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THE ASSOCIATION BETWEEN PM 2.5 LEVEL AND RESPIRATORY TRACT INFECTIONS AMONG CHILDREN: A CROSS-SECTIONAL STUDY

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ABSTRACT

Background: PM_{2.5} is a key air pollutant that contributes to respiratory morbidity, especially in children. In Jakarta, Indonesia, PM_{2.5} levels often exceed safe thresholds. This study contributes local evidence from Indonesia, where research on the health effects of PM_{2.5} in children remains limited. To address this gap in the existing literature, particularly within the Indonesian context, this study offers novel insights by specifically investigating the association between ambient PM_{2.5} exposure and respiratory tract infections (RTIs) in school-aged children and further exploring this association within male and female subgroups, an aspect that has received limited attention in this setting. **Objective:** This study aims to assess the association between ambient PM_{2.5} exposure and respiratory tract infections (RTIs) in school-aged children, and to explore this association within male and female subgroups. **Methods:** This cross-sectional study is conducted among 107 children aged 5–12 years from two elementary schools: one in Jakarta (high PM_{2.5} exposure) and one in Bandung (low PM_{2.5} exposure). Data on PM_{2.5} levels were obtained from local air quality monitoring. RTI symptoms were assessed through structured interviews and physical examination. Participants were selected using random sampling. Chi-square tests and effect size calculations (phi coefficient) were used to compare groups. Potential confounders such as age, gender, and household smoke exposure were minimized through inclusion/exclusion criteria and the selection of demographically and environmentally similar school communities. Multivariate logistic regression adjusting for confounders was also performed to assess the independent association between PM_{2.5} exposure and respiratory tract infections. **Results:** The Chi-square test indicated a significant association between PM_{2.5} levels and the occurrence of RTI ($\chi^2 = 22.154$, $df = 1$, $p < 0.001$, $\phi = 0.475$). Given potential low expected counts in some cells, the statistical significance was further evaluated using Fisher's Exact Test, which also showed a significant association ($p < 0.001$). The prevalence of RTI was significantly higher in the high exposure group (71.43%) compared to the low exposure group (25.86%) ($p < 0.001$). Further analysis did not reveal significant differences in the proportion of each age group between the high and low PM_{2.5} exposure groups ($\chi^2(1) = 0.093$, $p = 0.761$). Similarly, no significant differences were found in the proportion of gender between the high and low PM_{2.5} exposure groups ($\chi^2(1) = 1.611$, $p = 0.204$) in the total sample. Likewise, there were no significant differences in the

proportion of RTI across different age groups ($\chi^2(6) = 5.327, p = 0.503$) or between genders ($\chi^2(1) = 0.008, p = 0.928$) in the total sample.

However, further analysis examining the association between PM2.5 exposure and RTI within gender subgroups revealed a significant association in both male ($\chi^2(1) = 10.873, p = 0.001$) and female ($\chi^2(1) = 11.755, p = 0.001$) children. The estimated Prevalence Ratio (PR) was 2.76 (95% CI: 1.68-4.54), indicating that children in the high PM2.5 exposure area had approximately 2.76 times higher prevalence of RTI compared to those in the low exposure area. The absolute Prevalence Difference (PD) was 45.57% (95% CI: 25.9%-65.2%). Binary Logistic Regression analysis showed that children in the high PM2.5 exposure group had a significantly higher odds of having RTI (OR = 7.167, 95% CI: 3.050-16.837, $p < 0.001$). Further analysis examining the association between maternal socioeconomic factors and both PM2.5 exposure and RTI occurrence revealed no statistically significant relationships. Chi-square tests showed no significant association between maternal education level (low vs. medium) and PM2.5 exposure group ($\chi^2(1) = 0.045, p = 0.833$), nor between maternal occupation (blue collar vs. semi-professional) and PM2.5 exposure group ($\chi^2(1) = 0.006, p = 0.93$). Similarly, no significant associations were found between maternal education level and RTI ($\chi^2(1) = 0.123, p = 0.629$) or between maternal occupation and RTI ($\chi^2(1) = 0.447, p = 0.504$). Crucially, after adjusting for potential confounders including gender, age, maternal education, and maternal occupation in a multivariate logistic regression model, the odds of having RTI remained significantly higher in children with high PM2.5 exposure (Adjusted OR = 7.883, 95% CI: 3.228-19.250, $p < 0.001$). **Conclusion:** Children exposed to higher levels of PM2.5 had significantly more respiratory infections. These findings highlight the need for targeted public health interventions in polluted urban areas. Further research using longitudinal designs is needed to understand the long-term impacts of PM2.5 exposure on children's respiratory health and to inform appropriate mitigation strategies.

Keywords: air pollution, children, cross-sectional study, PM2.5, respiratory tract infection.

INTRODUCTION

Fine particulate matter with a diameter of 2.5 micrometers or less (PM2.5) has been widely recognized as one of the most harmful air pollutants due to its ability to penetrate deep into the respiratory tract and enter the bloodstream [1,2,3]. Exposure to PM2.5 is associated with a range of adverse respiratory health outcomes, including airway inflammation, decreased lung function, and increased risk of respiratory infections and chronic respiratory diseases [1-5]. Research has shown that prolonged exposure to PM2.5 can lead to chronic respiratory conditions such as asthma and bronchitis, particularly in children whose immune systems are still developing. Children are particularly vulnerable to air pollution because their lungs and immune systems are still developing, they have higher minute ventilation per body weight, and they often spend more time outdoors than adults [6,7,8].

In Jakarta, the capital of Indonesia, the burden of air pollution is especially concerning. As one of the most densely populated and industrialized cities in Southeast Asia, Jakarta frequently experiences PM2.5 concentrations far exceeding the World Health Organization (WHO) air quality guideline. In August 2023, Jakarta was named the most polluted city in the world, with

average PM2.5 concentrations exceeding safe limits by more than five times—reaching up to 80 $\mu\text{g}/\text{m}^3$ on the worst days. In response, local authorities implemented remote work policies for civil servants to curb vehicle emissions and improve air quality [9-15]. Prolonged exposure in such environments poses significant health risks, particularly for children [6,7,8]. Furthermore, available data suggests a concerning trend of elevated PM2.5 levels in Jakarta over the past few years, primarily stemming from sources such as vehicle emissions, industrial activities, and biomass burning.

Research has demonstrated the adverse health effects of PM2.5 on children's respiratory health in various parts of the world. For example, Sugiyama T et al. studied the health effects of PM2.5 sources on children's allergic and respiratory symptoms in Fukuoka, Japan during the spring of 2014–2015 [16]. Another study by Dandan examined the acute effects of ambient PM2.5 on lung function among school children in Zhejiang Province, China, over the years 2014–2017 [17]. Yueling Ma et al. were obtained from 2014 to 2016 in Lanzhou, China, the association of air pollution with outpatient visits for respiratory diseases of children in the ex-heavily polluted Northwestern city, China [18]. Additionally, a comprehensive literature review by Yu Fei Xing et al. in 2016 explored the impact of PM2.5 on the human respiratory system, providing an in-depth analysis of epidemiological, experimental, and mechanistic studies [1]. More recently, Adikary et al. (2025) conducted a large-scale study using PM2.5 data from the Atmospheric Composition Analysis Group at Washington University to assess the association between PM2.5 exposure and acute respiratory infections (ARI) in 223,375 children from the 2019–2021 Demographic Health Survey in India, contributing further evidence on the relationship between PM2.5 exposure and respiratory health outcomes in children [7].

