

# Occupational exposure limit compliance may underestimate health risks in silica dust exposed workplaces

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## Article

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# Abstract

Occupational exposure limits are widely used to judge the acceptability of workplace dust exposure, but their ability to capture the full health risk of respirable crystalline silica remains uncertain. This study evaluated the concordance between occupational exposure limit compliance and semi-quantitative occupational health risk classification among dust-exposed workplaces in Yongchuan District, Chongqing, China. Occupational hygiene data were collected from 42 enterprises, covering 231 dust-exposed positions and 1,177 samples, including total dust, respirable dust, and welding fume samples. Silica dust was the predominant hazard, accounting for 92.2% of assessed positions. Although 880 samples (74.8%) complied with occupational exposure limits, 318 samples (27.0%) were classified as high or very high risk by semi-quantitative assessment. At the position level, 110 of 213 silica dust-exposed positions (51.6%) were classified as high or very high risk, including 67 of 170 OEL compliant positions (39.4%). Non-metallic mineral mining had a particularly high risk burden, and drilling, crushing, loading or transportation, sand cleaning, moulding sand handling, and dry cutting were the main high-risk processes. Wet operations showed substantially lower risk. The false-negative rate among compliant respirable dust samples was higher than that among total dust samples. These findings indicate that OEL compliance alone may underestimate silica-related occupational health risks, particularly in jobs with high free SiO<sub>2</sub> content. Combining exposure-limit compliance with semi-quantitative risk assessment may improve risk stratification and support more targeted silicosis prevention.

## Introduction

Occupational exposure to crystalline silica has long been recognized as a serious and widespread hazard across a wide range of industrial activities worldwide<sup>1,2</sup>. Respirable crystalline silica (RCS), primarily quartz, is generated during numerous industrial processes, including mining, quarrying, stone cutting, non-metallic mineral processing, foundry operations, and construction material manufacturing<sup>3</sup>. Inhalation of RCS is causally associated with silicosis, a progressive, irreversible, and often fatal pneumoconiosis. Despite decades of regulatory efforts, silicosis continues to threaten workers' health globally. An estimated 1–2 million silicosis cases occur worldwide, with thousands of deaths each year attributable to occupational silica dust exposure<sup>4–6</sup>. China is among the countries most severely affected by silicosis, accounting for 88.3% of newly reported pneumoconiosis cases in 2019<sup>7</sup>, and having the highest age-standardized incidence and prevalence rates globally. Non-coal mining enterprises are particularly numerous in China, and many are characterized by outdated technologies and equipment, inadequate dust-control measures, and limited awareness of occupational health protection<sup>8–10</sup>.

Silicosis develops according to a cumulative exposure–response relationship, indicating that even long-term exposure at relatively low concentrations may lead to clinically significant pulmonary fibrosis<sup>11</sup>. This relationship highlights the importance of considering cumulative inhaled dose, rather than focusing solely on peak or time-weighted average concentrations, when assessing occupational risk<sup>12</sup>. In routine

occupational health practice, regulatory compliance is generally determined by whether measured airborne concentrations exceed established occupational exposure limits (OELs), such as the permissible exposure limit (PEL) in the United States or the Chinese PC-TWA<sup>10</sup>. OEL-based assessment provides a standardized and operationally feasible benchmark; however, it has important limitations. Specifically, it primarily reflects exposure intensity and does not fully incorporate key risk-modifying factors, including free SiO<sub>2</sub> content, exposure duration and frequency, particle-size distribution, engineering control measures such as wet dust suppression, and ventilation efficiency<sup>13</sup>. In China, the national technical standard GBZ/T 298–2017 recommends a semi-quantitative risk assessment model that integrates hazard severity, exposure level, exposure duration, exposure frequency, and control-measure effectiveness into a composite risk index. This approach is consistent with the broader international shift from exposure-limit compliance alone toward risk-based occupational health assessment and prevention.

