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Journal of Occupational Medicine and Toxicology (2024) 19:35
https://doi.org/10.1186/s12995-024-00433-6

Journal of Occupational Medicine and Toxicology

REVIEW

Open Access

Occupational, environmental, and toxicological health risks of mining metals for lithium-ion batteries: a narrative review of the Pubmed database

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Abstract

Background The global market for lithium-ion batteries (LIBs) is growing exponentially, resulting in an increase in mining activities for the metals needed for manufacturing LIBs. Cobalt, lithium, manganese, and nickel are four of the metals most used in the construction of LIBs, and each has known toxicological risks associated with exposure. Mining for these metals poses potential human health risks via occupational and environmental exposures; however, there is a paucity of data surrounding the risks of increasing mining activity. The objective of this review was to characterize these risks.

Methods We conducted a review of the literature via a systematic search of the PubMed database on the health effects of mining for cobalt, lithium, manganese, and nickel. We included articles that (1) reported original research, (2) reported outcomes directly related to human health, (3) assessed exposure to mining for cobalt, lithium, manganese, or nickel, and (4) had an available English translation. We excluded all other articles. Our search identified 183 relevant articles.

Results Toxicological hazards were reported in 110 studies. Exposure to cobalt and nickel mining were most associated with respiratory toxicity, while exposure to manganese mining was most associated with neurologic toxicity. Notably, no articles were identified that assessed lithium toxicity associated with mining exposure. Traumatic hazards were reported in six studies. Three articles reported infectious disease hazards, while six studies reported effects on mental health. Several studies reported increased health risks in children compared to adults.

Conclusions The results of this review suggest that occupational and environmental exposure to mining metals used in LIBs presents significant risks to human health that result in both acute and chronic toxicities. Further research is needed to better characterize these risks, particularly regarding lithium mining.

Keywords Lithium-ion batteries, Mining, Metal toxicity, Climate change, Environmental health, Occupational health

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Introduction

In recent years, the global market for lithium-ion batteries (LIBs) has grown exponentially in response to increasing economic and political interests in energy alternatives to fossil fuels [1]. LIBs are rechargeable batteries that are used in a multitude of products including electric motor vehicles, smartphones, laptops, power tools, and energy storage systems. Rapid economic growth is projected to continue, with the global LIB market currently valued around $54 billion and anticipated to increase by 20–30% annually until 2030 [2, 3]. Consequently, there has been a dramatic increase in efforts to mine the metals used to manufacture LIBs [4].

In addition to the titular lithium, LIBs contain transition metals that are typically used to construct the cathode of the battery system [5]. The anode is generally constructed of graphite. Cobalt, manganese, nickel, and lithium are four of the most heavily mined metals for LIB production [5]. Large quantities of these metals are often required for manufacturing. A single car battery, for example, can contain up to 20 kg of cobalt [6]. Significant expansion of mining activities for these metals is occurring on a global scale and poses potential health risks to mine workers and neighboring communities via occupational and environmental exposures [7]. Despite this, there is a paucity of data surrounding the risks of such increased mining activity.

Each of the metals in this study has well-documented toxicity. The respiratory effects of cobalt have been described for centuries, since German miners discovered that toxic gases were released during the smelting process [8]. The miners believed the metal was bewitched by devilish spirits and nicknamed the metal "kobold" or "goblin of the mines". Cobalt inhalation can cause direct respiratory toxicity, including hard metal lung disease, while systemic cobalt toxicity can cause cardiomyopathy, thyroid dysfunction, neurologic dysfunction, and aseptic lymphocyte-dominated vasculitis-associated lesions [9]. The neurotoxicity of manganese has been extensively documented and was described as early as the nineteenth century. Occupational and environmental exposures have been associated with numerous neurologic and psychiatric manifestations including Parkinsonism, motor deficits, cognitive impairment, and psychosis [10]. Nickel is a known genotoxin and carcinogen [11]. Occupational exposure primarily occurs through inhalation; however, toxicity can also develop via ingestion or skin absorption [12]. Lithium is nephrotoxic and thyrotoxic, can cause neuropsychiatric symptoms, and is a teratogen [13, 14].

