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Impact of particulate matter exposure on forced vital capacity and respiratory symptoms in landfill workers

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ABSTRACT

Introduction: Exposure to particulate matter in the workplace has been identified as a major contributing factor to respiratory diseases including decreased lung function. In developing countries, health and safety of landfill workers receives little attention. Thus, it is necessary to conduct an in-depth investigation into particulate matter exposure and its link to disease. This study to investigate the relationship between exposure of Particulate Matter ($PM_{2.5}$) on forced vital capacity and respiratory symptoms in landfill workers.

Materials and methods: Measurements of $PM_{2.5}$ parameter air samples were taken using an SNDWAY brand detector from five locations. Interviews using questionnaires with 49 landfill worker respondents were conducted to determine respiratory symptoms. Forced vital capacity was examined with a Voldyne 4000 incentive spirometer and the results were analyzed with chi-square statistical analysis.

Results: The highest $PM_{2.5}$ concentrations occurred during the day in the west, east, and center, which fall into the unhealthy category. Most of the respondents had abnormal forced vital capacity (32 people, 65.3%) and respiratory symptoms (43 respondents, 87.8%). Chi-square analysis showed a statistically significant association between $PM_{2.5}$ exposure and abnormal FVC with a p-value of 0.002 and an Odds Ratio (OR) of 10.0 (95% CI: 2.41–41.58).

Conclusion: This study found a significant association between $PM_{2.5}$ exposure and abnormal Forced Vital Capacity (FVC) in landfill workers (p = 0.002; OR = 10.0; 95% CI: 2.41–41.58). These findings indicate that workers exposed to $PM_{2.5}$ are at increased risk of lung function impairment, underscoring the need for routine respiratory health monitoring and targeted exposure mitigation in landfill environments.

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Introduction

Waste management through landfills is a critical component of urban sanitation systems. Activities in landfills are not without health risks, especially for workers who are exposed to various air pollutants, including Particulate Matter (PM). PM is a mixture of solid and liquid particles suspended in the air, originating from the decomposition of organic waste, emissions from transport vehicles, and the process of burning or destroying waste [1]. These particles, especially $PM_{2.5}$ and PM_{10}, have a microscopic size that can penetrate the respiratory tract and alveoli, triggering short-term and long-term health problems. Landfill workers are a vulnerable group due to chronic exposure to PM during daily operations, such as waste sorting, compaction, and transportation, which are often carried out with a lack of Personal Protective Equipment (PPE). The World Health Organization (WHO) report states that there are around 7 million deaths each year caused by exposure to air pollution [2]. A study of air pollution and lung disease conducted on 9,651 adults aged 18-60 over 11 years found that exposure to $PM_{2.5}$ was associated with a 3.4% decrease in Forced Vital Capacity (FVC) and a 1.6% decrease in forced expiratory volume in 1 second (FEV1) [3].

Exposure to PM has long been associated with decreased lung function and respiratory symptoms. Epidemiological studies show that fine particles can cause airway inflammation, oxidative stress, and lung tissue damage [4]. A study in Indonesia showed the effect of air pollution on the lung capacity of parking attendants in the C zone parking area of Surakarta City (p-value 0.000), which concluded that the higher the level of air pollution, the worse the lung capacity of the respondents [5]. Another similar study on the direct exposure of electronic waste workers to $PM_{2.5}$ caused a decrease in lung function and the risk of minor respiratory tract diseases such as asthma and Chronic Obstructive Pulmonary Disease (COPD) [6]. In the general population, exposure to $PM_{2.5}$ is associated with an increased risk of COPD, asthma, and lower respiratory tract infections [7]. The working environment at landfills often has PM concentrations that exceed the safe threshold set by the World Health Organization (WHO), especially in developing countries with less stringent waste management regulations. This condition increases the urgency to evaluate the cumulative impact of PM on workers respiratory health. Specific research on landfill workers is still limited, especially in Indonesia, even though their exposure intensity is much higher.

Forced Vital Capacity (FVC) is a key indicator of lung function that measures the maximum volume of air that can be exhaled after deep inhalation. A decrease in FVC is often an early sign of restrictive or obstructive lung disorders [8]. Exposure to particulate matter is thought to affect FVC through the mechanisms of chronic inflammation and pulmonary fibrosis [9]. In addition, landfill workers often report respiratory symptoms such as chronic cough, wheezing, and shortness of breath, which may be ignored because they are considered a "normal" impact of the work environment. In fact, these symptoms can develop into more serious conditions if left untreated. Previous studies have focused more on exposure to toxic gases (such as methane or hydrogen sulfide) in landfills, while the impact of PM as a dominant pollutant has not been comprehensively explored. This research is important to address the existing gap regarding the health risks faced by landfill workers, especially in regions with suboptimal waste management systems. Specifically, this study aims to test the hypothesis that exposure to $PM_{2.5}$ is significantly associated with reduced Forced Vital Capacity (FVC) and a higher prevalence of respiratory symptoms among landfill workers. By establishing this relationship, the study provides a scientific basis for the development of targeted occupational health interventions, including the use of personal protective equipment (PPE), implementation of air quality monitoring systems, and health education programs tailored to landfill workers. The findings are expected to inform international guidelines on permissible $PM_{2.5}$ exposure limits in informal waste environments, contributing to the achievement of Sustainable Development Goals (SDGs) related to good health and well-being (Goal 3) and sustainable cities and communities (Goal 11).

