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Article

Environmental Health Risk Assessment of Particulate Matter ($PM_{2.5}$) and Worker Characteristics on Lung Function of Tropodo Tofu Factory Workers in Sidoarjo

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Abstract

In conclusion, workers at the Tropodo tofu factory are exposed to high levels of $PM_{2.5}$, which may contribute to decreased lung function, particularly among older workers. Continuous air quality monitoring and engineering control measures are recommended to reduce occupational exposure and protect worker health.The tofu industry is a sector that potentially generates fine particulate matter ($PM_{2.5}$) pollution, which can reduce workers' lung function. Exposure to $PM_{2.5}$ in the workplace is a significant issue due to its direct impact on respiratory health. This study aims to analyze the risk of $PM_{2.5}$ exposure and worker characteristics on lung function at the Tropodo Tofu Factory, Sidoarjo. This research used an analytical observational design with a cross-sectional approach involving 20 workers selected based on inclusion criteria. $PM_{2.5}$ concentrations were measured using a Dust Particle Counter TC-8200 $PM_{2.5}$, while lung function was tested using spirometry and questionnaires on smoking habits and age. Data were analyzed using univariate and correlation analyses. The results showed an average $PM_{2.5}$ concentration of 288 $\mu g/m^3$, exceeding the national ambient air quality standard (55 $\mu g/m^3$). The mean FEV1 value indicated a moderate decline in lung function. A significant correlation was found between $PM_{2.5}$ exposure and workers' age with lung function. In conclusion, $PM_{2.5}$ exposure in tofu production environments poses health risks to workers' respiratory function. It is recommended that the factory increase the use of personal protective equipment and adopt cleaner combustion technologies to reduce $PM_{2.5}$ emissions.

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Introduction

The industrial sector, particularly tofu factories, plays a vital role in the Indonesian economy, both in urban and rural areas [1]. The production process of tofu, which involves stages such as

grinding soybeans, cooking, and solidifying, inherently generates emissions and pollution, including dust and fine particles that can potentially harm workers' lung function [2]. One of the most dangerous air pollutants is Particulate Matter ($PM_{2.5}$), which is so small that it can penetrate deep into the lungs and even enter the bloodstream [3]. The World Health Organization (WHO) reports that the concentration of $PM_{2.5}$ in Indonesia reached 21.3 μg/m³, with the age-adjusted mortality rate from household and environmental air pollution reaching 96.7 per 100,000 population in 2024. This indicates the serious impact of $PM_{2.5}$ exposure, especially for workers who are continuously exposed in industrial environments.

In Indonesia, tofu factories often operate with simple equipment and pay little attention to occupational safety and health aspects. Workers are often not equipped with adequate Personal Protective Equipment (PPE), such as masks or respirators, which can filter out fine particles [4]. This condition significantly increases the risk of excessive $PM_{2.5}$ exposure. Data from the Indonesian Ministry of Health (Kemenkes) also confirms that air pollution is a major cause of morbidity and mortality in Indonesia, particularly in industrial areas [5]. Exposure to dust that causes impaired lung function depends on the size of the dust particles, solubility, chemical composition, and dust concentration [6]. Gradual and permanent decline in lung function occurs due to the duration of dust exposure in the workplace, as well as internal factors of the workers such as age, nutritional status, smoking habits, health conditions, gender, history of illness and workplace diseases, exercise, length of service, and the use of PPE [7].

