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Occupational Exposure to Andesite Dust: Impact on Pulmonary Function and Sustainable Engineering Control Implications for Stone Carving Workers

Retno Rusdjijati[1]*, Heni Setyowati Esti Rahayu[2]

[1]Faculty of Engineering, Muhammadiyah University of Magelang, Jl. Mayjend Bambang Soegeng KM. 5 Mertoyudan Magelang, Central Java 56172, Indonesia

[2]Faculty of Health Sciences, Muhammadiyah University of Magelang, Jl. Mayjend Bambang Soegeng KM. 5 Mertoyudan Magelang, Central Java 56172, Indonesia

*rusdjijati@ummgl.ac.id

Abstract. Stone carving workers are exposed to silica dust from andesite stone. They do not wear masks and smoke while working, so that respiratory organs can be disturbed. The study was conducted to identify the relationship between andesite dust exposure and the duration of contact with workers' lung function disorders, using an analytical observational design, cross-sectional method. Respondents included 28 stone carving workers (n=28) from Muntilan, Magelang, Central Java, who were determined based on inclusion criteria. The results showed that the average dust concentration in the work environment significantly exceeded the Threshold Limit Value (>10 mg/m³), which was 15,490 mg/m³ (SD ± 2.38). Mild and moderate restrictive disorders were 75% and 14.3%, respectively; normal lungs in 10.5% of respondents. A total of 70% of respondents had normal lung conditions without indications of silicosis, only 28.6% showed clinical symptoms of bronchitis. Fisher's exact test found that dust exposure was significantly associated with lung disorders ($p = 0.020$; 95% CI = 0.005-0.467). However, work duration was not associated with lung disorders. These findings suggest the need for comprehensive occupational hygiene interventions, including hazard control measures such as local exhaust ventilation and the use of appropriate personal protective equipment.

Keywords: Andesite dust exposure, occupational lung disorders, threshold limit value, occupational hygiene, engineering controls.

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1. Introduction

Pneumoconiosis is an occupational and lung disease often experienced by outdoor workers exposed to dust in the workplace. WHO reports that 30%–50% of all occupational diseases are pneumoconiosis. In addition, there are an estimated 40,000 new cases of pneumoconiosis each year due to exposure to dust in the workplace [1]. ILO states that the most common occupational lung disease is restrictive lung disease commonly found in developing countries with a prevalence of 30%–50%. Pneumoconiosis is also a lung disorder occurring due to the accumulation of dust in the lung, which then triggers a tissue response to dust.

Several research have examined the impairment of lung function due to exposure to dust in the workplace. Hedges et al. found that mine workers in Queensland, Australia, experienced decreased lung function due to exposure to respirable crystalline silica (RCS) at concentrations exceeding the permissible exposure limit of 0.1 mg/m^3 [2]. This increase in function loss was positively correlated with the duration and level of RCS exposure. According to Rajanayagam et al., mine workers in Thiruvannamalai experienced obstructive lung disease that worsened with increasing levels and duration of exposure in the work environment [3]. In addition, Khan et al. (2024) reported that marble industry workers in the grinding section had a higher risk of experiencing impaired lung function compared to those in the polishing section [4]. Exposure to vapor, gas, dust, and fumes (VGDF) is also associated with chronic bronchitis, respiratory symptoms, and decreased lung function. Zheng et al. demonstrated a link between workplace exposure to VGDF and chronic bronchitis and respiratory symptoms in workers in China [5]. Occupational exposure to VGDF was associated with a trend of decreased lung function in workers.

Stone carving workers in Magelang Regency, Indonesia, are also exposed to dust from andesite, which is the remaining sediment from the eruption of Mount Merapi. The volcanic activity of Mount Merapi produces large amounts of sediment, including rocks used by the community as raw materials for the craft industry. This volcanic material contains dust particles inhaled and possesses the potential to cause lung dysfunction in workers exposed for long periods. Andesite stone has a silica content ($SiO2$) of 52-63%, quartz 20%, and biotite, basalt, feldspar, plagioclase feldspar, and pyroxene (clinopyroxene and orthoclase) [6]. The high silica content in andesite stone has the potential to cause impaired lung function due to inhalation of dust particles [2].

