, citing national security and economic reasons, expressed interest in acquiring Greenland, causing diplomatic frictions with its national government, Denmark and the European Union.

Responsible future expansion of mining in the Arctic will require that best practices for environmental protection be developed and enacted. Fugitive dust emissions from surface mining operations are a commonly reported source of annoyance with nearby communities during the

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exploration, operational and post-operational stages of mining. However, the emitted dust from mining may also be a respiratory hazard and can carry toxic metals that may contaminate soils, surface waters and biota (Csavina *et al.,* 2011, 2012). Given that surface (open-pit) mineral extraction is a common practice in northern regions (partly due to low population density), improving dust control and monitoring methods is essential for any ongoing and future Arctic mine development. Currently, consistent, socially relevant and effective tools and internationally accepted guidelines to control, monitor and mitigate mining dust emissions are still lacking.

Dust emissions from both natural and mining related sources within the Arctic are poorly quantified but may have local to regional significance to climate and the environment. Depending on the source and characteristics of dust, it may function as short-lived climate forcers (acting on surface and cloud albedo), as pollutants and/or sources of marine nutrients such as phosphorous or iron (Meinander *et al.*, 2022). local impacts from mining dust are likely to be exacerbated if the future Arctic seasonal snow cover extent declines, as many climate models project, thus enabling more dust entrainment by wind (Khani *et al.,* 2025). Hence, characterizing and quantifying current mining dust emissions and transport in the Arctic as well as their sensitivities to climate related factors (i.e., wind, soil moisture and snow cover) is an important goal. In this paper, we provide a brief overview of current practices for dust management and governmental regulation of mines in the Arctic, and we identify key environmental issue for future research to support responsible and efficient use of mineral resources while minimizing impacts on the environment.

Sources and impacts of dust from Arctic mines

Definitions and scope

We adopt the Arctic Monitoring and Assessment Programme (AMAP)'s definition of the Arctic region, encompassing many land areas as far south as 58° N which include vast mineral-rich regions of Russa, Greenland, Canada, Alaska, and Iceland. Mining activity refers to the excavation of minerals at and/or below the surface, the transport and hoisting of aggregates, ore dressing, and other processing of raw materials occurring on site. Dust emissions are most commonly associated with open-pit mines (bedrock-hosted or placer deposits) but can also occur when ore extracted underground is processed at the surface or transported overland. At present, approximately 35 mines with the potential to produce large dust emissions are either operating or in an advanced planning stage within the AMAP Arctic boundaries, excluding Russia (Table 1). The number of active mines across the Russian Arctic that are likely to generate large dust emissions is not presently known.

Country	Mine	Lat. (°)	Raw material(s)	Active	Temp. closed	Planned
Greenland *(Denmark)*	Qaqortorsuaq (White Mountain)	67	Anorthosite, Al, Si, Ca	X		
	Aappaluttoq	60	Rubies		X	
	Nalunaq	60	Au	X		
	Citronen	83	Zn			X
	Dundas	76	TiO_2			
	Tanbreez	61	REE			X
Norway	Engebøfjellet	61	TiO_2			X
	Ørtfjell/Storforshei	66	FeOx			
	Lillebukt	70	Nepheline	X		
	Sydvaranger	69	Fe		X	X
Sweden	Kirunavaara (Kiruna)	68	FeOx	X		
	Leveäniemi (Svappavara)	67	FeOx	X		
	Tapuli (Pajala)	67	FeOx			X
	Sahavaara (Pajala)	67	FeOx			X
	Palotieva (Pajala)	67	FeOx	X		
	Malmberget (Gällivare)	67	FeOx	X		
	Aitik (Gällivare)	67	Cu, Au, Ag	X		
Finland	Kittlilä	68	Au, Ag	X		
	Kevitsa	67	Ni, Cu, Co, PGE, Au	X		
	Hannukainen	67	Fe, Cu, Au			X
	Suhanko	66	Ni, Cu, Co, PGE			X
Canada	Ekati	64	Diamonds	X		
	Diavik	64	Diamonds	X		
	Gahcho Kué	63	Diamonds	X		
	Nechalacho	62	REE	X		
	Nechalacho - Thor Lake	62	REE, Zr			X
	Meadowbank - Amaruq	65	Au	X		
	Eagle Gold	64	Au, Ag		X	
	Mary River	71	FeOx	X		
	Back River	66	Au, Ag			
	Hope Bay	68	Au		X	
	Meliadine	63	Au	X		
USA	Red Dog	68	Pb, Zn, Ag	X		
	Fort Knox	65	Au	X		
	Pogo	64	Au	X		
	Usibelli	63	Coal	X		