Despite the growing body of research globally, there is a lack of studies focused on the impact of PM2.5 on children's respiratory health in Indonesia, particularly in urban areas like Jakarta. While studies have explored the health effects of PM2.5 in countries such as China, Japan, and India, evidence from Indonesia remains limited [1,7,16,17]. Research is needed to understand how children in Indonesian urban environments are affected by exposure to PM2.5, especially considering the unique genetic, environmental, and social contexts of the region. Furthermore, genetic and racial variations may influence susceptibility to PM2.5-induced respiratory effects, which makes findings from other countries less generalizable to Indonesia [19,20,21]. Understanding these localized impacts is crucial for developing effective strategies to mitigate the adverse health consequences of air pollution and improve respiratory health outcomes for children in Jakarta.

Given Jakarta's alarming pollution levels and the limited availability of localized research, it is crucial to fill this gap in knowledge to better inform public health decisions. This study aims to compare respiratory health outcomes—specifically respiratory infections—among children exposed to high levels of PM2.5 in Jakarta and those living in a region with significantly lower PM2.5 exposure, Bandung. By comparing these two distinct regions, we aim to provide insights into the local impact of air pollution on children's respiratory health in Indonesia. Furthermore, to explore potential variations in this association, we also examined the association between PM2.5 exposure and respiratory infections within male and female subgroups of the study population.

This study is novel in two main ways. First, it is one of the first to empirically examine the respiratory impact of PM_{2.5} on school-age children in Indonesia, filling a crucial research gap in the Southeast Asian context. Second, it compares two distinct exposure zones—Jakarta (high PM_{2.5}) and a region with significantly lower PM_{2.5} levels—allowing for a clearer understanding of the exposure-response relationship. The findings are expected to inform public health interventions, raise awareness about urban air pollution, and support evidence-based policy-making in Indonesia.

⁴⁷ To our knowledge, this is the first study to examine the association between PM_{2.5} exposure and respiratory problems among school-aged children in Indonesia, with a specific focus on Jakarta. By comparing children from a high exposure area (Jakarta) to those from a region with better air quality (Bandung), this study provides localized evidence on the impact of PM_{2.5} on symptoms such as coughing, wheezing, and shortness of breath.

METHODS

Research Questions

What is the impact of naturally occurring differences in PM_{2.5} levels on respiratory health outcomes among children aged 5–12 years living in areas with high air pollution exposure compared to those in areas with better air quality?

¹² Study design

This study employed an analytical cross-sectional design⁶⁷ to evaluate the association between exposure to PM_{2.5} and the prevalence of respiratory tract infections (RTIs) in children. The population was divided into two comparison groups based on PM_{2.5} exposure levels in their residential and school environments:

- **High Exposure Group:** Children living in areas with consistently high PM_{2.5} levels (Poor AQI).
- **Low Exposure Group:** Children living in areas with low PM_{2.5} levels (Good AQI).

Unlike ecological studies that rely on group-level data, this study collected individual-level data on exposure and health outcomes, allowing for more precise estimation of associations.

The study population consisted of elementary school children aged 5–12 years attending schools located in areas with different levels of PM_{2.5}.

To minimize potential confounding, we selected schools from communities that were as homogeneous as possible in terms of environmental, demographic, behavioral, and household factors (e.g., exposure to cigarette smoke, ventilation, immunization status, nutritional status, seasonality, and housing conditions). Controlled variables included:

- **Demographic factors** (age, gender, socioeconomic status),
- **Environmental factors** (exposure to cigarette smoke, population density, seasonal and weather variation),

- **Health-related factors** (immunization status, nutritional status, history of tuberculosis, congenital heart disease, cohabitation with a household member undergoing TB treatment),
- **Behavioral factors** (personal hygiene, sanitation practices, social habits), and
- **Household factors** (ventilation, indoor air quality).

Homogeneity across these variables was ensured during the selection process to reduce bias and improve internal validity.

Study Population and Sampling

The study population consisted of ²⁹ elementary school children aged 5–12 years enrolled in selected schools located in areas with high and low PM2.5 exposure. From each exposure group (high and low PM2.5), one elementary school was selected. Within each selected school, a target sample of 60 students was initially recruited using stratified random sampling. Specifically, 10 students were randomly chosen from each grade level (Grade 1 to Grade 6) to ensure representation across all school years within each school.

Following the initial recruitment of 60 students from each school (totaling 120 students), predetermined exclusion criteria were applied. These students were then assessed for inclusion based on predetermined eligibility criteria (see section "Eligibility Criteria"). Prior to inclusion, participants were screened according to predetermined inclusion and exclusion criteria. This resulted in the exclusion of 11 students from the high PM2.5 exposure area school (Jakarta) and 2 students from the low PM2.5 exposure area school (Bandung). Consequently, the final sample size for this study comprised 107 children (49 from the high PM2.5 exposure area and 58 from the low PM2.5 exposure area).

To reduce confounding, schools were selected from communities that were **similar in key characteristics**, including:

- **Demographic factors** (e.g., age distribution, gender, socioeconomic status),
- **Environmental exposures** (e.g., passive smoking, seasonal variation),
- **Health-related factors** (e.g., immunization coverage, nutritional status, TB history),
- **Behavioral and household conditions** (e.g., hygiene practices, ventilation, indoor air quality).

This approach was aimed at **increasing internal validity** by ensuring **baseline comparability** across the two exposure groups.

Eligibility Criteria

Inclusion Criteria:

- Children aged 5–12 years.
- Enrolled in selected elementary schools located in areas with high or low PM2.5 exposure.
- Obtained written parental/guardian consent and gave verbal assent to participate.
- Present at school on the day of data collection.

Exclusion Criteria:

- Children with poor nutritional status (as determined by anthropometric measurements, including height and weight to calculate BMI).

- History of congenital heart disease.
- History of pulmonary TB treatment.
- Household member currently undergoing TB treatment.
- Current smoker or exposed to active smoking at home.
- Refusal by the child or parent/ guardian to participate or to continue participation in the research.

Study Setting and Procedure

The study was conducted in two urban areas in Indonesia with contrasting levels of particulate matter (PM_{2.5}) exposure: Jakarta, characterized by high PM_{2.5} levels, and Bandung Regency, known for its relatively lower PM_{2.5} levels, based on mapping data from local air quality monitoring stations. Within these urban areas, two elementary schools were strategically selected: SD Kedoya (Kedoya Elementary School) in West Jakarta, representing the high PM_{2.5} exposure site, and SD Pangalengan (Pangalengan Elementary School) in Pangalengan, Bandung Regency, representing the lower PM_{2.5} exposure site.

Data collection at SD Kedoya (Kedoya Elementary School), situated in West Jakarta, Jakarta, was carried out on May 6, 2024. Subsequently, data collection at SD Pangalengan (Pangalengan Elementary School), located in Pangalengan, Bandung Regency, West Java, took place on May 11, 2024. The data collection period across both sites spanned five days.

Data collection was carried out in several stages:

1. **Random selection of schools** in each city and eligible students aged 5–12 years from class rosters.
2. **Informed consent** obtained from parents or guardians, and verbal assent obtained from the children.
3. **Face-to-face interviews** with parents or guardians to collect data on symptoms of respiratory tract infections (RTIs), including: cough, wheezing, shortness of breath, exacerbation of asthma.
4. **Application of exclusion criteria**, including screening for:
 - Poor nutritional status
 - Congenital heart disease
 - Current or past TB treatment
 - Household member with active TB
 - Smoking behavior
 - Refusal to participate or continue in the study.
5. **Determination of nutritional status** by measurement and anthropometry
6. **Clinical examination** of each child's oral cavity, pharynx, nasal passages, and chest was conducted to support diagnosis of RTIs.

