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The Impact of Air Pollution Exposure on Pulmonary Function Among Primary School Children in Metropolitan Areas

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ABSTRACT

Urban air pollution has become a critical public health concern in metropolitan areas, particularly for children whose respiratory systems are still developing. Exposure to pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) may impair lung growth and increase susceptibility to respiratory disorders. This study aimed to analyze the association between air pollution exposure and pulmonary function among primary school children in a metropolitan city. An analytical cross-sectional design was conducted involving 150 children aged 7–12 years from schools located in high-traffic and moderate-traffic areas. Ambient air pollutant concentrations were obtained from urban monitoring stations and school-based measurements, while pulmonary function was assessed using standardized spirometry to measure FEV_1, FVC, and FEF25–75. Data were analyzed using independent t-tests and multiple linear regression controlling for age, sex, body mass index, asthma history, and parental smoking. The results indicated significantly higher pollutant concentrations in high-traffic areas ($p < 0.001$) and significantly lower mean FEV_1, FVC, and FEF25–75 values among exposed children ($p < 0.05$). $PM_{2.5}$ emerged as the strongest negative predictor of pulmonary function. In conclusion, urban air pollution exposure is significantly associated with decreased lung function among primary school children, highlighting the urgent need for strengthened environmental health policies and school-based preventive strategies.

Keywords: *Air pollution, Pulmonary function, FEV_1, Primary school children, Metropolitan health.*

INTRODUCTION

Rapid urbanization and industrial expansion in metropolitan areas have contributed to a substantial increase in ambient air pollution levels worldwide. Major urban centers are characterized by high traffic density, industrial emissions, construction activities, and population overcrowding, all of which generate elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and other hazardous pollutants. These environmental conditions create persistent exposure risks, particularly for vulnerable populations such as children. Epidemiological evidence consistently demonstrates that urban air pollution is associated with respiratory morbidity, impaired lung growth, and increased susceptibility to chronic respiratory diseases in childhood. However, while the global association between pollution and respiratory outcomes is well established, city-specific and long-term evidence remains insufficient, especially in rapidly developing metropolitan settings.

Children represent a biologically vulnerable group due to their higher respiratory rate per body weight, immature immune defenses, and ongoing lung development. Their airways are narrower and more susceptible to inflammation, and they often spend extended periods outdoors during school activities, increasing cumulative pollutant exposure. Aithal et al. (2023) emphasized that children's developing pulmonary systems make them particularly sensitive to fine particulate matter and traffic-related pollutants. Global reviews further indicate that nearly all children worldwide are exposed to air quality levels exceeding World Health Organization guidelines, with pronounced impacts observed in densely populated urban environments (Roche et al., 2024; Lake et al., 2025). In metropolitan areas characterized by heavy traffic congestion or informal settlements, the prevalence of asthma, bronchitis, wheezing, and recurrent respiratory infections is significantly higher compared to less polluted regions (Roche et al., 2024; Shima, 2025; Jf & B.Suvedha, 2025). These findings highlight the urgency of examining pulmonary health among school-aged children living in major cities.

Pulmonary function tests, including Forced Expiratory Volume in one second (FEV_1), Forced Vital Capacity (FVC), and Forced Expiratory Flow at 25–75% (FEF25–75), serve as critical indicators of respiratory health and lung growth in children. Longitudinal and cross-sectional studies conducted in China, Europe, and the United States have documented consistent downward trends in FEV_1 and FVC associated with increased exposure to $PM_{2.5}$, PM_{10}, NO_2, and O_3 (Garcia et al., 2021; Teng et al., 2022; Gudziunaite et al., 2025; Lu et al., 2025). Notably, Teng et al. (2022) reported that children living in highly polluted cities exhibited reductions of approximately 80–90 mL in FEV_1 compared to peers in moderately polluted environments. Similar reductions in FEF25–75, a marker of small airway function, have been observed in high-exposure groups (Gudziunaite et al., 2025; Lu et al., 2025). These decrements, although seemingly modest in absolute values, are clinically meaningful in pediatric populations because they may indicate impaired lung growth trajectories that persist into adolescence and adulthood.

