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Original Research Paper

Risk analysis of $PM_{2.5}$ exposure among workers at railway station

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Abstract
Particulate matter 2.5 ($PM_{2.5}$) is a pollutant that negatively impacts environmental quality and poses health risks to populations exposed over long periods. In Yogyakarta, $PM_{2.5}$ is the primary pollutant, particularly in urban areas with heavy traffic, such as train stations. This study analyses the risk level of $PM_{2.5}$ exposure among workers at Yogyakarta Railway Station using an environmental health risk analysis approach. The data was obtained from BB Labkesmas Yogyakarta's study in October 2023, involving 15 respondents working in the station's waiting area. $PM_{2.5}$ analysis was conducted using a High-Volume Air Sampler (HVAS) with the gravimetric method, and respondents were selected through incidental sampling. The results show that the $PM_{2.5}$ concentration at Yogyakarta Railway Station (74.97 µg/m³) exceeds the air quality standards set by The Indonesian Ministry of Health Regulation No. 02/2023. Risk analysis calculations indicate that most workers remain within the safe category (HQ ≤ 1) for both a 30-year lifetime exposure projection and a real-time exposure projection. However, a respondent is exposed to an unsafe risk (HQ>1), so precautions must be taken to reduce the risk to a safe level. Additionally, it is necessary to conduct a risk analysis study based on a specific period in the future.

Keywords: air quality; health risk; $PM_{2.5}$; train station

1. Introduction

Air pollution is an environmental issue that significantly impacts human health, given its high contribution to morbidity and mortality rates in various countries (Fisher et al., 2021; Dettori et al., 2021; Geng et al., 2021). Globally, mortality rates due to air pollution are estimated to reach 8.34 million deaths per year (Lelieveld et al., 2023). $PM_{2.5}$ is an airborne particle with a diameter of 2.5 µm or smaller, composed of carbon compounds, water-soluble ions (SO_4^{2-}, NO_3^-, NH_4^+, etc.), and major and trace elements (Al, Si, Pb, Cd, etc.) (Allouche et al., 2024). $PM_{2.5}$ is a particularly concerning pollutant as it can lead to cardiovascular diseases (Liao et al., 2021), placental dysfunction (Nääv et al., 2020), increased lung cancer risks (Chen et al., 2022), and hormonal disruptions (Zhou et al., 2020). The World Bank estimates the global health costs due to $PM_{2.5}$ pollution at $5.7 trillion, equivalent to 4.8% of the global GDP (World Bank, 2020). The World Air Quality Report released in 2023 indicates alarming $PM_{2.5}$ concentrations in several Asian and African countries. In Indonesia, the average annual $PM_{2.5}$ concentration sharply increased to 37.1 µg/m³ in 2023, up more than 20% from 2022, ranking Indonesia 14th out of 134 countries with the highest $PM_{2.5}$ concentrations (IQAir, 2023). In Yogyakarta, $PM_{2.5}$ has become the primary air pollutant, especially in urban areas or high-traffic regions (IQAir, 2024).

High-risk populations exposed to $PM_{2.5}$ include workers in congested vehicle areas such as railway stations. $PM_{2.5}$ at railway stations can originate from outdoor environments, including industrial combustion, traffic emissions, exhaust emissions from engine combustion processes, as well as non-exhaust emissions such as brake wear, wheel-rail abrasion, and resuspended particles (Mantilla et al., 2023; Chang et al., 2024). Yogyakarta Railway Station, classified as a Type A station, experiences heavy traffic and is at high risk of $PM_{2.5}$ contamination. Station workers are continuously exposed to air pollution throughout their years of service. To date, there has been no evaluation of the impact of air pollution on the exposed population at the station (BBLabkesmas Yogyakarta, 2023). Given these conditions, it is necessary to conduct a risk analysis of $PM_{2.5}$ exposure among workers, particularly those consistently exposed to such pollutants daily.

Risk analysis is a method used to calculate or estimate risks to an organism, system, or (sub) population, considering the inherent properties of the substance under study and identifying uncertainties related to substance exposure. It is employed to assess the risks posed by hazardous agents in the environment to human health (Yang et al., 2024). This method has been utilized in various studies to predict the risk levels of exposure to hazardous agents through ingestion (Ardhaneswari & Wispriyono, 2022; Maksum & Tarigan, 2022) and inhalation routes (Latifah et al., 2021; Nurfadillah & Petasule, 2022). The study of $PM_{2.5}$ exposure risk analysis among workers at Yogyakarta Railway Station is crucial to estimate risk levels and implement preventive measures to reduce risks to safe levels. Previous studies have assessed the risk of $PM_{2.5}$ exposure in residential areas (Silvia et al., 2020), schools (Andriani & Wahyuni, 2021; Rosalia et al., 2018), and high-traffic areas (Sembiring, 2020; Maksum & Tarigan, 2022). This study focuses on the risk analysis of $PM_{2.5}$ exposure among station workers with varying work durations, particularly at railway stations, and formulates risk management strategies as preventive measures.

