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Association Between $PM_{2.5}$ Exposure and Anemia Among Junior High School Students in Citeureup, Bogor

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ABSTRACT

Exposure to particulate matter with an aerodynamic diameter of ≤2.5 µm ($PM_{2.5}$) is an environmental health concern that may be associated with anemia among adolescents. This study aimed to determine the association between $PM_{2.5}$ exposure and anemia among junior high school students in Citeureup District, Bogor Regency, in 2024. The study included 95 students in grades VIII and IX from four junior high schools in Citeureup. Data were analyzed using univariate, bivariate, and multivariate analyses. Multiple logistic regression was used to assess the association between $PM_{2.5}$ exposure and anemia after controlling for potential confounding variables. The bivariate analysis showed that $PM_{2.5}$ concentration (p=0.026), gender (p=0.007), and body mass index (BMI) (p=0.016) were significantly associated with anemia. In the multivariate analysis, $PM_{2.5}$ concentration was significantly associated with anemia (p=0.003; OR=0.140; 95% CI: 0.039-0.505) after controlling for heme and non-heme iron consumption, consumption of iron absorption enhancers, and physical activity. Heme iron consumption was also significantly associated with anemia in the final model (p=0.023; OR=4.239; 95% CI: 1.225-14.670). The study found a significant association between $PM_{2.5}$ exposure and anemia among junior high school students in Citeureup District, Bogor Regency, in 2024. Further studies with longer-duration $PM_{2.5}$ monitoring are needed to better characterize exposure patterns and their association with anemia.

Keywords: Anemia; Junior high school students; $PM_{2.5}$.

INTRODUCTION

Outdoor air pollution is a major environmental health concern that affects populations in both developed and developing countries. According to data from the World Health Organization (WHO), the global annual mean concentration of $PM_{2.5}$ reached 26.06 µg/m³ (95% uncertainty interval: 25.06-27.12 µg/m³) in 2023. This concentration was more than five times higher than the WHO Air Quality Guideline for annual mean $PM_{2.5}$ concentrations of 5 µg/m³, highlighting the continued high level of exposure to fine particulate matter globally (WHO, 2026).

Particulate matter with an aerodynamic diameter of ≤2.5 µm ($PM_{2.5}$) is one of the most concerning air pollutants because of its small particle size and ability to penetrate deeply into the respiratory tract. $PM_{2.5}$ can reach the alveolar region and subsequently contribute to systemic biological responses. $PM_{2.5}$ originates from various sources, including motor vehicle emissions, industrial activities, power generation, and other combustion processes. The composition and toxicity of $PM_{2.5}$ may vary depending on its emission sources and chemical constituents. Nevertheless, $PM_{2.5}$ mass concentration remains an important indicator of population exposure to fine particulate matter and its potential health impacts (Luo et al., 2024). In Indonesia, $PM_{2.5}$ remains an important environmental health concern, particularly in areas experiencing rapid urbanization, industrialization, and high traffic density.

Beyond its established respiratory and cardiovascular effects, increasing evidence suggests that $PM_{2.5}$ exposure may also affect the hematological system. $PM_{2.5}$ exposure can induce oxidative stress and systemic inflammation, which may subsequently interfere with erythropoiesis, iron metabolism, and red blood cell homeostasis. Epidemiological evidence has increasingly suggested an association between $PM_{2.5}$ exposure and adverse hematological outcomes, including lower hemoglobin levels and anemia, particularly following prolonged exposure (Dinh et al., 2026; Fongsodsri et al., 2021). However, the findings remain heterogeneous, with some studies reporting reductions in red blood cell and hemoglobin levels following short-term $PM_{2.5}$ exposure, while others have found no consistent associations (Gao et al., 2022; Z. Li et al., 2021). Overall, although evidence increasingly supports a potential association between $PM_{2.5}$

exposure and anemia, the available epidemiological evidence remains predominantly observational and heterogeneous, limiting definitive conclusions regarding causality (Dinh et al., 2026; Fongsodsri et al., 2021).