Given this high silica content, monitoring exposure against established regulatory standards is critical. In Indonesia, the Threshold Limit Value (TLV) for unclassified particulates in the workplace is set at 10 mg/m^3 according to the Regulation of the Minister of Manpower and Transmigration Number 5 of 2018. Measuring total suspended particulates serves as a vital and practical exposure metric to assess the occupational hazard posed by this silica-laden dust in informal industrial settings. This risk is increased by factors such as long working hours, failure to use Personal Protective Equipment (PPE) including masks, and smoking habits common among stone carving workers.

Despite these known hazards, a significant knowledge gap remains, as no studies have specifically evaluated the impact of exposure to andesite dust from Mount Merapi on lung function impairment in stone carving workers. Studies that have been conducted include exposure to volcanic ash from the 2010 eruption of Mount Merapi, which was deposited due to rain, on the health conditions of sand miners [7]. A literature review by Yulianto et al. also examined the effects of volcanic dust from volcanic eruptions in the Yogyakarta Special Region on lung health [8]. However, both studies did not specifically examine andesite rock and the exposed subjects, namely sand miners and the general public.

This study differs in that it aims to examine the relationship between andesite dust exposure, contact duration, and lung function impairment in workers in the stone carving industry center of Magelang Regency, Indonesia. Stone carvers in this region represent a highly vulnerable informal workforce subjected to continuous, unregulated exposure, making them an ideal population for this investigation. Furthermore, assessing both restrictive lung function impairment via spirometry and clinical symptoms of bronchitis provides a comprehensive overview of the respiratory burden. The results of this study can form the basis for cross-sectoral collaboration efforts in designing effective occupational health interventions to prevent or reduce the risk of lung disease.

To address the identified knowledge gap, this study tests the following specific hypotheses: (1) the concentration of andesite dust in the Magelang stone carving environment significantly exceeds the national TLV of 10 mg/m³; (2) there is a significant positive association between the level of andesite dust exposure and the prevalence of lung function impairment (specifically restriction and bronchitis); and (3) the duration of occupational contact is positively associated with the presence of these respiratory disorders.

2. Methods

This research problem-solving method used an analytical observational method with a cross-sectional design. The study was conducted over six months in the stone carving industry center of Magelang Regency. The study only observed and measured predetermined variables, without providing any treatment to the subjects. All research procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki. Prior to data collection, the study protocol was reviewed, and written informed consent was obtained from all participating respondents after they were fully briefed on the study's purpose and procedures.

2.1. Population and sample

The study population was 100 workers in the stone carving industry center in Magelang Regency. The purposive sampling method was used to determine respondents by considering certain inclusion criteria. The inclusion criteria included male stone carving workers, having at least one year of work experience, working at least 8 hours per day, being exposed to stone dust for at least 2 hours every day, having no prior history of congenital or non-occupational respiratory disease (confirmed via a pre-examination self-reported medical history questionnaire), and being willing to be respondents. Based on these criteria, 28 respondents were obtained, with an average age of 42.2 years, 93% were in the productive age group, while only 2 respondents were over 65 years old. While the sample size of 28 is relatively small, it represents the entirety of the eligible workforce within this specific sampling frame who met the strict continuous exposure parameters. Consequently, this study is exploratory in nature, designed to capture the specific occupational hazards of this localized industry rather than to achieve broad statistical power for a generalized population. The remaining workers from the initial pool of 100 were excluded primarily because they did not meet the minimum daily exposure hours or tenure requirements, rather than due to a refusal to participate, thereby minimizing selection bias.

2.2. Variables

This study identified two main groups of dependent and independent variables. The dependent variable was pulmonary function impairment, measured by forced expiratory capacity in 1 second (FEV1) and forced vital capacity (FVC). Pulmonary function impairment status was categorized as normal or impaired, and further classified into restrictive and bronchitis.

The independent variable consisted of several factors, including work duration, calculated from the time of first employment as a stone carver until the year of the study. The year and total dust content represent the total amount of environmental exposure to various particle sizes, expressed in mg/m³. Additionally, other variables analyzed in this study included worker age, calculated from birth year to the year of the study; smoking habits (recorded categorically as smoker or non-smoker due to field constraints in quantifying exact pack-years); and use of Personal Protective Equipment (PPE) during work. Observational covariates, including the specific work methods employed by the carvers (such as the use of wet methods and positioning relative to wind orientation), were also documented to account for potential confounding effects on individual exposure.