In this study, we conducted a narrative review of the occupational, environmental, and toxicological hazards associated with mining exposure to cobalt, lithium, manganese, and nickel to better characterize the risks associated with growing demand for LIBs.

Methods

We systematically searched the PubMed database using the pre-defined search term "((cobalt) OR (lithium) OR (manganese) OR (nickel)) AND ((health) OR (disease) OR (injury)) AND ((mine) OR (mining))" on January 24, 2024. We analyzed the results of the search in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [15]. We did not apply any other restrictions to the initial search. We imported all studies resulting from this search into Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia) for review. A minimum of two authors independently screened titles and abstracts for inclusion, with discrepancies resolved by a third author. We then reviewed full texts for all articles included in the screening.

We included studies if they (1) reported original research, (2) reported outcomes directly related to human health, (3) assessed exposure to mining for cobalt, lithium, manganese, or nickel, and (4) had an English translation that could be obtained electronically either via internet search or inter-library loan. We excluded studies that did not meet all inclusion criteria. Following review, we extracted the following variables from the articles meeting inclusion criteria, as applicable: date of publication, country or countries in which the study was conducted, study design, which of the four previously chosen metals (cobalt, lithium, manganese, or nickel) were included, report of human health or toxicological hazards, report of traumatic hazards, report of non-traumatic occupational hazards, and calculated health risk based on environmental data.

Results

The initial search term yielded 649 unique articles, of which 183 met inclusion criteria (Fig. 1). The final set of included articles contained 22 cohort studies, 3 case–control studies, 91 cross-sectional studies, and 4 case reports or series, in addition to 2 in vitro studies and 61 articles that calculated human health risk based on environmental sampling without including human participants. Included articles were published between 1955 and 2023 and came from 47 countries (Fig. 2). The countries that appeared most frequently were China (30 articles), the Democratic Republic of the Congo (12), Mexico (11), and South Africa (11). Manganese appeared in the most articles, while lithium appeared in the least. Many articles discussed more than one of the study metals.