However, empirical validation of such models, particularly regarding their concordance with OEL compliance status, remains limited. In this study, we sought to address this evidence gap by analyzing occupational hygiene data from 213 silica-exposed jobs across multiple industries in Yongchuan District, Chongqing, China. We systematically compared OEL compliance status with risk classifications derived from GBZ/T 298–2017 and identified industries, processes, and job types in which OEL compliance may misrepresent the true occupational health risk. Our findings aim to support a transition in occupational health management from purely compliance-driven assessment toward risk-stratified management.

## Results

### Characteristics of dust-exposed enterprises and work positions

This study included 42 enterprises with dust hazards in Yongchuan District, Chongqing, covering 231 dust-exposed positions and 1,177 silica dust-exposed job samples in 2025. Among these, there were 474 total dust samples, 607 respirable dust samples, and 96 welding fume samples. Silica dust was the predominant hazard, accounting for 92.2% of all assessed positions. Among the 213 silica dust positions, 72 (33.8%) had a free silica content greater than 50%, and 141 (66.2%) had 50% or less (Supplementary Table 1).

In terms of OEL compliance, 880 samples (74.8%) were compliant with the occupational exposure limit, while 297 samples (25.2%) exceeded the OEL (Fig. 1A). The distribution of semi-quantitative risk levels across all samples was as follows: negligible risk 98 (8.3%), low risk 324 (27.5%), medium risk 437 (37.1%), high risk 220 (18.7%), and very high risk 98 (8.3%). After combining low and medium risk as “lower risk” and high and very high risk as “higher risk”, 318 samples (27.0%) fell into the higher risk category (Fig. 1B).

In addition to sample-level analysis, the distribution of occupational health risk was also examined at the position level across different industries. As shown in Table 1, the non-metallic mineral mining industry had the highest proportion of high or very high risk positions (75.7%, 53 out of 70 positions), followed by the wholesale industry (100%, 6 out of 6 positions). In contrast, automobile manufacturing showed a much lower proportion (30.8%, 4 out of 13 positions). These industry-specific differences were statistically significant ( $\chi^2 = 22.30$ ,  $df = 9$ ,  $p = 0.008$ ), indicating that risk burden is not uniformly distributed across industries.

Table 1

Industry-specific distribution of occupational health risk levels among silica dust-exposed positions

| Industry                                         | Low risk,<br>n (%) | Medium risk,<br>n (%) | High risk,<br>n (%) | Very high risk, n (%) | Total,<br>n |
|--------------------------------------------------|--------------------|-----------------------|---------------------|-----------------------|-------------|
| Non-metallic mineral product manufacturing       | 27 (32.1)          | 27 (32.1)             | 22 (26.2)           | 8 (9.5)               | 84          |
| Non-metallic mineral mining                      | 4 (5.7)            | 13 (18.6)             | 29 (41.4)           | 24 (34.3)             | 70          |
| Metal products manufacturing                     | 5 (31.2)           | 3 (18.8)              | 4 (25.0)            | 4 (25.0)              | 16          |
| Automobile manufacturing                         | 7 (53.8)           | 2 (15.4)              | 4 (30.8)            | 0 (0.0)               | 13          |
| General equipment manufacturing                  | 2 (25.0)           | 2 (25.0)              | 3 (37.5)            | 1 (12.5)              | 8           |
| Wholesale industry                               | 0 (0.0)            | 0 (0.0)               | 0 (0.0)             | 6 (100.0)             | 6           |
| Special equipment manufacturing                  | 2 (50.0)           | 2 (50.0)              | 0 (0.0)             | 0 (0.0)               | 4           |
| Coal mining and washing                          | 0 (0.0)            | 0 (0.0)               | 4 (100.0)           | 0 (0.0)               | 4           |
| Electrical machinery and equipment manufacturing | 0 (0.0)            | 4 (100.0)             | 0 (0.0)             | 0 (0.0)               | 4           |
| Transportation equipment manufacturing           | 0 (0.0)            | 3 (75.0)              | 1 (25.0)            | 0 (0.0)               | 4           |
| Total                                            | 47 (22.1)          | 56 (26.3)             | 67 (31.5)           | 43 (20.2)             | 213         |

