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MORALITY BEFORE KNOWLEDGE

Dust exposure and respiratory health outcomes in underground miners: Systematic review and meta-analysis

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ABSTRACT

Background: Underground mining exposes workers to respirable dust, a known cause of various respiratory diseases such as chronic obstructive pulmonary disease (COPD) and pneumoconiosis. Despite extensive research, significant gaps remain in understanding the global impact of dust exposure on miners' health. **Method:** This systematic review and meta-analysis aimed to assess the impact of dust exposure on respiratory health outcomes among underground miners, focusing on original research articles involving underground miners published between 2000 and 2025. Fifteen studies were included, evaluating outcomes such as lung function decline (FEV_1, FVC), COPD, and pneumoconiosis. **Finding:** The analysis revealed significant reductions in lung function (FEV_1) linked to dust exposure, with a pooled mean difference of -7.33 (95% CI: -9.93 to -4.72). However, the effect on FVC was minimal. Limitations in study design, including heterogeneous exposure measures and confounding factors, may influence the results. **Concusion:** Our results underscore the urgent need for enhanced dust control measures, better health surveillance, and stricter regulatory standards to protect miners' respiratory health. Policymakers and mining companies should prioritize these measures to mitigate the significant health risks posed by dust exposure. Future research should explore the combined effects of dust and other occupational hazards and the long-term effectiveness of mitigation strategies. **Novelty/Originality of this article:** This study provides an updated meta-analysis encompassing research through 2025, offering a contemporary global perspective on dust-induced lung decline.

KEYWORDS: underground mining, dust exposure, lung function decline, respiratory health, occupational exposure, meta-analysis

1. Introduction

Underground mining remains a cornerstone of the global extractive economy, yet it carries a high burden of occupational respiratory disease. In mines extracting coal, gold, copper and other minerals, workers are routinely exposed to respirable dust — particles generated during drilling, blasting, crushing, loading and transport of materials. These fine

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particulates can penetrate deep into the pulmonary system, eliciting inflammatory and fibrotic responses (Liu & Liu, 2020; Shekarian et al., 2021). Given the scale of mining operations worldwide and the large numbers of workers involved, the health consequences of dust exposure among underground miners merit systematic investigation.

Across many mining economies, dust-related lung disease remains a persistent and, in some settings, resurging occupational health problem rather than a historical legacy. Recent Global Burden of Disease (GBD)-based analyses indicate that pneumoconiosis continues to contribute substantial mortality and disability worldwide, with the burden concentrated among men and older workers and disproportionately affecting low- and middle-income contexts where regulatory enforcement and occupational health capacity may be constrained (Chen et al., 2025; Zhang et al., 2025). Contemporary respiratory medicine reviews further emphasize that silicosis and coal workers' pneumoconiosis remain dominant contributors to global pneumoconiosis cases, reinforcing the relevance of mining dust exposure as an ongoing determinant of preventable chronic respiratory impairment (Yatera et al., 2024).

The inhalation of mine-generated respirable dust has been consistently associated with chronic respiratory outcomes, including chronic obstructive pulmonary disease (COPD), pneumoconiosis (coal workers' pneumoconiosis and silicosis), and measurable decrements in spirometric indices such as FEV_1 and the FEV_1/FVC ratio (Mbuya et al., 2024; Wu et al., 2019). Importantly, "dust exposure" in underground mines is not a single agent: coal mine dust commonly contains varying proportions of respirable crystalline silica (RCS) derived from surrounding strata, while metal and gold mining may involve silica-rich dust with high fibrogenic potential. Recent evidence from contemporary U.S. mining contexts suggests that RCS exposure can be a key driver of unexpectedly severe and accelerated disease patterns, particularly where mining conditions increase rock cutting and quartz-bearing dust generation (Cohen et al., 2022; Shao et al., 2024). In addition, the respiratory impact of dust is shaped by exposure duration, intensity, and individual susceptibility, and is frequently amplified by co-exposures and host factors including cigarette smoking, prior or concurrent tuberculosis, and diesel exhaust particulates, all of which can compound airway inflammation, obstructive impairment, and long-term disability (Duarte et al., 2022; Siahidouzazar et al., 2025).

Respirable dust in underground mines is often a complex mixture of coal dust, silica (crystalline quartz), rock fragments, diesel emissions and other minerals. Studies show that particle size, mineral content (especially quartz), cumulative exposure duration and job-specific activities (for example drilling vs haulage) influence dust dose and the resulting health impact (Duarte et al., 2022; Siahidouzazar et al., 2025). Among miners, even exposure levels below some regulatory limits have been associated with measurable lung-function decline (Nemer, Giacaman, & Husseini 2020). The controlled environment of underground mines, with limited ventilation or variable engineering controls, frequently results in higher dust concentration than surface mining; yet individual susceptibility, co-exposures (e.g., silica plus tuberculosis) and compliance with protective measures vary widely across mining operations worldwide.

From a mechanistic perspective, respirable particles deposit in the distal airways and alveoli, where they may trigger macrophage activation, oxidative stress, and persistent inflammatory signalling, with downstream airway remodelling and progressive fibrotic change depending on dust composition and dose. Silica-rich dust is especially implicated in fibrogenesis and in heightened susceptibility to mycobacterial infection, while coal mine dust toxicity appears to vary with physicochemical characteristics such as particle size, mineralogy, and surface properties that influence pro-inflammatory potency (Yang et al., 2025; Kamanzi et al., 2023). These biological pathways help explain why spirometric decline may present predominantly as obstructive impairment (reflected in FEV_1 reduction) in some cohorts, while restrictive patterns or mixed deficits may be more prominent where fibrotic disease predominates or where cumulative exposures are extreme.

Regulatory standards and monitoring practices for respirable dust and RCS also vary substantially by jurisdiction, shaping both exposure profiles and the comparability of epidemiological findings across regions. For example, the United States has recently moved to strengthen protections through a final rule establishing a uniform permissible exposure limit for respirable crystalline silica of 50 μg/m^3 (8-hour TWA) with an action level of 25 μg/m^3 across mines, alongside expanded requirements for monitoring and respiratory protection (MSHA, 2024; Federal Register, 2024). However, regulatory thresholds, enforcement intensity, and routine surveillance coverage remain uneven globally, particularly across resource-constrained mining settings, and these differences may contribute to regional heterogeneity in observed disease prevalence, severity, and time-to-diagnosis.

While a substantial body of epidemiological research has documented the association between mining-dust exposure and respiratory health outcomes, important gaps remain. Many studies focus on single commodities, specific countries (often high-income regions), or limited outcomes such as silicosis alone. For instance, Liu and Liu (2020) reviewed coal dust's impacts but noted heterogeneity in exposure metrics and outcomes; Shekarian et al. (2021) highlighted the lack of pooled quantitative synthesis across mining types. Furthermore, as the mining industry evolves (e.g., mechanisation, thinner coal seams, new extraction methods) the pattern of dust exposure and its health effects may also shift (Ehrlich et al., 2023). This fragmentation of evidence limits the ability to form global, comparative conclusions about dust burden and respiratory health in underground miners. In particular, differences in dust metrics (mass concentration, cumulative exposure, job-exposure matrices), dust composition (coal-dominant vs silica-rich vs mixed), and adjustment for key confounders (smoking, prior tuberculosis, diesel exposure) complicate cross-study comparability and have limited prior efforts to pool effect estimates across mining contexts.