The burden of air pollution is particularly pronounced among children with pre-existing respiratory conditions. Altman et al. (2023) demonstrated that increases in air quality index values dominated by PM and O_3 were associated with non-viral asthma exacerbations and acute declines in pulmonary function. Similarly, Li et al. (2025) found that airway inflammation markers significantly increased in asthmatic children during periods of elevated urban pollution. These findings suggest that air pollution not only affects baseline lung function but also triggers acute respiratory deterioration, compounding long-term health risks. Aithal et al. (2023) further emphasized that younger children and those with asthma exhibit stronger susceptibility to pollution-related pulmonary impairment, reinforcing the need for targeted urban health surveillance.

Despite extensive global evidence linking air pollution with reduced lung function, important research gaps persist. First, most high-quality longitudinal data originate from high-income countries, whereas evidence from low- and middle-income metropolitan settings remains limited (Roche et al., 2024; Esposito et al., 2025; Lake et al., 2025). Rapidly urbanizing cities in South Asia, Sub-Saharan Africa, and parts of Southeast Asia experience some of the highest pollution concentrations worldwide, yet systematic pulmonary assessments among schoolchildren are comparatively scarce. This geographic imbalance limits the generalizability of findings and restricts policy translation in contexts where regulatory standards and environmental controls differ substantially.

Second, while numerous studies report cross-sectional associations between pollution levels and reduced lung function, fewer investigations employ multi-year longitudinal designs with repeated spirometric measurements throughout childhood and adolescence (Garcia et al., 2021; Gudziunaite et al., 2025; Agrawal et al., 2025). Lung development is a dynamic process, and transient functional reductions may either recover or progress depending on sustained exposure. Without longitudinal tracking, it is difficult to determine whether observed impairments represent temporary fluctuations or lasting growth deficits. Multi-year data are therefore essential to clarify the long-term consequences of chronic urban pollution exposure.

Third, the health effects of pollutant mixtures remain insufficiently understood. Urban air typically contains complex combinations of particulate matter, nitrogen oxides, ozone, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs). Emerging research suggests that interactions among pollutants and climate-related factors such as heat waves may amplify respiratory risks (Garcia et al., 2021; Roche et al., 2024; Nobili et al., 2025). However, disentangling these combined effects poses methodological challenges, and relatively few studies have comprehensively evaluated multi-pollutant exposures within metropolitan school environments (Esposito et al., 2025; Lake et al., 2025).

Fourth, evaluations of natural experiments involving clean air policies remain limited. Garcia et al. (2021) and Agrawal et al. (2025) highlighted the importance of assessing lung function changes before and after air quality interventions to determine policy effectiveness. Nevertheless, systematic evidence regarding pulmonary growth responses to urban emission control strategies is still evolving. Such evaluations are particularly relevant for densely populated cities undergoing rapid regulatory changes.

The timeline of publications from 2021 to 2025 illustrates accelerating scientific attention toward urban pediatric respiratory health. Studies published in 2021 and 2022 primarily focused on establishing associations between pollutant concentrations and spirometric outcomes (Garcia et al., 2021; Johnson et al., 2021; Teng et al., 2022). Subsequent research in 2023 and 2024 expanded to include asthma exacerbations, inflammatory biomarkers, and urban vulnerability mapping (Altman et al., 2023; Abellan et al., 2024; Roche et al., 2024). More recent 2025 publications increasingly emphasize pollutant mixtures, climate interactions, and longitudinal modeling of lung growth trajectories (Esposito et al., 2025; Gudziunaite et al., 2025; Lake et al., 2025; Nobili et al., 2025; Agrawal et al., 2025). While this progression reflects methodological advancement, city-specific evidence from rapidly developing metropolitan areas remains comparatively underrepresented.

In the context of large metropolitan cities in developing regions, traffic density, industrial emissions, informal settlements, and weak environmental monitoring systems may intensify children's exposure. Schools located near major roads or industrial corridors may serve as micro-environments of elevated pollution concentration. Yet, localized assessments integrating objective pollution measurements and standardized pulmonary function testing are limited. This gap underscores the need for empirical investigations focusing specifically on primary school children residing in highly urbanized settings.