## Sample-level OEL compliance versus semi-quantitative risk

A cross-analysis was performed between OEL compliance (exceedance vs. non-exceedance) and semi-quantitative risk level (lower vs. higher). Among the 880 compliant samples, the majority were at low or medium risk: 408 (46.4%) were at medium risk, and 324 (36.8%) were at low risk (Fig. 2A). Notably, 50 compliant samples (5.7%) were classified as high risk, and none as very high risk. Thus, the

false negative rate (compliant but actually higher risk) was 5.7%. Among the 297 non-compliant samples, the risk distribution was markedly different: 170 (57.2%) were high risk and 98 (33.0%) were very high risk, totaling 268 (90.2%) in the higher risk group. The remaining 29 non-compliant samples (9.8%) were at medium risk, and none were at low or negligible risk. The difference in the proportion of higher risk between the exceedance and non-exceedance groups was statistically significant ( $\chi^2 = 805.12$ ,  $df = 1$ ; Fisher's exact  $p < 0.001$ ) (Fig. 2A).

The ROC curve for predicting higher risk (high/very high) using the semi-quantitative risk model showed an area under the curve (AUC) of 0.905, indicating excellent discriminative ability. At the maximum Youden index cut-off, the model achieved a sensitivity of 84.3%, specificity of 96.6%, positive predictive value of 90.2%, negative predictive value of 94.3%, and overall accuracy of 93.3% (Fig. 2B). These results demonstrate that the semi-quantitative risk assessment can effectively identify high-risk samples, especially when OEL exceedance is present.

## Position-level discordance between OEL compliance and risk

To complement the sample-level analysis, a position-level cross-classification was performed. Among the 213 silica dust-exposed positions, 170 were OEL-compliant and 43 were non-compliant. Strikingly, 67 of the 170 compliant positions (39.4%) were still classified as high or very high risk by the semi-quantitative assessment. In contrast, all 43 non-compliant positions (100.0%) were classified as high or very high risk. This difference was statistically significant (Fisher's exact  $p < 0.001$ ) (Table 2).

Overall, 110 of the 213 positions (51.6%) were categorized as high or very high risk. Among these, 43 (39.1%) came from the non-compliant group and 67 (60.9%) from the compliant group. This indicates that relying solely on OEL compliance would miss a substantial proportion of high-risk positions: nearly 40% of compliant positions still carry elevated risk.

Table 2

Position-level cross-classification of OEL compliance and occupational health risk among silica dust-exposed positions

| OEL-based classification | No. of positions | Low or medium risk (n, %) | High or very high risk (n, %) | Proportion of high/very high risk (%) |
|--------------------------|------------------|---------------------------|-------------------------------|---------------------------------------|
| OEL compliant            | 170              | 103 (60.6)                | 67 (39.4)                     | 39.4                                  |
| OEL non-compliant        | 43               | 0 (0.0)                   | 43 (100.0)                    | 100.0                                 |
| Total                    | 213              | 103 (48.4)                | 110 (51.6)                    | 51.6                                  |

## Variation in risk by work process

A process-based analysis revealed substantial differences in the proportion of high or very high risk positions across work processes. Drilling operations had the highest proportion (82.6%, 19 out of 23 positions), followed by crushing (74.2%, 23 out of 31 positions), loading/transportation (68.2%, 15 out of 22 positions), and sand cleaning (61.1%, 11 out of 18 positions). Moulding sand handling and dry cutting also showed considerable risk, with 56.3% (9 out of 16) and 48.1% (13 out of 27) elevated risk, respectively (Table 3).

In sharp contrast, wet operations (water grinding or wet cutting) had only 12.5% (3 out of 24 positions) classified as high risk and none as very high risk. Welding fume-exposed positions, included for comparison, had the lowest proportion of elevated risk (5.6%, 1 out of 18 positions). These differences among the eight work processes were statistically significant ( $\chi^2 = 23.05$ ,  $df = 7$ ,  $p = 0.002$ ) (Table 3), confirming that work process is a major determinant of risk level.