Table 1: Recension of Arctic mines susceptible to generating large dust emissions, based on data gathered from the internet web pages of operating companies or publicly available governmental sources, as of June 2025. Russia is excluded due to incomplete data. Only operating mines, or planned mines in advanced stages of development, are included.

Sources of dust emissions at Arctic mine sites

Dust emissions during mining and mineral processing may be produced by a range of activities including blasting to extract the ore from the ground, hauling the material, crushing it, and extracting the desired components (Fig. 1). All these processes produce dust with different elemental composition and particle size distribution (Csavina *et al.*, 2011, 2012; Saarikoski *et al.*, 2019; Saarikoski *et al.*, 2017). Blasting, crushing and grinding (milling) of ores for mineral liberation commonly produces concentrates of minerals or metals, waste rock and tailings that contain large amounts of particles <150 μm. If improperly stored and managed, these fine-grained materials are prone to wind deflation and dispersion of fugitive dust over distances of tens of kilometers or more. This is especially concerning for open-pit mines operating in treeless, windswept subarctic and Arctic landscapes, as dust storms in these regions are known to transport sediments over much longer distances, and even over open seas (e.g., Ranjbar *et al.* 2021, Baddock *et al.* 2025). Heavy vehicle operations over unpaved roads (e.g., for hauling ore, site construction, maintenance) further contribute to mobilize and disperse dust (Noble *et al.*, 2017). In mines that operate smelters to refine ores, the impacts of dust emissions on the local environment are further compounded with those of stack emissions, which can emit greenhouse gases, acidifying gases (when processing sulfide ores) and fine aerosols enriched in toxic compounds, such as arsenic trioxide dust released when processing some gold ores (Ettler 2016, Csavina *et al.*, 2011, 2012).

Fugitive dust arising from mining operations in the Arctic can be a serious concern to surrounding communities. This was recently illustrated by the Mary River iron oxide mine, Baffin Island, Canada, where local concerns about the impacts of dust dispersion from the mine brought a temporary halt to expansion plans (He *et al.*, 2023).