Biologically, $PM_{2.5}$ exposure may affect hemoglobin levels through interconnected pathways involving oxidative stress, systemic inflammation, and disrupted iron homeostasis. Inhaled $PM_{2.5}$ can generate reactive oxygen species (ROS) and trigger inflammatory responses that may progress to systemic inflammation, which can impair erythropoiesis and hematopoietic function (Ma et al., 2025; Marchini, 2023; Sangkham et al., 2024). In addition, inflammatory signaling, particularly through interleukin-6 (IL-6), may increase hepcidin production and promote ferroportin degradation, thereby reducing iron availability for hemoglobin synthesis (Ma et al., 2025; Sangkham et al., 2024). $PM_{2.5}$-related oxidative stress and inflammation may also disrupt the bone marrow microenvironment and hematopoietic stem and progenitor cell function, further contributing to impaired red blood cell production (Ma et al., 2025; Yu et al., 2025). Collectively, these mechanisms provide a biological rationale for the potential association between $PM_{2.5}$ exposure and reduced hemoglobin levels.

Anemia is characterized by a hemoglobin concentration below the level required to meet the physiological needs of the body (WHO, 2025). Hemoglobin is essential for transporting oxygen from the lungs to body tissues, and reduced hemoglobin levels decrease the oxygen-carrying capacity of the blood, potentially affecting physical fitness, cognitive function, and productivity (Adriani & Fadilah, 2023; Risma et al., 2024). Among adolescents, adequate hemoglobin status is particularly important because rapid physical growth and expansion of red blood cell mass increase iron requirements, making sufficient hemoglobin status crucial during this period (Samson et al., 2022; Yeboah et al., 2024).

Previous epidemiological studies have reported associations between $PM_{2.5}$ exposure and anemia or hemoglobin levels across different populations. Evidence from 36 low- and middle-income countries showed that higher annual $PM_{2.5}$ exposure was associated with increased odds of anemia and lower hemoglobin levels among young children (Odo et al., 2023). More recently, a large dynamic cohort of 33,900 primary and secondary school students in Shanghai found that $PM_{2.5}$ exposure was associated with trajectories of low hemoglobin and an increased risk of incident anemia (Zheng et al., 2026). These findings support a potential association between $PM_{2.5}$ exposure and adverse hematological outcomes. However, previous studies have predominantly focused on young children, adults, or older populations, while evidence among adolescents, particularly junior high school students, remains comparatively limited.

In Indonesia, Bogor Regency is an important setting for investigating the potential association between $PM_{2.5}$ exposure and anemia. $PM_{2.5}$ concentrations exceeded the applicable air quality standard, increasing from approximately 30 µg/m³ in 2022 to 40 µg/m³ in 2023 (*Direktorat Pengendalian Pencemaran Udara*, 2024). Citeureup District is particularly relevant due to its industrial activities and high motor vehicle activity, being the second most heavily traveled area in Bogor Regency *(Dinas Komunikasi dan Informatika Kabupaten Bogor*, 2023). Meanwhile, hemoglobin screening among junior high school students in 2022/2023 found an anemia proportion of 61.9% in the Citeureup Community Health Center area, compared with 37.9% and 4.0% in the Tajur and Leuwinutug areas, respectively (Dinas Kesehatan Kabup*aten Bogor*, 2024). The coexistence of elevated $PM_{2.5}$ exposure potential and a substantial local burden of anemia highlights the need to investigate their potential association among junior high school students in Citeureup District.

The available literature indicates that the association between $PM_{2.5}$ exposure and anemia has been investigated in several populations, but important gaps remain. Evidence among junior high school students is still limited, and findings from other settings may not be directly applicable to Citeureup, where $PM_{2.5}$ exposure and emission sources are influenced by local traffic, industrial activities, and environmental characteristics. Furthermore, because anemia in adolescents is influenced by nutritional and lifestyle factors, the relationship between $PM_{2.5}$ exposure and anemia should account for potential confounders, including dietary iron intake, iron absorption enhancers and inhibitors, physical activity, sex, and nutritional status.

Accordingly, the novelty of this study lies in examining the association between $PM_{2.5}$ exposure and anemia among junior high school students in an industrial and high-traffic setting in Citeureup District, Bogor Regency, while accounting for relevant dietary and lifestyle factors. In addition to assessing $PM_{2.5}$ exposure, this study considers heme and non-heme iron intake, iron absorption enhancers and inhibitors, and physical activity, providing context-specific evidence on the potential contribution of environmental $PM_{2.5}$ exposure to anemia among adolescents.

Therefore, this study aimed to determine the association between $PM_{2.5}$ exposure and anemia among junior high school students in Citeureup District, Bogor Regency, while controlling for potential confounding factors. The hypothesis was that $PM_{2.5}$ exposure is associated with anemia among junior high school students in Citeureup District, Bogor Regency.