2. Research Methods

This study used an Environmental Health Risk Analysis approach to quantify the magnitude of $PM_{2.5}$ exposure risk. This study has received ethical approval from the Ethics Committee of Ahmad Dahlan University with ethics number 012405116. The $PM_{2.5}$ ambient air measurements at Yogyakarta Station were based on secondary data from BB Labkesmas Yogyakarta (October 2023) and conducted in the station's waiting area, covering approximately 800 m². $PM_{2.5}$ analysis was performed using a High-Volume Air Sampler (HVAS) employing the gravimetric method. Interviews were conducted with 15 respondents, including PT KAI employees, porters, and cleaning staff. Respondents were selected using incidental sampling method. The respondents consist of 73% males and 27% females, with ages ranging from 25 to 70 years old and periods of exposure varying between 1 to 46 years (BBLabkesmas Yogyakarta, 2023). The acquired data underwent risk analysis in four steps: hazard identification, dose-response analysis, exposure analysis, and risk characterization.

In the first step, hazard identification involved recognizing the types of health-damaging effects from epidemiological studies on human populations, whether using experimental designs, epidemiology studies, toxicology studies, in-vitro and in-vivo toxicology studies (Sulsky et al., 2024). The second step involved dose-response analysis to establish quantitative toxicity values for each chemical species form of risk, using reference concentrations (RfC). RfC is a reference for agents entering via inhalation pathways, including $PM_{2.5}$. RfC values can refer to IRIS (Integrated Risk Information System) from the US EPA (Environmental Protection Agency); if unavailable on IRIS, they can be derived from other experimental doses like NOAEL (No Observed Adverse Effect Level), LOAEL (Lowest Observed Adverse Effect Level), MRL (Minimum Risk Level), or ambient air quality standards under NAAQS (National Ambient Air Quality Standard), with clear anthropometric factors noted (body weight, exposure duration, exposure frequency, and duration) (Przybyla et al., 2020; Abidin et al., 2023). The third step, exposure analysis, is conducted to measure chronic daily intake (CDI) or average daily dose (ADD) of the risk agent using the following equation (US EPA, 2024a):

$$\mathrm{ADD} = \frac{\mathrm{C \times InhR \times ET \times EF \times ED}}{\mathrm{BW \times AT}}$$

Explanation:

CDI/ADD	:	The total concentration of the risk agent (mg) that enters the human body per day per specific body weight (kg). The unit for intake is mg/kg/day.
Concentration (C):	:	The concentration results from measuring air quality parameters expressed in units of mg/m^3.
Inhalation rate (InhR)	:	The inhalation rate is the volume of air taken per hour (m^3/hour).
Exposure Time (ET)	:	Exposure time is the total number of exposure hours per day.
Exposure frequency (EF)	:	The number of exposure days per year (days/year).
Exposure duration (ED):	:	The duration or number of years of exposure.
Body Weight (BW)	:	Body weight of the respondent.
Average time (AT)	:	The average period for non-carcinogenic effects (days).

The fourth step involves risk characterization, which is the determination of risk levels expressed as a hazard quotient (HQ) for non-carcinogenic effects, using the following equation (US EPA, 2024b):

$$HQ = \frac{ADD}{RfC}$$

The risk level is considered safe if the intake ≤ its RfC, or expressed as HQ ≤ 1. The risk level is considered unsafe if the intake > RfC, or expressed as HQ>1.

3. Results and Discussion

3.1. Anthropometric Characteristics

A total of 15 respondents worked at Yogyakarta Railway Station daily. They include health post workers, passenger facility personnel, e-ticketing staff, mechanical-electrical staff, pass reaction staff, front liners, and security staff, each represented by one person. Additionally, there were two customer services, three cleaning services, and three porters. Anthropometric characteristics were obtained through interviews with the respondents (Table 1).

