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ORIGINAL

Exposure Analysis of Pulmonary Function Disorders in Workers At PT. X

Análisis de exposición a trastornos de la función pulmonar en trabajadores de PT. X

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ABSTRACT

Introducción: una encuesta preliminar en PT X, el mayor productor de cemento en el este de Indonesia, reveló que el deterioro de la función pulmonar se encuentra entre las 10 principales enfermedades de los trabajadores debido a la exposición a altos niveles de polvo de PM2.5 y PM10 que superan el umbral, especialmente en áreas de producción, con un mayor riesgo en los trabajadores que no utilizan equipo de protección personal o fuman.
Método: este estudio cuantitativo observacional transversal midió la exposición al polvo respirable y de cigarrillo y el uso de EPP en trabajadores PT X, verificando la capacidad pulmonar con un espirómetro digital y analizando los datos mediante SPSS utilizando análisis univariado, bivariado y de ruta para evaluar la relación entre las variables.
Resultados: el análisis mostró que la exposición al polvo redujo significativamente la capacidad pulmonar (estimación -0,029, p = 0,00), mientras que la actividad física y el uso de EPP la aumentaron con efectos positivos significativos (p = 0,021 y p = 0,00). Además, la capacidad pulmonar y la actividad física tuvieron un efecto positivo significativo en el deterioro de la función pulmonar, mientras que la edad, el estado nutricional y el tabaquismo no tuvieron un efecto significativo, ni directo ni indirecto, sobre la capacidad pulmonar (p > 0,05).
Conclusiones: la implicación es que el aumento de la actividad física y el uso de EPP son importantes para mantener la capacidad pulmonar y prevenir el deterioro de la función pulmonar en los trabajadores expuestos al polvo en el entorno laboral.

Keywords: Dust Exposure; Impaired Lung Function; Pulmonary Capacity; Physical Activity; PPE Use.

RESUMEN

Introducción: una encuesta preliminar realizada en PT X, el mayor productor de cemento del este de Indonesia, reveló que la insuficiencia pulmonar se encuentra entre las diez enfermedades más frecuentes entre los trabajadores debido a la exposición a niveles elevados de PM2,5 y PM10 que superan el umbral, especialmente en las zonas de producción, con un mayor riesgo para los trabajadores que no utilizan equipos de protección individual o que fuman.
Método: este estudio cuantitativo observacional transversal midió la exposición al polvo respirable y al humo del tabaco y el uso de EPI en los trabajadores de PT X, con un control de la capacidad pulmonar mediante un espirómetro digital y un análisis de los datos mediante SPSS utilizando análisis univariantes, bivariantes y de trayectoria para evaluar la relación entre las variables.
Resultados: el análisis mostró que la exposición al polvo disminuyó significativamente la capacidad pulmonar (estimación -0,029, p = 0,00), mientras que la actividad física y el uso de EPI aumentaron la capacidad pulmonar con efectos positivos significativos (p = 0,021 yp = 0,00). Además, la capacidad pulmonar y la

actividad física tuvieron un efecto positivo significativo sobre el deterioro de la función pulmonar, mientras que la edad, el estado nutricional y la exposición al tabaco no tuvieron ningún efecto significativo, ni directa ni indirectamente, a través de la capacidad pulmonar (p>0,05).
Conclusiones: la implicación es que el aumento de la actividad física y el uso de EPI son importantes para mantener la capacidad pulmonar y prevenir el deterioro de la función pulmonar en los trabajadores expuestos al polvo en el entorno laboral.

Palabras clave: Actividad Física; Capacidad Pulmonar; Deterioro de la Función Pulmonar; Exposición al Polvo; Uso de EPI.

INTRODUCTION

Exposure to cement dust directly contributes to decreased lung function and increased risk of chronic respiratory diseases such as COPD and lung cancer. Total suspended particulates (TSP) dust in the cement industry can damage the immune system, lower airway defenses, and reduce Pulmonary Capacity.[1] The effects include symptoms such as coughing, shortness of breath and decreased endurance, which reduce productivity and increase absenteeism. Anderson et al.[2] emphasized the importance of further research in Indonesia to formulate policies to protect workers from the effects of cement industry dust exposure.