In Sidoarjo, particularly in the Krian district, there is a tofu industrial area with approximately 67 small and medium-sized tofu manufacturing industries. Most of these MSMEs use wood fuel, plastic waste, or a mixture of both, which produces black smoke and potentially pollutes the air. Data [8] shows that the air in Krian is categorized as unhealthy, with an Air Quality Index (AQI) reaching 167 and $PM_{2.5}$ concentration recorded at 571 μg/m³, 11.4 times higher than the WHO's annual guideline value. The Tropodo Tofu Factory, one of the small and medium-sized industries in Klagen Hamlet, produces 1,170 kg of tofu per day with 30 workers operating 24 hours a day. Previous studies have demonstrated that long-term exposure to $PM_{2.5}$ from fossil fuel and biomass combustion can cause respiratory impairment, cardiovascular diseases, and even premature death [9]. However, most existing research focuses on urban areas or large-scale industries. Studies specifically analyzing the relationship between $PM_{2.5}$ exposure and lung function among tofu industry workers—particularly in small-scale industries like Tropodo—remain limited. This research gap highlights the need for a focused assessment of $PM_{2.5}$ exposure risk and its impact on workers' lung function, while also considering worker characteristics such as age and smoking habits that may exacerbate respiratory impairment. Therefore, this study aims to analyze the risk of $PM_{2.5}$ exposure and worker characteristics in relation to lung function among workers at the Tropodo Tofu Factory in Sidoarjo.

Materials and Method

Description of Materials or Research Subjects: The subjects of this study were 20 tofu factory workers at Tropodo, Sidoarjo, selected using inclusion criteria. The study also used ambient air samples taken from the tofu production area. The measurement of $PM_{2.5}$ concentration was conducted using a Dust Particle Counter TC-8200 $PM_{2.5}$, which was calibrated before use to ensure data accuracy. The measurement was carried out for 10 minutes, three times a day (morning, afternoon, and evening) over 7 consecutive days to obtain representative average exposure values. The inclusion criteria included active production workers, non-smokers and smokers, and workers willing to participate voluntarily.

Research design: This study used an observational analytic method with a cross-sectional approach, which observes exposure and health effects at a single point in time. The cross-sectional design was

chosen because it allows assessment of the relationship between $PM_{2.5}$ exposure and pulmonary function without manipulation of variables. The Environmental Health Risk Assessment (EHRA) approach was used to quantify risk levels from exposure to $PM_{2.5}$, with four main stages: hazard identification, dose-response assessment, exposure assessment, and risk characterization. The cross-sectional design was selected because it is cost-effective, fast, and suitable for assessing current exposure conditions in industrial workplaces.

Research procedure: Preparation: obtaining research permits, ethical approval, and calibration of the measuring instruments; Data collection: measuring $PM_{2.5}$ concentration, interviewing workers, and conducting lung function tests; Calculation and analysis: exposure dose, risk quotient (RQ), and statistical correlation analysis. The risk assessment calculation used the following formulas: Inhalation Intake (I), Reference Concentration (RfC), Risk Quotient (RQ). Control variables considered include length of employment, daily exposure time, and environmental conditions (temperature, humidity, ventilation) to minimize bias.

Instruments and Equipment: Dust Particle Counter TC-8200 $PM_{2.5}$ (manufacturer: Tenmars, Taiwan), calibrated prior to measurement; Spirometer (brand: Contec SP10, China) for measuring lung function (FEV1); Questionnaire to collect data on age, smoking habits, work duration, and use of personal protective equipment (PPE).

Method of collecting data: Direct measurement of $PM_{2.5}$ concentration in the production area.**,** Spirometry testing for workers' lung function (FEV1) and Structured interviews for demographic and work habit data.

Data analysis: Data were analyzed using univariate analysis to describe each variable (mean, SD, frequency) and multivariate analysis to multiple regression to examine the relationship between $PM_{2.5}$ concentration, worker characteristics (age, smoking habits), and lung function (FEV1).

Research Ethics: This study obtained ethical approval from the Research Ethics Committee of Poltekkes Kemenkes Surabaya, under the ethical clearance number No. 3340/KEPK. All respondents provided written informed consent prior to participation.

Results

Based on the research that has been conducted, the results can be seen, including measurements $PM_{2.5}$ concentration, Particulate Matter ($PM_{2.5}$) concentration, hazard identification, dose response analysis, public health hazards, exposure analysis, risk characterization, worker characteristics, measurement of worker lung function, exposure analysis $PM_{2.5}$ on workers' lung function, and analysis of worker characteristics on worker lung function.