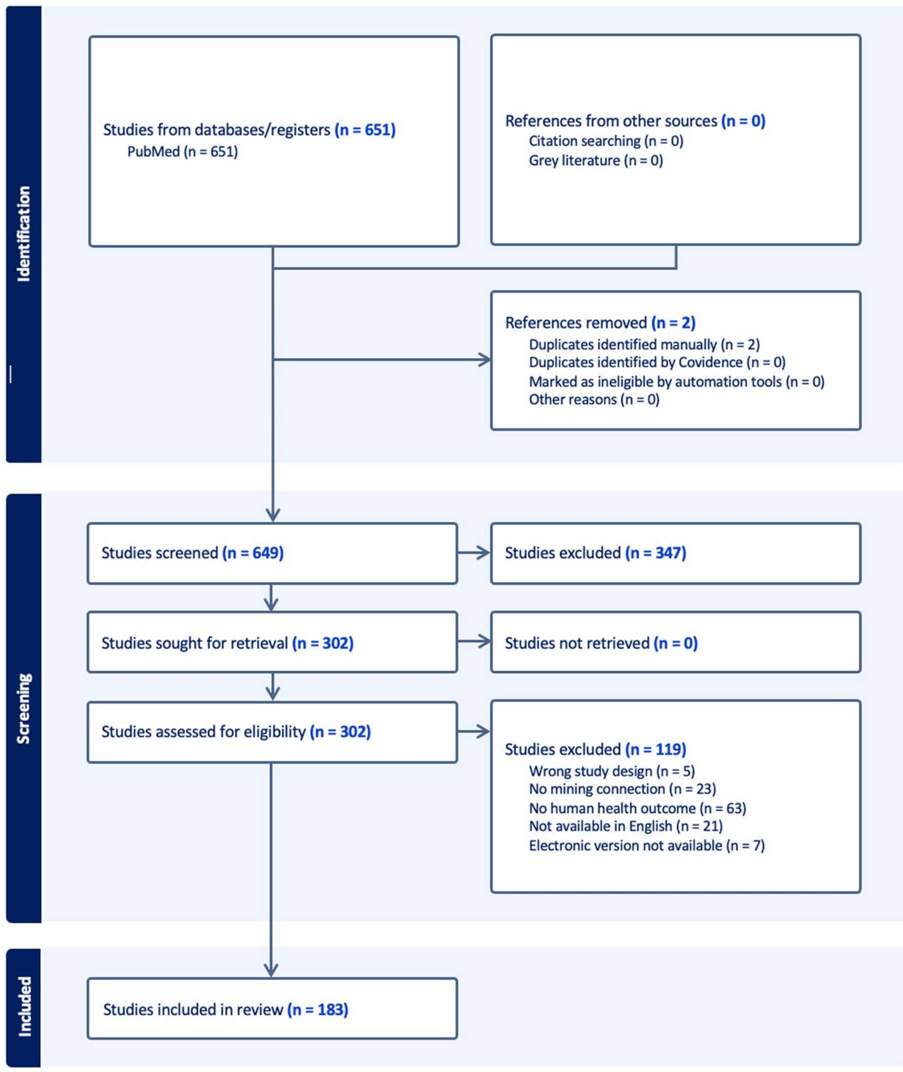

Fig. 1 PRISMA analysis of articles

Toxicological hazards: cobalt mining

Toxicity associated with exposure to cobalt mining was assessed in 28 articles [16–43]. Respiratory disease was the most common category of toxicological hazard reported in papers discussing cobalt exposure. Respiratory health problems described in populations exposed to cobalt mining included upper and lower respiratory infections, lung cancer, hard metal lung disease, pneumoconiosis, chronic bronchitis, and chronic mountain or altitude sickness [24, 25, 29, 39, 40, 42]. A case report discussed a patient in whom hard metal lung disease re-occurred even after a lung transplant [42]. Three studies conducted in areas of the Democratic Republic of the Congo known for cobalt mining described birth defects in children whose parents held mining-related jobs [26, 27, 43]. Several studies reported increased in vivo levels of heavy metals in populations exposed to mining compared to reference values or control groups [17, 18, 20, 22, 32, 36, 37]. Levels as much as 40 times greater than reference values were reported [17]. One such study also found that exposed children had higher urine levels of DNA oxidative damage markers, a difference that was not observed in adult participants [18]. In pregnant women exposed to cobalt mining, elevated maternal blood levels were associated with fetal levels, suggesting cross-placental transfer [28]. Cobalt mining work was also reported to be associated with male sexual dysfunction and decreased testosterone [33, 34].

Toxicological hazards: manganese mining

Toxicity associated with exposure to manganese mining was assessed in 73 papers, more than any other metal