Based on data from the World Health Organization, lung function disorders are one of the leading causes of morbidity and mortality worldwide. Pulmonary impairment ranks as the 5th leading cause of death in the world and is expected to become the 3rd leading cause of death by 2020. Cases of lung function disorders due to dust exposure in the work environment in Indonesia have a high prevalence. Occupational lung diseases, such as pneumoconiosis, chronic obstructive pulmonary disease (COPD) and occupational asthma, remain a major concern in occupational health and safety. Major risk factors include exposure to hazardous dusts, gases and vapors in the workplace. Therefore, it is important for workers and employers to implement preventive measures, such as the use of appropriate personal protective equipment (PPE) and exposure control in the work environment.[3]

The cement industry plays an important role in national infrastructure development, but its production process generates significant dust emissions that adversely affect workers' health. Cement dust contains fine particles such as crystalline silica and calcium oxide that can cause impaired lung function, chronic bronchitis, and COPD.[4] Dust particles <1 µm in size are able to reach the alveolus, and <0,1 µm can move in and out of the alveoli without settling, thus risking reducing oxygen levels and Pulmonary Capacity of workers.[5] Garcia et al.[6] research also confirms that occupational dust exposure triggers lung function abnormalities. For this reason, the application of mitigation such as air filtration and the use of PPE is very important in reducing the risk of respiratory disorders in the cement industry. Exposure to harmful dusts, such as free silica and calcium oxide, can damage lung tissue and increase its susceptibility to infection. According to Raza et al.[7] workers in the cement industry often report symptoms such as chronic cough, shortness of breath, and decreased Pulmonary Capacity due to exposure to such dust. Al-Neaimi et al.[8] found that the prevalence of respiratory disorders was higher in areas with the highest dust exposure, such as grinding and packaging. Mitigation through better ventilation, use of PPE, and strict environmental policies are essential to reduce health risks.

The International Labour Organization reports that every year there are about 40 000 new cases of pneumoconiosis worldwide. Pneumoconiosis is a disease of impaired lung function caused by the inhalation of mineral dust, such as silica or asbestos, which results in scarring of the lungs. Among all occupational diseases, 10 % to 30 % are pulmonary disorders. Worker mortality due to respiratory diseases ranked third with 21 % of cases.[9] Of these, around 1,2 million workers die from work-related accidents and diseases. Based on Health Insurance Administration Agency, or in Indonesia this institution is called BPJS on their Employment data, there were 225 000 work accidents and 53 cases of occupational diseases in 2020, some of which were caused by exposure to dust and other work environment factors.[10]

An initial survey at PT X, the largest cement producer in Eastern Indonesia, located in Biring Ere Village, Bungoro Subdistrict, Pangkep Regency, showed that pulmonary function disorder is one of the top 10 diseases suffered by workers. With 1571 hectares of land and 512 workers, the company operates every weekday from 08:00 to 16:00 WITA, and produces an average of 7,4 million tons of cement per year. High dust exposure, especially in the grinding, kiln and packaging areas, is suspected to be the main cause of respiratory complaints, as measurement results using a *Staplex High Volume Air Sampler* show PM2,5 and PM10 dust concentrations exceeding the threshold value (NAB). These fine particulates can enter the lower respiratory tract and cause lung function disorders, especially in workers who are less consistent in using personal protective equipment (PPE) or have other risk factors such as smoking. This study aims to analyze the relationship between cumulative dust exposure (which is calculated from dust levels, length of work, and tenure), age, nutritional status, physical activity, smoking exposure (measured by the smoking exposure index), use of personal protective equipment (PPE), Pulmonary Capacity, and impaired lung function in workers at PT X at a certain time. Therefore, the purpose of this study was to explain the relationship between dust exposure and individual factors such as age, nutritional status, physical activity, cigarette exposure, and the use of personal protective equipment on lung function disorders in workers at PT X.

METHOD

This study is a quantitative study with an analytical observational design using a cross-sectional approach.

Table 1. Objective Criteria, and Research Instruments

Variable	Operational Definition (OD)	Objective Criteria (OC)	Research Instrument(s)
Dust Exposure	Calculated as: dust concentration (mg/m³) × working hours/day × working days/year × years of service ÷ 2000	- Low: <50 mg/m³·year - Moderate: 50-100 - High: >100	Dust measurement tool (STMC Tonasa), air sampling equipment (e.g., Staplex), secondary data
Age	Measured in full years from date of birth to the date of data collection	- Young Adult: 18-35 - Middle Adult: 36-50 - Late Adult: 51-60	Structured questionnaire / interview
Nutritional Status	Based on Body Mass Index (BMI)	- Malnourished: BMI <18,5 - Normal: 18,5-24,9 - Overweight/Obese: ≥25	Height and weight scale, BMI calculator, questionnaire
Physical Activity	Weekly frequency, duration, and intensity of non-work physical activity (e.g., exercise, walking, chores)	- None (0) - Light (1): ≤3x/week, <30min - Moderate (2): ≥3x/week, ≥30min - Heavy (3): ≥3x/week, intense	Physical activity questionnaire, structured interview, observation sheet
Smoking Exposure	Pack-Years Index = (cigarettes/day × years smoked) ÷ 20	- Non-smoker: 0 - Mild: <10 - Moderate: 10-20 - Heavy: >20	Smoking behavior questionnaire, structured interview
PPE Usage	Frequency and consistency of using protective masks/respirators	- Routine Use: Code 2 - Occasional Use: Code 1	Observation sheet, questionnaire, interview
Pulmonary Capacity	Measured using spirometry (COPD-6) to assess FEV1 (Forced Expiratory Volume in 1 second)	- Normal: ≥80 % - Mild Obstruction: 70-79 % - Moderate: 51-69 % - Severe: <50 %	Spirometer COPD-6, 3 trial readings per person; best result used
Pulmonary Function Disorder	Diagnosis based on FEV1 from spirometry	- Disorder: FEV1 <80 % - Normal: FEV1 ≥80 %	Spirometry test (COPD-6)