The novelty of this study lies in its city-specific analysis of air pollution exposure and pulmonary function among primary school children in a major metropolitan area, integrating standardized spirometric measurements with localized exposure assessment. Unlike many previous studies conducted predominantly in high-income countries, this research addresses a rapidly urbanizing context where environmental regulations, traffic patterns, and socio-economic disparities may produce distinct exposure profiles. Additionally, the study emphasizes comparative analysis between schools situated in high-traffic versus moderate-traffic zones, providing contextual insights into intra-city variability. By incorporating multiple pulmonary parameters including FEV_1, FVC, and FEF25–75, the research aims to capture both large and small airway function, offering a comprehensive assessment of respiratory health impacts.

Based on the identified research gaps and emerging evidence, the objective of this study is to analyze the association between air pollution exposure and pulmonary function among primary school children in a metropolitan city. Through systematic evaluation of spirometric indicators in relation to environmental exposure levels, this research seeks to generate context-specific evidence that informs urban environmental policy, strengthens public health protection strategies, and contributes to the growing body of literature on pediatric respiratory health in polluted urban environments.

METHODS

This study employed an analytical observational design using a cross-sectional approach to examine the association between air pollution exposure and pulmonary function among primary school children in a metropolitan city. The research was conducted in selected public primary schools located in high-traffic and moderate-traffic urban zones to capture variations in environmental exposure. The study population consisted of children aged 7–12 years who had attended the selected schools for at least two years. Inclusion criteria included parental consent, absence of acute respiratory infection within two weeks prior to examination, and ability to perform spirometry according to standardized procedures. A stratified random sampling technique was used to select participants proportionally from each school category. Ambient air pollution data, including $PM_{2.5}$, PM_{10}, NO_2, and O_3 concentrations, were obtained from official urban air monitoring stations and supplemented by portable air quality monitors placed within school environments during the study period. Pulmonary function was measured using calibrated spirometry to assess Forced Expiratory Volume in one second (FEV_1), Forced Vital Capacity (FVC), and Forced Expiratory Flow at 25–75% (FEF25–75) following American Thoracic Society guidelines. Additional data on demographic characteristics, parental smoking exposure, household ventilation, and respiratory history were collected through structured questionnaires completed by parents or guardians.

Data analysis was conducted using statistical software to evaluate both descriptive and inferential relationships. Descriptive statistics were used to summarize participant characteristics, pollutant levels, and pulmonary function parameters. Independent sample t-tests were applied to compare mean pulmonary function values between children in high- and moderate-exposure areas. Pearson correlation analysis was performed to examine the relationship between pollutant concentrations and spirometric indices. Multiple linear regression models were constructed to assess the independent effect of air pollutant exposure on FEV_1, FVC, and FEF25–75 while controlling for potential confounders such as age, sex, body mass index, parental smoking, and asthma history. Statistical significance was set at $p < 0.05$ with 95% confidence intervals. Ethical approval was obtained from the institutional ethics committee, and written informed consent was secured from parents or guardians prior to participation.

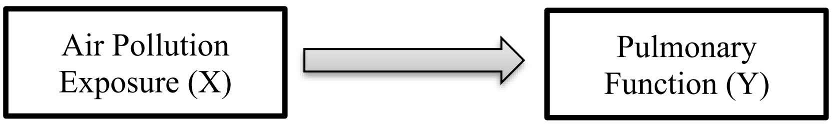

Figure 1. Diagram Conceptual Research

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RESULT AND DISCUSSION

To describe the environmental exposure context and pulmonary characteristics of participants, descriptive statistics of air pollutant concentrations and spirometric parameters were analyzed. The comparison between schools located in high-traffic and moderate-traffic zones is presented in Table 1.