Table 1. Anthropometric Characteristics of Respondents

Characteristics	Measurement Results (n=15)		
	Minimum	Maximum	Average
Weight	34	85	63
Working hours (ET)	8	10	8,5
Working days per year (EF)	260	312	302
Years of employment (ED)	0,83	23	8

Source: BB Labkesmas Yogyakarta, 2023

Table 1 presents variations in respondents' anthropometric characteristics. These factors, along with work conditions, are crucial in assessing health risks from $PM_{2.5}$ exposure (Rivai et al., 2021; Shetaya et al., 2024). Workers with longer shifts (8–10 hours per day) and more annual working days (up to 312 per year) face prolonged exposure to fine particulate matter. A study indicates that high exposure to $PM_{2.5}$ significantly increases mortality risk over the next 20–30 years (Xu et al., 2023). Long-term exposure to $PM_{2.5}$ is associated with poor general health, chronic illness, respiratory issues, mobility difficulties, and deafness (Rowland et al., 2024).

3.2.Hazard Identification

Particulate Matter 2.5 ($PM_{2.5}$), particles with a diameter of fewer than 2.5 micrometres, originates from both combustion and non-combustion activities released into the air and entering the human body through inhalation pathways. $PM_{2.5}$ mass primarily consists of inorganic ions, carbon compounds (black carbon and organic carbon, including secondary organic aerosols), and mineral dust (McDuffie et al., 2021). At railway stations, dust can originate from the mobility of trains and other parked vehicles that operate continuously, leading to ongoing fuel combustion processes and increased exhaust emissions. This scenario heightens the risk of exposure to particulate dust (Aziza et al., 2020). Hazard identification encompasses sources, environmental media, and PM concentrations, summarized in Table 2.

Table 2. Hazard Identification

Risk Agent	Source	Media	Concentration
Particulate matter 2,5	The activities at the Railway Station include train mobility and traffic around the station.	Air	0,0747 mg/m^3

Source: Primary Data, 2024

Based on the hazard identification results as shown in Table 2, it is known that the concentration of $PM_{2.5}$ at Yogyakarta City Station is 74.97 µg/m^3. This value surpasses the ambient air quality standard established by the Ministry of Health Regulation No. 02/2023, which sets the maximum allowable $PM_{2.5}$ concentration at 25 µg/m³. This value is higher compared to previous studies conducted in public places in Jakarta (including stations), which ranged from 10 to 58 µg/m³ (Pangestika & Wilti, 2021). Another study at stations in Southwest China found $PM_{2.5}$ levels ranging from 4 to 45 µg/m³ (Hu et al., 2024), while in Dublin, Ireland, $PM_{2.5}$ levels at stations ranged from 5 to 8.5 µg/m³ (Priyan et al., 2024).

The high concentration of $PM_{2.5}$ in the waiting area is influenced by the conditions of the space directly adjacent to the railway tracks. $PM_{2.5}$ pollutants are affected by train traffic activities and the proximity of the waiting area to the railway tracks. A study in Philadelphia has shown that $PM_{2.5}$ concentrations inside subway stations are quite high due to poor air distribution, with exposure levels being 2.6 to 5.1 times higher than outside (Shakya et al., 2020).

Besides being caused by train traffic, $PM_{2.5}$ levels are also contributed by ambient air conditions around Yogyakarta City Station, located in a densely trafficked area. The transportation sector is a major contributor to air pollution in large cities, leading to increased levels of PM2.5 and other parameters such as SO_2, NOx, CO, and O_3 (Meng et al., 2020; Li & Managi, 2021). $PM_{2.5}$ levels can also be affected by meteorological factors such as temperature, humidity, and wind direction. A study in Delhi has shown an exponential increase in $PM_{2.5}$ concentrations with decreasing temperatures, indicating a complex interaction of factors contributing to air pollution in the region (Vaishali et al., 2023). A study in Tianjin, China, suggests that increased humidity leads to the aggregation of fine particles, forming larger particles. Humidification is beneficial in preventing particles from entering the human respiratory system, thereby reducing the impact of particles on human health (Zhang et al., 2019). Wind plays a role in distributing or redirecting airborne particulate matter. As wind speed increases, particulate levels typically decrease (Tran et al., 2020). In railways, PM2.5 is also influenced by the condition of the wheel-rail surface, the friction between the wheel and rail, and engine combustion (Fruhwirt et al., 2023).