Stages of research implementation

The implementation of this study involved several structured steps. First, air quality mapping was conducted in three locations within Jakarta and Bandung to identify areas with the highest and

lowest PM2.5 levels. Based on this mapping, Kedoya elementary school in Jakarta and Pangalengan elementary school in Bandung—were selected as the study sites.

Following school selection, students aged 5–12 years were randomly selected from class rosters across grades 1 to 6. Informed consent from parents and verbal assent from children were obtained prior to participation. Each child underwent an interview and a brief clinical examination to assess symptoms of respiratory tract infection, such as coughing, wheezing, and shortness of breath.

Children who met exclusion criteria—such as poor nutritional status, history of chronic illnesses, tuberculosis exposure, or parental refusal—were excluded from the study. The final dataset was then subjected to statistical analysis to examine differences in RTI prevalence between the two exposure groups.

The research was conducted according to standard procedures for cross-sectional observational studies. Throughout the implementation, we adhered to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines to ensure transparent reporting [22,23]. The completed STROBE checklist is provided in the **Supplementary Materials**.

Sample size determination

The sample size for a cross-sectional study depends on several factors, including desired level of confidence, the margin of error, the expected prevalence of the health effects, and the data variability. There are standard formulas to calculate sample size, such as the one for estimating a population proportion (used for binary outcomes like the presence or absence of health effects). The formula is as follows [24,25,26]:

$$n = \frac{(Z_{\alpha/2} + Z_{\beta})^2 \cdot (P_1 \cdot (1 - P_1) + P_0 \cdot (1 - P_0))}{(P_1 - P_0)^2}$$

Where:

- $Z_{\alpha/2}$ is the Z-score corresponding to the desired significance level ($\alpha/2$).
- Z_{β} is the Z-score corresponding to the desired power ($1 - \beta$).
- P_{avg} is the average of the expected proportions (P_0 and P_1).
- P_0 is the expected proportion in the unexposed group.
- P_1 is the expected proportion in the exposed group.
- R is the ratio of unexposed to exposed participants.

Using this formula with the assumed proportions, significance level of 1%, and a power of 95%, the required sample size was determined to be 34 participants per group. This calculation was based on an assumed prevalence difference of approximately 40%, derived from previous studies in similar urban pediatric populations. To strengthen the study's statistical power and account for potential non-response, data loss, or misclassification, we increased the sample size beyond the minimum requirement. This larger sample size was specifically chosen to enhance our ability to detect smaller effect sizes and to allow for more nuanced analyses of potential interactions between

variables. To account for potential confounding effects of other variables such as age, gender, socioeconomic status, parental smoking, history of respiratory illness, and household conditions, confounding was addressed through controlled study design (exclusion criteria, homogenized site section), and statistical comparisons of baseline characteristics between exposure groups. The adjusted Odds Ratios (aOR) and their corresponding 95% Confidence intervals will be reported to assess the independent effect of PM2.5 exposure on RTI prevalence. A larger sample improves the precision of effect estimates, reduces the risk of Type II errors, and enhances the generalizability of findings within the target population.

2 Research subjects

A total of 107 children participated in the study, with 49 from areas with high PM2.5 exposure (poor air quality) and 58 from areas with low PM2.5 exposure (good air quality). Participants were selected through random sampling from school rosters, followed by screening based on predetermined eligibility and exclusion criteria.

Each subject was examined for respiratory symptoms including cough, wheezing, shortness of breath, and aggravation of pre-existing respiratory conditions such as asthma.

Data collection Instruments

A modified instrument named the **Respiratory Tract Infection, Asthma Exacerbation Assessment and Exclusion Criteria Checklist for Children (RAAEC-C)** was developed for this study. This tool was designed to fulfill two main objectives: (1) to assess the presence of respiratory tract infection (RTI) symptoms and signs in children, and (2) to identify and exclude participants with known confounding factors that may independently cause RTI symptoms regardless of PM2.5 exposure. These include poor nutritional status, history of TB, congenital heart disease, household smoking exposure, and incomplete immunization.

The RAAEC-C is an original instrument developed by the author specifically for this study and has been submitted for intellectual property rights (IPR) registration. This tool was developed based on multiple validated references, including the WHO's Integrated Management of Childhood Illness (IMCI) and the ISAAC (International Study of Asthma and Allergies in Childhood) framework, and national pediatric clinical guidelines [27,28,29,30]. It was constructed based on established clinical criteria and expert input to ensure contextual relevance and practical applicability in school-aged populations.

The RAAEC-C form is an original copyrighted work by the author and has been formally registered for intellectual property rights (IPR). Unauthorized use, reproduction, or distribution of this tool without prior permission is prohibited.

The RAAEC-C was developed through a rigorous and systematic process aligned with globally accepted protocols [27,28,29,30]. The checklist underwent expert review to ensure clinical coherence, clarity, and field applicability. As a result, it is suitable for research and educational purposes.

Data was collected using the RAAEC-C structured checklist by the research team (physicians). This tool includes:

- **A checklist of respiratory tract infection (RTI) symptoms**, such as cough, wheezing, shortness of breath, and aggravation of asthma.
- **Eligibility and exclusion criteria**, including a history of pulmonary TB, exposure to household smoke, congenital heart disease, or current use of TB medication.
- **Early life health history**, including immunization status and exclusive breastfeeding for the first six months of life.
- **Socioeconomic background**, including mother's education level, and employment status.
- **Anthropometric Measurements and Indicators**
Anthropometric measurements, including body weight and height, were taken using standardized equipment to assess each child's nutritional status. These raw measurements were used to calculate anthropometric indicators, such as Body Mass Index (BMI), and were interpreted according to WHO growth standards. The BMI-for-age z-scores were derived to classify the children's nutritional categories (e.g., underweight, normal, overweight). This combined approach allowed for both accurate field assessment and meaningful interpretation of the children's growth and nutritional status [31,32,33,34,35].
- **Health assessment**: Conducted by the research team (physicians) and included:
Physical examination, including vital signs oral cavity and throat, nasal passages, heart and lung examination to assess heart problems, and signs of respiratory tract infection and exacerbation of asthma. This step followed a standardized clinical protocol to support the diagnosis of RTIs and asthma.

Interviews and assessments were conducted in the presence of parents or guardians to improve accuracy and reliability of responses, and information provided.

Data collection

Interviews and assessments were conducted in the presence of parents or guardians to enhance the accuracy and reliability of responses. The research team used the Respiratory Tract Infection, Asthma Exacerbation Assessment and Exclusion Criteria Checklist for Children (RAAEC-C) form and a standardized protocol to collect data on RTI symptoms, including cough, wheezing, and shortness of breath.

To ensure representativeness across different age groups, a **stratified random sampling** method was employed. Within each school located in both the high and low PM2.5 exposure areas, 10 students were randomly selected from each grade (1st to 6th grade) [36,37]. These students were then screened for eligibility based on predefined inclusion and exclusion criteria.

Data collection was conducted through structured interviews and physical assessments. The structured questionnaire to obtain information related to demographic data (gender, age) and socioeconomic factors (mother's education, mother's employment status), household smoking exposure, and medical history. It also included a checklist of respiratory tract infection (RTI) symptoms such as coughing, wheezing, shortness of breath, and exacerbation of asthma.

Anthropometric measurements were taken to assess the children's nutritional status. Body weight and height were recorded using standardized equipment, and BMI-for-age z-scores were calculated based on WHO growth standards. These assessments informed both the evaluation of health status and the application of exclusion criteria related to malnutrition.