$PM_{2.5}$ Concentration Measurement

The $PM_{2.5}$ concentration measurements at three combustion sites in the Tropodo Tofu Factory are shown below.

Table 1. $PM_{2.5}$ Concentration Measurement Results

Location	Time (WIB)	$PM_{2.5}$ (μg/m³)	Average (μg/m³)
East of burning area	07.30 / 13.30 / 18.00	288 / 57 / 105	150.0
West of burning area	08.00 / 14.00 / 18.30	135 / 104 / 128	122.4
South of burning area	08.30 / 14.30 / 19.00	183 / 76 / 124	127.7

The highest $PM_{2.5}$ concentration (288 μg/m³) was recorded in the morning at east of burning area, exceeding the WHO 24-hour limit (15 μg/m³). The lowest concentration (57 μg/m³) was recorded during midday. Differences were influenced by temperature and air pressure variations.

$PM_{2.5}$ Exposure Categories

Table 2. $PM_{2.5}$ Concentration Categories at Incineration Sites

$PM_{2.5}$ criteria	Number of workers	Percentage (%)
0 – 15.5 μg/m³ (Healthy / Good)	-	0
15.6 – 55.4 μg/m³ (Medium)	-	0
55.5 – 150.4 μg/m³ (Unhealthy)	16	80
150.5 – 250.4 μg/m³ (Very Unhealthy)	2	10
> 250.4 μg/m³ (Dangerous)	2	10

Based on table 2, it can be seen that the concentration of $PM_{2.5}$ is in the unhealthy category for 16 workers (80%), category very unhealthy as many as 2 workers (10%), and dangerous category as many as 2 workers (10%).

Hazard Identification

The following is a table identification of Particulate Matter ($PM_{2.5}$) hazards in ambient air measured at each individual combustion location:

Table 3. Identification of Hazards at Incineration Sites

Location Point	$PM_{2.5}$ concentration(μg/m³)		
	Min	Max	Average
Point 1	57	288	172.5
Point 2	104	135	119.5
Point 3	76	183	129.5

Based on the table above, it can be seen that the average, minimum, and maximum concentration values of Particulate Matter ($PM_{2.5}$) are used to calculate the intake value at the exposure assessment stage. At location I, the minimum $PM_{2.5}$ concentration is 57 μg/m³, the maximum concentration is 288 μg/m³, and the average concentration is 172.5 μg/m³. Meanwhile, at location II, the minimum $PM_{2.5}$ concentration is 104 μg/m³, the maximum concentration is 135 μg/m³, and the average concentration is 119.5 μg/m³. At location III, the minimum $PM_{2.5}$ concentration is 76 μg/m³, the maximum concentration is 183 μg/m³, and the average concentration is 129.5 μg/m³. The average $PM_{2.5}$ concentration at all points exceeded national ambient air quality standards.

Exposure Analysis

Based on calculations at each combustion location, the following intake results were obtained.

Table 4. Exposure Analysis

Location	Min (mg/kg/day)	Max (mg/kg/day)	Mean ± SD (mg/kg/day)
Point 1	0.023	0.172	0.110 ± 0.052
Point 2	0.037	0.087	0.055 ± 0.018
Point 3	0.016	0.058	0.036 ± 0.015

These differences in intake values may be influenced by variations in measured $PM_{2.5}$ concentrations at each location, as well as other factors such as the inability to continue shifts and move locations. All intake values are expressed consistently in *mg/kg/day*.

Risk Characteristics

The following are the risk characteristics calculated for the minimum and maximum $PM_{2.5}$ concentrations at each location and individual.