Materials and methods

Design of research

This study uses an observational analytical design with a cross-sectional approach to investigate the relationship between exposure to Particulate Matter (PM) and a decrease in Forced Vital Capacity (FVC) and respiratory symptoms in landfill workers. This design selection allows for simultaneous measurement of PM exposure and health impacts over a period of time. The group of workers will be divided based on the level of PM exposure based on the work zone at the landfill (north, south, center, west, east) for comparative analysis. The research location is a waste landfill in Tambakrigadung Village, Lamongan Regency, covering an area of 7.8 ha. The research population consisted of 70 landfill workers employed full-time at the site. A total of 49 respondents were selected using purposive sampling, with the inclusion criteria being active employment at the landfill site for a minimum of 6 months and willingness to participate voluntarily. Exclusion criteria included a history of chronic respiratory diseases diagnosed before employment. The minimum sample size was determined based on expected prevalence of abnormal FVC in exposed populations and power calculations (α=0.05; power=0.80), ensuring sufficient statistical robustness for chi-square analysis. Recruitment was conducted through coordination with the landfill site management and health and safety representatives. All workers were briefed about the study objectives, procedures, potential risks, and confidentiality. Written informed consent was obtained prior to participation. Ethical approval for this study was granted by the Research Ethics Committee of the Faculty of Public Health, Universitas Airlangga (approval number: 260/EA/KEPK/2024).

$PM_{2.5}$ concentration

Measurement of $PM_{2.5}$ air sample collection was carried out using a $PM_{2.5}$ detector brand SNDWAY. $PM_{2.5}$ sampling was carried out at 5 points (See Fig. 1) with 3 sampling periods in the morning at 08.00, lunch at 12.00 and afternoon at 15.00 then converted to 24 hours. In addition to $PM_{2.5}$ measurements, there are also supporting data such as temperature and humidity measurements. $PM_{2.5}$ sampling results were interpreted based on the national air quality threshold set by the Indonesian Meteorology, Climatology and Geophysics Agency (BMKG), where concentrations above 55 µg/m³ are classified as "unhealthy".

Fig. 1. $PM_{2.5}$ sampling points

Forced vital capacity

Each respondent underwent a forced vital capacity examination, the examination used an incentive spirometer with the Voldyne 4000 brand. The forced vital capacity examination was carried out in accordance with the American Thoracic Society (ATS) guidelines. Forced vital capacity measurement is carried out 2-3 times to obtain consistent results. After each measurement, allow a few seconds for the subject to return to normal breathing before proceeding to the next measurement. The results of the forced vital capacity examination will be calculated using the Nomogram Formula [10]. The adjustments in the formula use the respondent's height and age data.

Statistical analysis

The data in this research were analyzed using Chi-Square statistical analysis with the help of IBM SPSS Statistics version 25. Chi-Square statistical analysis was used to see the effect of $PM_{2.5}$ exposure on forced vital capacity and respiratory symptoms of landfill workers.

Results and discussion

Meteorological data

The measurement of meteorological parameters is used as supporting data, this measurement is carried out simultaneously with sampling. Measurement parameters include temperature and humidity which can be seen in Table 1. Based on data analysis, it was obtained that throughout the measurement period the temperature varied from 31.5°C to 35.8°C and the air humidity ranged from 58% to 69%. The combination of temperature and humidity affects the formation and deposition of $PM_{2.5}$ particles. At high temperatures with low humidity, photochemical processes can increase the formation of fine particles, while low humidity reduces particle deposition. Conversely, at low temperatures with high humidity, thermal inversion can be inhibited, and larger particles can form, reducing $PM_{2.5}$ concentrations.

High temperatures can increase the volatilization of semi-volatile components in $PM_{2.5}$, such as ammonium nitrate (NH_4NO_3), which breaks down into NH_3 and HNO_3 gases [11]. High temperatures also accelerate photochemical reactions that form secondary particles (e.g., sulfates and organic compounds) through the oxidation of gas precursors [12]. Low temperatures increase atmospheric stability (temperature inversion) which inhibits the dispersion of pollutants. Hygroscopic particles (e.g., sulfates, nitrates) absorb water and increase in size, increasing the mass of $PM_{2.5}$. Very high relative humidity (e.g.,>90%) can trigger rain that cleans particles (wet deposition) [13]. Dry conditions increase the resuspension of particles from soil and roads, but reduce the growth of hydroscopic particles. The combination of high temperature and low relative humidity (for example in deserts) increases $PM_{2.5}$ from mineral dust. Conversely, low temperatures and high relative humidity (for example in mountain valleys) trigger $PM_{2.5}$ accumulation due to inversion and fog [14].

Table 1. Meteorological data measurements at the landfill

Point	Measurement time	Temperature (°C)	Humidity (%)
West	Morning (08.00)	32.5	66
	Lunch (12.00)	34.7	61
	Afternoon (15.00)	32.7	67
East	Morning (08.00)	31.5	66
	Lunch (12.00)	35	58
	Afternoon (15.00)	33.6	59
Middle	Morning (08.00)	32.5	68
	Lunch (12.00)	34.2	62
	Afternoon (15.00)	33.6	67
South	Morning (08.00)	32.5	66
	Lunch (12.00)	35.8	58
	Afternoon (15.00)	32	60
North	Morning (08.00)	30.5	69
	Lunch (12.00)	33.8	60
	Afternoon (15.00)	31.8	63

Particulate matter ($PM_{2.5}$) levels

$PM_{2.5}$ concentration in five locations (west, east, center, south, and north) at three measurement times (morning, lunch, afternoon) see Table 2. The west, east, and center locations have deteriorating air quality during the day, with an "unhealthy" category. In contrast, the south and north show more stable air quality and are in the "moderate" category throughout the day. The increase in $PM_{2.5}$ during the day in the western location is caused by the entry and exit of motorized vehicles. The western point is the entrance gate to the landfill and at this point there is also a parking lot for workers' trucks and motorbikes. At the eastern and central points, there has also been an increase due to dust from the landfill road that has not been paved because at this point it is the entrance and exit for waste trucks when they are going to pile up waste at the landfill. The loading and unloading of waste and the movement of waste by excavators also affect the increase in $PM_{2.5}$ concentration at the landfill.