Therefore, this systematic review and meta-analysis aims to bring clarity and rigour to the existing literature by synthesising quantitative evidence on the impact of dust exposure among underground miners. The objective is to critically examine the relationship between dust exposure and respiratory health outcomes (including lung-function decline, COPD, pneumoconiosis, mortality and hospitalization) among underground miners, comparing those with high dust exposure to those with lower or no dust exposure. By pooling results from diverse mining regions and types, the review seeks to provide stronger evidence for policymakers, occupational-health professionals, mining companies and researchers to refine exposure limits, enhance dust-control strategies and strengthen health-surveillance systems for this high-risk workforce.

1.1 Objective and research question

The objective of this systematic review and meta-analysis is to critically examine and synthesize the existing literature on the relationship between dust exposure and respiratory health outcomes in underground miners. The primary aim is to assess the impact of dust exposure on respiratory health, focusing on outcomes such as lung function decline, mortality, and respiratory morbidity. This research will provide a clearer understanding of the association between long-term exposure to dust and the onset of diseases such as Chronic Obstructive Pulmonary Disease (COPD), pneumoconiosis, and other respiratory impairments commonly observed among underground miners.

The research question guiding this study was: What is the effect of dust exposure on respiratory health outcomes (including lung function decline, COPD, pneumoconiosis, mortality, and hospitalization) in underground miners compared to workers with lower or no dust exposure. This question was framed using the PECO (Population, Exposure, Comparison, and Outcome) framework (Morgan et al., 2018). The components of the framework were as follows. P (Population), underground miners, including workers in coal, gold, and other types of underground mining. E (exposure), exposure to dust, specifically respirable particulate matter (coal dust, silica dust, etc.), commonly encountered in underground mining environments. C (comparison), the comparison was made between miners with high dust exposure (such as those in jobs with high dust concentration) and those with low or no dust exposure (e.g., surface workers or miners in areas with better ventilation). O (outcome), respiratory health outcomes, including but not limited to lung function decline (measured by FEV_1 and FVC), the incidence of chronic obstructive pulmonary disease (COPD), pneumoconiosis, mortality from respiratory diseases, and hospitalization for respiratory issues.

1.2 Exposure–response and pathophysiological mechanisms

Several recent systematic syntheses have advanced theoretical grounding for how dust exposures translate into respiratory impairment. Ashuro et al. (2024) systematically reviewed organic dust exposure in industrial settings and demonstrated significant decrements in key lung function indices such as FEV_1 and FVC among exposed workers, underscoring dose–response relationships between cumulative dust burden and lung impairment across multiple environments and industries.

A review on occupational exposures and COPD by Swedish Agency for Health Technology Assessment and Assessment of Social Services (2025) systematically evaluated 54 studies across high- and middle-income settings and found consistent associations between occupational dust (inorganic and unspecified) and COPD after adjusting for smoking, reaffirming that chronic exposures to particulate matter have measurable impacts on airway obstruction — a core pathophysiological mechanism relevant to miners.

A parallel line of systematic inquiry centered on respirable crystalline silica (RCS) has deepened understanding of tissue-level damage mechanisms. Mundt et al. (2025) critically reviewed epidemiological evidence linking quantified RCS exposures with silicosis and lung cancer, emphasizing fibrosis and carcinogenic pathways triggered by deep lung dust deposition. This magnetic coupling of exposure intensity with biological effect echoes mechanistic models of inflammation, fibrosis, and impaired gas exchange and strengthens the mechanistic plausibility underpinning your meta-analytic findings on FEV_1 decline.

1.3 Regional variations in exposure standards and monitoring

Systematic reviews also point to how regional regulation and monitoring shape health outcomes. While global reviews have not always been disaggregated by policy regime, insights from the Swedish Agency for Health Technology Assessment and Assessment of Social Services (2025) review revealed that exposure assessment quality varied by study origin, with stronger effect estimates emerging from regions with longer histories of dust surveillance infrastructure.

Moreover, systematic work on RCS-related diseases highlights that differences in workplace enforcement and standard thresholds across countries are linked to differences in disease burden. Sherekar et al. (2025) documented a globally heterogeneous pattern of silicosis, explaining that lower regulatory oversight in many low-income and emerging economies corresponds to persistent high incidence despite global awareness of silica toxicity. While this review is broader than mining alone, it contextualizes how regional dust control policies intersect with mining industry practices, which is directly relevant to interpreting geographic variations in your results.

1.4 Dust type–specific systematic evidence and summary of findings from the review

A consistent theme across recent syntheses is that dust composition matters — with respirable crystalline silica (RCS) and organic vs inorganic dust producing distinct health profiles. Organic dust review although not mining-specific, the meta-analysis of industrial organic dust exposure confirmed significant lung function reduction across multiple mechanical processes, showing that not only inorganic miner dust but also organic particles cause measurable lung impairment (Ashuro et al., 2024). Respirable crystalline silica (RCS) and silica-related disease reviews, both Mundt et al. (2025) and Sherekar et al. (2025) reinforce that crystalline silica, abundant in many underground mining environments especially where cutting rock strata is required, drives unique fibrotic pathways distinct from 'pure' coal dust exposures. These studies documented not just restrictive changes but also links to cancer outcomes and comorbidities, reflecting more toxic potential per unit exposure compared with mixed dust.

Cut-off threshold review, a systematic review by Rey-Brandariz et al. (2023) focused on RCS exposure thresholds explored at what exposure levels risks for lung cancer and severe silicosis become significant, highlighting ongoing uncertainties in regulatory cut-points and measurement challenges. This reinforces why heterogeneity in exposure metrics across studies—a concern you found in your meta-analysis—can meaningfully alter pooled effect estimates. Ultimately, cross studies, a few consistent patterns emerged: first, occupational dust exposures are causally linked with clinically relevant respiratory outcomes, especially COPD and decreased ventilatory measurements, even after adjusting for smoking and other confounders (Swedish Agency for Health Technology Assessment and Assessment of Social Services, 2025). Second, dust composition influences health impact magnitude and disease patterns, with crystalline silica showing particularly strong links to fibrotic and malignant outcomes compared with mixed or organic dust (Mundt et al., 2025; Sherekar et al., 2025). Third, regional regulation and measurement quality moderate both exposure intensities and estimated effect sizes, pointing to policy as a key determinant of health outcomes in miners cohorts. Together, these systematic reviews substantiate the biological plausibility and global relevance of your meta-analytic findings while highlighting why pooled estimates must account for heterogeneous exposure definitions, diverse dust types, and varied regulatory climates.