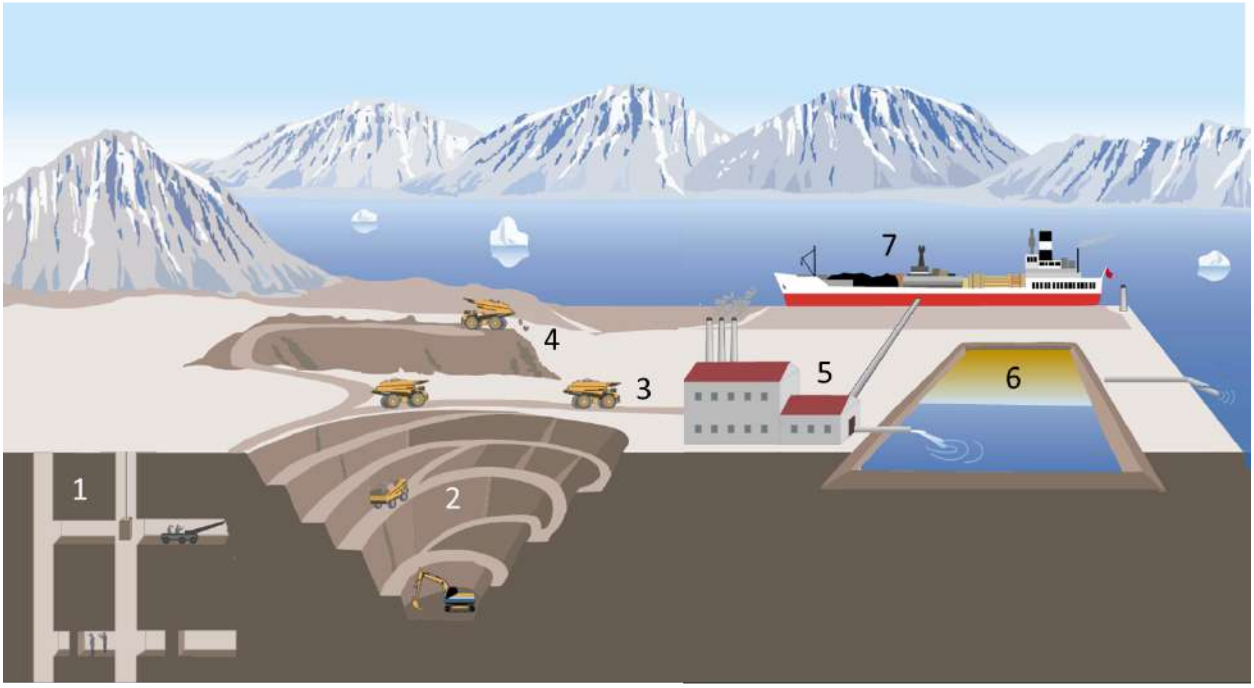

Figure 1. Common sources of dust emissions in Arctic mines. 1) Underground operations and ventilation; 2) fugitive emissions from blasting, crushing, conveying, stockpiling, loading and hauling of host rock and ore in open pits; 3) fugitive emissions from unpaved haul road transportation; 4) fugitive emissions from waste rock deposition; 5) point source and fugitive emissions from processing plants and smelters; 6) fugitive emissions from tailings storage facilities including tailings beaches for slurry deposition and uncovered dry stacks; 7) ports and unloading facilities (Modified from (Johansen *et al.,* 2001))

Potential impacts of mining dust on human health and environment

Emissions of mineral dust from mining operations can have negative impacts on surrounding environments and local communities (Cleaver *et al.*, 2021). Mineral dust may contain metals, metalloids or sulfide minerals that are harmful to the environment and cause an increase in toxic metal concentrations or acidity in soils, which may in turn reduce water quality in water bodies (Cleaver *et al.*, 2021). To quantify and mitigate the hazards posed by dust from mining operations it is crucial to understand both the mineralogy and geochemistry of the dust generated from all possible sources of emissions (Noble *et al.*, 2017). Characterization of country rock native to the area, as well as ore, waste rock and tailings, both before and after physical and chemical treatment of the mineral fractions, is essential for predicting the potential toxicity of dust in the terrestrial and aquatic environment.

Direct health risks commonly associated with mining are deterioration of air quality and inhalation of dust particles. Depending on the size, shape and composition of the dust particles these can penetrate into the respiratory system causing lung cancer, silicosis and other adverse impacts to the respiratory system (Noble *et al.*, 2017). In the Arctic, the remoteness of mining projects and low population density often limit exposure risks for local communities, as the majority of coarse mode particles most likely have settled out of the atmosphere before reaching local communities. In Greenland, Canada and Alaska the majority of active and/or approved mining operations are generally located far from local communities (PAME, 2025) creating isolated and local hotspots of industrial activity in otherwise pristine environments. At these locations, the potential impacts on human health are mostly limited to the mine.

Wind dispersal of mineral dust from the various emission sources in the mining project (Fig. 1) is a common pathway for the spread of both inert and reactive material into terrestrial and aquatic environments (Cleaver *et al.*, 2021). Depending on the type of mining operation and geochemical composition of the dust, the dispersal can lead to bioaccumulation of heavy metals in soils, sediment, water bodies and vegetation. While field evidence on mining-related bioaccumulation of heavy metals is limited in the Arctic, studies from other regions show that elements such as cadmium, zinc and lead have the highest potential impact on soil contamination and risk to fauna and flora (Brumbaugh *et al.,* 2011; Krasavtseva *et al.,* 2023; Wieczorek *et al.,* 2023)(Wieczorek *et al.*, 2023).

