

**OPTIMIZATION OF THE SILICOSIS PREVENTION PROGRAM FOR WORKERS IN
THE MINING INDUSTRY.**

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Abstract: Silicosis remains a critical occupational health problem in the mining industry due to prolonged exposure to respirable crystalline silica dust. This study aims to optimize silicosis prevention programs by analyzing the temporal variability of dust concentration and evaluating the effectiveness of integrated preventive measures under real mining conditions. Dust exposure was assessed during key technological operations, including drilling, blasting, loading, and material transportation, with particular attention to short-term peak concentrations. The results indicate that peak dust levels frequently exceed permissible exposure limits and represent a major contributor to occupational risk. Conventional control measures, such as ventilation and wet drilling, were found to be insufficient when applied independently. In contrast, integrated engineering controls combining ventilation, water spraying, fog-based suppression, and dust-binding films provided a more stable reduction of both average and peak dust concentrations. Polyvinyl alcohol-based dust-binding films demonstrated effective capture of fine particles and adequate mechanical strength at concentrations above 1.0 wt.%. The findings confirm that effective silicosis prevention requires an integrated approach emphasizing peak exposure control, supported by organizational and hygienic measures.

Keywords: Silicosis prevention; respirable silica dust; mining industry; dust suppression; polyvinyl alcohol; occupational exposure

INTRODUCTION

Silicosis remains one of the most severe occupational diseases affecting workers in the mining and mineral extraction industries. The disease is caused by prolonged inhalation of respirable crystalline silica dust, which leads to irreversible fibrotic changes in lung tissue. Despite long-standing awareness of the etiology of silicosis, the disease continues to pose a serious threat to occupational health, particularly in underground mining, open-pit operations, and quarrying activities where intensive drilling, blasting, and material handling processes are involved.

A distinctive feature of silicosis is its progressive and latent nature. Clinical symptoms often develop only after prolonged exposure, while pathological changes in the lungs may continue even after exposure has ceased. Fine dust particles with sizes below several micrometers are especially hazardous, as they can penetrate deep into the respiratory system and accumulate in the alveolar regions. Numerous studies have demonstrated that short-term peak concentrations of silica-containing dust during drilling and blasting operations may significantly exceed permissible exposure limits, thereby increasing the risk of disease development among workers.

Modern mining technologies, while improving productivity, have not eliminated the problem of dust generation. On the contrary, high-energy mechanical processes and large-scale blasting operations often result in intense dust emissions characterized by rapid temporal variations in concentration. These fluctuations complicate effective exposure control and require comprehensive preventive approaches that go beyond isolated technical measures. Traditional dust suppression methods, such as ventilation and wet drilling, although effective to some extent, may not provide sufficient protection when applied independently or without proper optimization. In this context, the optimization of silicosis prevention programs represents a critical and timely task for occupational health and industrial safety. An effective prevention strategy should integrate technological, organizational, and hygienic measures, taking into account the specific conditions of mining operations and the dynamic nature of dust formation. The optimization process requires a systematic assessment of dust generation sources, temporal patterns of exposure, and the effectiveness of applied control measures, with the aim of minimizing workers' inhalation of respirable silica.

The present study addresses these challenges by analyzing dust formation characteristics during key mining processes and evaluating preventive measures from the perspective of program optimization. By focusing on the rational combination and improvement of dust control methods, this work aims to contribute to the development of more effective silicosis prevention programs for workers in the mining industry, thereby enhancing occupational health protection and reducing long-term disease risks.

METHODS

This study was conducted using an integrated methodological approach aimed at optimizing silicosis prevention programs for workers employed in the mining industry. The research framework was based on the analysis of dust generation mechanisms, assessment of airborne dust concentration dynamics, and evaluation of preventive control measures applied under real mining conditions. The methodological basis combined industrial hygiene principles with empirical observations of production processes characterized by intensive dust formation, particularly during drilling, blasting, loading, and material transportation operations.