3.3.Dose-Response Analysis

The reference concentration (RfC) for $PM_{2.5}$ parameters is derived from NAAQS (US EPA, 2023) which states the maximum limit for this parameter is 35 µg/m^3 or 0.035 mg/m^3. From this value, RfC can be calculated as chronic daily intake of average daily dose, incorporating the $PM_{2.5}$ ambient air quality standard as the concentration value (C) and anthropometric factors using default values established by the US EPA. These values are: inhalation rate (InhR) of 20 m^3/day (converted to 0.83 m^3/hour), body weight (BW) of 70 kg, exposure time (ET) of 24 hours/day, exposure frequency (EF) of 350 days/year, and exposure duration (ED) over a lifetime of 30 years.

$$ADD = RfC = \frac{C \times InhR \times ET \times EF \times ED}{BW \times AT}$$

$$RfC_{PM2,5} = \frac{0{,}035\frac{mg}{m3} \times 0{,}83\frac{m3}{hours} \times 24\frac{hours}{day} \times 350\frac{days}{year} \times 30\ years}{70\ kg \times 365\frac{days}{year} \times 30\ years}$$

$$RfC = 0{,}009551\ mg/kg/day$$

The calculation of the RfC value is the same as that used in the previous study on $PM_{2.5}$ exposure in public places in Gorontalo (Maksum & Tarigan, 2022) and in the study on $PM_{2.5}$ exposure among informal workers at a landfill site (Abidin et al., 2023). In this study RfC serves as a safe exposure limit for air pollutants, ensuring no long-term health effects in humans, and is used to assess the risk of exposure to $PM_{2.5}$ and other pollutants by considering factors such as exposure duration and concentration (US EPA, 2024b).

3.4.Exposure Analysis

Exposure analysis is calculated using real-time anthropometric data, incorporating working hours as ET, working days as EF, and lifetime duration (30 years) as ED, resulting in the ADD values shown in Table 3. Additionally, calculations are conducted using real-time exposure duration, incorporating years of employment as Dt.

Table 3 Exposure analysis

ADD lifetime		ADD realtime	
Min	Max	Min	Max
0,0044	0,0125	0,0001	0,0130

Source: Primary Data, 2024

In Table 3, ADD of $PM_{2.5}$ over a lifetime is calculated assuming a 30-year exposure duration, which is the default for non-carcinogenic intake, expressed as ADD lifetime. Meanwhile, real-time exposure is calculated based on years of employment and expressed as ADD real-time. These intakes are projections assuming $PM_{2.5}$ concentrations remain consistent with those measured in October 2023. Concentrations in the past or future may vary, potentially affecting intake levels.

3.5.Risk Characterization

In this step, the ADD values obtained from the exposure analysis step are compared with the $PM_{2.5}$ concentration doses calculated in the dose-response analysis step. The risk characterization calculation results for the 30-year exposure projection show that the majority (93.3%) have HQ≤1, indicating the risk is considered safe for $PM_{2.5}$ exposure at a concentration of 0.0747 mg/m^3 daily. There is one respondent with HQ>1 for real-time exposure and another HQ > 1 for lifetime exposure. The high HQ value is due to low body weight, and in real-time exposure, it is also influenced by the high exposure duration (duration of employment). In real-time exposure, respondents with an HQ > 1 had a body weight of 51 kg, a work duration of 46 years, an exposure time of 7 hours per day, and an exposure frequency of 365 days per year. In lifetime exposure, respondents with an HQ > 1 had a body weight of 34 kg, with an exposure duration of 8 hours per day and an exposure frequency of 312 days per year.

Table 4. Risk Characterization

HQ lifetime		HQ realtime	
Min	**Max**	**Min**	**Max**
0,54	1,31	0,02	1,37

Source: Primary Data, 2024

The HQ value is influenced by the average daily dose (ADD), which is affected by hours of exposure, days worked per year, years of service, and body weight. Lower body weight and longer exposure hours increase the intake levels (US EPA, 2024a). The exposure analysis or ADD significantly impacts the risk level (HQ). Respondents with HQ values exceeding 1 in the lifetime projection are attributed to high exposure frequency (days worked per year) and low body weight. Based on the 30-year exposure projection, workers are at risk of health problems from $PM_{2.5}$ exposure if pollutant concentrations remain at or above the levels measured during the October 2023 assessment. Furthermore, one respondent has an HQ>1 in real-time exposure due to longer working hours. This study does not provide comparisons because historical $PM_{2.5}$ levels at Yogyakarta Railway Station are unknown.

The risk assessment principles in this study align with other environmental health risk assessment studies, where anthropometric characteristics significantly influence HQ values. A study by Latifah et al. (2021) characterized the risk of $PM_{2.5}$ exposure in elementary school children, finding HQ ≤ 1 for all respondents. Anthropometric factors influencing the study included short exposure times (about 6 hours per day) and an annual exposure frequency of approximately 240 days, corresponding to school hours (Latifah et al., 2021).