METHODS

Population and sample

The study population comprised all students in grades VIII and IX at SMP W, X, Y, and Z. The sample consisted of students in grades VIII and IX at these schools who met the inclusion and exclusion criteria. The inclusion criteria were being a student in grade VIII or IX, having attended the junior high school for at least one year, being willing to participate as a research respondent, and being present at school during data collection. The exclusion criteria were students who were menstruating at the time of the study or were ill and unable to participate in the interview. Students who were menstruating were excluded

as a measure to control for menstruation as a potential confounding factor in the assessment of anemia.

This study was conducted among junior high school students in Citeureup District, comprising two exposure groups: high and low $PM_{2.5}$ exposure. The minimum sample size was calculated using a two-sample comparison of means formula with a 95% confidence level ($\alpha = 0.05$; $Z_{1-\alpha/2} = 1.96$) and 90% statistical power ($Z_{1-\beta} = 1.28$). Based on a previous study, the expected mean hemoglobin levels were 14.87 ± 0.71 g/dL and 15.45 ± 0.87 g/dL for the two groups, respectively (Ataro et al., 2018). The calculation resulted in a minimum sample size of 30 students per group, or 60 students in total. After allowing for a 10% potential dropout, the minimum required sample size was 66 students. A total of 95 students participated in the study and were included in the analysis. The participants were selected from junior high schools located near and far from the highway, representing the high and low $PM_{2.5}$ exposure groups, respectively.

Data Collection

The sampling initially utilized stratified random sampling to meet the calculated minimum sample size of 66 respondents. The final sample consisted of 95 respondents, including additional students who participated from SMP X and SMP Z. Therefore, the final sampling approach combined stratified random sampling with accidental (convenience) sampling. The inclusion of additional respondents through accidental sampling may have introduced selection bias and is acknowledged as a limitation of this study.

Data collection using questionnaires was conducted through interviews, while anthropometric measurements were performed using digital scales and a microtoise. Data were collected by the researchers with two Bachelor of Public Health graduates, one nurse, and one officer from the Occupational Safety and Health Laboratory, Faculty of Public Health, Universitas Indonesia. Before data collection, all enumerators received training to standardize their understanding of the questionnaire and measurement procedures. Measurement instruments were checked and calibrated to ensure quality assurance. The EasyTouch GCHb device was calibrated using a control chip corresponding to the test strips.

Data on individual characteristics, including age, sex, physical activity, socioeconomic status (SES), secondhand smoke exposure, history of infection, and supplement use, were collected through interviews using a structured questionnaire. Physical activity was assessed using the second version of the standardized Global Physical Activity Questionnaire (GPAQ), developed by WHO for physical activity surveillance, covering activities at work, transportation, and recreation (WHO, 2021). Data on iron intake and consumption of iron absorption enhancers and inhibitors were collected using a Food Frequency Questionnaire (FFQ) adapted from Juliani (2011). The FFQ assessed the frequency of consumption of listed food items over a specified period, with responses recorded in daily, weekly, monthly, or yearly units and subsequently converted into weekly frequencies. The frequency of heme iron, non-heme iron, iron absorption enhancers (e.g., oranges, mangoes, and guavas), and inhibitors (e.g., tea and coffee) was categorized as "rarely" (<4 times/week) or "often" (≥4 times/week).

Measurement of $PM_{2.5}$ Exposure

Ambient $PM_{2.5}$ concentrations were measured outdoors at each school using a DustTrak instrument during students' break periods. Before each sampling session, the instrument was zero-calibrated using a zero filter to ensure measurement quality. Measurements were conducted at student activity areas for one hour during each break period, and the results were averaged for each school. Data were analyzed using TrakPro Data Analysis software and converted to estimated 24-hour exposure using the Canter Conversion Equation (P=0.17). $PM_{2.5}$ exposure was categorized using the median concentration of 151.5 µg/m³ as the cut-off point.