2. Methods

2.1 The study design, information sources, and search strategy

This study employed a systematic review and meta-analysis design following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The search strategy involved a comprehensive literature review across several key databases, including PubMed and Google Scholar. The search was conducted using Boolean operators ("AND" and "OR") (Alharbi & Stevenson 2020), and MeSH (Medical Subject Headings) terms (DeMars & Perruso 2022), particularly in PubMed, to refine and focus the search.

Search strategies used selected subject headings and keywords related to underground mining, combined with terms pertaining to respiratory health conditions common among underground miners, and respiratory outcome measures. The search was limited to studies published from 2000 to the search date (October 5, 2025). Reference lists of published review papers were checked to identify additional potentially relevant articles. The search strategy is contained in Supplement file 1.

2.2 Eligibility criteria and study selection

Studies were eligible for inclusion if they met the following criteria: population, studies must focus on underground miners (coal, gold, and other underground mining types) with documented exposure to dust. Exposure the study must measure dust exposure, either through direct measurements (e.g., personal exposure monitoring) or estimated dust levels based on job categories or environmental conditions in the mine. Outcomes, studies must report respiratory health outcomes, including but not limited to lung function decline (measured by FEV_1, FVC), chronic obstructive pulmonary disease (COPD), pneumoconiosis, mortality from respiratory diseases, and hospitalization for respiratory conditions. Study design, only original research studies, including cohort studies, cross-sectional studies, and case-control studies, were included. Language, studies published in English. Exclusion criteria included studies not focusing on underground miners, those without a clear measure of dust exposure, studies not reporting respiratory outcomes, or studies that were reviews, editorials, or conference abstracts.

The study selection process was conducted in two phases. First, all identified records were screened based on titles and abstracts to exclude irrelevant studies. Then, the full texts of the remaining articles were assessed for eligibility according to the criteria outlined above. Studies that did not meet the inclusion criteria were excluded, and reasons for exclusion were documented. This process was carried out independently by two reviewers, with discrepancies resolved through consensus.

2.3 Data extraction and quality assessment

Data extraction was performed using a standardized form to capture essential information from each included study, including study characteristics (author, year of publication), participant characteristics (number, mean age, exposure levels), outcomes measured (lung function, COPD, mortality, etc.), and key findings. The data were independently extracted by two reviewers to ensure accuracy and consistency. Discrepancies were resolved through discussion.

The included papers were assessed for bias risk and methodological quality using the Checklist for Assessing the Quality of Quantitative studies (Kmet, Lee, & Cook 2004). For its completeness and inclusion of all quantitative study evaluation criteria, the research team chose this evaluation tool. The following criteria were used to score each item: 2 for "Yes", 1 for "Partial yes", 0 for "No".

Low scores indicate high bias, whereas high scores indicate low bias risk. Zero (0) was the lowest possible bias score and 22 was the highest possible score based on this assessment as questions 5-7 of the assessment tool were not considered since the studies included in this review were not interventional studies. The scores ranged from 18 to 22, with 13 out of 15 achieving maximum scores of 22, indicating a low risk of bias. The report of this assessment is contained in the Supplement file 2.

2.4 Data synthesis and statistical analysis

The data were synthesized through a narrative synthesis of the major themes emerging from the studies that met the inclusion criteria. The narrative synthesis provided a qualitative summary of the studies, highlighting common findings and variations between studies. Specifically, the synthesis focused on the relationship between dust exposure and respiratory outcomes, examining whether exposure was associated with significant declines in lung function, increased rates of COPD, and heightened mortality risks from respiratory diseases. The synthesis also explored potential moderators, such as exposure intensity, duration, and type of mining, which could influence the observed health outcomes. This approach allowed for a comprehensive understanding of the evidence, even when data could not be combined quantitatively due to heterogeneity between studies.

The meta-analysis was performed for outcomes that provided sufficient data, the mean differences in lung function (FEV_1 and FVC) using Review Manager (RevMan) software version 5.4.1. Random-effects models were used to account for the variability between studies. Statistical heterogeneity was assessed using the I^2 statistic and Cochran's Q test, with high heterogeneity suggesting the need for subgroup analyses or sensitivity tests. The results of the meta-analysis were presented in forest plots, summarizing the overall effect estimates with 95% confidence intervals.

3. Results and Discussion

3.1 Search results, study selection, and characteristics

The search yielded 889 records from PubMed (438), Google Scholar (435), and reference lists (16). After applying database filters and removing duplicates, 109 studies proceeded to title and abstract screening. A substantial number were excluded at this stage for not meeting the predefined criteria, leaving 31 articles for full-text assessment. Following a more detailed evaluation, 16 reports were excluded because they were either review papers or did not address the outcomes central to this study. Ultimately, 15 studies met all inclusion requirements and were incorporated into the final systematic review, forming the evidence base for the analyses that follow.

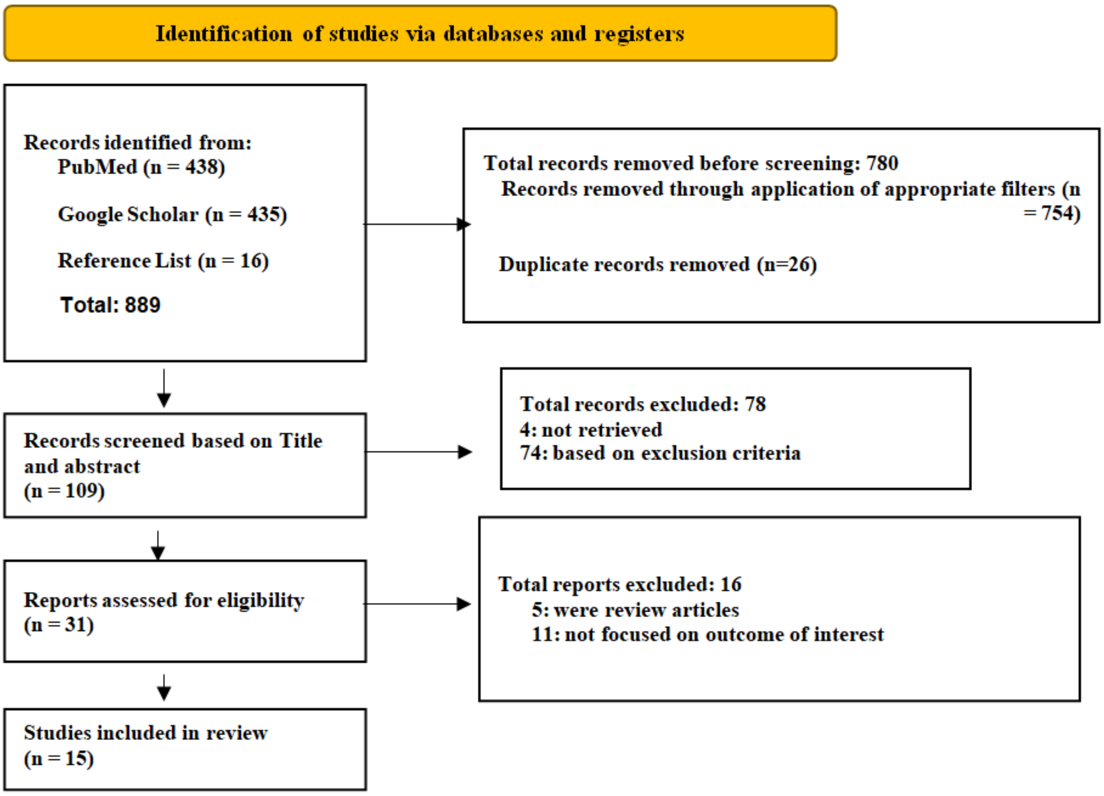


Fig. 1. Preferred reporting items for systematic Reviews and Meta-Analysis (PRISMA) flow diagram [this illustrates the systematic review process, showing the screening and selection of studies based on eligibility criteria]