Table 2. Results of $PM_{2.5}$ level analysis

Point	Measurement time	$PM_{2.5}$ (mg/m3)	Threshold value (mg/m3)	Categories
West	Morning (08.00)	44	15.6 – 55	Medium
	Lunch (12.00)	76	55.5 – 150.4	Unhealthy
	Afternoon (15.00)	47	15.6 - 55	Medium
East	Morning (08.00)	48	15.6 – 55	Medium
	Lunch (12.00)	58	55.5 – 150.4	Unhealthy
	Afternoon (15.00)	56	55.5 – 150.4	Unhealthy
Middle	Morning (08.00)	44	15.6 – 55	Medium
	Lunch (12.00)	62	55.5 – 150.4	Unhealthy
	Afternoon (15.00)	46	15.6 – 55	Medium
South	Morning (08.00)	42	15.6 – 55	Medium
	Lunch (12.00)	43	15.6 – 55	Medium
	Afternoon (15.00)	34	15.6 – 55	Medium
North	Morning (08.00)	32	15.6 – 55	Medium
	Lunch (12.00)	36	15.6 – 55	Medium
	Afternoon (15.00)	30	15.6 – 55	Medium

$PM_{2.5}$ concentrations in landfills are influenced by meteorological conditions, waste type, and management practices. High humidity (>80%) can suppress dust resuspension but triggers the growth of hydroscopic particles from salt compounds or organic acids [15]. Conversely, high wind speeds (>5 m/s) increase $PM_{2.5}$ dispersion but also lift particles from the surface of uncovered waste [16]. The concentration of $PM_{2.5}$ around landfills tends to be higher than in unpolluted areas, especially within a radius of up to 100 m from the center of the landfill. This is due to the anaerobic decomposition process of organic waste which produces harmful gases such as methane (CH_4) and Carbon monoxide (CO), which then contribute to the formation of fine particulate matter through chemical reactions in the atmosphere. For example, a study in Nigeria revealed that the concentration of $PM_{2.5}$ in landfills can reach 57.9 µg/m³ at a distance of 50 meters from the landfill center, far exceeding the control area which only recorded 13.1 µg/m³ [17]. Landfills in China found that $PM_{2.5}$ concentrations in the dry season are 2-3 times higher than in the rainy season due to lack of wet deposition and increased mechanical activity [18]. In addition, plastic and construction waste containing heavy metals (such as lead and cadmium) contributes to the toxicity of $PM_{2.5}$, exacerbating health risks.

Forced vital capacity

The majority of respondents (65.3%, 32 out of 49) in Table 3. showed abnormal forced vital capacity (FVC) results, indicating potential lung function issues, while 34.7% (17 respondents) had normal FVC results. The high prevalence of abnormality in this study (65.3%) exceeds the WHO global report (2021) which states that 30-40% of the urban population has impaired lung function due to air pollution, so it is necessary to study the specific risk factors for the local context [19]. These findings indicate the potential for significant impairment of lung function among the studied population. FVC abnormalities are often associated with various health conditions, including restrictive lung disease, ventilation disorders, and cardiovascular disease. Previous research has shown that a decline in FVC can be an important indicator for assessing the risk of long-term health complications, including an increased risk of morbidity and mortality [20].

A decrease in FVC can be caused by various factors, such as exposure to $PM_{2.5}$, a history of chronic disease, or conditions such as obesity and structural abnormalities in the respiratory system. In the context of this study, exposure to $PM_{2.5}$ that does not meet air quality standards is likely to be one of the main causes of FVC abnormality. Other studies support this relationship, where long-term exposure to $PM_{2.5}$ can cause chronic inflammation of the respiratory tract and damage to lung tissue, thus reducing the vital capacity of the lungs [21]. In addition, FVC abnormalities are also commonly found in patients with chronic diseases such as COPD or congenital heart disease, where impaired lung function is an independent predictor of poor clinical outcomes [22].

FVC abnormality not only reflects impaired lung function but can also be used as a biomarker to predict the risk of other health complications, such as decreased physical activity capacity and increased risk of hospitalization or death. For example, research in patients with COPD shows that a decrease in FVC is significantly correlated with a decrease in distance traveled in the six-minute walk test (6MWD), which is an indicator of physical capacity [23]. Routine evaluation of lung function using spirometry is strongly recommended for populations at high risk of exposure to air pollutants or with a history of chronic disease. Proactive interventions such as air quality control and chronic disease management can help reduce the adverse effects of FVC abnormalities in these populations.

Abnormal lung vital capacity is also caused by various factors such as smoking behavior. The mechanism of smoking can cause disturbances in respiratory flow, causing abnormal lung vital capacity measurements [24]. For each level of smoking exposure over the years, each individual's Forced Vital Capacity (FVC) is significantly lower [25]. The higher the degree of smoking, the lower the FVC value. If the FVC value is low, respiratory system disorders will appear [26]. Smoking can cause swelling, airway obstruction, restrictive disorders, and the risk of lung cancer. Research shows that the earlier a person starts smoking, the sooner the risk of lung cancer appears. This is because cigarette smoke has a more harmful effect on lung health than air pollution [27].

Respiratory symptoms

The results of the study in Table 4. show that most landfill workers experience symptoms of respiratory distress. Of the total 49 respondents, as many as 43 respondents (87.8%) reported respiratory symptoms, while only 6 respondents (12.2%) did not experience these symptoms. These findings are consistent with previous research showing that landfill workers have a high risk of respiratory disorders due to exposure to harmful gases produced by the decomposition of waste [28]. The high prevalence of respiratory symptoms is significantly related to exposure to pollutant complexes in the landfill environment.

Table 3. Results of forced vital capacity measurements

Forced vital capacity	Frequency (%)
Normal	17 (34.7)
Abnormal	32 (65.3)

Table 4. Results of respiratory symptoms data

Respiratory symptoms	Frequency (%)
Yes	43 (87.8)
No	6 (12.2)

Table 5. Common symptoms felt by respondents

Common symptoms	Frequency (%)	
	Yes	No
Cough	31 (63.3)	18 (36.7)
Flu	29 (59.2)	20 (40.8)
Shortness of Breath	6 (12.2)	43 (87.8)
Chest pain	5 (10.2)	44 (89.8)
Sore throat	14 (28.6)	35 (71.4)
Stinging on the nose	4 (8.2)	45 (91.8)
Bloody cough	1 (2.0)	48 (98.0)

Common symptoms felt by respondents include coughing, flu, sore throat, and chest pain (Table 5). In this study, cough was the most common symptom among respondents. Cough is often caused by respiratory tract irritation due to exposure to air pollutants such as $PM_{2.5}$, which can trigger inflammatory reactions and produce excessive mucus. Previous research has shown that coughing is one of the most common respiratory symptoms experienced by landfill workers due to exposure to harmful gases such as methane (CH_4), Carbon dioxide (CO_2), and Hydrogen Sulfide (H_2S) produced from the decomposition of waste [29]. Another symptom that arises due to the influence of $PM_{2.5}$ is the flu, which includes a runny nose and fever. These symptoms can be caused by viral infections that more easily attack individuals with weak immune systems due to exposure to air pollution. Exposure to air pollutants such as $PM_{2.5}$ can weaken the body's immune system, increasing the risk of Upper Respiratory Tract Infections (URTI) [30].