Hemoglobin Level Check

Hemoglobin levels were measured using the EasyTouch GCHb point-of-care testing device in May–June 2024 at four junior high schools in Citeureup District, Bogor Regency. The examination was performed by a registered nurse using capillary blood obtained from a single fingertip prick after disinfection with an alcohol swab. Before measurement, the EasyTouch GCHb was calibrated using a control chip corresponding to the test strip code, and the expiration date of the test strips was checked to ensure measurement quality. The fingertip was allowed to dry completely before blood collection to minimize potential sample dilution by alcohol. Hemoglobin concentrations were measured quantitatively using the EasyTouch GCHb according to the manufacturer's procedure.

Anthropometric measurements included body weight and height, which were used to determine Body Mass Index-for-Age (BMI-for-age) for respondents aged 5-19 years. BMI-for-age was calculated using WHO AnthroPlus, with nutritional status classified according to WHO standards as severe thinness (<−3 SD), thinness (<−2 SD), overweight (>+1 SD), and obesity (>+2 SD). The use of BMI-for-age as the sole anthropometric indicator is acknowledged as a limitation because other indicators, such as Mid-Upper Arm Circumference (MUAC), were not assessed.

Ethics approval and consent to participate

The Research and Community Engagement Ethics Committee of the Faculty of Public Health, Universitas Indonesia, granted ethical approval (approval letter number Ket-316/UN2.F10.D11/PPM.00.02/2024). Ethical principles were respected, and all participants signed an informed consent form.

RESULTS AND DISCUSSION

This study found that $PM_{2.5}$ concentrations at all junior high schools exceeded the applicable air quality standard, ranging from 120.01 µg/m³ at SMP X to 159.92 µg/m³ at SMP Z. The highest temperature, heat index, and wind speed were recorded at SMP W (40.53°C, 53.35°C, and 0.62 m/s, respectively), while the highest humidity and air pressure were recorded at SMP X (54.78% and 745.44

mmHg, respectively). The lowest temperature and heat index were recorded at SMP X (36.03°C and 45.11°C, respectively) and the lowest humidity at SMP W (46.38%), whereas the lowest air pressure and wind speed were recorded at SMP Y (739.87 mmHg and 0.41 m/s, respectively) (Table 1).

Table 1. Outdoor Environmental Conditions

Parameters	Measurement Results			
	Junior High School Located Near The Highway		Junior High School Located Far From The Highway	
	W	X	Y	Z
$PM_{2.5}$ (µg/m³)	153.51	120.01	151.47	159.92
Date	21/05/2024	22/05/2024	27/05/2024	28/05/2024
Time	09:55 AM	10:06 AM	09:51 AM	10:02 AM
Duration	60 minutes	60 minutes	60 minutes	60 minutes
Temperature (°C)	40.53	36.03	39.46	37.65
Humidity (%)	46.38	54.78	47.86	53.36
Heat Index (°C)	53.35	45.11	50.98	49.51
Air pressure (mmHg)	745.03	745.44	739.87	742.65
Wind speed (m/s)	0.62	0.55	0.41	0.52

Most respondents were 14 years old (41.1%; 39 students), followed by those aged 15 years (38.9%). The age range was wider among students attending junior high schools far from the highway (13-17 years) than among those attending schools close to the highway (13-15 years). Overall, male students predominated (56.8%; 54 students). However, the gender distribution differed by school location, with male students predominating in schools far from the highway (70.4%), while female students predominated in schools close to the highway (61.0%) (Table 2).

Overall, most students were non-anemic (75.8%) and had a normal Body Mass Index (BMI) (73.7%). The prevalence of anemia was higher among students attending schools located near the highway compared with those attending schools located farther from the highway (36.6% and 14.8%, respectively). Similarly, the proportion of students with an abnormal BMI was higher among those attending schools near the highway than among those attending schools farther from the highway (39.0% and 16.7%, respectively). Most students had adequate physical activity levels (70.5%), with similar proportions among students attending schools near the highway (73.2%) and those attending schools farther from the highway (68.5%) (Table 2).