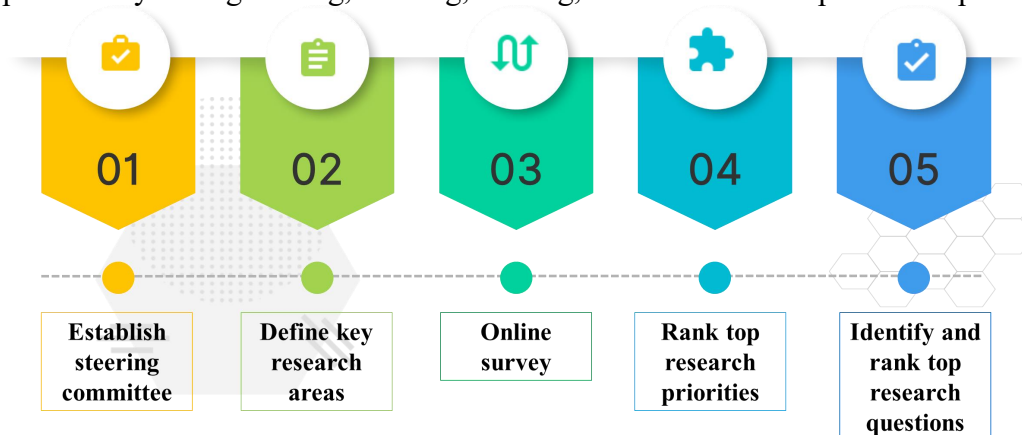


Figure 1. Overview of the silicosis research priority-setting framework

The assessment of dust exposure focused on respirable fractions of silica-containing dust, which pose the greatest risk for the development of silicosis. Special attention was given to the

temporal variability of dust concentration, as previous observations indicate that short-term peak exposures during specific technological stages significantly exceed permissible exposure limits and play a decisive role in disease development. Dust concentration behavior was analyzed before, during, and after high-intensity operations to identify critical exposure periods and to evaluate the effectiveness of applied control measures under dynamic production conditions.

In order to comprehensively evaluate therapeutic approaches applied in the management of silicosis, information on the pharmacological agents used in clinical practice and their mechanisms of action was systematized. The selection of medications was based on their relevance to disease pathogenesis, symptom control, and prevention of disease progression. The analysis focused on drug classes commonly employed in silicosis management, including anti-inflammatory, antifibrotic, bronchodilator, and supportive therapies. This approach allowed the assessment of therapeutic strategies as an integral component of the overall prevention and management framework considered in this study. The summarized information on applied medications and their effects is presented in Table 1.

Table 1. Pharmacological agents used in silicosis prevention and disease progression control

Drug group	Representative agents	Main therapeutic effect	Mechanism of action	Role in silicosis prevention program
Anti-inflammatory agents	Corticosteroids	Reduction of inflammatory response in lung tissue	Suppression of inflammatory mediators and immune cell activity	Used to limit inflammatory reactions associated with silica exposure
Antifibrotic agents	Pirfenidone, Nintedanib	Slowing of fibrotic progression	Inhibition of fibroblast proliferation and collagen deposition	Applied to reduce progression of pulmonary fibrosis
Antioxidants	N-acetylcysteine	Reduction of oxidative stress	Neutralization of reactive oxygen species induced by silica particles	Supportive measure to limit oxidative lung damage
Bronchodilators	Beta-agonists, anticholinergics	Improvement of airway patency	Relaxation of bronchial smooth muscle	Symptomatic support to improve respiratory function

Immunomodulatory agents	Methotrexate, azathioprine	Modulation of immune response	Regulation of immune-mediated tissue damage	Considered in selected cases with immune-mediated complications
Antimicrobial prophylaxis	Isoniazid	Prevention of tuberculosis activation	Suppression of latent mycobacterial infection	Used in workers with high tuberculosis risk associated with silicosis

Preventive measures were evaluated within the framework of the hierarchy of controls, emphasizing engineering, organizational, and hygienic interventions. Engineering controls included ventilation systems, wet drilling techniques, water spraying, and fog-based dust suppression methods designed to reduce airborne dust at the source and prevent its dispersion into the working environment. Their effectiveness was assessed through comparative analysis of dust concentration profiles under different operational scenarios. Organizational measures were analyzed in terms of work process regulation, timing of personnel presence during dust-intensive operations, and maintenance practices related to dust control equipment. Hygienic aspects included evaluation of workplace microclimate conditions, availability and proper use of personal protective equipment, and compliance with established sanitary standards.

The optimization of silicosis prevention programs was performed through a comparative assessment of individual and combined preventive measures, with particular emphasis on their ability to mitigate peak dust concentrations rather than only reducing average exposure levels. The analysis demonstrated that isolated preventive actions are insufficient under conditions of highly variable dust generation, and that effective prevention requires the rational integration of multiple control methods. Priority was given to preventive solutions that ensured stable reduction of dust exposure, operational reliability, and feasibility for long-term implementation in mining enterprises.

All data obtained during the study were systematized and analyzed using a comparative analytical approach, allowing identification of optimal combinations of technical and organizational measures. The resulting methodological framework provides a basis for developing optimized silicosis prevention programs that account for the specific technological and environmental characteristics of mining operations and enhance the overall effectiveness of occupational health protection.

RESULTS

The analysis of the collected data demonstrated that respirable silica dust exposure in mining operations is characterized by pronounced temporal variability, with the highest concentrations occurring during drilling, blasting, and material handling processes. Short-term peak dust concentrations were observed to substantially exceed permissible exposure limits, even in workplaces equipped with standard ventilation systems. These findings confirm that average dust concentration values alone are insufficient for assessing occupational risk and that peak exposure events play a critical role in the development of silicosis.