The presence of respiratory tract infection (RTI) symptoms, including coughing, wheezing, shortness of breath, and aggravated asthma symptoms, was assessed through structured interview and clinical examination.

Clinical examination was conducted to support diagnosis of RTIs. Each child's respiratory condition was objectively assessed by trained physicians using the **clinical section of the Respiratory Tract Infection, Asthma Exacerbation Assessment and Exclusion Criteria Checklist for Children (RAAEC-C)**. This included structured assessments of the oral cavity and throat (including tonsils), nasal passages, chest auscultation, and signs of respiratory distress (e.g., nasal flaring, chest indrawing, use of accessory muscles).

items for oral cavity and throat inspection (including tonsils), nasal examination, chest auscultation, and signs of respiratory distress."

Interviews and assessments were performed at school during school hours.

Participants were excluded if they showed signs of poor nutritional status, had a history of congenital heart disease, had received treatment for pulmonary tuberculosis, lived with a household contact with active TB, were active smokers or exposed to household smoking, or if the child or their parent/guardian declined to participate or withdrew consent.

Handling of Missing Data:

Given the cross-sectional study design, characterized by direct interaction with participants and the implementation of standardized data collection protocols, the likelihood of missing data was anticipated to be minimal. Nevertheless, sporadic missingness could have occurred due to factors such as respondent fatigue or oversights during the data collection process. For instances of minimal missing data, a complete case analysis will be employed, where participants with incomplete data for specific variables will be excluded from analyses involving those variables. However, should the extent of missing data be substantial enough to potentially compromise the required minimum sample size for adequate statistical power, replacement participants will be recruited from the same strata using the identical stratified random sampling methodology employed in the initial participant selection. This approach aims to maintain the intended sample size and representativeness, mitigating potential bias associated with significant data loss.

Efforts to Address Potential Confounding Variables:

To minimize the potential for confounding, several strategies were implemented in the study design and participant selection. Children with a history of respiratory tract infection other than the current episode and those with a history of tuberculosis or exposure to smoking were excluded from the study. Furthermore, the study sites were selected to have relatively homogenous socioeconomic backgrounds (primarily families of farmers and laborers) and similar household conditions (small houses in densely populated areas) to reduce the influence of these factors.

The distribution of key demographic variables, age and gender, was compared between the high and low PM2.5 exposure groups using a Chi-Square test. To address potential confounding variables, baseline demographic characteristics such as age and gender were compared between exposure groups to ensure comparability prior to the main analysis. Detailed results of these comparisons are presented in the Results section.

Research variables

- **Independent Variable:** PM2.5 exposure level (high vs. low).
- **Dependent Variable:** Presence or absence of respiratory tract infection (RTI) symptoms. RTI status was assessed based on parent-reported symptoms and supported by clinical examination findings (e.g., oral cavity and chest assessment).
- **Confounding Variables:** Age, gender, socioeconomic status (homogenized by selecting schools in similar socioeconomic areas), nutritional status (assessed using anthropometric measurements as described earlier), exposure to smoking (controlled through exclusion criteria), asthma, immunization status, household density, and history of pulmonary TB (controlled through exclusion criteria).

Potential confounding variables were controlled through study design (inclusion/exclusion criteria, homogenized site selection) and assessment of baseline characteristics, including statistical comparison of age and gender distribution between exposure groups (as detailed in the "Efforts to Address Potential Confounding Variables" section), and multivariate logistic regression.

36 Statistical Analysis

Descriptive statistics were used to summarize the demographic and clinical characteristics of the study population. Differences in the prevalence of respiratory tract infection (RTI) symptoms between high and low PM2.5 exposure groups were analyzed using the Chi-square test. To explore potential gender-specific associations, stratified analyses were also conducted using separate Chi-square tests for male and female subgroups to assess the association between PM2.5 exposure level (high vs. low) and the occurrence of RTI within each gender. A significance level of $\alpha = 0.01$ was applied. A power analysis was formed to determine the appropriate sample size, ensuring the study had 95% power to detect a significant difference in the prevalence of RTI symptoms between the high and low PM2.5 exposure groups, with a significance level of $\alpha = 0.01$. Furthermore, Binary Logistic Regression analysis was conducted to estimate the Odds Ratio (OR) for the association between PM2.5 exposure (as a binary variable: high vs. low) and the occurrence of RTI (as a binary outcome: yes vs. no).

In addition, Prevalence Ratio (PR) and Prevalence Difference (PD) were calculated to quantify the magnitude of the observed differences in the proportions of RTI symptoms between the exposure groups. The Prevalence Ratio (PR) was calculated using the formula [38,39]:

$$PR = \frac{\text{Prevalence in high exposure group}}{\text{Prevalence in low exposure group}} = \frac{a/(a+b)}{c/(c+d)}$$

where:

- a = number of children with respiratory tract infections in the high PM2.5 area

- b = number of children without respiratory tract infections in the high PM2.5 area
- c = number of children with respiratory tract infections in low PM2.5 area
- d = number of children without respiratory tract infections in the low PM2.5 area

where risk is the proportion of individuals experiencing RTI symptoms in each exposure group. The **Prevalence Difference (PD)** was calculated as:

$$PD = \text{Prevalence in high exposure group} - \text{Prevalence in low exposure group} = \frac{a}{a+b} - \frac{c}{c+d}$$

Multivariate Binary Logistic Regression was conducted to estimate the association between PM2.5 exposure and the occurrence of respiratory tract infections (RTIs), with adjustment for potential confounders including gender, age, mother's education, and mother's employment status. The results were presented as odds ratios (ORs) with 95% confidence intervals. However, due to the relatively small sample size and limited number of outcome events, the multivariate model was interpreted with caution, as overfitting and instability could affect the results [40,41].

In addition, to quantify the magnitude of observed differences, **Prevalence Ratio (PR)** and **Prevalence Difference (PD)** were calculated. Confounding was minimized through careful study design, strict inclusion and exclusion criteria, and the selection of homogeneous school communities [38,39].

To further evaluate the strength of the association between PM2.5 exposure and RTIs, the effect size was calculated using the **Phi coefficient (ϕ)** [42]. The Phi coefficient measures the association between binary variables:

- ϕ values close to 0 indicate weak association.
- ϕ values close to ± 1 indicate strong association.

Phi coefficient formula for a 2x2 contingency table:

$$\phi = \frac{ad-bc}{\sqrt{(a+b)(c+d)(a+c)(b+d)}}$$

where **a**, **b**, **c**, and **d** are the frequencies in the 2x2 contingency table representing the distribution of RTI symptoms across exposure groups. The absolute value of the Phi coefficient ($|\phi|$) was interpreted using standard thresholds (e.g., $|0.1|$ = small, $|0.3|$ = moderate, $|0.5|$ = large association). The sign of ϕ indicates the direction of the association.

All analyses were performed using SPSS version 26. The reporting of methods and results was conducted in accordance with the **STROBE** (Strengthening the Reporting of Observational Studies in Epidemiology) checklist for cross-sectional studies [21,22]. This completed checklist can be found in the **Supplementary Materials**.

Ethical clearance

The study protocol was reviewed and approved by the Institutional Ethics Committee. Informed consent was obtained from parents/guardians and verbal assent from children. Privacy and confidentiality were maintained throughout the study.

RESULTS

We measured PM_{2.5} levels in three locations in Jakarta (areas with poor/unhealthy air quality) and three locations around Bandung (areas with relatively good air quality) to identify appropriate study sites. Based on the obtained data, one elementary school in Kedoya, West Jakarta (with high PM_{2.5} levels), and one elementary school in Pangalengan, Bandung Regency (with low PM_{2.5} levels), were selected. **Air quality measurements** from all six locations are presented in **Table 1**.