Tundra ecosystems are sensitive to disturbance and slow to recover. To account for environmental costs of Arctic developments including mining, the cumulative impacts of dust emissions and dust deposition from all identified sources should be quantified (Myers-Smith *et al.*, 2006). In the Arctic, significant increases of mineral dust deposition on vegetation in grazing areas for sheep, reindeer and musk oxen could potentially have negative impacts on animals via increased tooth wear and stunted plant growth (Glaze *et al.*, 1982). Studies have shown that both dust and silica phytoliths contribute to reducing tooth volume during chewing. However, the way and the extent to which they individually contribute to tooth wear in natural conditions is unresolved and there is still debate as to whether dental microwear represents a dietary or an environmental signal (Merceron *et al.*, 2016). Despite the uncertainties on factors that may influence tooth wear on animals, two factors are most often mentioned: (1) the endogenous physical properties of ingested foods and (2) the exogenous grit adhering to them (Spradley *et al.*, 2016). Other studies have documented that increased anthropogenic dust inputs can have a direct impact on both substrate properties and changes in plant community composition over time (Myers-Smith *et al.*, 2006; Walker & Everett, 1987).

In large parts of the ice-free areas of Greenland, the vegetation cover is impacted by elevated dust deposition from natural sources such as proglacial outwash plains (Anderson *et al.*, 2017). An important knowledge gap exists regarding the natural resilience of current vegetation to the cumulative effects of increased dust inputs from expanded mining in these areas, and how the large grazers such as musk oxen and reindeer may be impacted. Similarly, additional dust emissions and depositions from proposed mining operations have raised significant concern amongst sheep farmers and non-governmental organizations (NGO's) in South Greenland (Andersen, 2018).

The perceptions of local reindeer herders in Finland and Sweden on the impacts of the mining industry on their environment and reindeer herding and how herders cope with the impacts of mining were investigated through interviews by Turunen *et al.* (pers. comm., 2025). They found a perceived increasing impact of mineral dust deposition on terrestrial tundra and boreal forest ecosystems, which provide the foundation for the ecosystem services for the Indigenous and local people in the Arctic. While the Turunen *et al.* study assessed that long-term dust deposition predominantly affects plant communities via impacts on soil, others have reported different and indirect routes of action through which mineral dust from mines can affect the physiological responses of plants and induce secondary stresses such as drought, insects, pathogens or allow penetration of toxic elements and/or phytotoxic gaseous pollutants (Farmer, 1993).

Another consequence of windborne dust dispersion in cold environments is to lower the albedo (reflectance) of snow and ice-covered surfaces on which the dust is deposited which in turn promotes accelerated thaw and melt (Painter *et al.*, 2018; Réveillet *et al.,* 2022; He *et al.*, 2023). This occurs because many types of dust, and especially those containing iron oxides, strongly absorb sunlight at visible to near-infrared wavelengths (e.g., Reynolds *et al.*, 2014). This albedo-lowering effect was one of the concerns raised by Baffin Island Inuit residing near the Mary River iron oxide mine, where dust dispersion caused local changes to the characteristics the coastal sea ice surface (CBC, 2019; *Nunatsiaq News*, 2022), an important consideration for people who seasonally travel, fish and hunt on the sea ice.