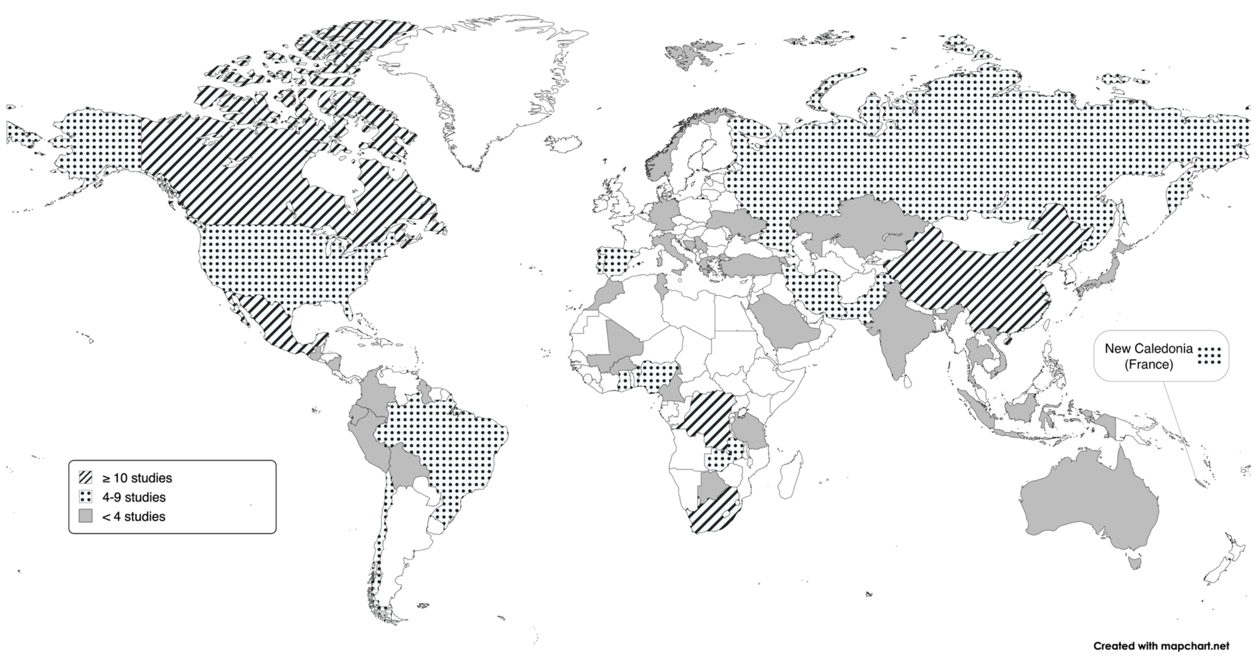

Fig. 2 Country locations of included studies

in this study [16–21, 23, 31, 32, 35, 37, 38, 41, 43–102]. Neurologic toxicity was the most cited category of disease, with studies reporting cognitive impairment, muscle weakness, gait instability, tremors, impaired motor control, hearing loss, memory problems, and Parkinsonism [46, 58, 61, 66, 68, 71, 89–92]. Psychiatric symptoms were described in multiple studies including higher scores on psychiatric distress assessments, emotional instability, disorganization, manic symptoms, and hallucinations [44, 89, 92]. Increased iron deficiency among manganese miners was reported in one study and rates of iron deficiency improved after reconstitution of drinking water [48]. Manganese mining exposure was also associated with prostate cancer, prolactin levels, and sexual dysfunction [81, 89, 92, 96, 99]. Respiratory disease was less commonly reported in papers discussing manganese mining than for cobalt or nickel, although studies did report associations between exposure to mining activities involving manganese and worse respiratory function metrics, pneumoconiosis, respiratory infections, and development of restrictive lung disease [47, 70, 89, 94]. Cytotoxic and immunotoxic effects in mining-exposed populations were described in multiple studies, including T-cell receptor mutations, and lower levels of CD3+and CD4+lymphocytes [55, 56]. In one in vitro study, exposure to manganese oxides obtained from mine dust was associated with DNA damage [45]. Multiple studies assessed risks in children. Studies reported that the concentration of manganese in the hair of children living near mines was elevated compared to controls and associated with worse performance on visuospatial and verbal learning and memory testing [63, 66]. Manganese in umbilical cord blood was reported to be associated with birth defects in a case–control study while cognitive and motor function in children was negatively associated with maternal levels of manganese [43, 54]. A study comparing children living in a manganese mining area to a control group found decreased performance on IQ testing [88]. Children exposed to manganese mining were also reported to have higher incidence of skeletal deformities [62]. Increased in vivo levels of manganese associated with mining exposure were also described in several studies [16, 20, 35, 38, 47, 48, 65, 66, 69, 84, 88, 93].