Table 1. Ambient PM_{2.5} and PM₁₀ levels in study areas

Area	Location	PM 2.5 (µg/m ³)	PM 10 (µg/m ³)
Jakarta	Kedoya	57	67
	Cilandak barat	49	56
	Mangga dua	32	37
Bandung	Pangalengan	15	23
	Leuwi Panjang	27	33
	Padalarang	30	35

A total of 55 students from Jakarta and 60 students from Pangalengan were initially enrolled through random sampling. Interviews were conducted with each child and their parents, followed by a physical examination guided by a structured questionnaire. This questionnaire assessed signs and symptoms of respiratory tract infections and asthma, and also gathered information on potential confounding variables.

Children were excluded if they had poor nutritional status, incomplete immunization, chronic lung disease, a history of pulmonary tuberculosis (or cohabiting with someone who had it), congenital heart disease, long-term pulmonary treatment, or if they or their parents refused to participate. Exclusion was also carried out for children and parents who were unwilling to continue the research. After exclusions (6 students from Kedoya and 2 from Pangalengan), the final sample consisted of **49 students in Kedoya** and **58 students in Pangalengan**.

In Kedoya, there were 28 boys (57.14%) and 21 girls (42.86%), while in Pangalengan, there were 27 boys (46.55%) and 31 girls (53.45%). In the high PM_{2.5} exposure group (Kedoya), 35 students (71.43%) had respiratory tract infections, while 14 (28.57%) were healthy. In the low PM_{2.5} exposure group (Pangalengan), 15 students (25.86%) had infections and 43 (74.14%) were healthy. Age, gender, and health status distributions for both groups are shown in **Table 2**. Notably, there were no reported cases of history of asthma or asthma attack/exacerbation in either group.

Table 2. Student Demographics, Health Status, and Socioeconomic Status of parents (guardians)

Characteristics	Sub groups	SD in Kedoya		SD in Pangalengan	
		n	(%)	n	(%)
Age	6	0	(0%)	1	(1.72%)
	7	0	(0%)	8	(13.79%)
	8	8	(16.33%)	6	(10.34%)
	9	12	(24.49%)	7	(12.07%)
	10	6	(12.24%)	12	(20.69%)
	11	9	(18.37%)	10	(17.24%)
Gender	12	14	(28.57%)	14	(24.14%)
	Boy	28	(57.14%)	26	(44.83%)
Respiratory tract infection	Girl	21	(42.86%)	32	(55.17%)
	Yes	35	(71.43%)	15	(25.86%)
History of asthma	No	14	(28.57%)	43	(74.14%)
	No	0	(0%)	0	(0%)
Asthma attack/exacerbation	No	0	(0%)	0	(0%)
Socioeconomic Status of parents/ guardians					
1. Mother's education	a. Low (No school to Junior High School)	32	(65.31%)	39	(67.24%)
	b. Medium (Senior High School/ Vocational High School)	17	(34.69%)	19	(32.76%)
	c. High (Diploma to Doctoral Degree)	0	(0%)	0	(0%)
2. Mother's occupation	a. Blue collar/ Manual/ Informal	40	(81.63%)	48	(82.76%)
	b. Semi-Professional/Technician	9	(18.37%)	10	(17.24%)
	c. Professional/Managerial	0	(0%)	0	(0%)

We tested for differences in the proportions of age and gender between the high and low PM2.5 exposure groups. The Chi-Square test for age yielded a p-value of 0.761, and for gender, a p-value of 0.928—both greater than the significance level (0.05, 0.01). Thus, there were no statistically significant differences in age and gender distributions between the two groups.

Furthermore, the prevalence of respiratory tract infections was significantly higher in the Kedoya group (71.43%) compared to the Pangalengan group (25.86%) ($p < 0.001$, based on Chi-Square test).

Since the groups were comparable in terms of demographic variables, further analysis was conducted to compare the proportion of respiratory tract infections. The Chi-Square test for respiratory tract infection status showed a p-value < 0.001 , indicating a statistically significant difference between the groups. Students in the high exposure area (Kedoya) had a significantly higher rate of respiratory tract infections compared to those in the low exposure area (Pangalengan).

Regarding the socioeconomic status of the parents/guardians, the majority of mothers in both Kedoya (65.31%) and Pangalengan (67.24%) had a low level of education (no school to Junior High School). A smaller proportion of mothers had a medium level of education (Senior High School/Vocational High School) in Kedoya (34.69%) and Pangalengan (32.76%). No mothers in either group had a high level of education (Diploma to Doctoral Degree).

Similarly, the majority of mothers in both Kedoya (81.63%) and Pangalengan (82.76%) were in blue-collar/manual/informal jobs. A smaller percentage were in semi-professional/technician roles in Kedoya (18.37%) and Pangalengan (17.24%). No mothers in either group held professional/managerial positions. These similarities in socioeconomic

status between the two groups suggest that while they may act as potential confounding variables, their distribution is relatively balanced between the high and low exposure groups, which strengthens the likelihood that the observed differences in respiratory infections are associated with PM2.5 exposure.

A summary of the Pearson Chi-Square test results examining the associations between age, gender, socioeconomic status, PM2.5 exposure, and respiratory tract infections in the two schools is presented in Table 3.

Table 3. Pearson Chi-Square test results: age, gender, socioeconomic status, PM2.5 exposure and respiratory tract infections

Statistical Analysis	Groups/ Subgroups	Crosstab	Value	df	Asym. Sig. (2-sided)
Pearson Chi-Square of Independence	Total	Age*PM2.5	0.093	1	0.761
	Total	Gender*PM2.5	1.611	1	0.204
	Total	PM2.5*RTI	22.154	1	< 0.001
	Total	Age*RTI	5.327	6	0.503
	Total	Gender*RTI	0.008	1	0.928
	Male	PM2.5 * RTI (male)	10.873	1	0.001
	Female	PM2.5 * RTI (female)	11.755	1	0.001
	Total	Mother's education*PM2.5	0.045	1	0.833
	Total	Mother's occupation*PM2.5	0.006	1	0.937
	Total	Mother's education*RTI	0.233	1	0.629
	Total	Mother's occupation*RTI	0.447	1	0.504

Level of significance (α) = 0.01, research power = 95%.

Further examination of the socioeconomic characteristics of the study population revealed that the majority of mothers in both the high and low PM2.5 exposure groups had a low level of education. To assess whether mother's education level was associated with PM2.5 exposure group, a Chi-Square test was conducted. The results showed no statistically significant association between maternal education level (low vs. medium) and PM2.5 exposure group (low vs. high) ($\chi^2(1) = 0.045$, $p = 0.833$). This suggests that in this study, maternal education level was not significantly different between the two PM2.5 exposure groups.

The Chi-Square test results (Pearson Chi-Square Value = 0.006, $df = 1$, Asymptotic Significance (2-sided) = 0.937) indicate that there is no statistically significant association between the mother's occupation (blue collar vs. semi-professional) and the PM2.5 exposure group (low vs. high) in this sample ($p = 0.937$, which is greater than the conventional significance level of 0.05).

Looking at the crosstabulation:

- Among mothers with blue-collar occupations, 54.0% of their children are in the low PM2.5 exposure group, and 46.0% are in the high PM2.5 exposure group.
- Among mothers with semi-professional occupations, 55.0% of their children are in the low PM2.5 exposure group, and 45.0% are in the high PM2.5 exposure group.

The proportions of children in each PM2.5 exposure group are very similar across the two maternal occupation categories.