Regulatory framework and current practices for Arctic mines

All eight Arctic states (Canada, Finland, Iceland, the Kingdom of Denmark/Greenland, Norway, the Russian Federation, Sweden and the United States) have national legislation on Environmental Impact Assessments (EIA), which include the following general steps and requirements (Arctic Council, 2019):

1. Screening phase to determine if EIA is needed for the proposed mining project.
2. Scoping phase where the content and extent of the EIA are defined.
3. Gathering of baseline data of pre-mining conditions.
4. Assessments and predictions of potential environmental impacts including the magnitude, probability of occurrence and extent of the identified potential impacts and their significance.
5. Definition of ways to mitigate impacts via mitigation plan or similar.
6. Summary EIA report compiles analysis of assessed impacts and forms the basis for public participation.
7. Plans for environmental monitoring are developed during the EIA.
8. Public display and quality control of EIA report after public participation.
9. The outcome of EIA is considered in decision-making and permitting.

The Environmental Law Alliance Worldwide (ELAW, 2010) and Global Reporting Initiative (GRI-Standards, 2024) both recommend that assessments and monitoring of fugitive dust dispersal and deposition be included in EIAs for mining projects. Such requirements are included in EIA-guidelines and/or in regulations for mining projects in the USA (Alaska), Canada, Greenland, Finland and Sweden, as described below. These regulations cover assessments of potential impacts from dust (step 4) and plans for mitigation (step 5) and monitoring (step 7). Direct involvement of local communities and local knowledge during the EIA process is an important step to ensure transparency in decisions and appropriate protection of traditional land-uses and rights of indigenous people.

In Alaska (USA), the General Mining Law is the primary legislation governing minerals on federal land, while the National Environmental Policy Act mandates environmental impact statements to evaluate the potential environmental effects of mining activities. In Alaska, the Department of Natural Resources oversees the exploration, development, and mining of the state's mineral resources and the Department of Environmental Conservation provides Alaska Pollutant Discharge Elimination System permits (PAME, 2025). However, the permitting and regulatory compliance processes are complex and can involve many other agencies (Adams *et al.*, 2025). For example, at the Red Dog gold mine, compliance with evolving regulations led to the gradual development of a comprehensive dust management plan by the mining company covering emissions from mine waste and haulage roads, accompanied by extensive monitoring of both airborne dust levels and deposition (Exponent, 2011).

In Canada, mining is regulated by frameworks designed to balance resource development with environmental protection and Indigenous rights. The Canadian Mineral and Metals Plan (2019) (Natural Resources Canada, 2019) sets directions to guide industry, government and stakeholder activities in the minerals and metals sector, along with approaches for environmental protection and responsible management. The federal government has gradually transferred responsibilities and powers over land and resources to provincial and territorial governments through devolution agreements (PAME, 2025). An example of this can be found in Yukon Territory's guidelines for mine waste management facilities (Hamilton *et al.*, 2023), which specify operational and active closure monitoring requirements for dust. These guidelines specify the frequency at which airborne dust (or dust fallout) should be sampled, depending on the proximity to the mine, and of the type of dust-borne contaminants to be monitored, including particulates with aerodynamic diameters smaller than 2.5 or 10 μm (PM2.5 and PM10) and toxic metals. Results from dust monitoring should be used to interpret the contaminant loading and dust transport, to inform an adaptive management response of mine waste, and to identify environmental effects or trends ((Hamilton *et al.*, 2023); see Table G-1).

In Finland, mining is regulated through the updated Mining Act (2023) (Finnish Ministry of Employment and the Economy, 2023). Provisions under this act are to be further adapted for mining activities in the Sámi Homeland, to secure the rights of the Sámi as an indigenous people to maintain and develop their language, culture and traditional livelihood. Dust monitoring is typically mandated through environmental permits issued under the Environmental Protection Act (Finnish Ministry of the Environment, 2021). These permits are tailored to each site, and air pollution dispersion monitoring is specified in each case. For example, in the Kevitsa open-pit nickel mine in Sodankylä, the granted mining permit specifies that ambient air concentrations of PM10 are to be measured at a minimum of two sites using continuous analyzers, over a period of at least 8 months, and subsequently at 3 year intervals, one such measurement period to coincide with the phase of maximum quarrying activity.