Table 5. Risk Quotient (RQ) of *$PM_{2.5}$* Exposure

Location Point	Risk Characteristics		Interpretation
	Min RfC Value	Max RfC Value	
Point I	0.176	1,317	High risk – control required
Point II	0.284	0.669	Acceptable risk
Point III	0.123	0.446	Acceptable risk

Based on the table above, the risk concentration at all points in the Tropodo Tofu Factory shows that the minimum concentration obtained RQ value is 0.123<1 and the maximum concentration obtained RQ 1.317<1. *RQ > 1* indicates an unacceptable risk, requiring control measures. Thus, Point 1 needs immediate mitigation.

Characteristics of Workers

Table 6. Demographic Characteristics of Workers

Worker Characteristics	Amount	Percentage (%)
Worker Age		
≤30 years	7	35
> 30 years	13	65
Smoking Habit		
1 – 10 cigarettes a day	14	70
11 – 20 cigarettes a day	4	20
>20 cigarettes a day	2	10

Based on Table 6, there are 7 respondents (35%) aged 30 years and 13 respondents (65%) aged > 30 years. Meanwhile, regarding the smoking habits of workers, it can be seen that 14 workers (70%) have a habit of smoking 1-10 cigarettes a day, 4 workers (20%) have a habit of smoking 11-20 cigarettes a day, and 2 respondents (10%) have a habit of smoking 1 cigarette a day ≤> 20. Most workers were over 30 years old and smoked daily, potentially compounding respiratory effects

Worker Lung Function (FEV_1)

The following are the results of measurements of the lung function of workers at each burning site in Tropodo Village, Krian District:

Table 7. Complaints of Respiratory Disorders Among Workers at the Tropodo Tofu Factory

Category	FEV_1 (%)	Number of workers	%
Normal	≥ 80	7	35
Mild obstruction	50-79	13	65
Moderate–severe	< 50	-	0

Based on the table above, it can be seen that there are 8 workers who do not experience respiratory problems, while 14 workers who experience respiratory problems, among which 5 workers (25%) have asthma, 3 workers (15%) have pneumonia, 3 workers (15%) have pulmonary tuberculosis, and 2 workers (10%) have COPD. Based on the interview results, it was found that workers who have a history of respiratory problems are workers who have a smoking habit and have worked for more than 1 year. Workers experience respiratory problems after working in a tofu factory and have no history of previous respiratory problems.

Correlation Between Variables

The following are the results of the analysis of worker characteristics regarding lung function:

Table 8. Correlation Between Worker Characteristics and FEV_1

Variables	Correlation coefficient	P-value	Interpretation
Age	.934	.001	Significant negative correlation
$PM_{2.5}$	.055	.727	Not significant
Smoke	-.021	.866	Not significant

Statistical testing used Pearson correlation rather than multiple regression, since only simple relationships among continuous variables were analyzed. Older workers had significantly lower FEV_1 values, while $PM_{2.5}$ concentration and smoking habit were not statistically significant within the sample.

Discussion

$PM_{2.5}$ concentrations can change over time and can exceed the threshold (NAB).[10]. Meteorological factors such as rainfall, air temperature, wind speed, and relative humidity influence differences in $PM_{2.5}$ concentration results in the field.[11] Weather factors such as temperature and humidity also significantly influence pollutant concentrations. The Earth's surface temperature is warmer during the day than a few hundred meters above it, and the temperature drops by 10°C for every 100 meters.[12] This condition causes the pollutant plume to rise several hundred meters above the chimney's height. This results in the lowest $PM_{2.5}$ concentrations occurring during the day and the highest in the morning.

Burning wood and plastic fuels at factory sites produces smoke containing $PM_{2.5}$, which can pollute ambient air and potentially cause health problems. Research by[13], The risk of acute and chronic respiratory diseases, cardiovascular disease, and lung cancer is closely related to exposure to air pollution. Intake analysis during the exposure assessment phase is crucial for understanding the extent to which workers are exposed to $PM_{2.5}$. By knowing the minimum, maximum, and average concentrations, further calculations can be performed to determine potential health risks.[14].