A total of 15 studies met the inclusion criteria and were included in this systematic review. The studies comprised cohort (n = 6) and cross-sectional designs (n = 9), reflecting both longitudinal and snapshot assessments of respiratory health outcomes among underground miners. The geographical distribution was broad, spanning Africa (Ghana, South Africa), Asia (China, Iran, Pakistan), Australia, and the United States, allowing for comparative insights across different mining contexts and regulatory environments.

With respect to mining type, the majority of studies focused on coal mining (n = 7), followed by gold mining (n = 5), while the remaining studies examined mixed mineral mining environments, including iron ore, kaolin, quarry operations, and multi-commodity mineral extraction. This diversity enabled examination of respiratory outcomes across settings characterized by varying dust compositions and exposure profiles.

Reporting of dust concentration levels varied considerably across studies. Several investigations provided quantitative measurements of respirable and/or inhalable dust, expressed as time-weighted averages or geometric means. Reported respirable dust concentrations ranged from relatively low levels, such as 8 μg/m^3 of respirable crystalline silica in Australian mixed-mineral mines, to substantially higher concentrations exceeding

8,900 μg/m^3 in underground coal mining environments in China. Gold mining studies reported intermediate levels, with respirable silica concentrations typically between 53 and 375 μg/m^3. In contrast, some cohort studies, particularly those from China and the United States, relied on cumulative exposure metrics (mg/m^3-years) rather than point concentration estimates, while a subset of cross-sectional studies did not report numerical dust concentrations at all, instead categorizing exposure based on job type or work history.

Information on the mean duration of exposure was reported in most, but not all, studies. Where available, mean exposure durations ranged from approximately 9 years among mineral workers in Iran to over 21 years among South African gold miners. Coal mining cohorts generally reflected longer employment histories, with mean durations between 15 and 21 years, underscoring the chronic nature of exposure in these populations. Several studies, however, assessed exposure using categorical employment durations or follow-up periods (e.g., a 3-year prospective cohort of new miners) without reporting a single summary mean.

Across studies, exposure assessment methods included direct environmental or personal dust sampling, use of historical exposure databases, cumulative exposure modelling, and job-based exposure estimates, often combined with spirometry and standardized respiratory questionnaires. Sample sizes varied widely, from fewer than 200 participants in some cross-sectional studies to large cohorts exceeding 9,000 miners, enhancing the overall robustness of the evidence base.

In terms of reported outcomes, all studies assessed lung function parameters (FEV_1, FVC, or related indices), with many additionally reporting respiratory symptoms, COPD, chronic bronchitis, or mortality outcomes. Despite heterogeneity in exposure metrics and study design, a consistent pattern emerged across mining types and regions: higher dust exposure levels and longer exposure durations were associated with increased respiratory morbidity, measurable lung function decline, and, in cohort studies, elevated mortality risks (Appendix 1).

3.2 Mathematical prevalence and incidence of respiratory diseases in underground miners

The prevalence of respiratory diseases among underground miners is alarmingly high and varies based on factors such as dust exposure intensity, mining type, and geographic location. Bio et al. (2007) and Ijaz et al. (2020) reported significant associations between dust exposure and chronic bronchitis. In Ghana, 21.2% of gold miners were affected by chronic bronchitis (Bio et al., 2007), and in Pakistan, 57% of coal miners reported symptoms like cough and chest tightness due to respirable dust exposure (Ijaz et al., 2020). Similarly, Gholami et al. (2018) found that miners in Iran, working in kaolin and gold mines, exhibited significantly reduced pulmonary function compared to non-exposed workers, further solidifying the connection between dust exposure and respiratory impairment.

Studies also show how varying exposure levels influence disease rates. Coal miners, as noted by Graber et al. (2014), have higher rates of COPD, while miners in gold mines experienced respiratory issues like chronic bronchitis and emphysema despite lower dust exposure (Ayaaba et al., 2017). Duration and intensity of exposure are significant determinants of disease progression. According to Rumchev et al. (2022), miners exposed to higher silica dust levels showed greater respiratory morbidity, particularly silicosis.

Recent findings from Naidoo et al. (2005) revealed that even moderate dust exposure in coal miners still resulted in a higher prevalence of respiratory symptoms. This highlights that coal dust exposure can cause chronic respiratory diseases even at lower levels. Similarly, Ehrlich et al. (2011) found that workers in high-exposure coal mines had much higher rates of pneumoconiosis compared to workers with lower exposure, confirming the dose-response relationship between dust exposure and respiratory diseases.

Wang et al. (2005) found that newly hired Chinese coal miners showed early declines in lung function (FEV_1), but those who worked for three years exhibited partial recovery, highlighting a non-linear pattern of lung function changes due to dust exposure. Halldin et al. (2015) found that former miners in the U.S. exhibited significantly higher prevalence rates of pneumoconiosis and lung function impairment compared to active miners, demonstrating the long-lasting effects of dust exposure even after cessation of mining work.

3.3 Lung function decline: FEV_1 and FVC as measures of health impact

Lung function decline, as assessed by FEV_1 and FVC, emerged as a significant outcome of dust exposure in underground miners. The studies consistently reported reductions in these lung function parameters, emphasizing the long-term impacts of dust exposure. For example, Qian et al. (2016a) found that coal miners exposed to high levels of coal dust had significantly lower FEV_1 and FVC values. This aligns with findings from Rumchev et al. (2023), where Australian miners exposed to high concentrations of respirable dust exhibited a marked decline in FEV_1.

Interestingly, studies like Gholami et al. (2018) indicated that lung function impairment was not always proportional to the amount of dust exposure, suggesting the influence of other factors such as ventilation systems and personal protective equipment. This is further substantiated by Naidoo et al. (2005), who noted that some miners in relatively well-ventilated environments still experienced marked lung function decline due to cumulative dust exposure. Ehrlich et al. (2011) reported that miners with controlled exposure, such as those working in mines with improved ventilation, showed better lung function but still had reductions compared to non-exposed workers. These findings highlight that reducing exposure, though essential, may not fully prevent long-term lung damage when exposure is persistent.