In Greenland, specific limit values for airborne dust concentrations are set to match international standards for air quality criteria for inhalable particulates (Mineral Resources Authority, 2015), which are typically in the range of 30-50 μg m^{-3} on a daily basis for PM2.5 and PM10 in most Arctic nations. An upper limit of 4 g m^{-2} is set for the monthly mean dust deposition rate at the border of a 500 m buffer zone around sources of dust emissions, which must be monitored for compliance by mining companies. In some cases, separate monitoring of background airborne dust concentrations at selected locations away from the mine may be required to evaluate the extent of dust dispersion. General environmental impacts by dust in the areas surrounding the mine are evaluated by the Environmental Agency for Mineral Resources Activities at the Government of Greenland and its scientific advisors.

In Norway, the Norwegian Government has the overarching ambition to develop the world's most sustainable industry as formulated in the Norwegian Mineral Strategy (Norwegian Ministry of Trade, 2023). In March 2025, the Ministry of Trade, Industry and Fisheries published a new Minerals Act to replace the current 2009 legislation (Nærings- og fiskeridepartementet, 2025). The proposal aims to modernize both the legal framework for mineral activities in Norway and emphasize the protection of Sámi interests and rights in all traditional Sámi areas (Sápmi).

In Sweden, mining is regulated via The Minerals Act and the Minerals Ordinance and administered by the Mining Inspectorate of Sweden. Dust and dust management are regulated at different steps of the mine life. While the main focus is on dust generated during the mine's operational phase, restrictions may also be defined during the permitting process under the Minerals Act regarding dust dispersion during exploration and trial mining. Occupational exposure to inhalable silica dust is also regulated by the Swedish Work Environment Authority. During operation, a mining company must monitor dust emissions from the site and, if limit values are exceeded, take measures to protect the surrounding environment and settlements. The maximum permissible dust fallout rate is defined in the mine permit. For example, at the Aitik copper mine, this limit is set at 200 g 100 m^{-2} per month, and the dust collected is also analyzed for metal content (Boliden, 2018). Enforcement is done by municipalities and county administrative boards who are responsible for ensuring that environmental quality standards are met in planning, decision-making and permitting (EQS, 2010).

Dust mitigation and management methods

Dust management at mining projects is crucial for both the protection of workers (occupational health) and the surrounding environment. Especially for occupational health, The Hierarchy of Controls is a method of identifying and ranking safeguards to protect workers from hazards (NIOSH, 2021). They are arranged from the most to least effective and include elimination, substitution, engineering controls, administrative controls and personal protective equipment.

Hazard controls should be applied in the following order.

1. Elimination—remove the hazard or the need to perform the hazardous activity.
2. Substitution—substitute a safer alternative.
3. Engineering controls—redesign or modify tools or equipment.
4. Administrative controls—use training, rules, procedures to reduce the risk of the hazard.

5. Personal protective equipment—provide fit-for-purpose protective equipment.

More than one control may be needed to adequately control the hazard. The controls used must be maintained to ensure they continue to remain effective, taking its feasibility into consideration. With mining dust, elimination and substitution of the dust hazard is often not possible due to the nature of operations and the protection of workers is commonly ensured by lower-level controls such as filtration and pressurization systems on enclosed cabs on mobile equipment to reduce dust exposure to operators, dry dust collection systems on drills etc. (NIOSH, 2021).

Best general practices for mitigating fugitive dust emissions from mining operations to the surrounding environment generally include (Barthe *et al.*, 2018).

1. Spraying of extractive waste and roads used to transport the extractive waste with water, chemical dust suppressants and/or hygroscopic salts.
2. Capping of extractive waste with temporary or permanent covers.
3. Covering of trucks or other machinery such as conveyors used for the transport of extractive waste.
4. Construction design of haul road surfaces using coarse-grain materials.
5. Use of pipelines to transport extractive waste resulting from mineral processing.
6. Use of wind barriers or fences.
7. Implementation of speed limits for trucks.
8. Implementation of wind speed restrictions for the handling of waste (no extractive waste handling in the case of strong winds).
9. Placement of ore crushing facilities in an enclosed environment with air filtration and dust collection.
10. Water sprays on material conveyors and water curtains on openings to the ambient atmosphere.
11. Landscaping and revegetation of dust prone surfaces.
12. Application of soil amendments to improve soil structure and promote plant growth.

