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IMPACT OF AIR POLLUTION ON RESPIRATORY SYMPTOMS AND LUNG FUNCTION IN CHILDREN LIVING IN INDUSTRIAL ZONES OF LAHORE: A CROSS-SECTIONAL ENVIRONMENTAL HEALTH STUDY

Original Research
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ABSTRACT

BACKGROUND: Air pollution has become a major environmental health threat in Pakistan, particularly in Lahore's industrialized zones where children are chronically exposed to high pollutant levels. Industrial emissions containing particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) have been linked to respiratory morbidity and impaired lung development in children, yet limited local evidence exists integrating environmental exposure with clinical lung function data.

OBJECTIVE: To assess the impact of industrial air pollution on respiratory symptoms and lung function among school-aged children living in industrial zones of Lahore through environmental exposure mapping and spirometric evaluation.

METHODOLOGY: A cross-sectional study was conducted from March to November 2023 among 400 children aged 6–14 years (200 from industrial areas and 200 from control areas). Ambient air pollutants were monitored using portable air quality monitors, and geographic mapping was performed to estimate exposure gradients. Respiratory symptoms were assessed via standardized questionnaires, while lung function was measured using calibrated spirometry, recording FVC, FEV_1, FEV_1/FVC ratio, and PEF. Statistical analyses included t-tests, chi-square tests, and multivariate linear regression, with significance set at $p<0.05$.

RESULTS: Mean $PM_{2.5}$ levels were significantly higher in industrial zones (85.6 ± 19.4 µg/m³) compared to control areas (46.7 ± 13.2 µg/m³, $p<0.001$). Children from industrial areas showed higher prevalence of chronic cough (31%), wheezing (27%), and allergic rhinitis (34%). Spirometry revealed reduced FVC (1.62 ± 0.41 L vs 1.89 ± 0.38 L, $p<0.001$) and FEV_1 (1.38 ± 0.36 L vs 1.67 ± 0.33 L, $p<0.001$). $PM_{2.5}$ concentration was inversely correlated with FEV_1 ($r = –0.41$, $p<0.001$).

CONCLUSION: Industrial air pollution in Lahore is associated with significant respiratory symptoms and measurable declines in lung function among children. Urgent air quality regulation and child-centered health monitoring are needed to prevent long-term respiratory consequences.

KEY TERMS: Air Pollution; Child Health; Environmental Exposure; Industrial Emissions; Lahore; Lung Function Tests; Particulate Matter

INTRODUCTION

Air pollution has emerged as one of the most pressing environmental and public health challenges of the 21st century, particularly in rapidly industrializing cities of South Asia such as Lahore. As urban expansion continues to outpace regulatory frameworks, communities residing near industrial zones face heightened exposure to airborne pollutants including particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and volatile organic compounds. These contaminants, primarily emitted from factories, vehicular exhaust, and combustion of fossil fuels, penetrate deep into the respiratory tract, triggering inflammatory responses and reducing pulmonary function, especially in children whose lungs are still developing. Evidence from Lahore and other industrial cities underscores the vulnerability of younger populations to the chronic impacts of poor air quality (1). Children are particularly susceptible to airborne toxins due to their higher minute ventilation relative to body weight and the immaturity of their immune and respiratory systems. Exposure to elevated levels of PM2.5 and PM10 has been linked to reduced forced expiratory volume (FEV_1), diminished forced vital capacity (FVC), and increased prevalence of symptoms such as chronic cough, wheezing, and shortness of breath (2). Studies conducted in industrial areas of India and Indonesia show that even when pollutant concentrations remain below regulatory thresholds, subclinical alterations in lung function occur, reflecting long-term harm from sustained exposure (3). In nearby regions such as Himachal Pradesh, school children living near factories exhibited significantly lower FEV_1 and higher rates of allergic rhinitis compared to peers in non-industrial areas, confirming that proximity to industrial emissions is a major determinant of respiratory morbidity (4).