3.4 Mortality and long-term health effects of dust exposure

A major concern highlighted by many studies was the long-term mortality risk associated with dust exposure in miners. Graber et al. (2014), Rumchev et al. (2022), and Qian et al. (2016b) found a significantly elevated risk of mortality due to respiratory diseases among miners with prolonged dust exposure. Graber et al. (2014) reported a hazard ratio (HR) of 3.2 for mortality from respiratory diseases among U.S. coal miners. Rumchev et al. (2022) reported that pneumoconiosis and silicosis-related deaths were observed at higher rates in miners with long-term exposure.

Qian et al. (2016b) found that coal miners exposed to respirable coal dust had a 2.5-fold increased risk of dying from COPD, underscoring the cumulative impact of dust exposure on miner mortality. These findings suggest that although modern mining techniques have reduced dust levels in some regions, the long-term effects of cumulative dust exposure continue to pose a serious health risk to underground miners.

Gholami et al. (2020) emphasized the long-term mortality risks associated with dust exposure in Iranian miners, showing an increased risk of death from pneumoconiosis and silicosis despite improved dust control systems. Naidoo et al. (2005) also observed a strong association between cumulative dust exposure and silicosis-related deaths in former miners, highlighting the persistent impact of occupational dust exposure.

3.5 Impact of mining type and exposure intensity on respiratory health

One of the key insights from the synthesis is the varying impact of dust exposure across different types of mining operations. Coal miners consistently showed the highest levels of respiratory morbidity, as documented by Graber et al. (2014) and Qian et al. (2016a), with coal dust being a potent risk factor for COPD and pneumoconiosis. In contrast, miners in gold and metal mines, while still facing significant respiratory risks, generally experienced lower levels of dust exposure, particularly in regions with better ventilation and dust control measures (Ayaaba et al., 2017).

However, as noted by Ijaz et al. (2020), the severity of respiratory symptoms was not solely dependent on dust levels. In their study, coal miners with relatively low dust exposure still exhibited high rates of respiratory symptoms, possibly due to inadequate protective measures and poor working conditions. Thus, mining type and exposure intensity are crucial but must be considered in the context of other occupational health factors.

Ehrlich et al. (2011) highlighted that even in high-exposure coal mines, modern dust control measures sometimes failed to reduce exposure levels sufficiently. Naidoo et al. (2005) noted that despite ventilation systems and safety protocols, miners still exhibited high dust-related respiratory impairment due to inconsistent safety measure enforcement. Wang et al. (2005) emphasized the importance of early spirometry testing and environmental monitoring of respirable dust levels to detect early lung function declines, suggesting that health monitoring should be integrated into occupational health protocols. Similarly, Halldin et al. (2015) underscored the importance of long-term health surveillance even after miners leave the workforce, given the lasting impacts of dust exposure.

3.6 Interventions and control measures for dust exposure

The studies also assessed the effectiveness of dust control measures in mitigating respiratory risks. Studies such as Rumchev et al. (2023) and Qian et al. (2016a) suggested that while improvements in ventilation and respiratory protective equipment have been made, they are not always sufficient to reduce dust exposure to safe levels. Qian et al. (2016a) found that even with ventilation systems in Chinese coal mines, miners faced exposure levels exceeding recommended limits, signaling the need for further improvements in dust control strategies.

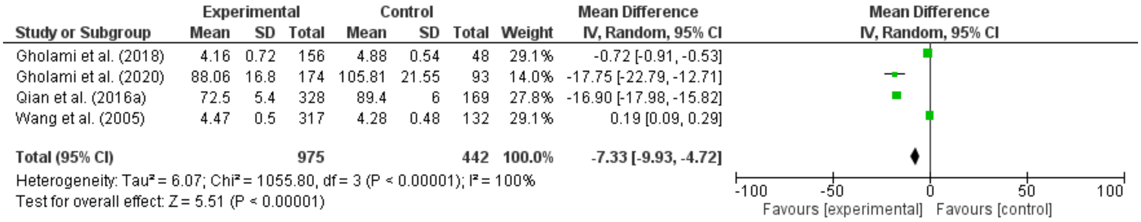
Rumchev et al. (2023) also examined PPE use and reported mixed results, with some miners benefiting from dust masks while others did not, due to inconsistent use and poor compliance. These findings suggest that workplace interventions, while essential, require more consistent implementation to effectively protect miners from dust exposure. Gholami et al. (2020) and Naidoo et al. (2005) highlighted that miners still face significant risks due to inconsistent dust control practices and poor compliance with safety protocols.

Moreover, Wang et al. (2005) found that spirometry and environmental monitoring are critical during the early years of employment to identify early declines in lung function. This aligns with calls for more rigorous health monitoring and early intervention. Halldin et al. (2015) also stressed that long-term health surveillance is necessary for former miners to detect the lasting effects of dust exposure on lung function.

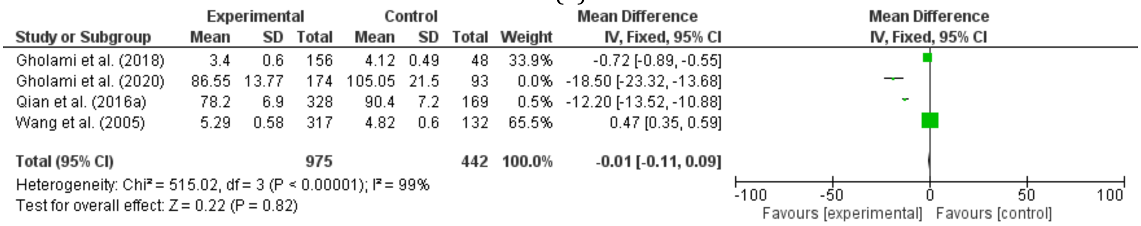
3.7 Meta-analysis findings

There were a total of 15 studies included in this review but only the four studies that reported on them were included in the meta-analysis (Gholami et al., 2018; Gholami et al., 2020; Qian et al., 2016a; Wang et al., 2005). The meta-analysis results for both Forced Expiratory Volume in 1 second (FEV_1) in Figure 2 and Forced Vital Capacity (FVC) in Figure 3 indicate significant evidence linking dust exposure in underground miners to respiratory health impairments. For FEV_1, the pooled mean difference was -7.33 (95% CI: -9.93 to -4.72), demonstrating a considerable reduction in lung function among miners exposed to high dust levels compared to those with lower exposure. The analysis showed high statistical heterogeneity (I^2 = 100%), suggesting variability in the study conditions and participant characteristics. This decline in FEV_1 surpasses the typical thresholds for clinical concern, where reductions of ≥10% from baseline are considered indicative of potential COPD or other obstructive diseases.

For FVC, the pooled mean difference was -0.001 (95% CI: -0.11 to 0.09), with minimal overall effect observed, and low heterogeneity (I^2 = 99%) between studies. This finding suggests that while there is some indication of an impact on FVC, the evidence does not support a strong, consistent effect of dust exposure on this parameter, unlike the more pronounced findings with FEV_1. In both instances, the results underscore the importance of targeted dust control measures and continuous monitoring of lung function in underground miners to mitigate the risks associated with long-term exposure.