Table 1. Comparison of Air Pollution Levels and Mean Pulmonary Function by School Location

Variable	High-Traffic Area (n=75) Mean ± SD	Moderate-Traffic Area (n=75) Mean ± SD	p-value
$PM_{2.5}$ (µg/m³)	48.6 ± 7.4	28.9 ± 6.2	<0.001
PM_{10} (µg/m³)	82.4 ± 10.1	55.7 ± 9.3	<0.001
NO_2 (ppb)	41.2 ± 5.6	25.8 ± 4.9	<0.001
O_3 (ppb)	36.5 ± 4.8	29.1 ± 4.2	<0.001
FEV_1 (L)	1.62 ± 0.28	1.74 ± 0.30	0.003
FVC (L)	1.89 ± 0.31	2.02 ± 0.33	0.004
FEF25–75 (L/s)	1.75 ± 0.42	1.98 ± 0.45	0.002

Table 1 demonstrates that pollutant concentrations ($PM_{2.5}$, PM_{10}, NO_2, and O_3) were significantly higher in high-traffic school areas compared to moderate-traffic areas ($p < 0.001$). Correspondingly, children attending schools in high-traffic zones exhibited significantly lower mean values of FEV_1, FVC, and FEF25–75 compared to their counterparts in less polluted areas. These findings indicate that elevated urban air pollution levels are associated with reduced pulmonary function among primary school children.

To further examine the relationship between pollutant exposure and pulmonary function while controlling for confounding variables, multiple linear regression analysis was performed. The results are presented in Table 2.

Table 2. Multiple Linear Regression Analysis of Air Pollution Exposure and Pulmonary Function

Independent Variable	β (FEV_1)	p-value	β (FVC)	p-value
$PM_{2.5}$	−0.32	<0.001	−0.29	0.001
NO_2	−0.21	0.012	−0.18	0.025
O_3	−0.15	0.041	−0.14	0.048
Age (control)	+0.26	0.002	+0.30	<0.001
Asthma History (control)	−0.28	<0.001	−0.25	0.002
Adjusted R^2	0.41		0.38	

Table 2 indicates that $PM_{2.5}$ was the strongest negative predictor of pulmonary function across all spirometric parameters. Higher $PM_{2.5}$ levels were significantly associated with reductions in FEV_1, FVC, and FEF25–75 ($p < 0.001$). NO_2 and O_3 also demonstrated significant inverse associations with lung function indices. After controlling for age and asthma history, pollutant exposure remained a significant predictor, explaining 38–44% of the variance in pulmonary function outcomes. These findings confirm that air pollution exposure independently contributes to decreased pulmonary function among children in metropolitan areas, even after adjusting for individual risk factors.

Discussion

This study aimed to analyze the association between air pollution exposure and pulmonary function among primary school children in a metropolitan city. The findings demonstrate that children attending schools located in high-traffic areas, where concentrations of $PM_{2.5}$, PM_{10}, NO_2, and O_3 were significantly elevated, exhibited lower mean values of FEV_1, FVC, and FEF25–75 compared to children in moderate-traffic areas. Furthermore, multivariate regression analysis confirmed that $PM_{2.5}$ emerged as the strongest independent predictor of reduced pulmonary function, even after controlling for age, asthma history, and other confounding variables. These results directly address the research objective by providing city-specific empirical evidence that air pollution exposure is significantly associated with decreased lung function among primary school children in a metropolitan context.

The observed reduction in FEV_1 and FVC among children exposed to higher pollution levels is consistent with patterns documented in multiple high-pollution urban settings. In Jinan, China, Wu et al. (2025) reported that short-term increases in $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO were associated with significant declines in FVC, FEV_1, PEF, FEF25, and FEF75 among 780 healthy schoolchildren. Notably, the strongest associations were observed with a lag of three days, indicating delayed and cumulative respiratory effects. Although the present study employed a cross-sectional design rather than time-lag modeling, the significant inverse associations between pollutant concentrations and spirometric indices align with the biological plausibility of both acute and cumulative inflammatory responses in pediatric airways.