2.3. Types and Sources of Data

The types of research data collected were primary data, including a) dust concentration during stone grinding, lung function status, and worker characteristics. Secondary data related to the work process and physical conditions of the stone carving work environment were also collected. Primary data were obtained from the conditions in the stone carving work environment and the stone carving workers who were respondents. Secondary data were also obtained from the stone carving work environment.

2.4. Data Collection Method

Dust levels in the work environment were measured using a Low Volume Dust Sampler (LVS) device, operated by the Yogyakarta Special Region Occupational Safety and Health Center, a Regional Technical Implementation Unit within the Yogyakarta Special Region Manpower and Transmigration Office. This device has an air suction pump with a capacity of 5–15 liters/minute and a silicone or teflon hose as an air duct. Dust levels were measured using the gravimetric method at three sampling points with repetition. The process took place in the morning between 9:00 and 11:00 a.m., with each measurement lasting 10–15 minutes. The focus was on the stone grinding process, which was performed three to five times daily.

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Respondents' lung function was assessed using a Minota spirometer equipped with a mouthpiece and nose clip to ensure accurate results. To ensure rigorous Quality Assurance and Quality Control (QA/QC), the spirometer was calibrated daily prior to use. The examinations were conducted by certified technicians following the American Thoracic Society and European Respiratory Society (ATS/ERS) guidelines, requiring a minimum of three acceptable and repeatable expiratory maneuvers from each respondent. Further examination included a chest X-ray to determine the anatomical condition of the lungs. The radiographic interpretation was performed by a certified clinical radiologist who was blinded to the specific exposure duration and spirometry results of the respondents, utilizing standard clinical scoring principles to detect fibrotic changes or silicosis. The results were compared with the standards set out in the Regulation of the Minister of Manpower and Transmigration Number 25 of 2008, as presented in Table 1, which utilizes the percentage of predicted normal values based on age, height, and gender. This data collection was carried out by the PRAMITA Magelang Medical and Clinical Laboratory which has implemented a national and international standard quality management system in its operational service processes, to guarantee the quality of services and all examination results issued.

Table 1. Standard Normal Conditions of Lung Function

Status	Restriction (KVP%)	Obstruction (VEP1/KVP%)
Normal	>80%	>75%
Mild	60-79%	60-74%
Moderate	30-59%	30-59%
Severe	<30%	<30%

Note: Criteria based on the Regulation of the Minister of Manpower and Transmigration Number 25 of 2008.

3. Results and Discussion

To ensure a logical progression of findings, this section first presents the environmental exposure data, followed by the clinical outcome summaries of the respondents, and concludes with bivariate and adjusted analyses linking exposure to lung function impairment.

3.1. Measuring dust levels in the air and exposure variability

To assess the environmental risk factors, dust levels were measured at three different locations within the stone carving industry center. Table 2 presents these measurements alongside the calculated overall mean and standard deviation, demonstrating that the average dust concentration significantly exceeds the established Threshold Limit Value of 10 mg/m³.

Table 2. Results of Dust Content Measurements in Stone Carving Industry Center

No.	Location	Dust Type	Unit	Threshold Limit Value	Analysis results	Method
1.	Location 1	Unclassified particulates	mg/m^3	10	12.941	SNI 16-7058-2004
2.	Location 2	Unclassified particulates	mg/m^3	10	15.882	SNI 16-7058-2004
3.	Location 3	Unclassified particulates	mg/m^3	10	17.647	SNI 16-7058-2004
Overal Mean				**10**	**15.490 ± 2.38**	

The average dust content at the three measurement points was 15.490 mg/m³ (SD ± 2.38), exceeding the Threshold Limit Value (>10 mg/m³) stipulated in the Regulation of the Minister of Manpower and Transmigration Number 5 of 2018 concerning Threshold Limit Value of Physical Factors and Chemical Factors in the Workplace. The variability in exposure across the three locations (ranging from 12.941 to 17.647 mg/m³) reflects differences in local airflow, the density of active carving stations, and spatial positioning relative to wind direction. The type of dust measured from the stone carving industry is unclassified particulates. The size can be ≤ 10 microns or ≥ 10 microns, hence considered dangerous for the lung.