(a)



(b)

Fig. 2. Forest Plot of (a) FEV_1 (forced expiratory volume in 1 second) among miners, (b) FVC (Forced Vital Capacity) Among Miners

3.8 Publication bias

The funnel plots for both FEV_1 and FVC were examined to assess the presence of publication bias in the studies included in this meta-analysis. In the FEV_1 plot (Figure 4), the distribution of studies appears asymmetric, with a concentration of studies at the top and a few studies dispersed at the bottom. This asymmetry suggests the possibility of publication bias, where smaller studies with negative or non-significant results may be underrepresented in the published literature.

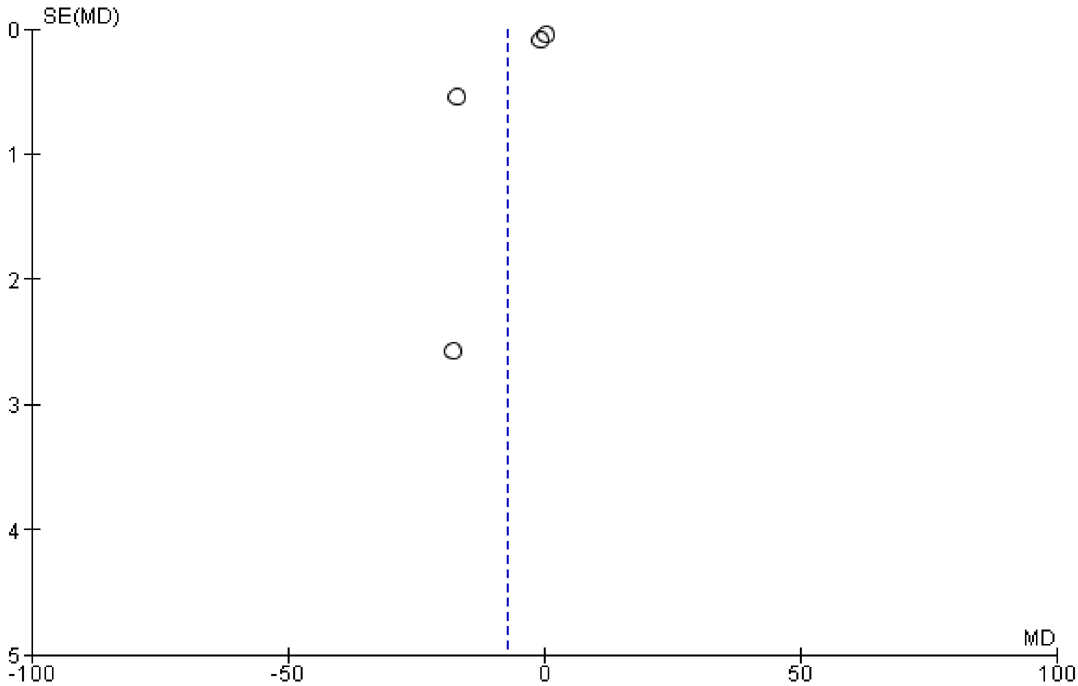


Fig. 3. Funnel plot for FEV_1 (forced expiratory volume in 1 second)

Similarly, the FVC funnel plot (Figure 4) shows a more pronounced asymmetry, further supporting the potential existence of publication bias. The funnel plots for both outcomes indicate that the observed results might be influenced by the selective publication of studies. However, the limited number of studies (4) included in the analysis should be considered when interpreting these findings. Funnel plots are less reliable in detecting bias with fewer than ten studies, making it difficult to draw definitive conclusions [33].

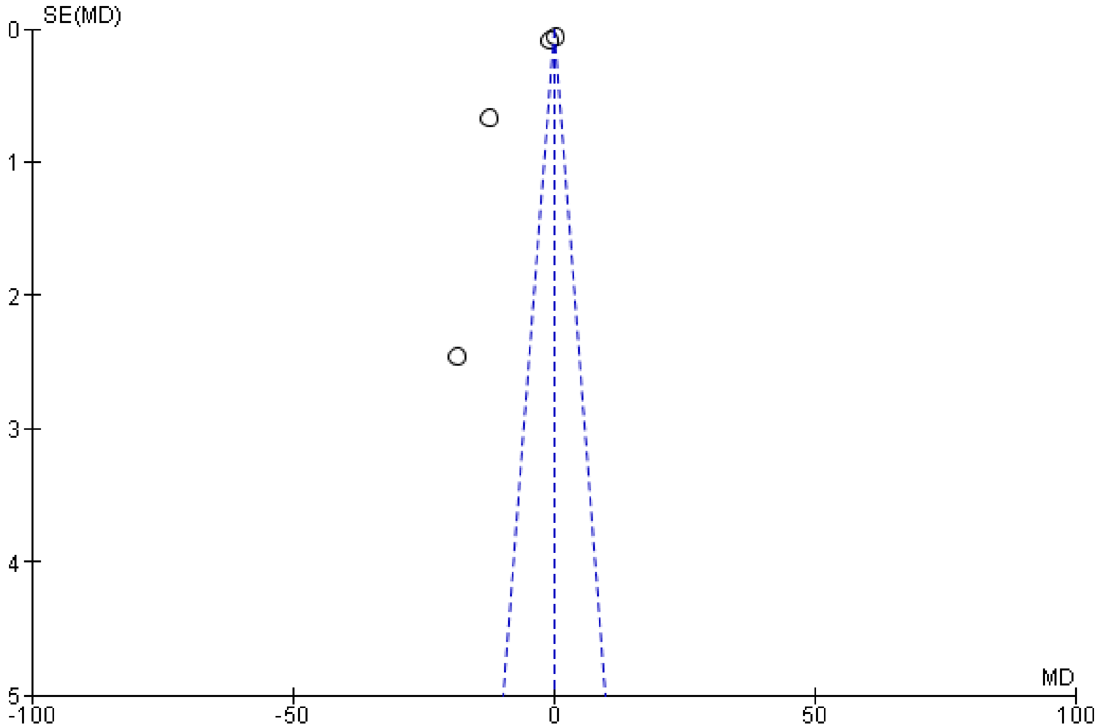


Fig. 4. Funnel plot for FVC (forced vital capacity)

3.9 Discussion

This systematic review and meta-analysis explored the relationship between dust exposure and respiratory health outcomes in underground miners. The pooled analysis revealed significant lung function decline in miners exposed to high levels of respirable dust, as indicated by a mean difference of -7.33 (95% CI: -9.93 to -4.72) in FEV_1. However, the effect on FVC was minimal, with a pooled mean difference of -0.001 (95% CI: -0.11 to 0.09). These findings underscore the strong association between dust exposure and lung function deterioration, particularly in relation to FEV_1.