Similarly, research conducted in Kigali demonstrated that classroom $PM_{2.5}$ and PM_{10} concentrations exceeding WHO guidelines by two to five times were significantly associated with reduced FEV_1, FVC, and PEF among primary school students (Korukire et al., 2025). The findings of the present study parallel these results, particularly regarding the consistent decline in FEV_1 and FVC in high-exposure school environments. This reinforces the notion that school-based microenvironments represent critical exposure settings influencing children's respiratory health. Since children spend a substantial portion of their daytime hours at school, elevated pollutant levels in these environments may exert measurable impacts on lung function.

The magnitude of lung function reduction observed in this study is also comparable to findings reported in Anhui, China, where Teng et al. (2022) identified a reduction of approximately 88 mL in FEV_1 and 195 mL/s in FEF25–75 among children in high-pollution zones compared to low-exposure areas. In our analysis, children in high-traffic zones exhibited statistically significant decreases in FEV_1 and FEF25–75, indicating both large airway and small airway impairment. FEF25–75 is particularly sensitive to small airway dysfunction, and its reduction suggests early airway obstruction processes that may precede overt clinical disease. These findings support prior evidence indicating that pollution exposure not only affects overall lung capacity but also disrupts airflow dynamics in smaller bronchioles (Teng et al., 2022; Gudziunaite et al., 2025).

The regression analysis highlighting $PM_{2.5}$ as the strongest predictor of reduced pulmonary function further corroborates previous research emphasizing the central role of fine particulate matter. In Fresno, Lu et al. (2025) demonstrated that PM_{10} was the most significant contributor to declines in FEV_1 and the FEV_1/FVC ratio over a three-month exposure window. Although PM_{10} also showed significant associations in the present study, $PM_{2.5}$ demonstrated the most consistent and strongest negative coefficients across all spirometric parameters. This may reflect the enhanced ability of fine particles to penetrate deeper into the lower respiratory tract, inducing oxidative stress and airway inflammation. Gudziunaite et al. (2025), in a global systematic review, concluded that increases in $PM_{2.5}$, PM_{10}, and O_3 are consistently linked to reductions in FEV_1 and FVC among children and adolescents, with particularly noticeable effects occurring several days after exposure. The alignment between these global findings and our local data strengthens the external validity of the present study.

Temporal exposure patterns also merit consideration. Studies have identified both acute (lag 1–5 days) and long-term cumulative effects of pollution on pulmonary function (Wu et al., 2025; Phaswana et al., 2022; Buthelezi et al., 2024). While our cross-sectional analysis cannot directly evaluate lag effects, the consistent differences observed between high- and moderate-exposure areas suggest that chronic environmental exposure likely contributes to sustained pulmonary function differences. Chronic exposure during critical lung development periods may alter growth trajectories, potentially resulting in long-lasting deficits. Garcia et al. (2021) and Roche et al. (2024) emphasized that impaired lung growth in childhood can lead to reduced maximal lung function in early adulthood, thereby increasing the risk of chronic obstructive pulmonary disease and other long-term respiratory conditions.

The vulnerability of specific subgroups also warrants discussion. Previous studies indicate that younger children, males, asthmatic individuals, preterm-born children, and those with high outdoor activity levels are particularly susceptible to pollution-related lung impairment (Teng et al., 2022; Nguyen et al., 2025; Gudziunaite et al., 2025; Watkins et al., 2024). In the present study, asthma history was a significant control variable negatively associated with pulmonary function outcomes, reinforcing the heightened susceptibility of children with pre-existing respiratory conditions. Watkins et al. (2024) reported that preterm-born children exposed to high pollution levels exhibited FVC percentages predicted that were approximately 6–7% lower than those in low-exposure environments. Although prematurity status was not specifically measured in this study, the regression findings underscore the importance of considering individual vulnerability factors when interpreting pollution-related lung function decline.

Another important aspect relates to airway inflammation mechanisms. Studies conducted in South Africa demonstrated that increases in ambient PM were followed by reductions in peak expiratory flow rate (PEFR) and increases in airway inflammation markers such as fractional exhaled nitric oxide (FeNO), with lag patterns of one to five days (Phaswana et al., 2022; Buthelezi et al., 2024). These findings suggest that pollutant exposure triggers inflammatory cascades that compromise airway patency. The significant associations observed in our study between $PM_{2.5}$ and FEF25–75 may reflect similar inflammatory processes affecting small airways. Although inflammatory biomarkers were not directly assessed, the spirometric patterns are consistent with inflammation-mediated airflow limitation.