The population in this study was all 512 workers in the PT X factory area. The sample size was determined using the Lemeshow formula, assuming a prevalence of 20 %, a confidence level of 95 % (Z=1,96), and a margin of error of 5 %. After adjusting for the limited population, the sample size was 166 respondents. The sampling technique used simple random sampling, which gave each worker who met the inclusion criteria an equal chance of being selected as a respondent. The inclusion criteria for this study were workers employed in the manufacturing area, aged 18–60 years, with a minimum of one year of service, and willing to participate as respondents. Exclusion criteria included workers not directly exposed to dust, those with a history of chronic lung disease, or those who refused to give consent to participate.

Data management was carried out in several stages, namely editing to check the completeness and consistency of data, coding to convert qualitative data into quantitative data, cleaning to remove errors or duplications, and processing and tabulation using SPSS software to facilitate analysis. Data analysis includes three stages: 1) Univariate, to describe the distribution of each variable, such as dust exposure, Pulmonary Capacity, and lung function impairment; 2) Bivariate with Chi-Square test, to examine the relationship between two variables, such as the influence of age, work history, nutritional status, cigarette exposure, and PPE use on Pulmonary Capacity and impairment; 3) Path Analysis, to test direct and indirect relationships between variables and the mediating role of Pulmonary Capacity in relation to dust exposure and lung function impairment. Bivariate analysis and path analysis used p-values with significance set at p<0,05. This study adheres to the ethical code issued by the Faculty of Public Health, Hasanuddin University, with reference number 429/UN4.14.1/TP.01.02/2025.

RESULTS

This research was conducted in the production area of PT X, Bungoro District, Pangkajene and Islands (Pangkep) Regency, South Sulawesi, which is the center of operational activities of the largest cement company in Eastern Indonesia. Although the sample method yielded 166 respondents, only 125 respondents could be studied in the field.

Univariate Analysis

Table 2. Measurement Results of Dust Exposure at PT X

Dust Exposure		n	%
Dust Content	5,90 mg/m³	26	20,8
	10,29 mg/m³	43	34,4
	17,15 mg/m³	22	17,6
	22,42 mg/m³	11	8,8
	30,35 mg/m³	18	14,4
	37,46 mg/m³	5	4,0
Working Hours	8 Hours/Day	125	100
Working Days per Year	250 Days/Year	125	100
Length of Service	>5 Years	23	18,4
	5-10 Years	23	18,4
	11-15 Years	26	20,8
	16-20 Years	23	18,4
	21-25 Years	13	10,4
	26-30 Years	15	12
	31-35 Years	1	0,8
	36-40 Years	1	0,8
Cumulative Value of Dust Exposure	>150	54	43,2
	150-300	30	24
	301-450	18	14,4
	451-600	9	7,2
	601-750	6	4,8
	750-900	4	3,2
	901-1050	2	1,6

Data from respondents which 125 workers at PT X on table 2, the majority of workers at PT X are exposed to dust levels between 10,29 mg/m³ and 17,15 mg/m³, with 34,4 % and 17,6 % of workers in each respective range. All respondents work 8 hours per day and 250 days per year, with over 43 % having cumulative dust exposure values above 150. Additionally, most workers have worked for more than 5 years, with the highest proportion (20,8 %) in the 11–15 year service range, indicating prolonged exposure duration.