Table 2. Age, Gender, Anemia, BMI, and Physical Activity Distribution of Respondents Based on Junior High School Location

Variables	Junior High School Located Near The Highway		Junior High School Located Far From The Highway		Total	
	n	%	n	%	n	%
Age						
13 years old	5	12.2	10	18.5	15	15.8
14 years old	19	46.3	20	37.0	39	41.1
15 years old	17	41.5	20	37.0	37	38.9
16 years old	-	-	3	5.6	3	3.2
17 years old	-	-	1	1.9	1	1.1
Gender						
Female	25	61.0	16	29.6	41	43.2
Male	16	39.0	38	70.4	54	56.8
Anemia						
Anemia	15	36.6	8	14.8	23	24.2
Non-Anemic	26	63.4	46	85.2	72	75.8
Body Mass Index (BMI)						
Abnormal BMI	16	39.0	9	16.7	25	26.3
Normal BMI	25	61.0	45	83.3	70	73.7
Physical Activity						
Inadequate	11	26.8	17	31.5	28	29.5
Adequate	30	73.2	37	68.5	67	70.5

The average age of respondents was 14.33 years, ranging from 13 to 17 years. Among respondents attending junior high schools close to the highway, the age ranged from 13 to 15 years. The 95% confidence interval for the overall mean age was 14.16–14.49 years. Furthermore, the average $PM_{2.5}$ concentration in junior high schools far from the highway was 156.48 µg/m³, with a minimum of 151.47 µg/m³ and a maximum of 159.92 µg/m³. In junior high schools close to the highway, the average $PM_{2.5}$ concentration was 131.45 µg/m³, ranging from 120.01 to 153.51 µg/m³. $PM_{2.5}$ concentrations in both groups exceeded the applicable air quality standard (Table 3).

Respondents attending junior high schools far from the highway had a mean hemoglobin level of 13.49 g/dL, ranging from 10.10 to 17.00 g/dL, whereas those attending schools close to the highway had a mean hemoglobin level of 12.48 g/dL, ranging from 8.60 to 16.70 g/dL. The mean hemoglobin levels in both groups were within the non-anemic category (≥12 g/dL) (Table 3).

Table 3. The Age, $PM_{2.5}$ Concentration, and Hemoglobin Level by Junior High School Location

Variables	n	Junior High School Located Near The Highway	n	Junior High School Located Far From The Highway	n	Total	Data Normality
Age (year)							
Mean ± SD	41	14.29±0.680	54	14.35±0.914	95	14.33±0.818	Normal
Median		14.00		14.00		14.00	
Min-Max		13-15		13-17		13-17	
95% CI		14.08-14.51		14.10-14.60		14.16-14.49	
$PM_{2.5}$ Concentration (µg/m³)							
Mean ± SD	41	131.45±16.08	54	156.48±4.19	95	145.68±16.59	Not normal
Median		120.01		159.92		151.5	
Min-Max		120.01-153.51		151.47-159.92		120.01-159.92	
95% CI		126.37-136.53		155.33-157.62		142.30-149.06	
Hemoglobin Level (g/dL)							
Mean ± SD	41	12.48±2.08	54	13.49±1.57	95	13.05±1.87	Normal
Median		12.70		13.50		13.00	
Min-Max		8.60-16.70		10.10-17.00		8.60-17.00	
95% CI		11.82-13.13		13.06-13.92		12.67-13.43	

Multivariate logistic regression showed a statistically significant association between $PM_{2.5}$ exposure and anemia ($p = 0.003$), with an OR of 0.140 (95% CI: 0.039–0.505). Students exposed to $PM_{2.5}$ concentrations >151.5 µg/m³ had lower odds of anemia compared with those exposed to concentrations ≤151.5 µg/m³, after controlling for heme iron consumption (chicken eggs), non-heme iron consumption (green beans, cassava, fermented soybean cake (*oncom*), and tofu), consumption of iron absorption enhancers (melon and guava), and physical activity (Table 4).

Table 4. Final Model of Multivariate Analysis

Variables	B	p value	OR	95% CI	
				Lower	Upper
$PM_{2.5}$ Concentration	-1.963	0.003	0.140	0.039	0.505
Physical Activity	0.823	0.199	2.277	0.650	7.977
Fermented soybean cake (*Oncom*) Consumption	-3.326	0.053	0.036	0.001	1.038
Melon Consumption	2.253	0.196	9.514	0.314	288.547
Green Beans Consumption	20.562	0.999	851061039.8	0.000	-
Cassava Consumption	21.175	0.999	1570618732	0.000	-
Tofu Consumption	0.405	0.626	1.499	0.294	7.641
Guava Consumption	0.768	0.421	2.156	0.332	13.991
Chicken Egg Consumption	1.444	0.023	4.239	1.225	14.670

This study demonstrated a significant association between ambient $PM_{2.5}$ exposure and anemia status among junior high school students. Interestingly, multivariate analysis revealed an inverse association, with students exposed to $PM_{2.5}$ concentrations above 151.5 µg/m³ having lower odds of anemia than those exposed to concentrations ≤151.5 µg/m³ (OR = 0.140, 95% CI: 0.039–0.505), after adjustment for potential confounding factors. This finding contrasts with previous epidemiological evidence generally suggesting that higher $PM_{2.5}$ exposure is associated with an increased risk of anemia (Acharya & Bhatta, 2026; He et al., 2023; X. Li et al., 2025). Several explanations may account for this unexpected inverse association.