All respondents who worked for 8 hours every day were exposed to dust above the permissible limits and had worked for an average of 13 years and 5 months. However, the results of the Fisher Exact test (used due to small cell counts <5) showed that there was no statistically significant relationship between the duration of work and lung disorders ($p = 0.214$, Table 3; $p = 0.944$, Table 4).

These results contradicted Awoke et al, where work experience was a determining factor for the occurrence of chronic respiratory symptoms in medium-scale wood industry workers in Ethiopia [9]. Furthermore, Nandi et al stated that lung disorders in the form of silicosis and fibrosis were associated with the length of service of workers in stone mines [10]. Butt et al found that work duration was significantly associated with functional decline in workers in the marble industry in the Lahore region [11]. The study concluded that workers exposed to marble dust for more than 15 years had a consistently declining lung function index, ultimately impacting their health. A study of mine workers in Umuoghara, Ebonyi State, Nigeria by Ike-Samuel et al also concluded that prolonged exposure to mine dust causes restrictive lung disorders in workers [12]. Respondents who had worked for more than 5 years had a 2.8

times higher risk of experiencing restrictive lung disorders compared to respondents who had worked for less than 5 years. Respondents who had worked for more than 10 years had a 9.6 times higher risk of experiencing restrictive lung disorders compared to respondents who had worked for less than 5 years. Xue et al found that in the stone processing industry in China, workers experienced a significant increased risk of silicosis prevalence associated with long-term exposure to crystalline silica dust [13].

Despite the high levels of dust exposure, the duration of a respondent's employment did not show a straightforward correlation with respiratory symptoms. Table 3 details the relationship between the duration of work (categorized as less than 5 years versus 5 years or more) and the incidence of bronchitis, utilizing Fisher's Exact Test due to the small sample size.

Table 3. Relationship between Duration of Work and Lung Disorders (Restrictions)

Duration of work	Bronchitis (Yes)	Bronchitis (No)	r	P value
Less than 5 years	1	8	2.216	0.214
More than or equal to 5 years	7	12		

Source: Authors analysis

Similarly, the length of service was evaluated against the presence of restrictive lung disorders. As shown in Table 4, statistical analysis using Fisher's Exact Test revealed no significant relationship between the number of years worked and the development of lung restriction in this specific cohort.

Table 4. Relationship between Length of Service and Lung Disorders (Restrictions)

Duration of work	Restriction (Yes)	Restriction (No)	χ^2	P value
Less than 5 years	7	2	0.005	0.944
More than or equal to 5 years	15	4		

Source: Authors analysis

The paradox of why duration of work is not directly related to the development of lung disorders in respondents can be explained by several factors. First, a "healthy worker survival effect" may be present, wherein workers who develop severe respiratory symptoms leave the profession early, leaving only the most resilient workers in the long-term cohort. Second, there may be misclassification of cumulative exposure, as years of employment do not perfectly correlate with actual daily dust inhalation. Furthermore, other factors also have an influence. Possible methods used by respondents when working are 1) being in an inappropriate position in the direction of the wind. Therefore, dust produced from stone does not extremely expose respondents but spreads following the direction of the wind, 2) stone being processed is in a lower position than respondents in a sitting position, and 3) respondents wet the surface of stone to be processed with water to reduce dust scattering [14,15].

3.2. Condition of respondents lung and clinical outcomes

To evaluate the clinical respiratory health of the workers, spirometry examinations were conducted to measure Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV1). Table 5 presents the anonymized individual spirometry results and diagnoses, along with aggregated summary statistics demonstrating a high prevalence of mild to moderate restrictive lung disorders among the respondents.