Exposure to air pollution in landfill areas can cause respiratory symptoms in individuals living or working in the vicinity. One of the main factors is the emission of harmful gases such as methane, ammonia, and hydrogen sulfide produced during the waste decomposition process. These gases can irritate the respiratory tract, causing coughing, shortness of breath, and other respiratory symptoms. Dust particles generated from activities in the landfill area also contribute to respiratory problems. These particles can be inhaled and enter the lungs, increasing the risk of respiratory tract infections and chronic respiratory diseases such as bronchitis and asthma. Long-term exposure to air pollution in landfill areas can lead to decreased lung function and increase the risk of chronic respiratory disease [31]. Studies show that individuals who live or work near landfills have a higher prevalence of respiratory symptoms compared to those who live in unexposed areas [32].

Other factors that affect respiratory symptoms in the landfill area include unsanitary environmental conditions and the lack of Personal Protective Equipment (PPE) such as masks. Landfill workers are often exposed to harmful gases such as methane (CH_4), Carbon dioxide (CO_2), and Hydrogen Sulfide (H_2S) which are produced from the decomposition of waste. The use of PPE that is uncomfortable or not suitable for working conditions can result in workers not wearing it consistently. Lack of compliance with the use of proper PPE increases the risk of exposure to air pollution in landfill areas [33]. Studies show that discomfort and lack of training in the correct use of PPE can reduce the effectiveness of protection against respiratory symptoms [34]. It is important to ensure that the PPE used is appropriate for the type of pollutants in the landfill area and is fitted correctly. Adequate training in the use and maintenance of PPE is also very important to improve worker compliance and the effectiveness of protection against respiratory symptoms. Thus, the risk of respiratory symptoms due to exposure to air pollution in landfill areas can be minimized.

Impact of $PM_{2.5}$ exposure to forced vital capacity

The results in Table 6. illustrate the distribution of cases based on $PM_{2.5}$ exposure level and lung vital capacity (Forced Vital Capacity, FVC). In the group with $PM_{2.5}$ above the threshold, there were 10 cases with normal FVC and 4 cases with abnormal FVC, bringing the total number of cases in this group to 14. Meanwhile, in the group with $PM_{2.5}$ below the threshold, there were 7 cases with normal FVC and 28 cases with abnormal FVC, for a total of 35 cases. This distribution shows a striking difference between the two groups. Although the number of cases of normal FVC at $PM_{2.5}$ above the threshold is higher than at $PM_{2.5}$ below the threshold, there is a significant increase in the number of cases of abnormal FVC in the group with $PM_{2.5}$below the threshold. This indicates a difference in exposure patterns and impact on respiratory function.

Table 6. Analysis impact of $PM_{2.5}$ exposure to force vital capacity

$PM_{2.5}$ Status	Force Vital Capacity (FVC)		Total	P-Value	OR	95% CI
	Normal	Abnormal				
Above threshold	10	4	14			
Below threshold	7	28	35	0,002	10,000	2,405 – 41,577
Total	17	32	49			

Further statistical analysis shows that this difference is significant with a p-value of 0.002. This value indicates that the difference in distribution between the groups does not occur by chance, but has a statistically significant association. In addition, the reported Odds Ratio value is 10,000 with a confidence interval of 2,405–41,577, which indicates a very high strength of association between $PM_{2.5}$ exposure status and FVC abnormality.

Overall, these statistical results reveal that there is a significant relationship between $PM_{2.5}$ levels and respiratory function, where lower exposure to $PM_{2.5}$ is correlated with a higher number of cases of abnormal FVC. These findings emphasize the importance of monitoring and controlling $PM_{2.5}$ exposure in an effort to protect respiratory health, although the interpretation of the very high Odds Ratio value needs to be reviewed further in the context of the research design and the population studied. The heatmap result in Fig. 2 shows that the number of cases with $PM_{2.5}$ below the threshold and abnormal FVC (28 cases) is the highest compared to other combinations. This shows that even though $PM_{2.5}$ is below the threshold, the likelihood of experiencing abnormal FVC remains high. In contrast, the number of cases with $PM_{2.5}$ above the threshold with both Normal and Abnormal FVC is lower (10 and 4 cases, respectively). This data supports the finding that although exposure to $PM_{2.5}$ below the threshold may have an impact, there is still a higher proportion of cases with abnormal FVC.

Fig. 3 visualizes the relationship between $PM_{2.5}$ exposure and Forced Vital Capacity (FVC) status based on the data obtained. In the plot, the blue dot indicates an Odds Ratio value of 10,000, with an error bar depicting a 95% Confidence Interval ranging from 2.405 to 41.577. The vertical line at value 1 indicates a neutral point (no effect); because the error bar does not include the value 1, this indicates that the association found is statistically significant, which is also supported by a p-value of 0.002. These results imply that individuals with $PM_{2.5}$ exposure above the threshold have a much higher risk of FVC abnormality than those exposed to $PM_{2.5}$ below the threshold. In other words, there is a very strong relationship between increased $PM_{2.5}$ exposure and impaired respiratory function, making the management and control of $PM_{2.5}$ exposure very important in maintaining respiratory health.