Demographic distribution played a significant role; the majority of respondents in the high-exposure schools were males, who physiologically maintain higher baseline hemoglobin levels (above 12 g/dL) due to androgenic stimulation of erythropoiesis (Mancera-Soto et al., 2021; Murphy, 2014). The observed $PM_{2.5}$ exposure reflects short-term ambient concentrations measured at the school rather than chronic personal exposure. Acute environmental stressors may induce a temporary physiological compensation mechanism, such as transient hemoconcentration, which elevates hemoglobin readings before any chronic depletion occurs (Fongsodsri et al., 2021). Robust nutritional intake or general baseline health in this specific demographic may have acted as a biological buffer, temporarily mitigating the acute oxidative stress induced by the pollution (George et al., 2025; Lee et al., 2024).

Importantly, the presence of normal hemoglobin levels among some students despite relatively high $PM_{2.5}$ exposure does not necessarily indicate an absence of biological effects. In this study, mean hemoglobin levels remained within the non-anemic range in both exposure groups, at 13.49 g/dL in the group farther from the highway and 12.48 g/dL in the group near the highway, despite differences in anemia prevalence. This may reflect individual differences in susceptibility and other determinants of hemoglobin status, including sex, nutritional status, dietary iron availability, and physical activity, which may not be fully captured by school-level ambient $PM_{2.5}$ measurements.

The inverse association observed in this study does not negate the biological plausibility that long-term $PM_{2.5}$ exposure may adversely affect the hematological system. Mechanistic and epidemiological evidence suggests that $PM_{2.5}$ exposure may initiate oxidative stress and

inflammatory responses in the lungs, which can progress to systemic inflammation and disrupt iron homeostasis and erythropoiesis (Dinh et al., 2026; Elbarbary et al., 2020; Honda et al., 2017). Inhaled $PM_{2.5}$ can induce reactive oxygen species (ROS) and pro-inflammatory mediators, including IL-6, TNF-α, and IL-1β, through several inflammatory signaling pathways (Liao et al., 2025; Park et al., 2024; Thangavel et al., 2022). Increased IL-6 may stimulate hepatic hepcidin production, which promotes ferroportin degradation, reduces intestinal iron absorption, and limits iron availability for erythropoiesis (Bhattarai et al., 2024; He et al., 2023).

Furthermore, oxidative stress and persistent inflammation may impair hematopoietic stem cell and erythroid progenitor function in the bone marrow, potentially reducing erythropoiesis and hemoglobin production (Ma et al., 2025; Yu et al., 2025). Therefore, the absence of the expected positive association in this study may reflect the context of exposure rather than contradicting the established biological mechanisms, as hematological effects may differ according to exposure duration, particle characteristics, and population characteristics (Elbarbary et al., 2020; Fongsodsri et al., 2021; Q. Zhang et al., 2026).

The discrepancy in exposure levels, where schools located farther from the highway recorded a higher average $PM_{2.5}$ concentration (156.48 μg/m³) than schools located near the highway (131.45 μg/m³), highlights the complex dynamics of local air pollution. This finding suggests that $PM_{2.5}$ concentrations may not be determined by proximity to major roads alone, but also by local emission sources, pollutant transport, and meteorological conditions. During the measurement period, active garbage burning was observed near the school located farther from the highway, which may have contributed to the elevated $PM_{2.5}$ concentration at this location. Open waste burning has been reported as an important local source of $PM_{2.5}$ and can produce substantial increases in particulate concentrations over a relatively small spatial area (Krecl et al., 2021; Peter & Nagendra, 2021).