Toxicological hazards: nickel mining

Toxicity associated with exposure to nickel mining was assessed in 56 papers [17, 20, 21, 23, 31, 32, 35, 37–39, 41, 45, 55, 56, 60, 67, 77, 83, 87, 97, 102–137]. Like cobalt, respiratory toxicity was the most common type of pathology reported. Respiratory manifestations associated with nickel mining included lung cancer, chronic bronchitis, respiratory infections, and nasal obstruction/rhinitis [39, 109–111, 118, 119, 123, 128, 133]. Increased mortality due to other types of cancer and cardiovascular disease was also reported in populations exposed to nickel mining and refining.[120,125] One study found that 75% of participants living in a nickel mining region who used dug wells as a water source had elevated urinary creatinine

[131]. Mine workers exposed to nickel were found to have higher urinary nickel and cystatin C levels than steel plant workers [135]. A large cross-sectional study found increased diabetes in nickel miners compared to office workers [136]. Constitutional growth delay was reported at several times greater prevalence in a population exposed to manganese and nickel pollution relative to a control population [102]. Studies also reported elevated markers of DNA damage, inflammatory markers, and auto-antibodies among populations exposed to nickel mining [105, 108, 112, 122]. DNA damage was also shown to be induced by in vitro exposure to mine evaporite [124]. Populations exposed to mining were found to have elevated nickel levels in blood, urine, hair, and breast milk compared to reference values or control groups [20–22, 31, 32, 37, 41, 60, 77, 97]. Elevated physiologic levels were observed multiple decades after the cessation of mining activity, indicating the longevity of environmental contamination [107].

Toxicological hazards: lithium mining

No studies identified in this review described toxicological effects associated with lithium exposure due to mining.

Infectious disease hazards

Infectious disease hazards were described in three articles. Two studies reported outcomes from a Histoplasmosis outbreak among manganese mine workers in Guyana in 2019 [98, 100]. The third study was a survey conducted in a South African mining community, in which miners expressed concerns regarding high rates of communicable diseases, including tuberculosis and HIV. The miners cited residential overcrowding, inadequate toilet facilities, and prostitution as contributing factors [86].

Traumatic/physical hazards

Six articles were found that reported traumatic injuries or fatalities associated with mine work. Studies reported a variety of traumatic hazards, including falls, cave-ins, explosions, and mine fires [95, 117, 138] These hazards were reported to be associated with the quality of working conditions and factors such as poor visibility, extreme noise, and inadequate ventilation. Injuries related to machinery were cited in multiple studies and attributed to both inadequate training and malfunctioning or outdated equipment. Interviews with manganese miners reported insufficient personal protective equipment as a hazard and described a culture in which reluctance to work in unsafe conditions is penalized by supervisors, potentially resulting in job loss [86]. Two large retrospective studies of mortality among Canadian nickel workers found significantly increased mortality due to injury or violence compared to expected values [104, 127]. Although these studies did not differentiate between fatal injuries that occurred in occupational versus non-occupational settings, injury mortality was particularly increased among underground miners.

Psychiatric/mental health hazards

Psychiatric illness and effects on mental health were reported in six papers. Chronic stress was described in multiple papers and occupational stress was associated with worse perceived quality of life [86, 121]. Higher scores on a standardized survey of psychological distress were recorded among participants residing in areas with increased levels of metal contamination [44]. An early study of mine workers with manganese poisoning described multiple psychiatric symptoms including mood instability and psychosis [92]. A survey of over 1000 nickel miners in China reported symptoms of burnout in more than 80% of participants [130]. Increased mortality due to suicide was also reported among miners [104].

Environmental sampling

A total of 61 studies measured levels of metals in environmental samples from areas contaminated by mining activity and calculated health risk via pre-determined acceptable values [139–199]. These studies did not directly involve human participants. A variety of substrates were sampled including soil, water, air, plants, and animal tissue. Non-carcinogenic health risks were reported in many studies and determined from the Total Hazard Quotient or Hazard Index. A smaller subset of studies also reported carcinogenic risks, which were calculated based on standardized cancer slope factors and compared to acceptable levels determined by the International Agency for Research on Cancer. Of the studies, 43 reported a Hazard Index >1 or lifetime cancer risk $>1\times10^{-4}$ for one or multiple metals in at least one assay, indicating unacceptable levels of risk. In 14 of these studies, reported risks were increased for children compared to adults.