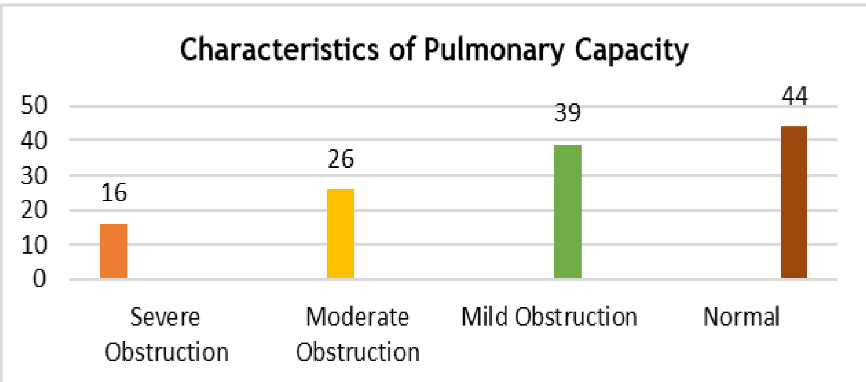

Figure 1. Characteristics of Pulmonary Capacity by Respondents

Based on figure 1, most respondents had normal pulmonary capacity (44 individuals), while the rest experienced varying levels of obstruction—mild (39), moderate (26), and severe (16). This indicates that more than half of the workers show signs of impaired lung function, with 52,8 % experiencing some degree of obstruction.

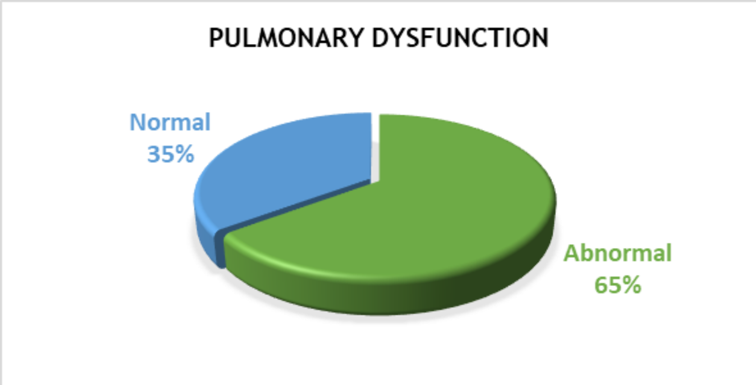

Figure 2. Characteristics of Pulmonary Dysfuction by Respondents

Figure 2 shows that out of the total respondents, 81 (64,8 %) experienced pulmonary dysfunction, while only 44 (35,2 %) had normal pulmonary function. This indicates a high prevalence of respiratory issues among workers, likely associated with prolonged exposure to industrial dust in the work environment.

Bivariate Analysis

Table 3. Relationship between Dust Exposure and Lung Function Disorders in Workers at PT X

Dust Exposure	Pulmonary Dysfunction				P-value
	Abnormal		Normal		
	n	%	n	%	
High	75	84,30	14	15,70	0,000
Medium	5	38,50	8	61,50	
Low	1	4,30	22	95,70	

The analysis of 125 PT X workers showed that 81 workers (64,8 %) had abnormal lung function, with the majority (84,3 %) exposed to high dust. In contrast, of the 44 workers with normal lung function, most (95,7 %) were at low dust exposure. The Chi-Square test showed a p-value of 0,00 (<0,05), which means there is a significant relationship between the level of dust exposure and impaired lung function in workers.

Table 4. Relationship between Age and Lung Function Disorders in PT X Workers

Age	Pulmonary Dysfunction				P-value
	Abnormal		Normal		
	n	%	n	%	
End	15	88,2	2	11,8	0,000
Madya	46	78,0	13	22,0	
Young	20	40,8	29	59,2	

The results of the analysis of 125 PT X workers showed that of the 81 workers with abnormal lung function, the majority were in the late age group (88,2 %) and middle age (78,0 %), while only 40,8 % were from young age. In contrast, of the 44 workers with normal lung function, most (59,2 %) were from the young age group. The Chi-Square test yielded a p-value of 0,00 (<0,05), indicating a significant association between age and impaired lung function in workers.

Table 5. Relationship between Nutritional Status and Pulmonary Function Disorders in Workers at PT X

Nutrition Status	Pulmonary Dysfunction				P-value
	Abnormal		Normal		
	n	%	n	%	
Obesity	22	81,5	5	18,5	0,068
Normal	59	60,2	39	39,8	

Based on statistical analysis of 125 workers, there were 81 workers with abnormal lung function and 44 workers with normal lung function. Among workers with lung disorders, 81,5 % had obese nutritional status and 60,2 % had normal nutritional status. Meanwhile, among workers with normal lung function, 18,5 % were obese and 39,8 % had normal nutritional status. The Chi-Square test results showed a p value of 0,068 (> 0,05), so it can be concluded that there is no significant relationship between nutritional status and lung function disorders in workers at PT X.