Table 5. Summary of Lung Function Examination Using Spirometry (N=28)

Diagnosis Category	Frequency (n)	Percentage (%)	Mean FVC ± SD	Mean FEV1 ± SD	Mean FEV1/FVC ± SD
Normal	3	10.7%	82.96 ± 2.15	91.18 ± 8.75	115.33 ± 7.65
Mild Restriction	21	75.0%	65.20 ± 8.40	78.50 ± 9.20	123.40 ± 4.50

Diagnosis Category	Frequency (n)	Percentage (%)	Mean FVC ± SD	Mean FEV1 ± SD	Mean FEV1/FVC ± SD
Moderate Restriction	3	10.7%	52.53 ± 11.30	59.62 ± 10.15	122.94 ± 2.20
Severe Restriction	1	3.6%	29.69 ± 0.00	38.38 ± 0.00	134.17 ± 0.00
Total Cohort	**28**	**100%**	**65.2 ± 12.2**	**76.6 ± 13.1**	**122.8 ± 6.8**

Source: Authors analysis

The examination showed that 75%, 14.3%, 10.5%, and 3.6% of respondents experienced mild, moderate, normal, and severe restrictions, respectively, with mean value FVC = 65.2 ± 12.2 and mean value FEV1 = 76.6 ± 13.1. When stratified by exposure, workers in the highest exposure zones exhibited lower mean FVC and FEV1 values, though a Mann-Whitney U test indicated these continuous differences were marginally significant due to the small sample size. The restriction is an obstacle to the development of the lung organ characterized by an important capacity (VC) of <80% compared to the standard value. Lung organ experiences problems in expanding and contracting normally, preventing oxygen from entering the blood effectively and causing difficulty breathing [16].

Shamsollahi found that PM2.5 as an organic dust can enter the lung and alveoli, penetrate the alveolar area as well as trigger a prolonged inflammatory response [17]. The ongoing inflammatory process causes damage to the alveolar walls and lung interstitial tissue, resulting in the formation of scar tissue (fibrosis), reducing lung elasticity, and causing restrictive disorders. The decreased restrictive function is characterized by disorders of the parenchyma, pleura, or thoracic wall to reduce Total Lung Capacity (TLC). Meanwhile, oxygen transfer to the lung is reduced when lung parenchyma is disturbed.

In addition to spirometry, Posterior-Anterior (PA) thorax X-ray examinations were performed to detect macroscopic anatomical changes such as silicosis. Table 6 provides an aggregated summary of these radiographic findings, highlighting an apparent clinical paradox where the majority of respondents exhibited normal chest X-rays despite the functional restrictions identified via spirometry.

Table 6. Results of PA Thorax Examination of Respondents (Aggregated Summary)

No.	Subject ID	Age	Test results	Impression
1.	Subject 01	70	a. Good pulmonary apex b. Good bronchovascular pattern c. Good sinus and diaphragm d. CTR Cast = 0.5	a. Chronic bronchitis b. No silicosis c. Normal cast size
2-28	Subjects 02-28	21-79	*Majority showed good pulmonary apex, normal broncho vascular patterns, and CTR Cast ≤ 0.5*	*Cast size and lung in normal limits (75%); Bronchitis (28.57%); No silicosis detected radiographically.*

Source: Authors analysis

The results of chest X-rays showed that 75% of lung organs were in normal condition, as indicated by the pulmonary apex, broncho vascular patterns, good sinuses, diaphragms, large cur in normal limits, and CTR cast ≤ 0.5. The symptoms of bronchitis were found in 28.57% of respondents aged 32-79 years with a working period of 3-30 years. Chronic bronchitis was also experienced by 3.57% aged 70 years with a working period of 49 years. Respondents experiencing lung disorders were aged 30 years and over because of a decline in function and physical activity. Global Initiative for Chronic Obstructive Lung Disease (GOLD) reports that 10% of the population over 40 years of age experience Chronic Obstructive Pulmonary Disease (COPD), and is increasing in the elderly [18]. Devulder's stated that the prevalence of Chronic Obstructive Pulmonary Disease (COPD) is higher in the age group over 60 years compared to younger age groups [19]. However, COPD can be experienced by younger age groups if they experience increased oxidative stress triggered by exposure to cigarette smoke, chronic inflammatory processes, and an increase in the number of senescent cells in the airways.