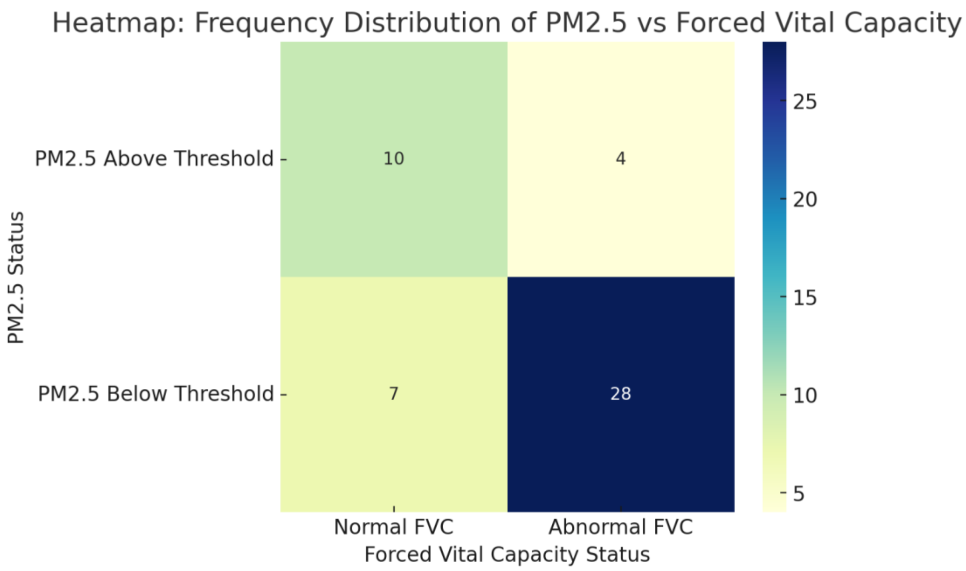

Fig. 2. Heatmap from frequency distribution of $PM_{2.5}$ and force vital capacity

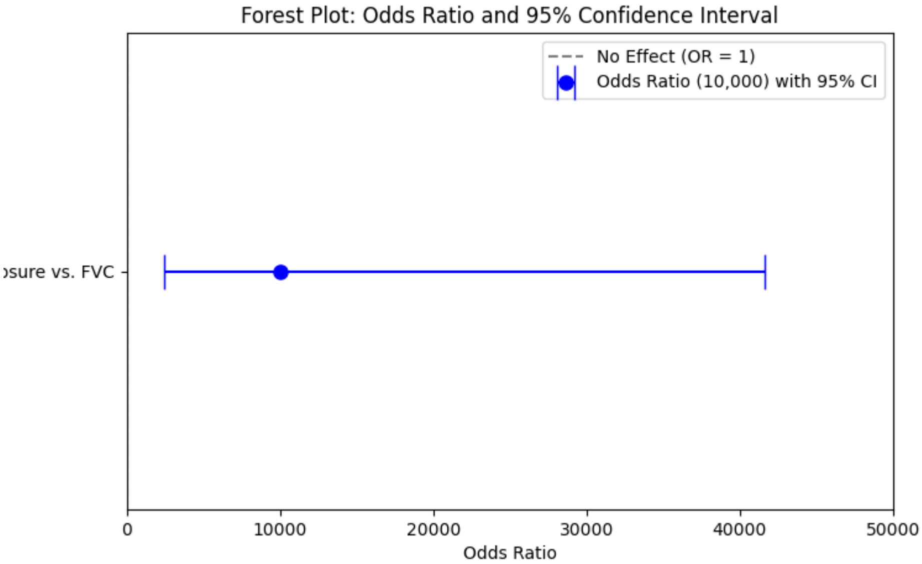

Fig. 3. Forest plot between $PM_{2.5}$ exposure and Forced Vital Capacity (FVC) status

The Chi-Square Distribution Plot presented in Fig. 4 illustrates the distribution of Chi-Square values in statistical testing, which is used to evaluate the relationship between $PM_{2.5}$ exposure and Forced Vital Capacity (FVC) status. In this case, this distribution is used to assess whether the difference between groups exposed to $PM_{2.5}$ above or below the threshold and FVC status (normal or abnormal) is statistically significant. From the test results, a Chi-Square value of 9.51. With a very low p-value (0.002), can conclude that there is a significant relationship between $PM_{2.5}$ exposure and FVC status. A p-value less than 0.05 indicates that the difference observed in the data distribution does not occur by chance, but rather reflects a strong relationship between the two variables.

This plot also shows a very high Odds Ratio, which is 10,000, with a confidence interval between 2,405 and 41,577. This Odds Ratio indicates that individuals exposed to $PM_{2.5}$ above the threshold are much more likely to experience abnormal FVC than those exposed to $PM_{2.5}$ below the threshold. This confirms that higher $PM_{2.5}$ exposure can contribute to decreased lung function, which is reflected in FVC abnormalities. This plot also displays an area below the Chi-Square statistic value (9.51), which represents a critical area in the distribution. This area shows that results greater than 9.51 will lead to a conclusion that supports a significant relationship between $PM_{2.5}$ and FVC, which is reflected in the very low p-value. Overall, this Chi-Square Distribution Plot illustrates a statistically significant relationship between $PM_{2.5}$ exposure and FVC status, with results strongly supporting the hypothesis that $PM_{2.5}$ exposure plays a major role in affecting lung health, as reflected in the increase in cases of abnormal FVC in groups with $PM_{2.5}$ above the threshold.