The RfC value for $PM_{2.5}$ was 0.013 mg/kg/day. This value indicates that exposure to $PM_{2.5}$ above this threshold can potentially have negative health impacts, especially for workers exposed continuously over long periods of time.[15]Workers who work in dusty workplaces have a higher risk of experiencing respiratory problems compared to workers who work in the same environment but do not have a smoking habit.[16]. The importance of monitoring air quality and controlling $PM_{2.5}$ exposure in the workplace is essential to protect workers' health.

These differences in intake values may be influenced by variations in measured $PM_{2.5}$ concentrations at each location, as well as other factors such as duration and frequency of exposure. The higher intake values at Point I may be due to higher $PM_{2.5}$ concentrations at that location, resulting from more intensive combustion or the use of more polluting fuels.

In this study, the RQ value was calculated for the minimum and maximum $PM_{2.5}$ concentrations at each location.[17] The RQ value indicates that current exposure is safe, but the recapitulation of respiratory disorders experienced by workers indicates that there is a potential health risk that needs attention. Therefore, although the calculation results indicate that current exposure is safe, appropriate follow-up is needed to monitor and control air quality in the work environment.[18].

The predominance of workers over 30 years old indicates the need to ensure that the Tropodo tofu factory can retain an experienced workforce. However, the high smoking rate among workers also

raises concerns about occupational health and safety.[19]Therefore, interventions to reduce smoking habits in the workplace need to be considered.

The majority of workers experience significant lung function decline, although not in the most severe categories. Lung function decline, as measured by FEV1 values, can be influenced by various factors, including exposure to air pollution and hazardous materials in the workplace. According to research by[20]Long-term exposure to various pollutants, especially fine particles like $PM_{2.5}$ and PM_{10}, can affect mental health, cardiovascular health, nervous system health, and respiratory health. This study shows that workers exposed to air pollution have a higher risk of developing respiratory disorders.

This study was limited by small sample size and short-term exposure measurement. The *cross-sectional* design prevents causal inference and does not account for cumulative or chronic effects of $PM_{2.5}$. Furthermore, variations in workers' tasks and movement between stations may introduce measurement bias. Instrument reliability, while ensured through calibration, may still be affected by environmental factors such as humidity and temperature during field measurement. Future studies should use longitudinal designs, larger samples, and continuous exposure monitoring to obtain more accurate risk estimations and identify chronic health outcomes associated with $PM_{2.5}$ exposure.

Conclusions

The analysis results show that the $PM_{2.5}$ concentrations in the Tropodo Tofu Factory exceeded the recommended safety limits, particularly at Point 1, where the highest concentration reached 288 μg/m³ in the morning. The corresponding Risk Quotient (RQ) value was 1.317 (>1), indicating a high health risk and the need for immediate control and mitigation measures.

The mean FEV_1 value of workers was 73.8 ± 9.5%, reflecting mild obstructive impairment. Among all observed factors, age showed a significant correlation with decreased lung function ($p < 0.05$), while $PM_{2.5}$ concentration and smoking habits were not statistically significant within the small sample size. Therefore, it can be concluded that $PM_{2.5}$ exposure poses a significant risk to workers' respiratory health, particularly for older workers exposed for prolonged periods.

Recommendations

Implementation of control measures is urgently required at combustion points with RQ > 1, including the installation of localized exhaust ventilation or particulate filters. Substitution of fuel from mixed plastic and wood to cleaner alternatives such as LPG or biomass briquettes to reduce $PM_{2.5}$ emissions. Mandatory use of Personal Protective Equipment (PPE), especially N95 or equivalent respirators, during the production process. Periodic air quality and health monitoring, including spirometry tests every six months. Worker education programs on the importance of respiratory protection, safe fuel handling, and healthy lifestyle practices (e.g., reducing smoking). The implementation of these recommendations is essential to minimize $PM_{2.5}$ exposure, protect workers' lung function, and support sustainable and safe tofu production practices.

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