Conversely, longer exposure durations, as studied by Nur et al. (2021) on PM_{10} exposure in residential areas with concentrations of 150 µg/Nm^3, 17 hours of exposure per day, and an exposure frequency of 339 days/year resulted in an HQ of 4.87, indicating significant health risks for residents living in those environments (Nur et al., 2021). Similarly, Ridayanti et al. (2022), examining $PM_{2.5}$ exposure in the home industry brick kilns, found average HQ values of 1.6-2.45 due to 24-hour exposure during brick burning times (Ridayanti et al., 2022).

This study has limitations, as $PM_{2.5}$ data was collected only once at one location. Consequently, the data obtained cannot capture fluctuations in $PM_{2.5}$ levels on different days or variations in $PM_{2.5}$ levels in different indoor or outdoor locations. Nevertheless, this study provides a projection of risk levels as a reference for risk management, particularly for the exposed population.

Risk management is not a risk assessment process but a follow-up action necessary when projections indicate unsafe risk levels. Risk management should be based on logical considerations, taking into account various factors including risk management strategies (US EPA, 2024c). Risk management strategies can involve reducing concentration levels, exposure hours, exposure frequency, or safe exposure durations. An example of reducing $PM_{2.5}$ concentrations is seen in Ryu et al. (2019), using plants to reduce $PM_{2.5}$. Plant transpiration increases humidity, causing dust particles to aggregate and settle on leaf surfaces, effectively filtering them out (Ryu et al., 2018). Other studies have shown plant that leaves can decrease air speed and temporarily lower $PM_{2.5}$ concentration for 9-15 minutes (Poothong et al., 2020). Implementing this method could involve greening efforts at Yogyakarta Railway Station, particularly in waiting areas. Strategies for managing safe exposure times involve reducing working hours.

Strategies to reduce exposure frequency can involve reducing the number of workdays per year, while strategies for safe exposure durations can involve limiting the length or years of working in locations with high $PM_{2.5}$ levels (Ejohwomu et al., 2022). If feasible, employee rotation can limit $PM_{2.5}$

exposure times. Since not all workers at the Railway Station are in the formal sector, this strategy may not be suitable for all.

Personal protection can be an alternative in managing risks, although it is not the best long-term solution compared to efforts to reduce overall air pollution concentrations. N95 masks offer good protection against fine particles like $PM_{2.5}$ (Siegel & Brook, 2020). These masks filter $PM_{2.5}$ and reduce exposure by more than 14 times (Kodros et al., 2021). It is even effective in filtering smaller particles. A study in Vietnam shows that N95 masks have an efficiency of 60–80% in filtering ultrafine particles (<50 nm), whereas surgical and cloth masks have efficiencies of 25–60% (Velasco et al., 2022).

Health risk management from pollutant exposure involves several strategic steps, starting with scientific risk assessment to determine the toxicity and health impacts of various pollutants, followed by the development of environmental quality standards. From the available alternative risk management strategies, further screening is necessary to select the most effective approach based on logical considerations (US EPA, 2022). To implement effective air quality control strategies, a combination of technological, socio-economic, and institutional approaches is required. Technologically, this includes infrastructure that promotes low-emission transportation, such as bike lanes, low emission zones, and electric vehicle adoption. While technologies like air filtration or pollutant-absorbing plants are being developed, their effectiveness remains limited compared to comprehensive transport system changes. Socio-economic measures, such as financial incentives for electric vehicle purchases and accessible public transport, can empower communities to transition toward greener options. Institutionally, strong policy support is needed to enforce regulations like low-speed limits and low-emission zones, ensuring these measures work synergistically for greater impact, as seen in cities with the highest air quality standards (Quarmby et al., 2019). For example, if greening initiatives are to be implemented in the station area, it requires policy support from the authorized management in terms of funding and its application.

4. Conclusion

The concentration of $PM_{2.5}$ in the waiting area of Yogyakarta City Station exceeds the air quality standards set by The Indonesian Ministry of Health Regulation No. 02/2023. The results of risk characterization assessments indicate that the majority are still at safe levels, but there are instances of real-time and lifetime HQ>1, indicating unsafe exposure for workers at Yogyakarta Railway Station. Risk management efforts can be implemented by reducing pollutant concentrations through greening initiatives or by providing personal protection such as wearing masks during work. This study has limitations, as it was based on a single-point measurement and did not assess the health symptoms experienced by workers. Further comprehensive research is required to better understand the impact of $PM_{2.5}$ on station workers.

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