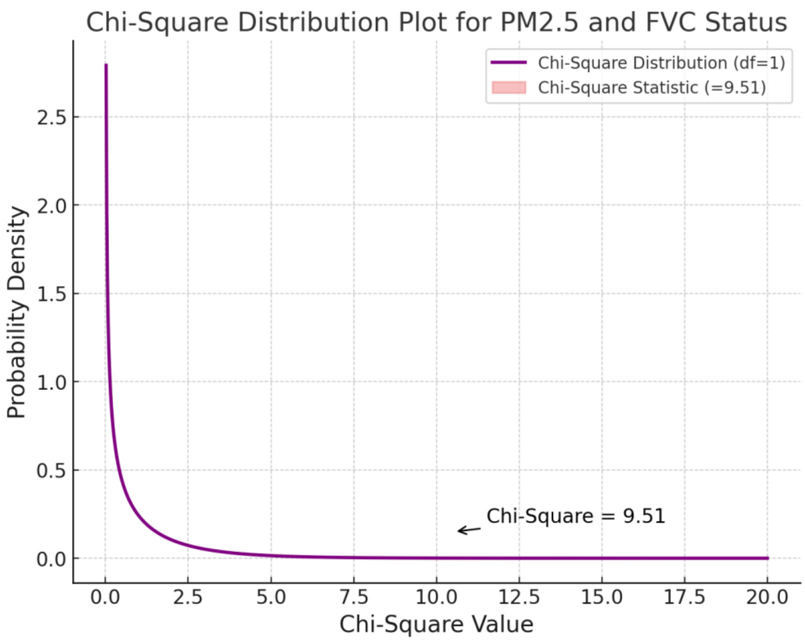

Fig. 4. Chi-square distribution plot between $PM_{2.5}$ exposure and Forced Vital Capacity (FVC) status

Exposure to $PM_{2.5}$ has a significant impact on lung function, especially on the Forced Vital Capacity (FVC) parameter. Exposure to $PM_{2.5}$ triggers a systemic inflammatory response through the activation of alveolar macrophages and the release of pro-inflammatory cytokines (IL-6, TNF-α) and free radicals (ROS) [35]. These fine particles penetrate the alveolar membrane, causing damage to the lung epithelium and interstitial fibrosis, which reduces the elasticity of the lung tissue and decreases FVC. In vivo studies show that exposure to $PM_{2.5}$ 50 µg/m³ for 12 weeks reduces rat FVC by 22% through the activation mechanism of the NF-κB pathway [36, 37]. In humans, 8-isoprostane levels (a marker of oxidative stress) in sputum increase significantly in workers exposed to $PM_{2.5}$ >35 µg/m³, correlating with a 15% decrease in FVC [38, 39].

A cohort study in China (n=3,124) found that annual $PM_{2.5}$ exposure >50 µg/m³ correlated with a decrease in FVC -126 mL (95% CI: -189 to -63 mL) compared to exposure <25 µg/m³ [40]. In Brazilian landfills, workers exposed to $PM_{2.5}$ 85 µg/m³ had an FVC of 2.3 L vs. 3.1 L in the control group ($p < 0.001$), indicating restrictive pulmonary disorders (41). These findings are consistent with user research data showing 80% abnormal FVC in the $PM_{2.5}$ < threshold group (OR=10,000; p = 0.002), thought to be due to cumulative exposure to secondary pollutants (e.g., H_2S) [42]. Acute exposure to $PM_{2.5}$ (>100 µg/m³ in 24 h) causes a temporary FVC decrease of -4.7% through reflex bronchoconstriction, while chronic exposure (>5 years) induces airway remodeling and a permanent FVC decrease of -12% (43). A study in India found that highway workers with cumulative $PM_{2.5}$ exposure >200 µg·year/m³ experienced a decrease in FVC -310 mL vs. the control group (p=0.002) [44].

Interventions to reduce exposure to $PM_{2.5}$, such as the use of indoor air purifiers, have shown benefits in improving respiratory health. However, their effectiveness is limited to small areas and cannot overcome external exposure. Therefore, air pollution control efforts at the community level and broader public policies are essential to protect lung health. Overall, the available evidence indicates that exposure to $PM_{2.5}$ has a significant negative impact on

FVC and overall lung health. It is important to raise awareness of this risk and implement effective mitigation strategies to protect people's respiratory health. However, our study presents a deviation from most existing literature, particularly the finding that FVC abnormalities were prevalent even among those exposed to $PM_{2.5}$ levels below the national threshold. Several contextual explanations may contribute to this deviation: (1) the cumulative exposure to secondary landfill pollutants (H_2S, CH_4) that were not directly measured but are known to co-occur with $PM_{2.5}$ in open waste environments; (2) the relatively small sample size (n=49), which may limit statistical power and widen confidence intervals, potentially amplifying the observed Odds Ratio (OR=10); and (3) inconsistent or inadequate use of Personal Protective Equipment (PPE), as well as prolonged exposure duration among workers who remained on site for over 8 hours daily. Moreover, local meteorological conditions such as high humidity and poor air circulation within the landfill basin may lead to pollutant entrapment, increasing actual exposure levels beyond what single-time $PM_{2.5}$ readings can capture. These factors together may explain the stronger association observed in this study and its divergence from controlled population studies conducted in urban or indoor settings.

Impact of $PM_{2.5}$ exposure to respiratory symptoms

The analysis in Table 7 shows no statistically significant relationship between $PM_{2.5}$ exposure and respiratory symptoms (p=0.659), as also reflected by the wide confidence interval (OR=2.167; 95% CI: 0.230–20.424). Although the OR suggests a potential trend, the statistical evidence does not support a reliable association in this sample. This may be attributed to the limited sample size or unaccounted confounding factors. Further research with a larger sample size and stricter control of other confounding factors is needed to determine whether $PM_{2.5}$ exposure really has a significant impact on respiratory symptoms.

Table 7. Analysis impact of $PM_{2.5}$ exposure to respiratory symptoms

$PM_{2.5}$ Status	Respiratory Symptoms		Total	P-Value	OR	95% CI
	Yes	No				
Above threshold	13	1	14			
Below threshold	30	5	35	0.659	2.167	0.230 – 20.424
Total	43	6	49			

The forest plot in Fig. 5 illustrates the relationship between $PM_{2.5}$ exposure (above the threshold) and respiratory symptoms in exposed individuals, based on the calculated Odds Ratio (OR). The results of the plot show an OR of 2.167 with a very wide 95% confidence interval, ranging from 0.230 to 20.424. An Odds Ratio (OR) of 2.167 indicates that individuals exposed to $PM_{2.5}$ above the threshold are more likely to experience respiratory symptoms than those exposed to $PM_{2.5}$ below the threshold. However, this value is not very strong because the confidence interval (CI) is very wide and includes the number 1, which indicates high uncertainty in this effect size. The wide confidence interval (CI) (0.230 to 20.424) indicates that although there is an indication of a relationship between $PM_{2.5}$ exposure and respiratory symptoms, the very wide range on the CI indicates that this relationship cannot be firmly established.