Discussion

The results of this literature review demonstrate the breadth of adverse outcomes on health and wellbeing associated with occupational and environmental exposure via mining to the four metals historically most used in the construction of LIBs. Our results are largely consistent with known pathologic mechanisms; cobalt and nickel mining were more commonly discussed in articles describing respiratory disease, while all studies reporting neurologic pathology involved manganese exposure.

Given the exponential growth of mining for these metals in recent years, it is likely that effects on human health will increase without mitigation efforts.

The lack of studies examining the health effects of lithium mining is noteworthy given the recent exponential increase in the global market for this metal, which has been termed "white gold". Pathologic manifestations of both acute and chronic lithium toxicity have long been recognized medically given its common use as a treatment for psychiatric illness and its narrow therapeutic index. Less is known about the effects of environmental lithium, although studies have reported associations between naturally occurring lithium concentrations in ground water and psychiatric illness, thyroid dysfunction, and adverse birth outcomes [200–202]. Lithium mining has also been shown to increase the concentration of other heavy metals, such as arsenic, in surrounding surface water [203]. In traditional lithium mining, salt-rich brine is pumped from deep in the earth to the surface, forming man-made lakes that are then allowed to evaporate [204]. Lithium can also be mined from hard rock ores. Given the methods used in lithium mining, it is reasonable to hypothesize that there is a significant risk of environmental contamination, which might lead to toxicity from lithium and other metals. Additional chemicals are often added to the brine to facilitate the precipitation of unwanted compounds. Multiple instances of lithium mining affecting nearby communities have attracted media attention, such as the 2016 contamination of the Liqi River in Tibet resulting in the destruction of the local water supply and the death of livestock and fish used as a food source [205]. Despite these high-profile incidents, no studies could be found examining the health effects of exposure to lithium mining.

Our review revealed other concerning gaps in the literature, specifically a paucity of studies describing infectious and traumatic hazards. Mine workers often reside in overcrowded conditions with poor sanitation, infrastructure, and inadequate access to medical care. These conditions promote the transmission of communicable diseases such as malaria and tuberculosis [206]. In addition, the construction of mining facilities often encroaches on the natural habitats of wild animals that may expose workers to zoonotic pathogens [207]. Sexually transmitted diseases including HIV are also prevalent in many mining communities, which can be sites of prostitution and sex trafficking [32, 208, 209] Similarly, few articles discussed traumatic and violent injuries, even though it is well known that many miners work in unsafe conditions and are subjected to falls, cave-ins, injuries from machinery, and other hazards [210]. Traumatic hazards arise from the essentially dangerous nature of mining work and are often compounded by a lack of safety regulations and cultural and economic systems that incentivize workers to perform unsafe tasks.

There are multiple likely explanations for this lack of data. The populations most affected by mining activities are inherently vulnerable. They are often poor, and many are migrants. In some countries, they are subject to human rights violations [209]. People depend on the mines as a source of income and may therefore be less likely to engage with researchers or report accidents for fear of retribution or loss of employment. This can be compounded by the fact that small-scale mining practices are often carried out in violation of local laws. Additionally, access to healthcare is inadequate in many areas, and health systems that do exist may lack the ability to track and report outcomes. Further research and illumination of the plight of miners may also represent a conflict of interest with mining companies that benefit from a source of cheap, exploitable labor. The logistics of carrying out studies are therefore more difficult.

In response to these issues, some mining areas have implemented environmental management programs (EMP) aimed at mitigating the exposure to these metals in mining communities [48, 57, 58]. The strategies utilized by these EMPs are aimed at decreasing dust emissions to decrease the particulate matter in the air. This includes improving clean water availability; updating to equipment that decreases emissions; paving roads and frequently travelled routes; and reforesting the areas. Studies have shown EMPs in manganese mining communities decreased the air concentration of manganese; however there have been variable results regarding the effect on health outcomes [57, 58]. Nevertheless, EMPs are an important step in decreasing the health risks. Other potential interventions to help mitigate health risks include increasing the use and availability of personal protection equipment as well as implementing a medical surveillance program to monitor exposures [48].