Dust generated during loading, transportation, and preparatory operations in the mining industry can, in many cases, be effectively suppressed by artificial air humidification methods such as fine water spraying or “light rain” systems. However, one of the most challenging issues remains the removal of dust deposited in working faces, which can be re-entrained into the air during material handling and auxiliary operations. It has been established that, under these conditions, dust concentrations may increase by 5–10 times compared to non-operational periods, significantly raising the likelihood of exceeding permissible occupational exposure limits. These factors highlight the necessity of optimizing silicosis prevention programs through the improvement of dust suppression technologies, enhancement of industrial hygiene monitoring, and reduction of the duration and intensity of workers’ exposure to respirable silica-containing dust in mining environments.

Evaluation of engineering control measures revealed that conventional ventilation systems provide partial reduction of airborne dust levels but are limited in their ability to suppress rapid concentration spikes. Wet drilling and water spraying techniques showed a noticeable reduction in dust generation at the source; however, their effectiveness was strongly dependent on operational conditions, water supply stability, and maintenance practices. Fog-based dust suppression methods demonstrated improved performance in capturing fine respirable particles and reducing their dispersion in the working zone, particularly during blasting and post-blasting periods.

The combined application of multiple engineering controls resulted in a more stable reduction of dust concentration over time compared to isolated measures. Integrated approaches that included ventilation, wet drilling, and localized fogging systems were more effective in mitigating both average exposure levels and short-term peaks.

The dust-binding capability of the polyvinyl alcohol-based film and the morphological characteristics of captured dust particles are illustrated in Figure 1.

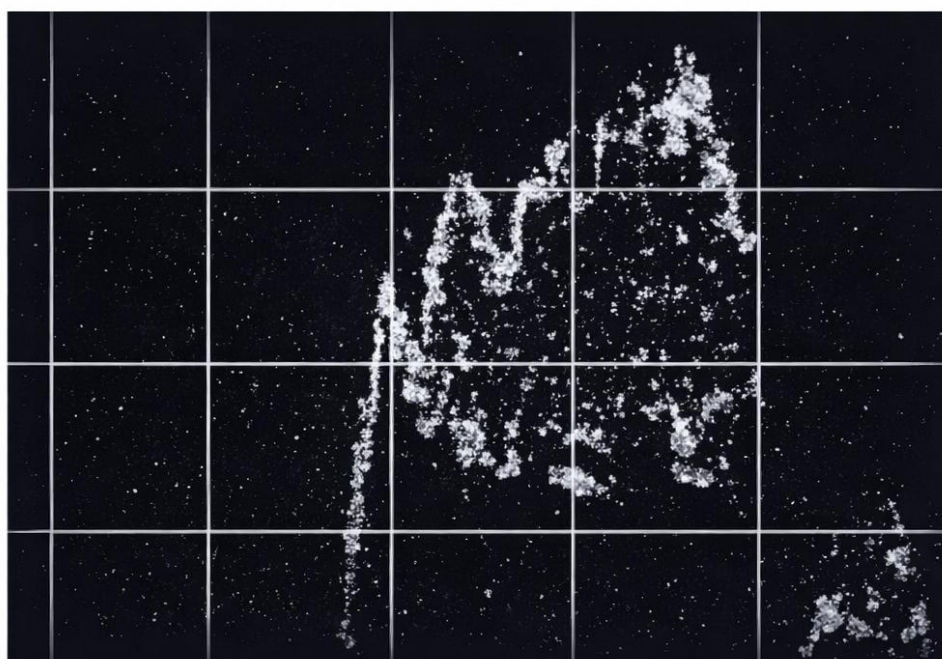


Figure 1. Micrograph of a dust-binding film made of polyvinyl alcohol.

These results indicate that optimization of silicosis prevention programs requires the coordinated implementation of complementary control methods rather than reliance on single technical solutions. Figure 2 presents the temporal variation of dust concentration in the air of the preparatory working over one production cycle, clearly demonstrating the differences in dust generation under various technological conditions and stages of the mining process, which form the basis for the analysis discussed in the Results section.

The assessment of hygienic measures highlighted the importance of workplace microclimate control and consistent use of personal protective equipment. While personal respiratory protection reduced individual exposure, its effectiveness depended on proper selection, correct usage, and worker compliance. The results suggest that personal protective equipment should be considered a supplementary measure rather than a primary control strategy within optimized prevention programs.