Table 3  
Proportion of high or very high occupational health risk by work process among silica dust-exposed positions

| Work process                                                                                                                                 | No. of positions | Low risk, n | Medium risk, n | High risk, n | Very high risk, n | High or very high risk (%) |
|----------------------------------------------------------------------------------------------------------------------------------------------|------------------|-------------|----------------|--------------|-------------------|----------------------------|
| Drilling                                                                                                                                     | 23               | 1           | 3              | 11           | 8                 | 82.6                       |
| Crushing                                                                                                                                     | 31               | 2           | 6              | 14           | 9                 | 74.2                       |
| Sand cleaning/cleaning                                                                                                                       | 18               | 3           | 4              | 7            | 4                 | 61.1                       |
| Moulding sand handling                                                                                                                       | 16               | 2           | 5              | 6            | 3                 | 56.3                       |
| Loading/transportation                                                                                                                       | 22               | 2           | 5              | 10           | 5                 | 68.2                       |
| Dry cutting                                                                                                                                  | 27               | 5           | 9              | 8            | 5                 | 48.1                       |
| Wet operation                                                                                                                                | 24               | 12          | 9              | 3            | 0                 | 12.5                       |
| Welding fumes                                                                                                                                | 18               | 9           | 8              | 1            | 0                 | 5.6                        |
| Note: Chi square test for differences among the eight work processes: $\chi^2 = 23.05$ , $df = 7$ , $p = 0.002$ (statistically significant). |                  |             |                |              |                   |                            |

## False negative rates and representative high-risk examples

Among compliant samples, the false negative rate (compliant but actually high risk) differed markedly by dust fraction. For respirable dust, 379 compliant samples contained 35 high-risk samples, yielding a false negative rate of 9.2%. For total dust, 406 compliant samples contained 15 high-risk samples, a false negative rate of 3.7%. This difference was statistically significant ( $\chi^2 = 10.09$ ,  $df = 1$ ,  $p = 0.0015$ ) (Table 4), indicating that reliance on total dust measurements may underestimate the hidden high-risk proportion compared with respirable dust measurements.

Table 4  
Comparison of false negative rates between total dust and respirable dust

| Type            | Total compliant | High-risk count | False negative rate (%) | Chi-square | p value |
|-----------------|-----------------|-----------------|-------------------------|------------|---------|
| Respirable dust | 379             | 35              | 9.2                     | 10.09      | 0.0015  |
| Total dust      | 406             | 15              | 3.7                     |            |         |

To further illustrate why some OEL-compliant positions remain at high risk, representative examples are provided in Table 5. These positions had measured dust concentrations below the corresponding OEL but were classified as high risk due to high free SiO<sub>2</sub> content, prolonged exposure duration, dry operations, or inadequate ventilation. For instance, a loading position in non-metallic mineral mining had a dust concentration of 0.47 mg/m<sup>3</sup> (compliant) but a free SiO<sub>2</sub> content of 67.4%; a cutting position in non-metallic mineral product manufacturing had a dust concentration of 0.51 mg/m<sup>3</sup> and 46.4% free SiO<sub>2</sub>; and a moulding sand handling position in metal products manufacturing had a dust concentration of 0.41 mg/m<sup>3</sup> and a free SiO<sub>2</sub> content of 94.5%. All three were classified as high risk despite OEL compliance.

Table 5  
Representative OEL-compliant but high-risk silica dust-exposed positions

| Industry                                   | Work process           | Dust concentration (mg/m <sup>3</sup> ) | Free SiO <sub>2</sub> content (%) | OEL status    | Risk classification |
|--------------------------------------------|------------------------|-----------------------------------------|-----------------------------------|---------------|---------------------|
| Non-metallic mineral mining                | Loading                | 0.47                                    | 67.4                              | OEL compliant | High risk           |
| Non-metallic mineral product manufacturing | Cutting                | 0.51                                    | 46.4                              | OEL compliant | High risk           |
| Metal products manufacturing               | Moulding sand handling | 0.41                                    | 94.5                              | OEL compliant | High risk           |