Table 6. Relationship between physical activity and lung function disorders in workers at PT X

Physical Activity	Pulmonary Dysfunction				P-value
	Abnormal		Normal		
	n	%	n	%	
No physical activity	74	77,1	22	22,9	0,000
There is physical activity	7	24,1	22	75,9	

Based on the results of statistical analysis of 125 workers, 81 workers had abnormal lung function and 44 workers had normal lung function. Of the workers with abnormal lung function, 77,1 % did not perform physical activity, while only 24,1 % performed physical activity. In contrast, among workers with normal lung function, 75,9 % regularly performed physical activity and 22,9 % did not perform physical activity. The Chi-Square test results showed a p value of 0,00 (<0,05), which means there is a significant relationship between physical activity and lung function disorders in workers at PT X.

Table 7. Relationship between Cigarette Exposure and Lung Function Disorders in Workers at PT X

Cigarette Exposure	Pulmonary Dysfunction				P-value
	Abnormal		Normal		
	n	%	n	%	
Weight	43	91,5	4	8,5	0,000
Lightweight	6	37,5	10	62,5	
Medium	21	56,8	16	43,2	
No Smoking	11	44,0	14	56,0	

Based on statistical analysis of 125 workers, 81 had abnormal lung function and 44 had normal lung function. Among workers with abnormal lung function, 91,5 % had heavy cigarette exposure, 56,8 % moderate cigarette exposure, 37,5 % light cigarette exposure, and 44,0 % did not smoke. Whereas in workers with normal lung function, 8,5 % had heavy cigarette exposure, 43,2 % moderate cigarette exposure, 62,5 % light cigarette exposure, and 56,0 % did not smoke. The Chi-Square test results showed a p value of 0,00 (<0,05), indicating a significant relationship between cigarette exposure and impaired lung function in workers at PT X.

Table 8. Relationship between the Use of PPE with Pulmonary Function Disorders in Workers at PT X					
Usage PPE	**Pulmonary Dysfunction**				**P-value**
	Abnormal		**Normal**		
	n	**%**	**n**	**%**	
Sometimes	11	100	0	0,0	0,008
Routine	70	61,4	44	38,6	

Based on the statistical analysis of 125 workers, 81 had abnormal lung function and 44 had normal lung function. Of the workers with abnormal lung function, 100 % used PPE occasionally, while 61,4 % used PPE routinely. In contrast, among workers with normal lung function, 38,6 % routinely used PPE. The results of the Chi-Square test showed a p value of 0,008 (<0,05), which means that there is a significant relationship between the use of PPE and lung function disorders in workers at PT X.

Table 9. Relationship between Pulmonary Capacity and lung function disorders in workers at PT X					
Pulmonary Capacity	**Pulmonary Dysfunction**				**P-value**
	Abnormal		**Normal**		
	n	**%**	**n**	**%**	
Severe Obstruction	16	100	0	0,0	0,000
Moderate Obstruction	26	100	0	0,0	
Mild Obstruction	39	100	0	0,0	
Normal	0	0,0	44	100	

Based on the statistical analysis of 125 workers, there were 81 workers with abnormal lung function and 44 workers with normal lung function. All workers with abnormal lung function had Pulmonary Capacity with severe (16 workers), moderate (26 workers) or mild (39 workers) obstruction. Meanwhile, all 44 workers with normal lung function had normal Pulmonary Capacity. The Chi-Square test results show a p value of 0,00 (<0,05), which indicates a significant relationship between Pulmonary Capacity and lung function disorders in workers at PT X.