The vertical line at OR = 1 serves as a reference, showing the point at which there is no effect (OR=1 means there is no difference between groups). Because the CI includes the number 1, this indicates that the relationship between $PM_{2.5}$ and respiratory symptoms is not statistically significant. The p-value of 0.659 indicates that the observed difference in the data is not statistically significant. A p-value greater than 0.05 indicates that the difference found between individuals exposed to $PM_{2.5}$ above and below the threshold may be coincidental, and not strong enough to conclude that there is a clear relationship between $PM_{2.5}$ exposure and respiratory symptoms. This forest plot shows that although there is a slight tendency for $PM_{2.5}$ exposure to increase the likelihood of respiratory symptoms, the high p-value and wide confidence interval suggest that this relationship is not strong or consistent enough to be considered a significant factor.

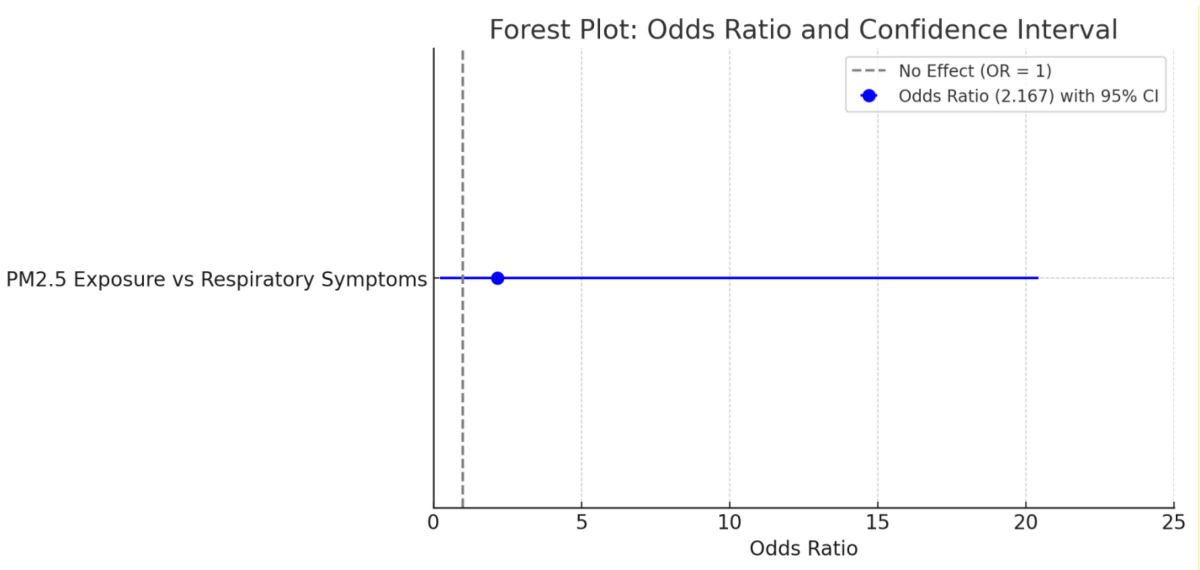

Fig. 5. Forest plot between $PM_{2.5}$ exposure and respiratory symptoms

The Chi-Square Distribution Plot generated in Fig. 6 shows that statistical testing of the relationship between $PM_{2.5}$ exposure (above or below the threshold) and the presence of respiratory symptoms (with or without symptoms). The p-value of 0.659 indicates that the relationship between $PM_{2.5}$ exposure and respiratory symptoms is not statistically significant. A p-value greater than 0.05 means that there is insufficient evidence to reject the null hypothesis, which states that there is no strong association between the two variables. In other words, although there is a difference in the number of cases between the groups exposed to $PM_{2.5}$ above and below the threshold, this difference may be due to random variation. An Odds Ratio (OR) of 2.167 indicates that exposure to $PM_{2.5}$ above the threshold is slightly more likely to be associated with respiratory symptoms than exposure below the threshold, but the confidence interval (0.230–20.424) is very wide. This indicates high uncertainty regarding the effect of $PM_{2.5}$ exposure on respiratory symptoms. The interval that includes the number 1 confirms that the odds ratio is not significant, which is in line with the large p-value.