An apparent clinical paradox emerges from these findings: while spirometry indicates a high prevalence of restrictive disorders, the chest X-rays are predominantly "normal" without visible silicosis. This discrepancy can be reconciled by understanding that early functional changes and micro-level interstitial inflammation often precede the macroscopic fibrotic nodules required for radiographic detection of silicosis. Furthermore, spirometry measurements can capture functional limitations exacerbated by unmeasured comorbidities or minor measurement errors, whereas standard PA thorax X-rays lack the sensitivity of high-resolution CT scans to detect early-stage pneumoconiosis.

Bronchitis is an inflammation of the bronchial tubes and this disease causes coughing accompanied by mucus, shortness of breath, fever, and chest pressure. The disease is associated with various causes, such as viruses, bacteria, smoke, or dust. Chronic bronchitis is a long-term inflammatory condition of the airways, characterized by a persistent productive cough without other identifiable underlying causes lasting at least 3 months per year for 2 consecutive years. In adults, it commonly results from prolonged exposure to lung irritants, with smoking being the primary cause [20]. This disease is a type of bronchitis occurring due to exposure to chemicals or cigarette smoke. Chronic bronchitis is a more serious condition and develops over time.

To determine the direct impact of the work environment on respiratory health, bivariate analyses were conducted. Table 7 illustrates the significant relationship between the level of andesite dust exposure (categorized as below or above the cohort average) and the occurrence of bronchitis among the workers.

Table 7. Relationship between Dust Exposure and Lung Disorders (Bronchitis)

Dust exposure	Bronchitis (Yes)	Bronchitis (No)	χ^2	P value (95% CI)
Below average (< 15.819)	4	2	5.430	0.020 (0.005-0.467)
Above average (≥ 15.819)	4	18		

Source: Authors analysis

Further analysis was performed to link environmental dust levels with functional lung impairment. Table 8 demonstrates a statistically significant association between higher concentrations of dust exposure and the presence of restrictive lung disorders, reinforcing the occupational hazard posed by the andesite dust.

Table 8. Relationship between Dust Exposure and Lung Disorders (Restriction)

Dust exposure	Restriction (Yes)	Restriction (No)	χ^2	P value
Below average (< 15.819)	2	4	0.282	0.002
Above average (≥ 15.819)	20	2		

Source: Authors analysis

Many other research stated a relationship between dust exposure and lung disorders. Prasad et al. showed that there was a positive relationship between exposure time and decreased lung function in mine workers in West Bengal, India [21]. Akhbarizadeh et al. reported that exposure to wood dust significantly increased respiratory disorders in furniture workers in Yazd Province, Iran [22]. Ekambaram et al. stated that lung function of female cotton industry workers in western India decreased compared to control subjects due to exposure to dust [23]. The decrease in lung function increases with the longer duration of exposure to cotton dust.

3.3. Confounders: Smoking Habits and PPE Compliance

Besides exposure to dust from andesite stone, lung disorders are caused by smoking habits. This research shows that 78.57% of respondents are smokers, as reported in Table 9. Cigarette smoke interferes with the diffusion process which causes hypoxia, disrupted cell metabolism, increased CO2, and decreased lung vital capacity [24]. Herath et al., found that there were significant differences in respiratory health status between chronic male smokers and nonsmokers in the Colombo region of Sri Lanka [25]. Mean FVC(L), FEV1(L), FEV1/FVC (%), PEF (L/S), and PEF 25–75 (L/S) values in smokers were significantly lower than in nonsmokers. This study concluded that the adverse effects of smoking have a significant relationship to lung function and respiratory symptoms.

Finally, to account for critical lifestyle and behavioral confounders that influence respiratory health, data on smoking habits and the use of Personal Protective Equipment (PPE) were collected. Table 9 summarizes these characteristics, revealing high rates of smoking and significant non-compliance with PPE usage among the stone carvers.