Positions with the highest false negative rates (compliant samples that were nevertheless high risk) are listed in Table 6. Drilling-2 and cleaning positions had a false negative rate of 100% (2 out of 2 and 5 out of 5 compliant samples were high risk, respectively). Loading-1 had a false negative rate of 55.6% (5 out of 9 compliant samples were high risk), followed by drilling-1, melting, and loading-2, each with 50% false negative rates. These positions also had high average risk scores (ranging from 19.73 to 32.47) and high average free SiO<sub>2</sub> content (53.5% to 78.7%). These findings confirm that even when measured dust concentrations do not exceed the OEL, high silica content and specific job types can still lead to elevated risk.

Table 6  
Top positions with compliant but high-risk (false negative) samples

| Sampling point | Compliant samples | High-risk samples | False negative rate (%) | Average risk score | Average SiO <sub>2</sub> (%) |
|----------------|-------------------|-------------------|-------------------------|--------------------|------------------------------|
| Drilling-2     | 2                 | 2                 | 100.0                   | 28.81              | 69.5                         |
| Cleaning       | 5                 | 5                 | 100.0                   | 32.47              | 78.7                         |
| Loading-1      | 9                 | 5                 | 55.6                    | 22.73              | 56.8                         |
| Drilling-1     | 2                 | 1                 | 50.0                    | 24.01              | 69.5                         |
| Melting        | 4                 | 2                 | 50.0                    | 22.91              | 63.8                         |
| Loading-2      | 8                 | 4                 | 50.0                    | 19.73              | 53.5                         |

## Discussion

OEL compliance should not be interpreted as indicating low occupational health risk in silica dust-exposed positions, because 67 of 170 OEL compliant positions (39.4%) were still classified as high or very high risk by the semi-quantitative assessment (Table 2). By contrast, all 43 OEL non-compliant positions were classified as high or very high risk, indicating that OEL exceedance has strong positive predictive value for identifying clearly hazardous positions (Table 2). These findings suggest that although OEL-based judgement is effective in identifying excessive exposure, it may underestimate risk when used as the sole basis for risk classification.

OEL compliance mainly indicates whether measured airborne concentrations remain below the prescribed limit during a defined assessment period, whereas the health risk associated with respirable crystalline silica is also shaped by hazard potency, free SiO<sub>2</sub> content, exposure frequency and duration, production processes, and control measures<sup>13</sup>. Respirable crystalline silica has long been recognized as a serious occupational hazard, and silicosis remains the disease most strongly associated with such exposure<sup>14</sup>. Accordingly, exceedance judgement and semi-quantitative risk assessment play distinct but complementary roles. OEL exceedance provides a direct, regulation-oriented indicator of unacceptable exposure, whereas semi-quantitative risk assessment incorporates additional dimensions, including hazard severity, exposure probability, exposure duration, and existing control measures, thereby enabling risk prioritization even when measured concentrations do not exceed the OEL<sup>8,15,16</sup>.

Notably, OEL compliant samples were not concentrated solely in low-risk categories. Among the 880 compliant samples, 36.8% were classified as low risk, whereas a substantial proportion—46.4% (408 samples)—fell into the medium-risk tier, and an additional 5.7% were classified as high risk. Thus, more than half of the “compliant” samples still represented moderate or higher health risks. Because silicosis is a cumulative occupational disease with a well-established dose–response relationship<sup>6</sup>, a single or short-term measurement below the OEL does not necessarily indicate negligible long-term risk.

Continuous exposure in a medium-risk environment over many years, for example 10–20 years, may still generate a cumulative exposure dose sufficient to contribute to silicosis development<sup>17–19</sup>.