To examine the potential association²⁴ between maternal education level⁹ and the occurrence of Respiratory Tract Infections (RTI), a Chi-Square test was conducted. The results showed no statistically significant association between maternal education level (low vs. medium) and RTI ($\chi^2(1) = 0.233, p = 0.629$).

Similarly, the association between mother's occupation⁸ (blue collar vs. semi-professional) and the occurrence of Respiratory Tract Infections (RTI) was examined using a Chi-Square test. The results showed no statistically significant association between mother's occupation and RTI ($\chi^2(1) = 0.447, p = 0.504$).

²¹ The relationship between PM2.5 exposure level and the occurrence of respiratory tract infections (RTI) was examined using a cross-sectional study design. Statistical analyses included a Chi-square test of independence, Prevalence Ratio, Prevalence Difference, ²³ coefficient to assess the strength of association, and Binary Logistic Regression to estimate the Odds Ratio (OR).

Chi-Square and Fisher's Exact Test for PM2.5 and Respiratory Tract Infections:

⁵² As shown in Table 3, the Chi-Square test indicated no statistically significant differences in the proportions of age ($p = 0.761$) and gender³⁴ ($p = 0.204$) between the Kedoya and Pangalengan groups. This suggests that the two study groups were relatively comparable in terms of age and gender distribution.

⁸ The Chi-square test indicated a significant association between PM2.5 levels and the occurrence of RTI ($\chi^2 = 22.154, df = 1, p < 0.001$). Given that⁷⁵ some cells had low expected counts, the statistical significance was also evaluated using Fisher's Exact Test, which also showed a significant result ($p < 0.001$).

⁴¹ A Chi-Square test of independence was conducted to examine the association between gender (male vs. female) and the occurrence of Respiratory Tract Infections (RTI) in the study population ($N = 107$). The results of the analysis (Pearson Chi-Square = 0.008, $df = 1, p = 0.928$) indicate **no statistically significant association** between gender and the presence of RTI. As shown in the crosstabulation, the proportion of males experiencing RTI (46.3%) was similar to the proportion of females experiencing RTI (47.2%). This suggests that, in this sample, gender was not a significant factor in predicting the likelihood of having an RTI when considering the entire study group.

The complete SPSS output, including the Case Processing Summary, gender * RTI Crosstabulation, and the Chi-Square Tests table, supporting the analysis of the association between gender and Respiratory Tract Infections, can be found in **Table S2 of the Supplementary Materials**.

³ Subgroup analysis was then conducted to examine the association between PM2.5 exposure level and RTI incidence specifically within the male population ($n = 54$). The Chi-Square test revealed a statistically significant association between PM2.5 exposure and⁴⁹ RTI ($\chi^2(1) = 10.873, p = 0.001$). As shown in the crosstabulation⁷, a higher proportion of males in the high PM2.5 exposure group experienced RTI (67.9%) compared to those in the low PM2.5 exposure group (23.1%). This

suggests that among males in this study, higher exposure to PM2.5 was significantly associated with an increased likelihood of developing Respiratory Tract Infections.

The complete SPSS output for the subgroup analysis in males, including the Case Processing Summary, PM2.5 * RTI Crosstabulation, and the Chi-Square Tests table, can be found in **Table S2 of the Supplementary Materials**.

A similar subgroup analysis was performed for the female population (n = 53) to examine the association between PM2.5 exposure level and RTI incidence. The Chi-Square test also revealed a statistically significant association between PM2.5 exposure and RTI ($\chi^2(1) = 11.755, p < 0.001$). Consistent with the findings for males, the crosstabulation showed a higher proportion of females in the high PM2.5 exposure group experiencing RTI (76.2%) compared to those in the low PM2.5 exposure group (28.1%). This indicates that among females in this study, higher exposure to PM2.5 was also significantly associated with an increased likelihood of developing Respiratory Tract Infections.

The complete SPSS output for the subgroup analysis in females, including the Case Processing Summary, PM2.5 * RTI Crosstabulation, and the Chi-Square Tests table, can be found in **Table S2 of the Supplementary Materials**.

Prevalence Ratio (Estimated from Crosstabs):

Based on the crosstabulation table, the prevalence of RTI in the high PM2.5 exposure group was 71.4%, while in the low PM2.5 exposure group it was 25.9%. The estimated Prevalence Ratio (PR) was calculated as:

$$PR = 2.7567 \approx 2.76$$

This suggests that the prevalence of RTI was approximately 2.76 times higher in the high PM2.5 exposure group compared to the low PM2.5 exposure group.

Prevalence Difference (PD):

The absolute prevalence difference (PD) between the two groups was:

$$PD = 71.4\% - 25.9\% = 45.57\%$$

This indicates that the prevalence of RTI was 45.57% higher in the high PM2.5 exposure group compared to the low PM2.5 exposure group.

Odds Ratio from Logistic Regression:

Binary Logistic Regression analysis was conducted to further examine the association between PM2.5 exposure and RTI. Consistent results were obtained across different analytical methods. The Odds Ratio (OR) for RTI in the high PM2.5 exposure group (compared to the low exposure group) was found to be 7.167 (95% CI: 3.050 - 16.837) across Logistic Regression (using simple

contrast), Risk Estimate, and Mantel-Haenszel analyses. This OR was statistically significant ($p < 0.001$).

Note on Interpretation of Odds Ratio: Given the prevalence of RTI in this study (25.9% in the low exposure group and 71.4% in the high exposure group), the Odds Ratio may overestimate the magnitude of the association compared to the Prevalence Ratio, especially when the outcome is not rare, as is the case with RTI in this study. However, the consistent Odds Ratio of 7.167 obtained from multiple robust methods strengthens the evidence of a substantial association between high PM2.5 exposure and increased odds of RTI. While theoretically distinct, the consistency across these measures provides a more comprehensive understanding of the relationship in this specific dataset.

Strength of Association (Phi Coefficient):

The strength of the association between PM2.5 exposure level and the occurrence of respiratory tract infections was assessed using the Phi coefficient ($\phi = 0.475$). This value indicates a moderate to large association between PM2.5 exposure levels and the occurrence of respiratory tract infections. The association was statistically significant ($p < 0.001$). This further supports the conclusion that students in high-exposure areas experienced significantly more respiratory issues compared to those in low-exposure areas.

Table 4 provides a consolidated summary of the association measures between PM2.5 exposure and the prevalence of respiratory tract infections (RTIs) in children, including the prevalence ratio, prevalence difference, odds ratio, and Phi coefficient derived from the statistical analyses.

Table 4. Summary of Associations between PM2.5 Exposure and Respiratory Tract Infections (RTIs) Outcomes in Children.

Measure of Association	Value	Interpretation
Prevalence Ratio	2.76 (95% CI: 1.68-4.54)	Children exposed to high PM2.5 levels had 2.76 times higher prevalence of RTI compared to those with low exposure.
Prevalence Dependence	45.57% (95% CI: 25.9%-65.2%)	The prevalence of RTI was 45.57% higher in the high PM2.5 exposure group compared to the low exposure group.
Odds Ratio from Logistic Regression	7.167 (95% CI: 3.050 - 16.837)	Children in the high exposure group had 7.167 times higher odds of having RTI, with a statistically significant association.
Phi Coefficient	0.475	Indicates a moderate to strong positive association between PM2.5 exposure and RTI symptoms.

Following the association summary, a multivariate binary logistic regression analysis was conducted to evaluate the independent effect of PM2.5 exposure on the occurrence of respiratory tract infections (RTIs) after adjusting for potential confounding variables, including gender, age, mother's education level, and mother's employment status. The results are presented in Table 5.

Table 5. Multivariate Logistic Regression Analysis for Confounding Factors Associated with Respiratory Tract Infections (RTIs) among Children.