Multivariate Analysis

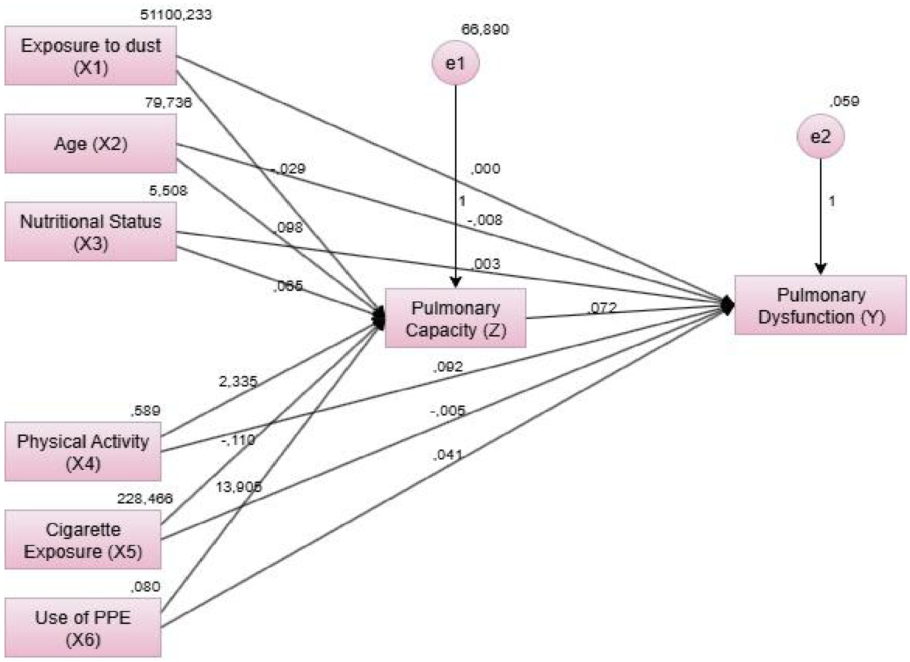

Figure 3. Path Analysis Model

Table 10. Parameter and Hypothesis Testing of Direct Effect

Influence	Estimate	S.E.	C.R.	P-value
Dust Exposure → Pulmonary Capacity	-0,029	0,005	-5,910	0,000
Age → Pulmonary Capacity	0,098	0,118	0,825	0,409
Nutrition Status → Pulmonary Capacity	0,065	0,323	0,202	0,840
Physical Activity → Pulmonary Capacity	2,335	1,010	2,313	0,021
Cigarette Exposure → Pulmonary Capacity	-0,110	0,058	-1,882	0,060
Use of PPE →Pulmonary Capacity	13,905	2,754	5,049	0,000
Pulmonary Capacity → Pulmonary Dysfunction	0,072	0,003	26,871	0,000
Dust Exposure → Pulmonary Dysfunction	0,000	0,000	0,065	0,948
Age → Pulmonary Dysfunction	-0,008	0,004	-2,327	0,020
Nutrition Status → Pulmonary Dysfunction	0,003	0,010	0,311	0,756
Physical Activity → Pulmonary Dysfunction	0,092	0,031	3,019	0,003
Cigarette Exposure → Pulmonary Dysfunction	-0,005	0,002	-3,056	0,002
Use of PPE → Pulmonary Dysfunction	0,041	0,090	0,453	0,651

The table 10 is the result of the direct effect test in this study. The analysis shows that the variables of age, nutritional status and smoking exposure do not have a significant effect on Pulmonary Capacity, with p-values totaling 0,409, 0,840 and 0,060 respectively as well as nutritional status on lung function disorders, so it can be concluded that nutritional status does not directly affect Pulmonary Capacity as well as lung function disorders. Furthermore, the variables of dust exposure, nutritional status and the use of PPE have no significant effect on lung function disorders with p-values totaling 0,948, 0,756 and 0,651 respectively, so it can be concluded that dust exposure, nutritional status and the use of PPE have no direct effect on lung function disorders.

In contrast, dust exposure showed a significant negative effect on Pulmonary Capacity with an estimate value of -0,029 C.R -5,910 and a p-value of 0,00. This indicates that the higher the dust exposure experienced by workers, the Pulmonary Capacity tends to decrease, besides that age also shows a significant negative towards lung function disorders with an estimate value of -0,008 C.R -2,327 and a p-value of 0,020 which indicates that the increasing age of workers, lung function disorders tend to decrease. Likewise, smoking exposure to lung function disorders shows a significant negative with an estimate value of -0,005 C.R -3,056 and a p-value of 0,002 which indicates that increasing smoking exposure to workers, lung function disorders tend to decrease.