In addition, meteorological conditions can influence the dispersion and accumulation of $PM_{2.5}$, particularly through wind speed, temperature, and humidity (X. Zhang et al., 2022). In this study, the school farther from the highway had a lower wind speed (0.41 m/s) compared with the school near the highway (0.62 m/s). Lower wind speeds can restrict pollutant dispersion and promote the accumulation of fine particles near the surface, whereas higher wind speeds may enhance pollutant dispersion and dilution. Therefore, the higher $PM_{2.5}$ concentration observed at the school farther from the highway may reflect the combined influence of localized emission sources, particularly waste burning, and less favorable dispersion conditions, rather than traffic proximity alone.

Regarding sociodemographic factors, this study found no significant association between age and anemia. This finding may be explained by the relatively narrow age range of the respondents, as most participants were adolescents at a similar stage of biological development, potentially limiting variation in growth and hematological requirements. A similar finding was reported among students in a pesantren in Situbondo, where age was not significantly associated with anemia (Nurhasanah, 2026). In contrast, gender showed a strong and statistically significant association with anemia, with female students having 4.297 times higher odds of experiencing anemia than male students. This finding is consistent with evidence identifying female sex and menstruation as important risk factors for adolescent anemia (S. Li et al., 2022; Wiafe et al., 2023). Adolescent girls have greater iron requirements partly because of menstrual blood loss, while androgen-related stimulation of erythropoiesis contributes to higher hemoglobin levels in males (Braat et al., 2024). Thus, the higher odds of anemia among female students in this study are biologically plausible and may reflect the combined influence of menstrual iron loss and sex-related differences in erythropoiesis.

Body Mass Index (BMI) was also significantly associated with anemia in this study, with students with abnormal BMI having 3.798 times higher odds of experiencing anemia compared with those with normal BMI. This finding is consistent with studies among Indonesian adolescents showing significant associations between BMI or BMI-for-age and anemia, particularly among underweight adolescents (Aghadiati et al., 2025; Fauziah et al., 2024). Abnormal nutritional status may reflect inadequate intake or availability of essential nutrients, including iron, folate, vitamin B12, and vitamin C, which are required for erythropoiesis and hemoglobin synthesis (Kusbandiyah et al., 2024; Rahmatina et al., 2025). Conversely, excess adiposity may contribute to impaired iron metabolism through chronic low-grade inflammation and hepcidin-mediated reductions in iron absorption and utilization (Rahmatina et al., 2025; Yunita et al., 2024). Therefore, the higher odds of anemia among students with abnormal BMI may indicate the importance of nutritional status in maintaining adequate iron availability and hematological health.

Physical activity was not significantly associated with anemia in this study, consistent with several studies among school-aged adolescents (Patrisia et al., 2025; Pibriyanti et al., 2021). This lack of association may be related to the relatively homogeneous activity levels of the respondents, which were predominantly within the light-to-moderate range and may not have been sufficient to produce physiological changes that substantially affect hemoglobin concentrations. Exercise-induced hemolysis is more commonly observed during prolonged endurance exercise or repeated mechanical impact and is generally mild and transient (Lippi & Sanchis-Gomar, 2019). Overall, the findings suggest that gender and nutritional status were more strongly associated with anemia in this study, as reflected by the higher odds among female students (OR = 4.297) and those with abnormal BMI (OR = 3.798), whereas age and physical activity showed no significant associations. This pattern supports the importance of considering menstrual status and nutritional adequacy when addressing anemia among adolescents.

Dietary intake of heme and non-heme iron was not significantly associated with anemia in this study. The lack of association between heme iron consumption and anemia may be related to its low frequency of consumption, as the majority of respondents consumed heme iron sources less than four times per week. Although heme iron has substantially higher bioavailability, with approximately 15-35% absorbed compared with only 1-10% of non-heme iron, its contribution to total dietary iron is generally relatively small (Kalman et al., 2025; Piskin et al., 2022; Skolmowska et al., 2022). Consequently, the respondents appeared to rely more heavily on non-heme iron sources, including tofu, green beans, cassava, and green leafy vegetables. The absorption of non-heme iron is considerably lower and is strongly influenced by dietary components such as phytate and polyphenols, as well as food processing practices (Skolmowska et al., 2022). Therefore, the absence of a significant association may reflect the relatively homogeneous dietary pattern and limited variation in the frequency and amount of iron-rich food consumption among respondents, rather than indicating that dietary iron is irrelevant to anemia.