Spraying of water on dust prone materials is often the preferred option at mine sites as it often provides a low-cost and readily available solution. However, the frigid climate at Arctic mines limits the use of water-based solutions to dust suppression as spraying of water can lead to build up of ice on surfaces causing both operational and safety hazards. An alternative is to employ so-called chemical "dust suppressants" such as calcium chloride, hydrocarbon-based fluids or antifreeze emulsions that can be used in sub-freezing temperatures (Agnico Eagle, 2020; Dominion Diamond Mines 2020; Xia *et al.,* 2024). However, the toxicity of commercially available dust suppressants is often unknown or poorly documented and efforts are now being directed at developing more innocuous and biodegradable versions of such products (Kunz *et al.*, 2022). Finding workable alternatives to water application for efficient suppression of fugitive dust at Arctic mines thus remains a challenge and a topic for future research and development.

Dust monitoring methods

At most mine sites, monitoring of dust emissions is an essential part of the dust management strategy and control of environmental compliance (Noble *et al.*, 2017). Dust management plans for mines in the Arctic typically include a combination of approaches including identification of potential sources of dust emission and control and technological ways to reduce emissions to mitigate dust dispersal, defining dust criteria for environmental compliance and systematic monitoring of deposition rates and geochemical properties of deposited dust, if the dust contains heavy metals or other deleterious substances.

Depending on the location of the mine, the operational procedures and the geochemical properties of the dust, a number of standardized monitoring methods can be applied varying both in sophistication (e.g., passive vs. active samplers) and adequacy for a given purpose (e.g., determination of different size fractions or collection of airborne particulates). The specific locations of monitoring stations and instrumentation should be planned to cover all potential sources of dust emissions as identified in the EIA and/or operational plans for the mine site and include control stations outside the area of potential impact by dust dispersal (Noble *et al.*, 2017).

Passive samplers include various types of dust deposition gauges, such as the Bergerhoff sampler, dry foam frisbee samplers, directional samplers and more recently dry deposition samplers (Cleaver *et al.*, 2022). The fundamental principle for all samplers is that they generally monitor total suspended particulates (TSP), do not require electrical power, are generally inexpensive to purchase and deploy and do not require extensive training or specialized skills to operate. In this way, passive samplers provide a cost-effective means to monitor dust in remote areas but can be prone to non-controlled sample loss by turbulent resuspension of collected dust from the receptacles and/or over-icing under sub-zero weather conditions frequently present in the Arctic. For example at the Malmberget and Kiruna iron oxide mines in Sweden, dust fallout over the nearby populated areas is monitored using passive samplers and the data are publicly reported for specific elements of concern, such as trace metals (LKAB 2025)

Active samplers such as high and/or medium volume air samplers can be fitted with size selective inlets and thereby also sample particles in the PM2.5 and/or PM10 size range. The flow rate of air is controlled and recorded using flow regulators and microcontrollers by which known volumes of air can be passed through a filter media onto which the particles in the air stream are deposited for gravimetric determination and/or chemical analysis. Medium volume samplers can be operated also by batteries for possible measurements at off grid monitoring stations with operations extended by solar panels during the part of the year where sufficient incoming solar radiation is available.

While active and passive samplers provide measurements of average dust deposition and concentrations over the sampling period, real-time dust monitors can provide time-series on the variations of dust concentrations in the air based on measurement principles such as light scattering in optical particle counter and tapered element oscillating microbalances.