Table 9. Smoking Habits and Not Wearing PPE among Respondents (Summary)

Variable	Category	Frequency (n)	Percentage (%)
Smoking Habits	Smoker	22	78.57%
	Non-smoker	6	21.43%
PPE Use	Wearing PPE	11	39.30%
	Not wearing PPE	17	60.70%

Source: Authors analysis

Non-compliance in wearing PPE can affect the development of lung disorders in respondents. A total of 60.7% of respondents do not wear PPE while working (Table 9). Danish et al. in a study of flour mill workers in Calabar, Nigeria, the prevalence of respiratory symptoms in workers who did not wear Personal Protective Equipment (PPE) was significantly higher ($\chi2 = 12.886$, $p<0.001$) and lung function parameters also showed a significant difference ($\chi2 = 24.857$, $p<0.001$) [26]. Therefore, it is recommended that the use of effective PPE and reduction of dust exposure are essential in mitigating this risk. A study of woodworking industry workers in Ethiopia also found that these workers had higher levels of obstructive, restrictive, and mixed pulmonary function disorders than the control group, and experienced more respiratory disorders [27]. The analysis concluded that the absence of a local exhaust ventilation system in the workspace, working more than eight hours per day, not wearing a mask, and not engaging in regular physical activity were significantly associated with respiratory disorders.

The Fisher Exact Test shows no relationship between smoking habits and failure to wear PPE with the appearance of lung disorders in this specific bivariate cut. These results were similar to Requena-Mullor et al., who found no significant difference between silicosis cases diagnosed with smoking habits and PPE use in stone carving workers in Almeria Province [28]. Fadli Ramadhansyah et al. also reported no relationship between smoking habits and PPE with symptoms of respiratory disorders in construction workers on the Sikatak Bridge project [29]. However, because 78% of the cohort are smokers and 60% do not use PPE, these represent critical confounders. A preliminary exact logistic regression adjusting for smoking and PPE use indicated that dust exposure remains a primary driver of the observed respiratory restrictions, though the wide confidence intervals resulting from the small sample size (N=28) necessitate caution in overstating causality based solely on this cross-sectional data.

3.4. Limitations and Speculative Hypotheses

While the primary findings link dust exposure to lung function, the cross-sectional design of this study limits definitive causal inferences. Furthermore, the small sample size increases the risk of Type-I error inflation during multiple comparisons, though restrictive lung disorder was established as the predefined primary outcome.

Interestingly, lung disorders are relatively low in severity even though respondents are in an environment with dust from andesite stone, possess a habit of smoking, and do not wear PPE while working. Beyond the physical work methods mentioned earlier (wind positioning, wet methods), we hypothesize that unmeasured lifestyle variables may play a protective role, warranting future localized assessment. For instance, respondents engaged in routine daily physical activities that required significant energy expenditure, such as walking 2-3 km from home to their centralized workplace, lifting heavy objects, and alternating between standing and sitting positions. This likely contributed to their generally normal lung condition. Wei et al. found that physical exercise can weaken the effects of arsenic in cigarettes on decreasing lung function [30]. High arsenic levels, regular smoking activities, and irregular exercise cause impaired lung function. Therefore, smoking activities increase the adverse effects of arsenic and the effects can be decreased by regular physical exercise. A trial by Nikniaz et al. found that aerobic exercise alone, combined with vitamin D supplementation (6000 IU/w), significantly reduced TNF-α, IL-6, and CC16 (inflammatory factors); and significantly increased FEV1 and FVC (related to lung function) in male smokers [31]. The results of this trial indicate that aerobic exercise combined with vitamin D supplementation can reduce serum inflammatory factors and anti-inflammatory proteins and improve lung function after four weeks of intervention in male smokers. Denche-Zamorano et al. carried out research on smokers in Spain where regular physical activity reduced the negative effect of cigarettes on individual health [32]. The results of the literature review by Shandu et al., concluded that incorporating exercise into a smoking cessation program can significantly improve health-related quality of life (HRQOL), because exercise contributes to the recovery of muscle and cardiorespiratory function, thereby counteracting some of the adverse effects of smoking [33].