The risk of silicosis also varies substantially across ore types and mining methods. Previous studies have shown higher dust exposure levels and predicted incidence in non-metallic mines, nonferrous metal mines, small-scale mines, and open-pit operations, while metal miners face a higher risk of silicosis than ceramic workers<sup>20,21</sup>. Accordingly, primary regulation should avoid a one-size-fits-all approach.. Higher monitoring frequency and prioritized technical and engineering support should be directed toward high-risk mineral types, such as non-metallic mines, gold mines, and tungsten mines, as well as high-risk tasks such as crushing, blasting, and drilling. Beyond traditional mining and manufacturing sectors, our survey unexpectedly found that all wholesale industry positions (6 of 6) were classified as very high risk (Table 1), primarily involving the handling and unpacking of bagged powder materials. This finding suggests that the circulation and handling of bulk powder materials may pose a severe but often overlooked dust exposure hazard.

This issue is particularly relevant for small enterprises. In the United States, mines with fewer than 20 employees account for approximately two-thirds of all mining operations, and small enterprises commonly face limited resources, manager-centred decision-making, and weak safety culture<sup>22</sup>. Small mines may have fewer financial, technical, and managerial resources than larger enterprises, which can limit their capacity to conduct systematic exposure assessment, maintain engineering controls, provide effective respiratory protection, and employ dedicated occupational health personnel. Previous reports on mine safety also emphasize the importance of continuous training, regulatory enforcement, and reliable occupational health data for improving safety performance<sup>23,24</sup>.

Process-based analysis further clarified the sources of risk heterogeneity. As shown in Table 3, the proportions of high- or very high-risk positions for drilling, crushing, and dry cutting all exceeded 48%, whereas wet operations, including water grinding and wet cutting, had only 12.5% elevated risk and no very high-risk cases. This contrast underscores the central role of wet dust suppression in preventing and controlling silica dust exposure. Regulatory agencies should prioritize the replacement of dry processes with wet processes in non-metallic mineral processing and stone-cutting industries as a key engineering control to reduce silicosis risk. In addition, the high-risk positions with the highest false-negative rates (Table 6), such as cleaning operations (100% false-negative rate, average risk score 32.47, free SiO<sub>2</sub> 78.7%) and drilling-2, were often auxiliary rather than primary production tasks, such as sweeping and slag cleaning, and may therefore be easily neglected by enterprises. Enterprises should explicitly include these “auxiliary high-risk” posts in priority control lists, rather than focusing exclusively on main production lines.

This study has several limitations. First, the data were obtained from a single district, which may limit the generalizability of the findings. Second, the cross-sectional design precluded assessment of temporal exposure trends and causal links between risk classification and health outcomes. Third, the semi-quantitative assessment relied on field investigation and predefined scoring criteria, which may have

introduced information bias or misclassification. In addition, individual cumulative exposure, repeated personal sampling, biological monitoring, and clinical outcomes were not available. Future studies with larger, multi-region samples and longitudinal designs should integrate environmental monitoring, individual exposure assessment, and occupational health examination data to further validate the combined use of OELs and semi-quantitative risk assessment in occupational health management.

## **Materials and Methods**

### **Data sources and study population**

This study used dust monitoring data and field investigation records collected in 2025 from enterprises with occupational dust hazards in Yongchuan District, Chongqing, China. The dataset was provided by the Yongchuan District Center for Disease Control and Prevention. Enterprises and work positions exposed to hazardous dusts, mainly silica dust and welding fume, were included. Dust exposure characteristics were analyzed at both the enterprise and work-position levels by dust type, enterprise size, economic type, industry category, and production process or job type.

### **Instruments and analytical standards**

The main instruments included personal dust samplers (Gilian), dust samplers (CCZ30), an analytical balance with a sensitivity of 0.1 mg (QUINTIX224-1CN, Sartorius), an analytical balance with a sensitivity of 0.01 mg (XS205DU, METTLER TOLEDO), and a ceramic fiber muffle furnace (TC-8-10, Zhongxing). Workplace dust sampling and analysis were performed primarily in accordance with the Chinese national standard GBZ/T 192.2. For comparison with international practice, reference was also made to the gravimetric methods described in the NIOSH Manual of Analytical Methods, including NIOSH Method 0500<sup>25</sup> for total particulate matter and NIOSH Method 0600<sup>26</sup> for respirable particulate matter.