Qualitative monitoring of dust deposition in the Arctic can also be achieved using biota such as lichens (Riget *et al.*, 2000; Cleaver *et al.*, 2022; Pouillé *et al.*, 2024) and is now included in most monitoring programs at Greenland mine sites as well as in other mines in subarctic Scandinavia such as the Aitik copper mine, Sweden (Boliden, 2018). Since lichens have no roots, all metals accumulated in the tissue comes from atmospheric deposition. Hence, metal accumulation by lichens is a qualitative indicator of dust dispersion and deposition in areas surrounding mine site. However, the direct correlation between metal accumulation rates in lichens and the corresponding dust deposition remains poorly quantified, especially in the Arctic where snow-covered periods may shorten dust exposure periods for ground-based lichens.

Summary and priorities for future research

The area of impact of fugitive dust emissions from Arctic mining operations is potentially far-reaching. This is exemplified in the dust monitoring at the Mary River iron mine where dust impacts on snow albedo were observed more than 60 km away from the site, exceeding the distance between the mine and ground-based dust sampler reference sites installed for monitoring (He *et al.*, 2023). Similar long-reaching impacts has been observed at Maarmorilik mine in Greenland where elevated metal concentrations in sediment and lichens where detectable up to 35 km from the mine (Søndergaard *et al.*, 2011). These examples demonstrate that the monitoring of environmental impacts from dust has to be considered at not only the local but also regional scale.

The particles size distribution of particulate matter originating from open pit mining area is typically dominated by submicron particles (PM1) resulting from vehicular emissions and super micron particles (PM1–PM10) for general mining activities, including re-suspended road dust (Timonen *et al.*, 2018). For submicron particles, the particles can have a high contribution of black carbon and organics as is typical for engine emissions, whereas the coarse particles more directly reflect the mineralogical sources materials. Fine particulates such as those resulting from smelting operations may also disperse more readily into the environment and become more bioavailable due to their high specific surface area (Csavina *et al.*, 2011). Appointment of various sources of dust emitted within a mine project has successfully been achieved using portable X-ray fluorescence spectroscopy and multivariate statistics to establish the geochemical fingerprint of emitted dust (Søndergaard & Jørgensen, 2021). Results indicate that this analytical approach may be an appropriate tool for quick and cost-effective dust source characterization for efficient identification of unexpected dust emissions at mine sites.

Sources of particles and dust due to mining activities remain poorly characterized in the scientific literature. This complicates the evaluation of environmental impacts of mining and health impact assessments. Important environmental knowledge gaps have been identified for the future improvement of dust management in Arctic mines (Huntsman *et al.*, 2025). A strengthened focus on effective dust management strategies and techniques will improve the development of responsible mining in the Arctic, including reduction of emissions of dust and contaminants to air, water and soil encouraging both regulators and mining companies to adopt sustainable practices.

In our review, the following main topics for future research have been identified:

1. Better characterization of dust monitoring techniques suitable for cold and remote Arctic conditions, including passive, active and biological samplers.
2. Improved understanding on the dust sampling efficiency of site-specific species of lichens for long-term qualitative dust monitoring.
3. More focus on the cumulative ecological impacts of mining dust on flora and fauna, including expanded investigations over space and time.

4. New methods for dust source apportionment – both within mining operations and in the surrounding environment.
5. Expanded geochemical and mineralogical characterization of site-specific mining dust.
6. Better understanding on the fate of dust in the environment in both the terrestrial and aquatic environment, including potential for bioaccumulation and immobilization of heavy metals.
7. Better understanding on the impacts of mining dust on wildlife in surrounding areas, including feedback between feedstock quality and quantity.
8. Better understanding of the impacts of mining dust on the cryosphere (e.g., snow, glaciers and sea-ice) and feedback to climate change.
9. Targeted methods and techniques for minimizing dust emissions at mining operations in the Arctic, including fugitive emissions from unpaved roads and tailings facilities.
10. Definition of Best Available Technologies (BAT) and Best Environmental Practices (BEP) for dust management at Arctic mines.
11. More focus on testing procedures to predict the chemical and mineralogical properties of mineral dust from mining operations.
12. More focus on bridging the information gap between regulators, mining companies and local communities, including safeguarding the quality of habitats in respect and traditional, cultural and spiritual values of Indigenous communities.

Notes

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