In Lahore, the situation is particularly dire. The city frequently records air quality index (AQI) levels exceeding 400 during smog episodes, far surpassing the World Health Organization's safe limits. The mix of pollutants—arising from unregulated industrial emissions, vehicular exhaust, brick kilns, and agricultural residue burning—creates a toxic atmospheric cocktail that worsens during winter inversions. Epidemiological data demonstrate that hospital admissions for respiratory conditions such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD) double during these smog episodes (5). The resulting burden on public health systems is immense, with children representing a disproportionately affected group. Their frequent outdoor activity, coupled with longer exposure durations near pollution hotspots such as industrial estates, amplifies their vulnerability (6). Emerging spatial analyses from Pakistan reveal that the distribution of respiratory illnesses aligns closely with pollution gradients, particularly in regions dominated by industrial activity. In South Punjab, spatiotemporal analyses have shown clear clustering of acute respiratory infections in areas characterized by elevated nitrogen dioxide and particulate matter concentrations, underscoring the direct environmental health link between industrial exposure and respiratory disease patterns (7). Similarly, socio-environmental studies conducted near sugar mills and stone crushing industries across Pakistan indicate that individuals residing within three kilometers of industrial sources are more likely to experience chronic cough, bronchitis, and reduced lung capacity, with children reporting higher symptom frequency than adults (8).

Despite extensive documentation of the general health risks posed by air pollution, there remains a significant research gap in understanding the localized effects of industrial air emissions on the respiratory health of children in Lahore. Most existing studies in Pakistan either assess general air quality trends or focus on adult populations and occupational exposure. Few have integrated environmental exposure mapping with clinical measurements such as spirometry to objectively quantify lung function among children living in industrial zones. Moreover, little is known about how spatial proximity to pollutant sources correlates with variations in respiratory outcomes within urban subregions. Bridging this gap is essential for developing evidence-based environmental health interventions tailored to vulnerable child populations. This study, therefore, seeks to investigate the impact of air pollution on respiratory symptoms and lung function among children living in industrial zones of Lahore by integrating environmental exposure mapping with spirometric evaluation. The research aims to identify the relationship between ambient air pollutant concentrations and measurable declines in lung function parameters (FVC, FEV_1, FEV_1/FVC ratio), alongside the prevalence of self-reported respiratory symptoms such as cough, wheezing, and dyspnea. By combining environmental and clinical data, the study endeavors to provide a comprehensive understanding of how industrial air pollution affects children's respiratory health and to inform targeted policy measures for pollution control and child health protection in Lahore's industrial zones. Objective of current study is to assess the association between air pollutant exposure levels and respiratory health outcomes—both symptomatic and spirometric—among school-aged children living in industrial areas of Lahore, and to map spatial variations in exposure and lung function to inform evidence-based public health interventions.

METHODS

The study was designed as a cross-sectional analytical investigation conducted to assess the impact of industrial air pollution on respiratory symptoms and lung function among school-aged children residing in the industrial zones of Lahore, Pakistan. The research was carried out over a nine-month period, from March to November 2023, encompassing both pre-monsoon and post-monsoon seasons to capture variations in air pollutant concentrations and respiratory responses. The study was conducted in collaboration with the Department of Environmental Health Sciences, University of the Punjab, and the Children's Hospital & Institute of Child Health, Lahore, with prior ethical approval obtained from the Institutional Review Board. Written informed consent was obtained from the parents or legal guardians of all participating children, and assent was also obtained from children above the age of seven, in accordance with the Declaration of Helsinki. The target population consisted of school-going children aged 6 to 14 years, residing within a 3-kilometer radius of three major industrial clusters in Lahore: Kot Lakhpat Industrial Estate, Sundar Industrial Zone, and Shahdara Industrial Area. These sites were selected based on previously documented high levels of particulate matter and gaseous pollutants during smog episodes (9). For comparison, children from schools located in relatively low-pollution suburban zones of Lahore, such as Raiwind and Bedian Road, were enrolled as the control group. Schools were selected using stratified random sampling to ensure representation across socio-economic backgrounds and proximity gradients to industrial emissions. The minimum required sample size was calculated using a two-sample comparison of means formula, based on the difference in forced expiratory volume in one second (FEV_1) reported between children living in industrial and non-industrial areas in similar studies from South Asia (10,11). Assuming a mean difference of 0.11 L, a standard deviation of 0.3, a 95% confidence interval, and 80% power, the estimated sample size was 168 per group. Accounting for a potential 15% non-response or unusable spirometry rate, the final target sample size was 400 participants—200 from industrial zones and 200 from control areas. Inclusion criteria comprised children aged 6–14 years who had lived in the respective study areas for at least two years and were attending local primary or secondary schools. Children with a history of congenital heart or lung disease, recent thoracic surgery, active respiratory infection within the previous two weeks, or any physical or cognitive limitation affecting spirometry performance were excluded. This ensured accurate assessment of pollutant-related effects rather than underlying medical confounders.