Similarly, consumption of iron absorption enhancers was not significantly associated with anemia. Although vitamin C is an important enhancer of non-heme iron absorption by reducing ferric iron (Fe^{3+}) to the more readily absorbed ferrous form (Fe^{2+}), its effectiveness depends on sufficient intake and consumption close to iron-containing meals (Skolmowska et al., 2022). In this study, most respondents consumed iron absorption enhancers less than four times per week, and the amount consumed and its synchronization with iron-rich meals may have been insufficient to produce a measurable effect on hemoglobin status. This interpretation is consistent with findings among adolescent girls in Indonesia showing that vitamin C intake was not significantly associated with iron status when vitamin C-rich foods were not consumed simultaneously with iron sources (Gunec, 2023; Rahfiludin et al., 2021). Thus, the frequency of consumption alone may not adequately capture the potential contribution of dietary enhancers to iron bioavailability.

The consumption of tea and coffee, which contain polyphenols and tannins that can inhibit non-heme iron absorption, also showed no significant association with anemia in this study. Specifically, tea consumption ($p = 0.893$) and coffee consumption ($p = 0.107$) were not significantly related to anemia. This finding may be explained by the relatively infrequent consumption of these beverages, with 64.2% of respondents rarely consuming tea and 83.2% rarely consuming coffee (less than four times per week). In addition, the inhibitory effect of tea and coffee is strongly influenced by timing, with the greatest effect occurring when consumed with or close to meals (Gunec, 2023). Similar findings have been reported among adolescent girls in Depok, where tea and coffee consumption were not significantly associated with anemia (Fitripancari, 2023). Overall, the findings suggest that dietary factors affecting iron status may be better understood through the overall composition, bioavailability, amount, and timing of food consumption rather than the frequency of individual food groups alone.

Several limitations of this study should be acknowledged. The cross-sectional design does not allow causal relationships between $PM_{2.5}$ exposure and anemia or nutritional status to be established, as exposure and outcomes were assessed at the same time. Ambient $PM_{2.5}$ measurements were conducted for one hour at each school and at varying times, which may not capture daily variations in air pollution. In addition, school ambient measurements may not fully represent individual exposure because exposure at home and during commuting was not assessed. An unexpected localized emission event involving open waste burning near one of the schools located far from the highway may also have temporarily influenced the $PM_{2.5}$ measurement at that location.

The use of accidental sampling for additional participants may have introduced selection bias if students who volunteered differed systematically from those who declined to participate. Dietary data were collected using a self-reported Food Frequency Questionnaire (FFQ), which may be subject to recall bias due to inaccurate reporting of food consumption frequency. Furthermore, the FFQ was adopted from a previous source that did not provide information on its validity and reliability. Therefore, the measurement properties of the instrument could not be independently confirmed in this study, which may have introduced measurement error in the assessment of dietary intake. Nutritional status was assessed using BMI-for-age as the sole anthropometric indicator, while other nutritional indicators were not assessed.

CONCLUSIONS

Ambient $PM_{2.5}$ exposure was significantly associated with anemia among junior high school students in Citeureup District, Bogor Regency. The observed association was inverse, indicating that students exposed to higher ambient $PM_{2.5}$ concentrations had lower odds of anemia. This finding should be interpreted cautiously because the cross-sectional design does not establish a causal relationship, and school-based ambient $PM_{2.5}$ measurements may not fully represent individual exposure. Gender and BMI were also associated with anemia, while age, physical activity, iron consumption, and consumption of iron absorption enhancers and inhibitors were not significantly associated with anemia. The association between $PM_{2.5}$ exposure and anemia remained after adjustment for relevant dietary and physical activity factors, suggesting that $PM_{2.5}$ exposure may be an important factor associated with anemia in this population.

SUGGESTION

Based on the findings, a comprehensive and multi-sectoral approach is recommended to mitigate the health impacts of $PM_{2.5}$ exposure on adolescents. The local government and environmental agencies should enhance cross-sector coordination to enforce air quality regulations and regularly monitor ambient air near schools, particularly those adjacent to industrial zones. Concurrently, health and

education offices need to collaborate in expanding School Health Units (UKS) and empowering youth health cadres to conduct routine anemia screenings and promote balanced, iron-rich dietary habits among students. At the community level, residents are encouraged to wear masks outdoors, utilize public transportation to reduce emissions, and ensure adequate nutrition at home. Finally, future studies should implement continuous 24-hour ambient $PM_{2.5}$ monitoring and conduct comprehensive red blood cell examinations to better evaluate the risk of anemia in exposed populations.

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