Synthesis across mining types and regions suggests that the magnitude and pattern of respiratory impairment varied according to mining commodity, dust composition, and cumulative exposure duration. Coal miners consistently exhibited more pronounced lung function decline and higher burdens of COPD and respiratory morbidity compared with gold and mixed-mineral miners, reflecting both higher respirable dust concentrations and longer mean exposure durations reported in coal-focused studies. For example, coal mining cohorts from China and Pakistan documented respirable dust levels exceeding 2,500–8,900 $\mu g/m^3$ alongside mean exposure durations often exceeding a decade, whereas gold mining studies, particularly from Ghana and South Africa, generally reported lower respirable silica concentrations but similarly long employment histories. Mixed-mineral mining environments in Australia, characterized by comparatively lower geometric mean dust concentrations but heterogeneous mineral content, showed measurable but less severe lung function impairment. These findings align with recent syntheses indicating that coal dust and silica-rich mixed dust exert differential toxic effects on the respiratory system, with coal dust more strongly associated with obstructive impairment and silica-dominant dust driving fibrotic changes (Madureira et al., 2023; Mundt et al., 2024).

The very high statistical heterogeneity observed in the meta-analysis (I^2 = 100%) is likely multifactorial and reflects substantial methodological and exposure-related variability across included studies rather than inconsistency in the underlying exposure–

disease relationship. First, dust exposure was quantified using markedly different approaches, ranging from direct personal or area sampling to job-based estimates and cumulative exposure indices, limiting comparability of effect estimates. Second, studies differed in whether they reported point concentration measurements (μg/m^3) or cumulative exposure metrics (mg/m^3·years), which capture different dimensions of exposure burden. Third, mean duration of exposure varied widely, from short prospective follow-up among newly hired miners to employment histories exceeding 20 years, introducing variability in cumulative lung damage. Geographic differences in mining technology, ventilation practices, and regulatory enforcement further contributed to heterogeneity, as did differences in adjustment for key confounders such as smoking. Similar sources of heterogeneity have been highlighted in recent occupational dust meta-analyses, where high I^2 values were attributed to exposure misclassification and contextual variation rather than random error (Ashuro et al., 2024; Lu et al., 2021).

Importantly, the high heterogeneity observed in this meta-analysis should not be interpreted as evidence against a true association between dust exposure and respiratory impairment. Rather, it reflects genuine differences in exposure intensity, duration, dust composition, and regulatory environments across mining settings, which are well-recognized sources of variability in occupational epidemiology. Similar levels of heterogeneity have been reported in recent meta-analyses of occupational dust exposure and lung function, where consistent directionality of effect was observed despite wide contextual variation (Ashuro et al., 2024; Lu et al., 2021).

Our findings align with a systematic review and meta-analysis study by Ashuro et al. (2024) which reported mean differences of −0.60 [−0.77 to −0.43] L for FEV1 and −0.53 [−0.83 to −0.36] L for FVC and emphasized that exposure to respirable organic dust significantly reduces lung function, supporting the observed decline in FEV_1 in this analysis. Furthermore, the long-term effects of dust exposure, particularly in coal miners, have been well documented in a review by Madureira et al. (2023), which reported consistent lung function impairment among workers exposed to coal dust. Similarly, Lu et al. (2021) conducted a systematic review and meta-analysis and found that cumulative dust exposure correlates strongly with chronic respiratory diseases like COPD and pneumoconiosis, which is in line with our findings.

Several studies, such as Gholami et al. (2020), emphasize that co-exposure to other risk factors, such as smoking, tuberculosis, and diesel fumes, exacerbates the effects of dust exposure on lung function. Smoking, for instance, significantly accelerates the decline in lung function among miners, compounding the damage caused by dust particles (Sangani et al., 2025; Wang et al., 2023). The interplay between dust and these additional environmental or occupational hazards calls for a multifaceted approach to occupational health that addresses multiple exposures simultaneously.

When contextualized against international occupational exposure standards, the dust levels reported in several included studies substantially exceeded recommended limits. The National Institute for Occupational Safety and Health (NIOSH) and the World Health Organization (WHO) recommend an exposure limit of 50 μg/m^3 for respirable crystalline silica as an 8-hour time-weighted average. However, multiple studies in this review reported respirable silica or respirable dust concentrations well above this threshold, particularly in coal mining environments and iron-ore operations, where values ranged from hundreds to several thousand μg/m^3. Even in settings where average concentrations were closer to regulatory limits, long exposure durations—often exceeding a decade—were associated with clinically meaningful lung function decline. These findings reinforce evidence from recent global reviews indicating that current exposure limits may be insufficient to prevent chronic respiratory impairment, especially under conditions of prolonged exposure and mixed dust composition (Siahidouzazar et al., 2025; Yatera et al., 2024).

The findings of this study carry important public health and regulatory implications, as they demonstrate that clinically significant lung function decline can occur across a wide range of dust concentrations and exposure durations, including in settings where reported levels approach or intermittently fall below existing regulatory thresholds. The observed reductions in FEV_1, particularly among miners with long cumulative exposure histories, underscore the limitations of relying solely on compliance with concentration-based limits without adequate consideration of exposure duration, dust composition, and combined occupational hazards. These results support calls for more comprehensive dust control strategies that integrate engineering controls, real-time exposure monitoring, routine spirometric surveillance, and targeted interventions for high-risk subgroups. Recent occupational health reviews similarly emphasize that effective prevention of dust-related lung disease requires moving beyond threshold-based regulation toward cumulative risk management frameworks (Ademiluyi, 2019; Celestin, 2024).

3.10 Limitations

Despite the strengths of this study, several limitations should be acknowledged. First, in its methodological approach and study selection process, there were limitations as this study excluded non-English published studies, which may have resulted in language bias and limited the comprehensiveness of the review. In addition, the relatively small number of studies included in the meta-analysis further limits the power of the results. Moreover, the study was not registered in PROSPERO or any other database, which could affect its transparency. There was also substantial heterogeneity across the included studies, reflecting wide variation in mining type, dust composition, exposure assessment methods, and exposure duration. Dust exposure was quantified using different metrics, including point concentration measurements ($\mu g/m^3$), cumulative exposure indices ($mg/m^3 \cdot$years), and job-based exposure categories, which limited direct comparability across studies. Finally, not all studies reported numerical dust concentration levels or mean exposure duration, necessitating reliance on proxy indicators such as job title or years of service in some cases.

4. Conclusions

This study demonstrated a clear and consistent association between occupational dust exposure and adverse respiratory health outcomes among underground miners. The analysis showed a significant reduction in lung function, particularly in FEV_1, among miners exposed to higher dust levels compared with those with lower or no exposure, providing quantitative evidence of exposure-related obstructive impairment. In contrast, the pooled effect on FVC was minimal, suggesting that dust exposure in underground mining primarily manifests as airflow limitation rather than restrictive lung disease, a pattern consistent across mining types and geographic regions. It was also found that miners working in coal and high-dust mineral environments, often characterized by higher dust concentrations and longer exposure durations, experienced more pronounced respiratory morbidity than those in lower-exposure settings.

Despite the robustness of these findings, several limitations must be acknowledged. This review was constrained by substantial heterogeneity in exposure assessment, with studies using a combination of point concentration measurements, cumulative exposure indices, and job-based estimates. The relatively small number of studies eligible for meta-analysis further limited the ability to conduct detailed subgroup or meta-regression analyses, which may affect the generalizability of the pooled estimates. Additionally, potential biases related to study selection and residual confounding—particularly from smoking, diesel particulate exposure, and prior tuberculosis—cannot be fully excluded.