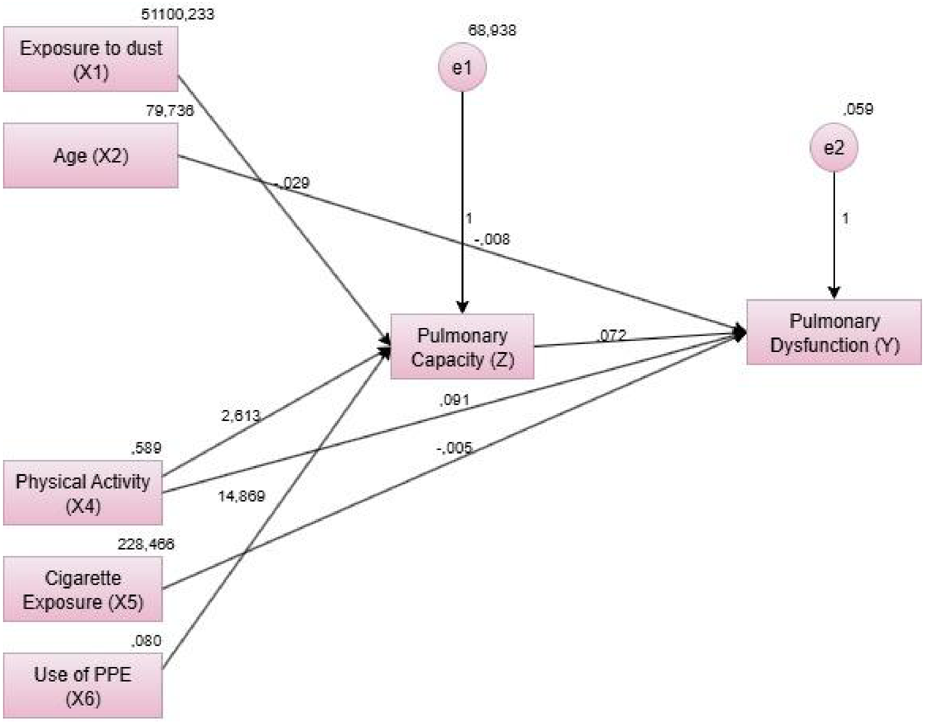

Figure 4. Construction of the Latest Path Analysis Model

Meanwhile, the physical activity variable on Pulmonary Capacity shows a significant positive towards Pulmonary Capacity with an estimate value of 2,335 C.R 2,313 and a p-value of 0,021 which indicates that the more physical activity workers do, the more Pulmonary Capacity increases. Likewise, the use of PPE on new capacity shows a significant positive towards Pulmonary Capacity with an estimated value of 13,905 C.R 5,049 and a p-value of 0,00 which indicates that the more the use of PPE by workers increases, the more Pulmonary Capacity increases.

Likewise, the Pulmonary Capacity variable on lung function disorders shows a significant positive with an estimated value of 0,072 C.R 26,871 and a p-value of 0,00, which means that the increase in Pulmonary Capacity felt by workers will increase lung function disorders as well as physical activity on lung function disorders which shows significant positive results with an estimated value of 0,092 C.R 3,019 and a p-value of 0,003, which means that the increase in physical activity carried out by workers will increase lung function disorders. There are several significant direct relationship results, the following is the construction of the latest path analysis model can be seen in figure 4.

Table 11. Parameter and Hypothesis Testing of Indirect Effect

Influence Path	Path Coefficient	P-value
Dust Exposure → Pulmonary Capacity → Pulmonary Dysfunction	-0,002	0,014
Age → Pulmonary Capacity → Pulmonary Dysfunction	0,007	0,416
Nutrition Status → Pulmonary Capacity → Pulmonary Dysfunction	0,005	0,926
Physical Activity → Pulmonary Capacity → Pulmonary Dysfunction	0,167	0,004
Cigarette Exposure → Pulmonary Capacity → Pulmonary Dysfunction	-0,008	0,204
Use of PPE → Pulmonary Capacity → Pulmonary Dysfunction	0,994	0,013

The indirect effect analysis reveals that physical activity and use of personal protective equipment (PPE) have significant positive effects on pulmonary dysfunction through pulmonary capacity, as indicated by their path coefficients (0,167 and 0,994) and low p-values (0,004 and 0,013). This suggests that these two factors contribute meaningfully to improving lung function and, in turn, reducing dysfunction, emphasizing the importance of promoting active lifestyles and consistent PPE usage in occupational settings. On the contrary, the indirect effects of age, nutrition status, and cigarette exposure were statistically insignificant, indicating that their influence on pulmonary dysfunction is either too weak or occurs through different pathways not captured in this model. Interestingly, dust exposure shows a small but statistically significant negative indirect effect (path coefficient = -0,002; p = 0,014), suggesting that even minimal dust exposure can still impair lung function, reinforcing the critical need for dust control strategies. Overall, the findings highlight that while some personal factors may not directly mediate through pulmonary capacity, workplace interventions focusing on physical activity and PPE compliance can play a pivotal role in preventing lung health deterioration among workers.