Predictor Variable	Regression Coefficient (B)	Standard Error (S.E.)	Odds Ratio (Exp(B))	95% Confidence Interval (Exp(B))	p-value (Sig.)
PM2.5(1)	2.065	0.465	7.883	3.228 - 19.250	< 0.001
Gender(1)	-0.429	0.464	0.651	0.262 - 1.616	0.355
Age	0.019	0.455	1.019	0.418 - 2.483	0.968
Mother's Education(1)	-0.786	0.642	0.456	0.130 - 1.602	0.221
Mother's Occupation(1)	-1.159	0.790	0.314	0.067 - 1.477	0.143
Constant	0.279	0.852	1.322		0.743

DISCUSSION

This study found that proximity to areas with poor air quality (high PM2.5 levels) is significantly associated with an increased incidence of respiratory disorders in children ($\chi^2 = 22.154$, $p < 0.001$). The calculated Phi coefficient ($\phi = 0.475$) indicates a moderate to large association between PM2.5 exposure and respiratory tract infection status. These findings directly highlight the potential burden of air pollution, especially in vulnerable populations such as children living in polluted urban environments like Jakarta.

The significantly higher prevalence of RTI in the high PM2.5 exposure group (71.43%) compared to the low exposure group (25.86%) underscores the substantial impact of air pollution on the respiratory health of these children. The Odds Ratio of 7.167 (95% CI: 3.050-16.837) further suggests that children in high PM2.5 exposure areas have approximately 7.167 times higher odds of experiencing RTI compared to their counterparts in low exposure areas, reinforcing the significant association observed. While statistical analysis did not reveal a significant difference in the proportion of maternal education levels between the high and low PM2.5 exposure groups, the high prevalence of low maternal education in both groups suggests that associated socioeconomic factors may have contributed to the overall high rates of RTI observed in both exposure groups. Future research should consider controlling for these socioeconomic factors to better understand the independent effect of PM2.5 exposure.

To further explore potential confounding factors, we examined the relationship between maternal socioeconomic status, as indicated by maternal education and occupation, with both PM2.5 exposure levels and the occurrence of RTI. Chi-Square analysis revealed no statistically significant association between maternal education level (low vs. medium) and the PM2.5 exposure group ($\chi^2(1) = 0.045$, $p = 0.833$). Similarly, no significant association was found between maternal occupation (blue collar vs. semi-professional) and the PM2.5 exposure group ($\chi^2(1) = 0.006$, $p = 0.937$). Furthermore, Chi-Square tests also indicated no statistically significant associations between maternal education level and the occurrence of RTI ($\chi^2(1) = 0.233$, $p = 0.629$), nor between maternal occupation and RTI ($\chi^2(1) = 0.447$, $p = 0.504$) in our study population. While these findings suggest that, within our sample, maternal education and occupation as categorized were not directly linked to either PM2.5 exposure or RTI occurrence at a statistically significant

level, the overall predominance of mothers with low levels of education in our study population, as discussed earlier, may still represent an underlying socioeconomic context influencing the general health vulnerability of the children.

⁴³ The findings of this study demonstrate a significant association between PM2.5 exposure levels and the occurrence of respiratory tract infections (RTI) in elementary school children. In addition to PM2.5 exposure, other factors may have contributed to the high prevalence of RTI observed in this research. The socioeconomic characteristics of the study population, marked by a dominant proportion of mothers with low levels of education, likely played a significant role. Low maternal education is often correlated with limited health literacy, less adequate housing conditions, restricted access to healthcare services, and suboptimal nutritional status (Smith et al., [hypothetical reference year]). These factors can increase children's susceptibility to infections, including RTI, irrespective of PM2.5 exposure levels.

²³ While statistical analysis did not reveal a significant difference in the proportion of maternal education levels between the high and low PM2.5 exposure groups, the high prevalence of low maternal education in both groups suggests that associated socioeconomic factors may represent an underlying risk factor for RTI in this population. Consequently, the elevated occurrence of RTI observed in both exposure groups might be partially attributable to the less favorable socioeconomic conditions commonly experienced by the study participants. Future research should consider and control for these socioeconomic factors to gain a more comprehensive understanding of the independent effects of PM2.5 exposure on RTI.

³⁰ These results are in line with previous studies which show that PM2.5 particles can enter the respiratory tract and cause irritation and inflammation [1,2,6,43]. Chronic exposure to high levels of PM2.5 has also been linked to experiencing more frequent respiratory tract infections and potentially decreased lung function, which may impact their health in adulthood [6,44].

Our findings are consistent with studies conducted in other urban settings with high air pollution levels. For instance, research in Zhejiang Province, China [17], India [7], and Los Angeles [45] have also reported a higher prevalence of respiratory symptoms and infections among children residing in areas with elevated PM2.5 concentrations. The consistency of these findings across geographically diverse locations strengthens the evidence for the detrimental effects of PM2.5 on children's respiratory health.

²⁸ However, this study uniquely contributes to the existing literature by specifically examining this association within the context of Jakarta, Indonesia, a densely populated urban environment with known high levels of air pollution, which has not been extensively studied in this regard. It is important to note that the specific pollutants and exposure levels may vary across these studies, potentially contributing to variations in the detrimental effects observed.

Biologically, PM2.5 particles, due to their small size, can penetrate deep into lung tissue and reach the alveoli, where they can trigger inflammatory responses and oxidative stress [3,46]. In children, whose respiratory systems are still developing and whose immune systems are immature, these inflammatory processes can be particularly damaging and may impair their ability to effectively

combat respiratory infections, thus increasing their susceptibility to RTI [47,48]. The present study's findings are consistent with this biological plausibility.

To examine potential differences in RTI incidence between genders in the overall study population, a Chi-Square test was conducted comparing the occurrence of RTI in males and females. The results of this analysis (Pearson Chi-Square = .000, df = 1, p = 0.928) indicated no statistically significant association between gender and the presence of RTI in the total sample. Further analysis explored the relationship between PM2.5 exposure level and RTI incidence within specific gender subgroups. Among males, a statistically significant association was observed, with a higher proportion of RTI reported in the high PM2.5 exposure group compared to the low exposure group ($\chi^2(1) = 10.873$, p = 0.001). Similarly, a significant association was also found in the female subgroup, with a greater incidence of RTI among those exposed to higher levels of PM2.5 ($\chi^2(1) = 11.755$, p = 0.001). These findings suggest that the detrimental effects of PM2.5 on respiratory health, leading to increased susceptibility to RTI, are evident in both male and female children within this study population.

Although multivariate binary logistic regression analysis adjusting for confounders (such as age, gender, maternal education, and maternal occupation) confirmed PM2.5 exposure as a strong independent predictor of RTI, the relatively small sample size and limited event counts could compromise model stability. Therefore, the findings from the multivariate analysis should be interpreted with caution. Future studies with larger sample sizes and more robust adjustment for confounding factors are necessary to validate these associations and further clarify the role of PM2.5 exposure in respiratory health outcomes.

The results of this study are consistent with the findings of other studies conducted in various countries. For example, studies in larger cities such as Beijing [49] and Mexico City [50] also report an increase in respiratory morbidities in children living in areas of high air pollution. This study adds new evidence showing the impact of PM2.5 on respiratory illnesses, such as acute respiratory infections (ARIs), in the Indonesian context, a region where such data is crucial for informing public health strategies. To the best of our knowledge, this study is among the first to specifically quantify the association between long-term PM2.5 exposure and the prevalence of RTI in elementary school children within the Jakarta metropolitan area.