### **Classification of basic characteristics**

Enterprise size was classified according to the Statistical Classification of Large, Medium, Small and Micro Enterprises (2017) issued by the National Bureau of Statistics of China. Economic type was classified according to the Provisions on the Classification of Registered Enterprise Types. Based on field investigation records and job information, enterprises were categorized by industry type. Dust-exposed work positions were classified as silica dust positions or welding fume positions according to the predominant hazardous agent.

### **Classification of free silica content**

Free silica ( $\text{SiO}_2$ ) content was determined for relevant dust-exposed work positions and categorized as low (< 10%), medium (10–50%), high (50–80%), or very high (> 80%). Dust containing > 10% free silica was classified as silica dust. This classification was used to analyze the distribution of work positions and risk characteristics across different free silica content levels.

### **Assessment of occupational exposure limit exceedance**

Occupational exposure limit (OEL) exceedance was determined according to GBZ 2.1–2019, Occupational Exposure Limits for Hazardous Agents in the Workplace-Part 1: Chemical Hazardous Agents. Measured concentrations at each dust-exposed work position were compared with the corresponding permissible concentration-time weighted average (PC-TWA), and positions were classified as OEL compliant or OEL non-compliant. For silica dust, the applicable OEL was determined by free silica ( $\text{SiO}_2$ ) content. For welding fume, exceedance was assessed using the corresponding OEL specified in GBZ 2.1–2019. Although NIOSH Methods 0500 and 0600 were considered when interpreting particulate measurements, exceedance classification in this study was based exclusively on the Chinese national standard.

## Occupational health risk assessment

A semi-quantitative occupational health risk assessment was conducted for all dust-exposed work positions in accordance with GBZ/T 298–2017, Technical Guidelines for Occupational Health Risk Assessment of Chemical Hazards in the Workplace. Based on the carcinogenicity classifications of the International Agency for Research on Cancer (IARC)<sup>27</sup>, silica dust and welding fume were assigned the highest hazard rating coefficient (10) in the risk model. According to field investigation findings, exposure duration was treated as continuous exposure, and the exposure index was assigned a value of 4. The risk index (R) was then calculated and classified as negligible ( $R \leq 1$ ), low ( $1 < R \leq 6$ ), medium ( $6 < R \leq 24$ ), high ( $24 < R \leq 96$ ), or very high ( $R > 96$ ). For comparison between groups, low and medium risk were combined as lower risk, and high and very high risk were combined as higher risk.

## Process-based risk analysis

Based on field investigation data and job titles, silica dust-exposed work positions were further grouped into major process categories, including drilling, crushing, sand cleaning/material cleaning, molding sand handling, loading/transport, dry cutting, and wet operations (water grinding/wet cutting). The distribution of risk levels across these process categories was analyzed to identify priority high-risk operations.

## Cross-classification of OEL compliance and risk

To examine whether OEL compliance alone could adequately identify high-risk silica dust-exposed work positions, positions were classified as OEL compliant or OEL non-compliant according to whether measured dust concentrations exceeded the corresponding OEL. Positions were also grouped as lower risk or higher risk based on the semi-quantitative risk assessment results. Cross-classification analysis was then performed to compare the proportion of higher-risk positions between the two OEL compliance groups.

## Statistical analysis

Categorical variables were expressed as frequencies and percentages. Differences in proportions were compared using the chi-square test or Fisher's exact test, as appropriate. A two-sided  $p < 0.05$  was considered statistically significant. The chi-square test was used to compare the proportion of higher-

risk positions between dust types (silica dust vs. welding fume), process categories (df = 7), and industries (df = 9). Fisher's exact test was used to compare the proportion of higher-risk positions between the OEL compliant and OEL non-compliant groups in a 2 × 2 contingency table. Comparisons between wet operations and corresponding dry operations were performed using the chi-square test or Fisher's exact test, as appropriate.

## Declarations

## Ethics declarations

This study was based on workplace dust monitoring and field investigation data collected for occupational hygiene assessment. The data did not involve human participants, human biological samples, personal medical records, or individual health information.

## Conflict of interest

The authors declare no competing interests.