DISCUSSION

The analysis of indirect effects highlights how several factors—both occupational and individual—contribute to pulmonary dysfunction through changes in pulmonary capacity, with varying degrees of influence. Dust exposure showed a statistically significant indirect effect on pulmonary dysfunction mediated by reduced pulmonary capacity (path coefficient = -0,002; p = 0,014), reinforcing the biological plausibility that prolonged inhalation of fine particulates such as PM_{10} and $PM_{2.5}$ leads to chronic respiratory inflammation and fibrosis, which in turn impairs lung mechanics. This is consistent with previous findings showing that long-term exposure to cement dust significantly decreases FEV_1, increases the risk of chronic obstructive pulmonary disease (COPD), and causes irreversible histopathological changes in the lung parenchyma.[11] In line with the threshold limit value (TLV) concept, even marginal exposure beyond safe limits can cause a progressive decline in pulmonary capacity, especially when personal protective equipment (PPE) is inconsistently used. Notably, the use of PPE demonstrated the strongest positive and statistically significant indirect effect (path coefficient = 0,994; p = 0,013), suggesting that proper and consistent PPE usage is a key determinant in reducing the adverse effects of dust inhalation. This aligns with Choudhry et al.[12] who emphasized that the effectiveness of PPE is determined not only by its availability but also by adherence, correct usage, and maintenance. Hence, at PT X, strict PPE enforcement policies and OHS supervision should be considered a frontline defense in mitigating occupational lung risks.

On the other hand, age and nutritional status showed no significant indirect effects (0,007; p = 0,416 and 0,005; p = 0,926, respectively), although age remains a known determinant of declining lung function. Workers over the age of 45 are more likely to experience cumulative effects of dust exposure, and natural aging of lung tissue further exacerbates the risk of pulmonary dysfunction. Previous studies have shown that older workers have up to twice the likelihood of developing respiratory issues when exposed to irritants in poorly ventilated environments.[13] However, the nonsignificant statistical result in this study could be due to overlapping effects with other variables such as duration of service and baseline respiratory health. Meanwhile, nutritional status did not emerge as a significant mediator, which can be explained by the fact that most workers at PT X maintained normal nutritional levels due to the physically demanding nature of their job and the company's rigorous health selection criteria. This aligns with the findings of Chen et al.[14] and Munyra et al.[15] who noted that mild obesity or variations in nutritional status do not significantly affect lung function in populations with overall good health. Nevertheless, poor nutrition in more extreme forms may still exacerbate respiratory conditions, and thus should not be disregarded entirely in occupational health planning.

Importantly, physical activity demonstrated a significant protective indirect effect (path coefficient = 0,167; p = 0,004), supporting the hypothesis that increased pulmonary capacity can be preserved through regular exercise. This echoes the studies of Huang et al.[16] and Costa et al.[17] which showed that active workers exhibit better respiratory muscle strength, enhanced ventilation efficiency, and resilience to occupational exposure to harmful particles. This suggests that PT X could benefit from integrating structured physical activity programs into their workplace wellness initiatives to maintain or even improve pulmonary outcomes among workers. Conversely, cigarette exposure, despite having a negative indirect path coefficient (-0,008), was statistically insignificant (p = 0,204). However, this does not discount its relevance, as previous evidence shows that long-term exposure to cigarette smoke—both active and passive—triggers oxidative stress and chronic inflammation, accelerating the deterioration of lung function.[5] The lack of significance in this context may stem from overlapping exposure to dust and underreporting of smoking habits among respondents. Nevertheless, the implementation of smoke-free workplace policies and targeted smoking cessation interventions remains a necessary component of respiratory health strategies.

Ultimately, the findings underscore the central role of pulmonary capacity as a mediating variable. Decreased pulmonary capacity—measured through spirometry indicators like FEV_1—is closely associated with an increased risk of obstructive pulmonary disorders among industrial workers, particularly those in high-risk environments such as cement factories.[18] This confirms the importance of early detection via regular spirometry testing and supports the inclusion of pulmonary capacity as a critical health outcome in occupational surveillance programs. Interventions aimed at minimizing dust exposure, promoting physical activity, enforcing PPE usage, and preventing tobacco exposure should be prioritized in designing an integrated occupational health system at PT X. By identifying and acting on these modifiable risk factors, it is possible to break the causal chain leading from workplace exposure to irreversible respiratory disease.

CONCLUSIONS

Based on the findings and analysis conducted, it can be concluded that protecting the lung health of workers in the cement industry requires a comprehensive and sustainable approach. The implications of this study underscore the importance of strengthening Occupational Health and Safety (OHS) programs that not only focus on the use of Personal Protective Equipment (PPE) but also include health behavior education, increased physical activity, and the creation of a work environment that supports a smoke-free lifestyle. Companies need to integrate routine lung function monitoring as part of early screening and implement evidence-based interventions to reduce particulate exposure in the workplace. The recommendations include increasing management commitment to OSH policies, providing regular training for workers on dust exposure risks, and collaborating with medical professionals and nutritionists to strengthen workers' physical resilience against long-term respiratory hazards. This multidisciplinary approach is expected to create a healthy, productive, and sustainable work environment.

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