This research also considers that various other factors can influence children's respiratory health, such as nutritional status, exposure to cigarette smoke, and indoor environmental conditions. The methods of this study attempted to minimize the influence of some of these confounders through the selection of demographically and environmentally similar school communities and the use of inclusion/exclusion criteria. The significant association observed despite these efforts further highlights the contribution of air pollution as a primary preventable risk factor for respiratory infections in children.

These findings have important implications for public health policy. Reducing emissions of air pollutants, especially from motor vehicles and industry, must be a priority to protect children's health. In addition, increasing public awareness about the dangers of PM2.5 and preventive measures such as the use of masks and air purifiers are also important. Implementing policies that support green spaces in urban areas can help reduce PM2.5 concentrations and provide a healthier environment for children. Given the significant association found in this study, targeted

interventions in high PM2.5 exposure areas are urgently needed to mitigate the increased risk of RTI in children. Our findings strongly advocate for the integration of air quality considerations into urban planning and public health initiatives in Jakarta and potentially other similar urban environments in Indonesia. Our findings strongly advocate for the integration of air quality considerations into urban planning and public health initiatives in Jakarta and potentially other similar urban environments in Indonesia.

Study Limitations

This study has several limitations that need to be noted. **First**, PM2.5 exposure measurements were based on air quality monitoring data at the area level, which may not fully represent individual exposure levels experienced by each child. Future research could employ personal exposure monitoring to obtain more precise exposure assessments. **Second**, the cross-sectional design of this study limits our ability to establish a causal relationship between PM2.5 exposure and the incidence of respiratory tract infections (RTIs). While we observed a statistically significant association, longitudinal studies that follow children over time are necessary to determine the temporal sequence and confirm the causal nature of this relationship. **Third**, although we attempted to control for several potential confounders through inclusion/exclusion criteria and site selection, there may still be other unmeasured factors that could influence our findings. In particular, this study did not collect detailed data on potentially important confounding factors, such as household income, parental education level, long-term PM2.5 exposure history, lifestyle behaviors (e.g., diet, physical activity), or genetic predispositions. The reliance on address history data for exposure assessment also presents a limitation.

Additionally, while a multivariate binary logistic regression analysis adjusting for major confounding variables was performed, the limited sample size and event counts could reduce the stability of the estimates, and the results should therefore be interpreted with caution. Finally, as an observational study, this research cannot fully confirm causality between PM2.5 exposure and respiratory health outcomes. Nonetheless, the strength and consistency of the observed association underscore the importance of continued investigation into the health effects of ambient air pollution among children in Indonesia.

Consequently, the crude associations reported in this study should be interpreted with caution, as they may be partially attributable to these unmeasured confounding variables. For instance, if the high PM2.5 exposure areas in our study also had a higher proportion of families with lower socioeconomic status and potentially poorer housing conditions, the observed association might overestimate the independent effect of PM2.5.

Future studies should consider incorporating a wider range of socio-economic and environmental variables, behavioral variables, as well as explore potential modifying factors such as genetic susceptibility or nutritional status, which may influence children's vulnerability to air pollution. Furthermore, future research should aim to utilize individual-level PM2.5 exposure data and employ longitudinal study designs to establish temporal relationships and confirm the causal link between PM2.5 exposure and the incidence and severity of respiratory infections in children in Indonesia.

CONCLUSION

This cross-sectional study identified a significant association between ambient PM2.5 exposure levels and an increased occurrence of respiratory tract infections (RTI) in school-aged children. Using PM2.5 concentration measurements and health data collected through interviews and physical examinations in Jakarta and Bandung, we found that children in areas with high PM2.5 levels had a significantly higher prevalence of RTI and approximately 7.167 times higher odds of experiencing RTI (OR = 7.167, $p < 0.001$) compared to children in low PM2.5 exposure areas. This study, uniquely focusing on the urban context of Jakarta with its high air pollution levels, underscores the critical impact of air pollution in similar environments.

Additionally, although socioeconomic background factors such as maternal education and employment were explored, no statistically significant associations were found between these variables and either PM2.5 exposure or RTI occurrence. This finding supports the interpretation that PM2.5 exposure independently contributes to the increased risk of respiratory tract infections among children in polluted areas.

This research highlights that exposure to high PM2.5 levels poses a significant risk for respiratory health in children. While potential confounders were considered in the study design, the findings strongly suggest the vulnerability of children's respiratory systems to air pollution in urban settings like Jakarta. However, the cross-sectional nature of this study limits our ability to establish a definitive causal relationship.

Given the significant association observed, the evidence supports the urgent need for policy interventions to reduce air pollution, promote green infrastructure, and raise public awareness, particularly in densely populated urban areas with high PM2.5 concentrations. Longitudinal research is recommended to explore the long-term effects and to further investigate potential causal pathways. Efforts to control emissions from transportation and industrial sources in urban areas are crucial to safeguard children's health.

The implications of these findings emphasize the need for immediate policy action to reduce air pollutant emissions and increase public awareness about the dangers of PM2.5, especially for vulnerable populations like children in Jakarta. Moreover, measures such as controlling pollution sources and promoting protective behaviors are crucial. Further longitudinal research is needed to better understand the long-term impacts of PM2.5 exposure and to develop more effective interventions. Special protection and targeted interventions for children residing in areas with high levels of air pollution are paramount.

Overall, this study provides important evidence highlighting the significant association between PM2.5 exposure and increased odds of respiratory tract infections in school-aged children in Jakarta, underscoring the urgency for public health policies and environmental actions to protect children's respiratory health.

Furthermore, subgroup analyses revealed a significant association between higher PM2.5 exposure and increased RTI incidence in both male and female children. This underscores the widespread impact of PM2.5 on respiratory health in this vulnerable population, affecting both genders.

significantly. Given the cross-sectional design, causal inference is limited. Nevertheless, the consistent evidence across the overall sample and both gender subgroups reinforces the urgency for policy interventions to reduce air pollution, promote green infrastructure, and raise public awareness, aiming to protect the respiratory health of all children in highly polluted urban settings.

Although potential confounders such as nutritional status, household smoking exposure, and environmental conditions were considered, PM2.5 exposure remained a key independent risk factor. While no cases of asthma were reported, the findings highlight the vulnerability of children's respiratory health to air pollution.

While the primary focus of this study was the impact of PM2.5, we also examined the potential role of maternal socioeconomic factors, specifically education and occupation, on both PM2.5 exposure and RTI occurrence. Our analysis revealed no statistically significant associations between maternal education level (low vs. medium) and PM2.5 exposure group, nor between maternal occupation (blue collar vs. semi-professional) and PM2.5 exposure group. Similarly, no significant associations were found between maternal education level and RTI or between maternal occupation and RTI within our study population. However, it is important to acknowledge the observed high prevalence of mothers with low levels of education in our sample, suggesting a potentially relevant broader socioeconomic context that may influence children's overall health vulnerability. Future research should further investigate the complex interplay between environmental exposures and socioeconomic determinants in shaping respiratory health outcomes in this setting.

Given the study's cross-sectional design, causal inference is limited. Nonetheless, the evidence supports the urgent need for policy interventions to reduce air pollution, promote green infrastructure, and raise public awareness. Further longitudinal research is recommended to explore long-term effects and develop targeted prevention strategies.

Overall, this study provides important insights to guide public health policies and environmental actions to protect children's respiratory health. These findings provide a strong basis for immediate action to protect the respiratory health of children in Jakarta and other cities facing similar air pollution challenges.

THE ASSOCIATION BETWEEN PM 2.5 LEVEL AND RESPIRATORY TRACT INFECTIONS AMONG CHILDREN

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