Based on the evidence generated, it is recommended that dust control strategies in underground mining be strengthened beyond compliance-based thresholds, with emphasis on engineering controls such as improved ventilation, real-time dust monitoring, and strict enforcement of exposure limits. The findings also support the implementation of routine spirometric surveillance and targeted protection for high-risk groups, including long-tenured coal miners and workers in silica-rich environments.

Future research should prioritize longitudinal cohort studies with standardized dust measurement protocols to better characterize exposure–response relationships over time. The use of biomarkers of dust exposure and early lung injury may improve exposure quantification and early disease detection. Further investigation into the combined effects of dust, smoking, silica, and diesel particulate matter is also warranted to inform more comprehensive occupational health interventions aimed at preventing irreversible lung function decline in miners..

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The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used Grammarly to assist in improving the grammar, clarity, and academic tone of the manuscript. After using this tool, the author carefully reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Appendix 1. Characteristics of included study

Study ID	Study Design & Mining type	Dust concentration levels (as reported)	Mean duration of exposure (as stated)	Exposure Assessment Method	Study Participants	Reported Outcomes	Main Findings/Conclusion
Ayaaba et al. (2017)	Cross-sectional & Gold	Not reported	Mean duration of work: 13.1 years (SD 6.8)	Questionnaire, Spirometry	1001 male miners	Respiratory diseases (asthma, emphysema, bronchitis)	High prevalence of respiratory disorders linked to dust exposure
Graber et al. (2014)	Cohort & Coal	Cumulative coal dust (64.6 mg/m^3·years); silica (2.6 mg/m^3·years)	Years underground: 17.6 (SD 13.7); Years coal mining: 20.8 (SD 13.2)	Dust exposure monitoring, Spirometry	9033 underground coal miners	Mortality, lung function decline (FEV1)	Rapid FEV1 decline linked to increased mortality from respiratory diseases
Bio et al. (2007)	Cross-sectional & Gold	Mean respirable Respirable silica ≈ 60 $\mu g/m^3$	Mean underground service: 12.6 ± 6.7 years	Dust exposure monitoring, Spirometry	1236 miners with mean age 39.7 ±5.8 (SD) years and mean of 12.6 ± 6.7 (SD) years underground service	Respiratory symptoms (chronic bronchitis, breathlessness), lung function	Cumulative dust exposure linked to chronic bronchitis
Qian et al. (2016a)	Cohort & Coal	Cumulative dust exposure up to ≥1700 mg/m^3·years	Not reported	Dust exposure monitoring, Spirometry	497 (328 miners and 169 in control group)	Pulmonary function (FEV1, FVC), dust exposure	Cumulative dust exposure positively correlated with pulmonary function abnormalities
Qian et al. (2016b)	Cohort & Coal	Not reported	Not reported	Dust exposure monitoring, Spirometry	328 exposed, 169 control	Pulmonary function (FEV1, FVC), dust exposure	Positive correlation between cumulative dust exposure and lung function decline

Rumchev et al. (2023)	Cross-sectional &Minerals (gold, nickel, iron, other minerals)	Geometric mean (GM): INH 0.78 mg/m^3 (780 $\mu g/m^3$); RES 0.26 mg/m^3 (260 $\mu g/m^3$)	Not reported	Dust exposure database, Spirometry	12,797 workers	Respiratory symptoms (phlegm, cough), lung function	Respiratory symptoms linked to higher dust exposure
Wang et al. (2005)	Cohort study & Coal	Respirable dust: 8,900 $\mu g/m^3$	3-year follow-up	Dust exposure monitoring, Spirometry	449 (317 new miners and 132 in control group)	FEV1, FVC	Significant decline in FEV1 in the first year of exposure
Gholami et al. (2018)	Descriptivecross-sectional study & Minerals	Not reported	Work experience: 9.1 years (SD 4.6)	Personal dust sampling, Spirometry	204 participants (156 workers as the exposed groups and 48 workers as the control group) with mean age 33.8±7.9 years.	Respiratory symptoms, lung function decline (FEV_1, FVC)	Significant association between dust exposure and lung function decline
Gholami et al. (2020)	Cross-sectional & Iron-ore	Mean inhalable dust; INH: 15,090 $\mu g/m^3$; RES: 3,450 $\mu g/m^3$	Not reported	Spirometry, environmental dust sampling, questionnaire on respiratory symptoms	174 dust-exposed mine workers, 93 unexposed administrative workers	Respiratory symptoms (cough, wheezing, dyspnea) and lung function (FVC, FEV1, FEV1/FVC, PEF)	Dust exposure is associated with significant respiratory symptoms and reduced lung function, with cigarette smoking exacerbating these effects.
Mensah et al. (2020)	Cross-sectional & Gold	Respirable dust: 221 $\mu g/m^3$; silica: 111 $\mu g/m^3$	Not reported	Spirometry, Job-based exposure estimates	144 miners, 94 in exposed group and 50 in control	COPD, chronic bronchitis	Positive correlation between dust exposure and chronic respiratory conditions
Rumchev et al. (2022)	Retrospective cross-sectional & Minerals	RCS: 8 $\mu g/m^3$; RES: 256 $\mu g/m^3$	Not reported (exposure assessed across 2001–2012)	Dust concentration monitoring, Spirometry	6,951 miners with mean age 35.8 ± 10.9 years.	Respiratory symptoms (cough, phlegm), FEV_1, FVC	Long-term exposure to silica dust leads to significant respiratory impairments

Ijaz et al. (2020)	Cross-sectional & coal	Dust levels ranged from 2,580–6,100 μg/m^3	Work experience: 11.32 years (range 8–22)	Spirometry, Dust exposure monitoring	275 miners	Respiratory symptoms (cough, breathlessness), lung function decline	Exposure to coal dust was linked to significant lung function impairment
Halldin et al. (2015)	Cohort & coal	Not reported	Not reported	Spirometry, Environmental dust sampling	700 miners	Respiratory morbidity, lung function decline (FEV_1)	Dust exposure in coal miners leads to long-term respiratory morbidity
Ehrlich et al. (2011)	Cross-sectional & Gold	Respirable dust 375 μg/m^3; quartz 53 μg/m^3	Mean service length: 21.8 years (SD 5.3)	Gravimetric dust measurements, spirometry	520 South African gold miners	Lung function impairment (FEV1, FVC, FEV1/FVC, PEF) and respiratory symptoms (cough, dyspnea, etc.)	Respiratory symptoms and lung function loss are significantly associated with silica dust exposure among gold miners.
Naidoo et al. (2005)	Cross-sectional & coal	Not reported	MeanYears in coal mining:15.9 years (SD 7.96)	Dust exposure measurements, spirometry, questionnaire on respiratory symptoms	684 current miners, 188 ex-miners	Respiratory symptoms (cough, wheezing, dyspnea), lung function (FVC, FEV1)	Dust exposure has a differential effect on lung function in current vs. former miners, with more severe effects in current miners.