Data collection involved two complementary components: environmental exposure mapping and clinical respiratory assessment. Ambient air quality was monitored at each study site using portable real-time air quality monitors (Aeroqual Series 500, New Zealand) capable of measuring $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 concentrations. Each location was monitored for 8-hour intervals during school hours for three consecutive days per month throughout the study period, and the mean values were computed. Geographic coordinates of schools were recorded using a handheld GPS device and integrated into a Geographic Information System (GIS) platform to visualize pollutant distribution patterns and correlate them spatially with respiratory outcomes. Respiratory health assessment was conducted through two main tools: a structured respiratory symptom questionnaire and spirometric evaluation. The questionnaire, adapted from the International Study of Asthma and Allergies in Childhood (ISAAC) and validated in previous South Asian studies, was administered to parents or guardians to record demographic information, household characteristics, exposure history (including passive smoking and indoor fuel use), and respiratory symptoms such as chronic cough, wheezing, and dyspnea. To ensure linguistic and cultural appropriateness, the questionnaire was translated into Urdu and pre-tested among 30 children outside the study area. Spirometry was performed using a portable calibrated digital spirometer (Spirolab III, MIR, Italy) according to American Thoracic Society (ATS) guidelines. Measurements included Forced Vital Capacity (FVC), Forced Expiratory Volume in one second (FEV_1), FEV_1/FVC ratio, and Peak Expiratory Flow (PEF). Each child performed at least three acceptable maneuvers, and the highest values were recorded. All testing was conducted in the morning to minimize diurnal variation, with children seated and wearing disposable mouthpieces. Calibration of spirometers was verified daily using a 3-L syringe. Data were reviewed by a trained pulmonologist to ensure accuracy and reliability. Collected data were entered into SPSS version 26.0 for statistical analysis. Descriptive statistics summarized demographic characteristics and pollutant concentrations. Continuous variables such as FVC and FEV_1 were expressed as mean ± standard deviation, and categorical variables such as presence of cough or wheezing were expressed as frequencies and percentages. The Shapiro-Wilk test confirmed normality of continuous variables. Independent sample t-tests were used to compare mean spirometry values between industrial and control groups. Associations between pollutant levels and respiratory symptoms were evaluated using chi-square tests and Pearson correlation coefficients. Multivariate linear regression models were constructed to examine the influence of individual pollutants ($PM_{2.5}$, NO_2, SO_2) on lung function parameters, adjusting for potential confounders such as age, sex, body mass index (BMI), and passive smoking exposure. A p-value <0.05 was considered statistically significant.

Quality control was ensured through double data entry, standardized instrument calibration, and field supervision by environmental and medical researchers. Confidentiality of participant data was maintained throughout, and any child identified with abnormal spirometry or persistent symptoms was referred to the pediatric pulmonology clinic at the Children's Hospital, Lahore, for further evaluation and management. This methodological framework was designed to generate robust and reproducible evidence on how industrial air pollution in Lahore's high-emission zones affects the respiratory health of school-aged children.