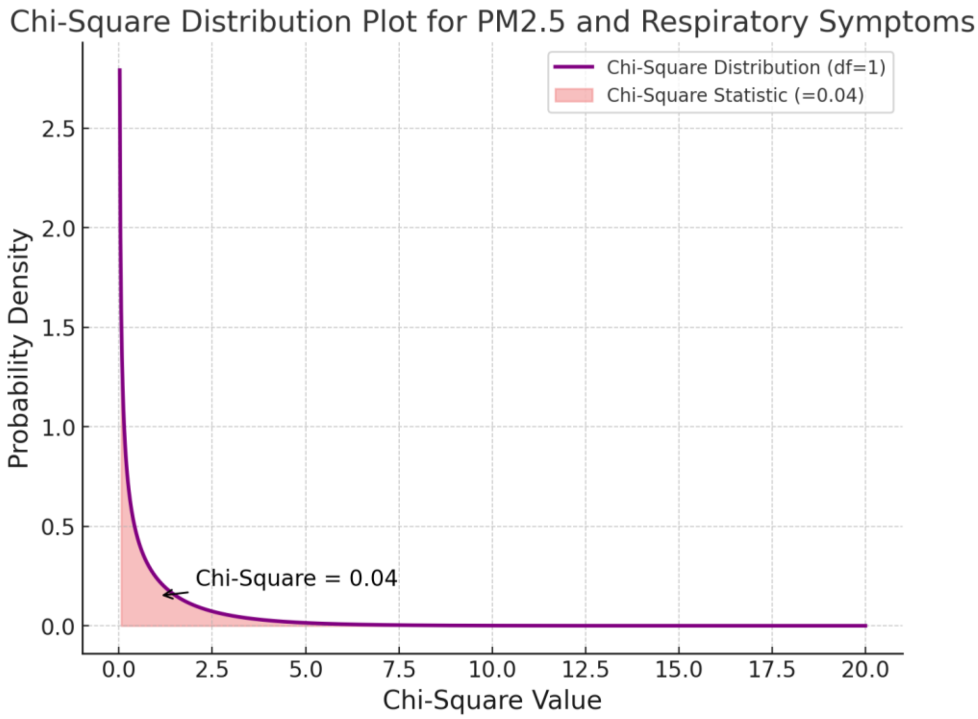

Fig. 6. Chi-square distribution plot between $PM_{2.5}$ exposure and respiratory symptoms

The Chi-Square test results produced a value that showed that the difference in the distribution of cases between the groups ($PM_{2.5}$ above the threshold and below the threshold) was not large enough to be considered a significant association. A p-value higher than 0.05 indicates that the relationship found is more likely to be caused by random factors than a real relationship. Although there is a tendency to see more cases of respiratory symptoms in the group exposed to $PM_{2.5}$ below the threshold (30 cases), the high p-value and wide confidence interval on the odds ratio indicate that there is no significant association between $PM_{2.5}$ exposure and respiratory symptoms in this data. Therefore, although there are observed differences, there is insufficient statistical evidence to support that $PM_{2.5}$exposure plays a direct role in causing respiratory symptoms in the studied group.

Although many studies show that exposure to $PM_{2.5}$ has a significant impact on respiratory symptoms, some studies may report that there is no significant impact of $PM_{2.5}$ exposure on respiratory symptoms under certain conditions. However, keep in mind that most studies find a strong link between $PM_{2.5}$ exposure and an increased risk of respiratory symptoms. Several factors can influence the results of research on the impact of $PM_{2.5}$ on respiratory symptoms. These factors include the level of exposure, duration of exposure, the basic health condition of the respondent, and the use of Personal Protective Equipment (PPE) such as masks [45]. A study around a coal-fired power plant showed that higher $PM_{2.5}$ concentrations were associated with an increase in respiratory symptoms such as coughing and eye irritation in the exposed group compared to the unexposed group [46].

Some studies show that not all individuals exposed to $PM_{2.5}$ experience respiratory symptoms [47]. Research published in Environmental Health Perspectives found that although exposure to $PM_{2.5}$ is associated with a decrease in Forced Vital Capacity (FVC) in the general population, not all exposed individuals experience respiratory symptoms [48]. Factors such as genetics, general health status, and level of exposure can affect an individual's response to $PM_{2.5}$ [49]. Another study shows that although exposure to $PM_{2.5}$ increases the risk of developing chronic obstructive pulmonary disease (COPD) in previously healthy individuals, not all exposed individuals experience respiratory symptoms [7, 50, 51].

Environmental factors such as humidity, temperature, and other pollutants can also affect the impact of $PM_{2.5}$ on respiratory health [52, 53]. The interaction between $PM_{2.5}$ and other environmental factors can modulate the inflammatory response in the respiratory tract, which in turn affects the onset of respiratory symptoms [7]. However, it is important to note that while some individuals may not exhibit immediate respiratory symptoms from exposure to $PM_{2.5}$, long-term exposure can still increase the risk of chronic respiratory disease. Therefore, air pollution control efforts remain important to protect the overall respiratory health of the community. Despite these findings, this study has several limitations that should be considered when interpreting the results. First, the cross-sectional design limits our ability to infer causality between $PM_{2.5}$ exposure and the observed respiratory outcomes. Longitudinal studies are needed to confirm the temporal relationship between exposure and health effects. Second, the use of a single-day measurement to represent $PM_{2.5}$ exposure may not reflect the variability of pollutant levels over time, potentially introducing exposure misclassification bias. Third, respiratory symptoms were assessed through self-reported questionnaires, which may be subject to recall bias and subjective interpretation. These factors could either overestimate or underestimate the association between $PM_{2.5}$ and health outcomes. In addition, although this study found a high prevalence of abnormal FVC even at $PM_{2.5}$ levels below the national threshold, this finding may reflect contextual influences such as cumulative exposure to unmeasured landfill pollutants, small sample size (n=49), and poor compliance with Personal Protective Equipment (PPE) use. These limitations highlight the need for cautious interpretation of the very high Odds Ratio (OR = 10.0) and underscore the importance of validating these findings in larger, more rigorously controlled studies. Nonetheless, the study provides valuable evidence from an underrepresented occupational group in a real-world exposure context, which remains a key strength of the current research.

Conclusion

The study on the impact of particulate matter (PM) exposure on Forced Vital Capacity (FVC) and respiratory symptoms in landfill workers highlights a potential relationship between PM exposure and reduced lung function. The research observed that workers exposed to higher levels of particulate matter, particularly $PM_{2.5}$, tended to have lower FVC, which is a key indicator of lung health. Additionally, the study documented an elevated prevalence of respiratory symptoms among these workers, such as coughing, shortness of breath, and wheezing. Statistical analysis showed no significant association between $PM_{2.5}$ exposure and the occurrence of respiratory symptoms ($p = 0.659$; OR = 2.167; 95% CI: 0.230–20.424), indicating that the observed trend may not reflect a robust causal relationship. Nonetheless, the high prevalence of respiratory symptoms warrants further investigation with a larger sample size and improved exposure assessment to clarify this potential link. The results indicate a need to explore the potential benefits of mitigating exposure to particulate matter through better protective measures, air quality control, and worker health monitoring. This study supports the consideration of stronger policies and interventions to safeguard occupational health in environments with high pollution levels.

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Competing interests

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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Ethical considerations

This study has been approved by the ethics committee of the Faculty of Public Health, Universitas Airlangga, No: 260/EA/KEPK/2024. “Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely ob-served by the authors.”

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