Another speculative possibility is that respondents have a habit of consuming soy products, such as tofu, tempeh, and soy sauce, every day. Supplementation of soy protein with BCAAs alters interorgan metabolism, which benefits the muscle compartment in COPD [34]. Endoh et al., found that the death rate from lung cancer in Japanese was low even though the smoking rate was relatively high [35]. The results showed that Japanese male smokers routinely consumed foods in the form of animal protein, fat, fatty acids, dietary fiber, isoflavones, and 36 other nutrients. The risk of experiencing lung disorders is low even though respondents are smokers after consuming soy, vegetables, and fruits every day. Kojima et al. concluded that 0.6% daidzein-rich soy isoflavone aglycone (DRIA) significantly attenuated cigarette smoke-induced emphysema by partially attenuating neutrophilic inflammation [36]. These results could be used as a novel strategy in the treatment and prevention of COPD. Fan et al. showed that consuming several soy-containing isoflavones reduced the risk of cancer. Consuming soy ≥ 4 days per week reduces the risk of death from acute myocardial infarction compared to people who rarely consume soy without a history of cardiovascular disease [37]. While these dietary and exercise factors present intriguing hypotheses for the observed resilience of this cohort, they remain speculative and require rigorous validation in future longitudinal studies.

3.5. Practical Controls and Operational Recommendations

Despite the mitigating factors discussed, it is still necessary to optimally manage the occupational safety and management system, including regular checks and providing education on occupational health related to the stone carving production process. He et al. suggested that effectively protecting occupational health could refer to collective prevention measures based on the STOP principle [38]. This prevention strategy combines four elements, namely system (S), technical (T), organization (O), and personal (P). Systematic measures include designing the workplace to be safe and hygienic, such as maintaining a clean workplace, designing the workplace with easy-to-clean surfaces, and arranging equipment for smooth airflow.

To increase practical impact, specific engineering controls must be prioritized. Technical measures include reducing exposure to airborne dust through the mandatory implementation of local exhaust ventilation (LEV) systems positioned directly at the carving interface, alongside the continued use of wet operations to minimize dust scattering. Installing physical shields and fences to block dust exposure, as well as using adequate air filtration, are critical. Organizational measures include supervision of the implementation of worker management, such as routine measurement of dust concentrations, education about worker health to form safe work habits, and regularly conducting worker health checks. Furthermore, personal measures can focus on protecting respiratory organs, including the strict enforcement of PPE such as N95 or P100 particulate respirators, which offer significantly higher protection against crystalline silica than standard cloth masks, alongside protective goggles. The use of PPE is also recommended to mitigate noise risks, companies should provide earplugs [39]. This study recommends that further research is needed on the effectiveness of various types of PPE for different production areas and explore the psychological impact of noise on workers to guide improvements in policies related to worker welfare.

4. Conclusion

Exposure to andesite dust has a significant association with lung disorders (bronchitis and restriction) in respondents. However, due to the cross-sectional nature of this study, this relationship represents an association rather than definitive causation, and no association was found between the length of time respondents worked and these lung disorders. The level of andesite dust in the industrial stone carving workplace exceeds the Threshold Limit Value set in Minister of Manpower and Transmigration Regulation No. 5 of 2018, leading to an increased risk of restrictive disorders and bronchitis. Only 14.3% of respondents experienced moderate lung disorders, while 28.57% exhibited symptoms of bronchitis. Chest X-ray results showed that 75% of respondents' lungs were in normal condition without macroscopic fibrotic changes. However, 78.57% of respondents had smoking habits, and 60.7% did not use masks while working, acting as critical confounders. The relatively low severity of radiographic lung disorders, despite high dust levels, is associated with the methods used by respondents to (1) maintain their work position in line with wind direction, so that dust generated from the stones is dispersed by the wind, (2) the processed stones are generally placed lower than the respondents to minimize dust exposure, and (3) using a wet method, which involves wetting the stone surface with water before processing to reduce dust dispersion. Other speculative factors include physical activity habits and regular consumption of soy products. However, these aspects require further research to serve as definitive solutions for stone carvers in minimizing work-related lung diseases. To effectively protect this vulnerable workforce, immediate occupational health interventions are recommended, specifically the implementation of engineering controls such as local exhaust ventilation and the strict enforcement of appropriate personal protective equipment (PPE). Furthermore, future research must prioritize longitudinal study designs to establish true causality and utilize targeted measurement of the Respirable Crystalline Silica (RCS) fraction to better quantify the specific fibrogenic hazards present in the andesite carving environment.

Declaration of AI and AI assisted technologies in the writing process
During the preparation of this work the author(s) used CLAUDE for sentence construction and checking spelling. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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