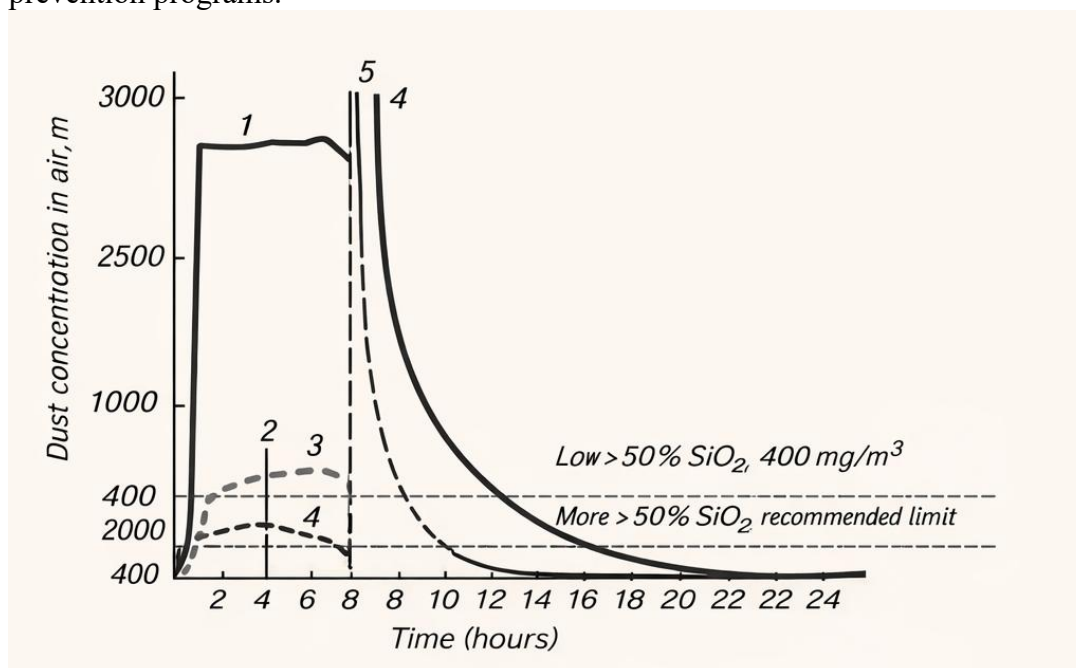


Figure 2. Temporal variation of dust concentration in the air of a preparatory working during one production cycle. 1 – dust concentration during dry drilling; 2 – dust concentration during wet drilling; 3 – dust concentration during heading without blasting; 4 – dust concentration after blasting; 5 – dust concentration after blasting with aerosol (mist) formation.

Organizational measures significantly influenced the overall effectiveness of preventive strategies. Regulation of work processes, restriction of personnel presence during high-exposure operations, and systematic maintenance of dust control equipment contributed to measurable reductions in worker exposure. The analysis further showed that inadequate implementation and monitoring of organizational controls can substantially diminish the benefits achieved through engineering interventions.

Table 2. Effect of polyvinyl alcohol concentration on the impact strength of the dust-binding film

Polyvinyl alcohol concentration, wt.%	Impact strength, kgf/cm ²	Relative increase compared to 0.1 wt.%	Observed mechanical behavior
0.1	0.45	1.0	Low cohesion, insufficient film integrity
0.5	1.60	3.6	Improved particle binding, moderate strength
1.0	2.50	5.6	Stable film formation with enhanced resistance
2.0	4.00	8.9	High mechanical stability and effective dust fixation

Scientific note: An increase in polyvinyl alcohol concentration leads to a pronounced improvement in the impact strength of the dust-binding film. At concentrations above 1.0 wt.%, the film exhibits stable mechanical behavior, indicating enhanced intermolecular bonding and improved resistance to mechanical stress. This effect is critical for preventing secondary dust entrainment under dynamic mining conditions.

Overall, the findings demonstrate that effective silicosis prevention in the mining industry is achieved through the integration of engineering, organizational, and hygienic measures, with particular emphasis on controlling peak dust exposures. The optimized prevention framework derived from the analysis provides a more robust and sustainable approach to reducing occupational silica exposure and lowering the long-term risk of silicosis among mining workers.

CONCLUSION

This study demonstrates that respirable silica dust exposure in mining operations is characterized by pronounced temporal variability, with short-term peak concentrations representing a major determinant of occupational risk and silicosis development. The results confirm that average dust concentration values alone are insufficient for effective exposure assessment and prevention. Integrated engineering control strategies combining ventilation, wet drilling, water spraying, and fog-based dust suppression were shown to be more effective than isolated measures in reducing both average and peak dust concentrations. The application of polyvinyl alcohol-based dust-binding films further enhanced dust control efficiency by effectively capturing fine particles and preventing their secondary entrainment. Mechanical testing indicated that films with polyvinyl alcohol concentrations above 1.0 wt.% exhibit sufficient strength for use under dynamic mining conditions. Organizational and hygienic measures were found to significantly enhance the effectiveness of technical controls, while personal protective equipment should be regarded as a supplementary rather than a primary preventive measure. Overall, the findings highlight the

necessity of an optimized, integrated approach to silicosis prevention focused on controlling peak dust exposures in mining environments.

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