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## Author Contribution

M.W. and H.Y. conceived and designed the study. M.W., H.D., J.W. and Y.L. collected the occupational hygiene monitoring data and participated in field investigation. M.W. and H.D. performed data cleaning, statistical analysis and occupational health risk assessment. J.W. and Y.L. contributed to laboratory testing, exposure assessment and interpretation of occupational hygiene data. M.W. drafted the manuscript. H.Y. supervised the study, reviewed and revised the manuscript, and provided overall project guidance. All authors reviewed and approved the final manuscript.

## Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality restrictions related to workplace exposure data, but are available from the corresponding author on reasonable request.

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Figures

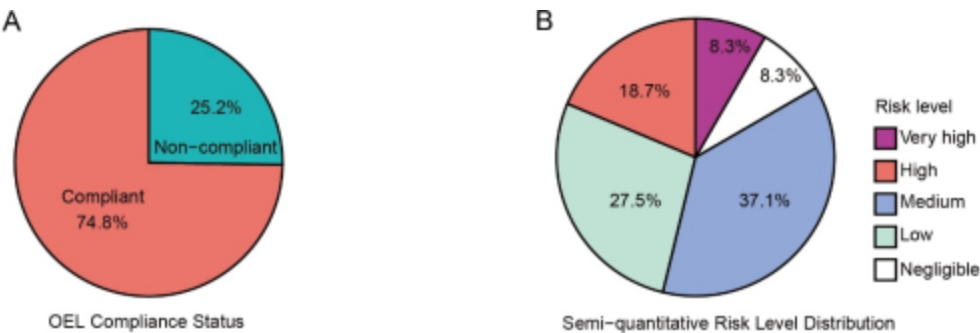


Figure 1

**A.** Pie chart showing the distribution of occupational exposure limit (OEL) compliance among silica dust-exposed samples. **B.** Pie chart showing the distribution of semi-quantitative risk levels among silica dust-exposed samples.

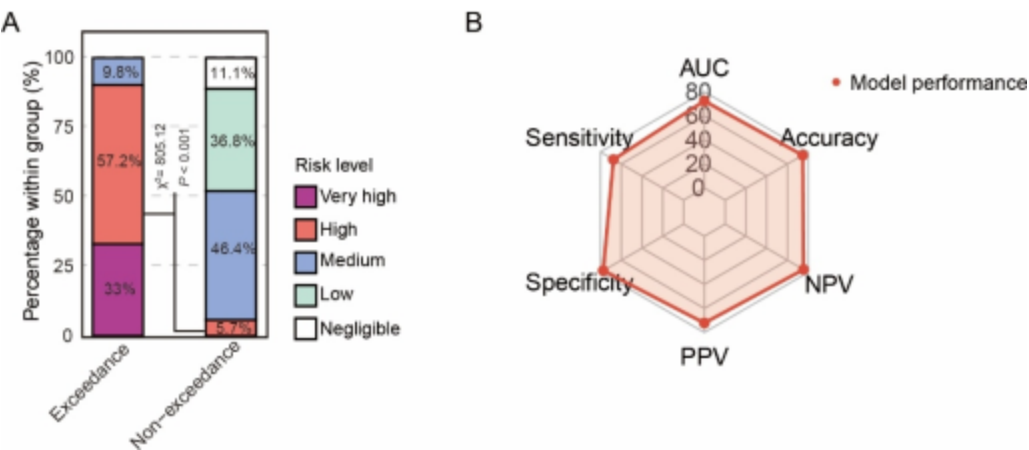


Figure 2

**A.** Stacked bar chart showing the distribution of semi-quantitative risk levels (negligible, low, medium, high, very high) among non-exceedance (n=880) and exceedance (n=297) samples. The proportion of high/very high risk is markedly higher in the exceedance group (90.2%) than in the non-exceedance group (5.7%). ( $\chi^2$  test  $p < 0.001$ ). **B.** Radar chart of the semi-quantitative risk model’s performance for predicting high/very high risk. The filled area illustrates the model’s excellent discriminative ability.

Supplementary Files

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- [SupplementaryTable1.xlsx](#)