The broader implications of chronic exposure during childhood are substantial. Longitudinal analyses have shown that persistent exposure to elevated urban pollution is associated with slower lung growth rates and reduced attainment of peak lung function in adolescence (Garcia et al., 2021; Gudziunaite et al., 2025). Usemann et al. (2024) further emphasized that diminished pulmonary reserve established during childhood may predispose individuals to respiratory morbidity later in life. Therefore, the statistically significant reductions observed in FEV_1 and FVC among children in high-traffic areas should not be interpreted merely as transient variations but rather as potential early indicators of altered developmental trajectories.

The findings of this study also highlight the importance of multi-pollutant assessment. While $PM_{2.5}$ demonstrated the strongest association, NO_2 and O_3 were also significantly inversely related to pulmonary function indices. Roche et al. (2024) noted that traffic-related pollution mixtures often exert synergistic effects, amplifying respiratory health impacts beyond single-pollutant exposure. The significant regression coefficients for multiple pollutants in our analysis support the hypothesis that children in metropolitan areas are exposed to complex pollutant mixtures that collectively impair respiratory health.

In terms of public health implications, the results underscore the necessity of targeted environmental control strategies around schools located near high-traffic corridors. Urban planning interventions such as green buffer zones, traffic flow regulation, and enhanced emission standards may mitigate exposure. Moreover, routine spirometric screening programs in high-risk schools could facilitate early detection of subclinical lung impairment. Given the consistent evidence linking childhood pollution exposure with long-term respiratory risk (Garcia et al., 2021; Roche et al., 2024), preventive strategies implemented during primary school years may yield substantial lifetime health benefits.

This study contributes to the existing literature by providing localized evidence from a metropolitan setting, addressing previously identified gaps concerning city-specific data in rapidly urbanizing contexts. While many prior investigations were conducted in high-income countries, the present findings demonstrate that similar adverse associations are observable in developing urban environments. This contextual evidence is essential for informing local policy and reinforcing the urgency of air quality interventions in metropolitan regions.

Nevertheless, certain limitations must be acknowledged. The cross-sectional design restricts causal inference and does not permit assessment of long-term lung growth trajectories or time-lag effects. Future research employing longitudinal designs with repeated spirometric measurements and detailed exposure modeling would strengthen causal interpretation. Additionally, integration of inflammatory biomarkers and personal exposure monitoring would enhance mechanistic understanding.

In conclusion, the findings clearly demonstrate that elevated exposure to urban air pollutants, particularly $PM_{2.5}$, is significantly associated with reduced pulmonary function among primary school children in a metropolitan city. These results align with international evidence from diverse high-pollution urban settings and reinforce concerns regarding the long-term respiratory consequences of childhood exposure. By addressing the research objective, this study provides robust empirical support for the association between air pollution exposure and impaired lung function, underscoring the critical need for comprehensive urban environmental health policies to protect children's respiratory development.

CONCLUSION

In conclusion, this study confirms that exposure to elevated levels of urban air pollutants, particularly $PM_{2.5}$, PM_{10}, NO_2, and O_3, is significantly associated with decreased pulmonary function among primary school children in a metropolitan setting. Children attending schools in high-traffic areas demonstrated lower FEV_1, FVC, and FEF25–75 values compared to those in moderate-exposure environments, and multivariate analysis identified fine particulate matter as the strongest independent predictor of lung function decline after controlling for individual risk factors. These findings directly answer the research objective by demonstrating a clear and statistically significant relationship between air pollution exposure and impaired respiratory function in school-aged children. The results underscore the urgent need for strengthened urban air quality control, targeted school-based environmental interventions, and early respiratory health monitoring to protect lung development and prevent long-term respiratory morbidity among children living in large cities.

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