An interesting subset of studies in this review collected qualitative information via interviews that present the perspectives of people who work in and live near mining sites [32, 49–52, 86, 109–111, 117]. Overall, there is evidence that affected populations are aware that mining poses significant health risks; however, there is economic and social pressure to tolerate health hazards to make a living. Participants reported that engaging in protests or voicing opposition to mining development placed them at risk of violent suppression from police or military forces or ostracization from other members of the community. In interviews, people living near the mines reported a perceived connection between the growth of mining activities and various health problems including acute and chronic symptoms (e.g., respiratory illnesses, chest pain, chronic headaches), impaired cognitive development in children, pollution of air and water, and destruction of farmland. Displacement of local populations by expansion of mining sites was also reported. These studies highlight the complex effects, both positive and negative, of mining presence in a community.

The results of this review are consistent with well-documented prior data suggesting that children are at disproportionately increased risk from metal toxicity compared to adults [211–213]. Children are at increased risk for toxicity due to heavy metal exposure for multiple reasons including their smaller body size, tendency to ingest non-food materials, hand-to-mouth behaviors, and the increased risks of exposure during physiologic and cognitive developmental periods. Multiple studies in our review reported increased adverse health outcomes in children relative to adults in the same populations [17, 18, 32, 40, 41, 76]. Child labor is also unfortunately common in many mining industries. An estimated 40,000 children work in cobalt mines in the Democratic Republic of Congo [7]. In addition to the physical hazards associated with mine work, they also face the consequences of lost years of education and mental health trauma.

A significant number of studies in this review focused on measuring levels of metals in environmental substrates such as soil, water, plant, and animal specimens to calculate estimated carcinogenic or non-carcinogenic health risks. While there was significant heterogeneity in the type of environmental substrate studied, collection method, and study design, the totality of results suggests significant environmental contamination across a variety of media poses a significant risk. Most studies reported calculated health risks above standard acceptable levels in at least one assay. While these studies do not measure health outcomes in human participants, environmental sampling can be used as a viable method of identifying populations that may be at risk of health effects from mining and should guide the development of future studies measuring direct health outcomes.

Limitations

Our study had several important limitations. First, our results are limited by the quality of studies included in our review; all data were observational, thus limiting the certainty of our findings. Types of bias likely introduced by this limitation include selection bias as well as reporting bias, with many consequences of mining going unreported. Second, our review was limited to articles available in English. Given the locations where mining typically occurs are low- and middle-income countries, there are likely many reports that were not captured in our search. Third, our review was limited to the PubMed database. Finally, while our search criteria were systematic in nature, the aim of this manuscript was not to conduct a systematic review of the literature. Our review was not prospectively registered and study quality and bias were not assessed. Therefore, for all of the above reasons, our results should be viewed as supportive of further research into this important field. The above limitations additionally reflect the current landscape of research into the hazards faced by miners. In that context, additional, comprehensive evaluation of the consequences inherent in such mining practices should be undertaken, and should aim to characterize additional key topics, such as the health effects of mining-related lithium toxicity and traumatic and infectious hazards associated with mining.

Conclusions

The information gathered in this narrative review strongly suggests that the global demand for LIBs and exponential growth of mining for cobalt, lithium, manganese, and nickel presents a significant risk to human health via occupational and environmental exposures that result in both acute and chronic toxicities. This is compounded by the facts that human rights violations are common in the mining industry and that the people most affected are often members of vulnerable populations, including children. Further research, particularly regarding the health and environmental effects of mining for lithium, is crucial to understanding and addressing the risks of the world's growing reliance on LIBs.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12995-024-00433-6.

Supplementary Material 1.

Acknowledgements

Figure 1 was generated by Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia). Figure 2 was generated at www.mapchart.net.

Authors' contributions

CB wrote the main manuscript text and prepared all figures. All authors contributed to article review for inclusion and approved the final manuscript text.

Funding

We received no funding for this study.

Availability of data and materials

No datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

Ethics approval was not obtained given this study is a review of previously published work and does not include human or animal participants

Competing interests
The authors declare no competing interests.

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Received: 11 May 2024 Accepted: 9 August 2024
Published online: 27 August 2024

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