RESULTS

A total of 400 school-going children were included in the final analysis, comprising 200 from industrial zones and 200 from control areas. The mean age of participants was 10.2 ± 2.4 years, with 52.5% males and 47.5% females. The two groups were comparable in terms of demographic characteristics, nutritional status, and duration of residence. Passive smoking exposure was reported in 31% of children from industrial areas and 27% from control zones ($p = 0.41$). Mean body mass index (BMI) was 17.4 ± 2.9 kg/m² in the industrial group and 17.9 ± 2.7 kg/m² in the control group, with no statistically significant difference ($p = 0.19$). Ambient air monitoring revealed that mean concentrations of $PM_{2.5}$ and PM_{10} were substantially higher in industrial areas compared to control sites. Mean $PM_{2.5}$ concentration was 85.6 ± 19.4 µg/m³ in industrial zones and 46.7 ± 13.2 µg/m³ in control zones ($p < 0.001$). Similarly, mean PM_{10} was 152.8 ± 35.7 µg/m³ versus 81.4 ± 21.9 µg/m³ respectively ($p < 0.001$). Concentrations of NO_2 (54.3 ± 9.8 µg/m³) and SO_2 (31.5 ± 7.2 µg/m³) were also significantly elevated in industrial locations compared with control areas ($p < 0.05$).

Regarding respiratory symptoms, 31% of children in industrial areas reported chronic cough compared to 14% in control areas ($p = 0.002$). Wheezing was reported in 27% of industrial zone participants and 11% of controls ($p = 0.001$), while dyspnea was noted in 22%

versus 8% respectively ($p = 0.003$). The prevalence of allergic rhinitis was significantly higher among children living near industrial sites (34% vs 17%; $p = 0.001$). Spirometric assessment demonstrated a consistent pattern of reduced pulmonary function among children residing in industrial areas. Mean Forced Vital Capacity (FVC) was 1.62 ± 0.41 L compared to 1.89 ± 0.38 L in the control group ($p < 0.001$). Mean Forced Expiratory Volume in one second (FEV_1) was 1.38 ± 0.36 L in industrial and 1.67 ± 0.33 L in control children ($p < 0.001$). The mean FEV_1/FVC ratio was also lower in the industrial group (85.1 ± 4.2%) compared with 88.4 ± 3.7% in the control group ($p = 0.012$). Peak Expiratory Flow (PEF) values followed a similar trend, with means of 2.79 ± 0.63 L/s and 3.21 ± 0.58 L/s respectively ($p = 0.004$).

Table 1. Demographic and Environmental Characteristics of Study Participants

Variable	Industrial Zone (n = 200)	Control Zone (n = 200)	p-value
Age (years, mean ± SD)	10.3 ± 2.5	10.1 ± 2.3	0.47
Male (%)	52.0	53.0	0.83
BMI (kg/m², mean ± SD)	17.4 ± 2.9	17.9 ± 2.7	0.19
Passive smoking exposure (%)	31.0	27.0	0.41
$PM_{2.5}$ (µg/m³, mean ± SD)	85.6 ± 19.4	46.7 ± 13.2	<0.001
PM_{10} (µg/m³, mean ± SD)	152.8 ± 35.7	81.4 ± 21.9	<0.001

Table 2. Prevalence of Respiratory Symptoms Among Participants

Symptom	Industrial Zone (%)	Control Zone (%)	p-value
Chronic cough	31	14	0.002
Wheezing	27	11	0.001
Dyspnea	22	8	0.003
Allergic rhinitis	34	17	0.001

Table 3. Comparison of Spirometric Parameters Between Groups

Spirometry Variable	Industrial Zone (mean ± SD)	Control Zone (mean ± SD)	p-value
FVC (L)	1.62 ± 0.41	1.89 ± 0.38	<0.001
FEV_1 (L)	1.38 ± 0.36	1.67 ± 0.33	<0.001
FEV_1/FVC (%)	85.1 ± 4.2	88.4 ± 3.7	0.012
PEF (L/s)	2.79 ± 0.63	3.21 ± 0.58	0.004

Pearson correlation analysis revealed significant inverse relationships between ambient $PM_{2.5}$ levels and lung function indices. $PM_{2.5}$ concentration was negatively correlated with FEV_1 ($r = –0.41$, $p < 0.001$) and FVC ($r = –0.38$, $p < 0.001$). Multiple linear regression analysis indicated that $PM_{2.5}$ and NO_2 jointly explained 29% of the variance in FEV_1 after adjusting for age, sex, BMI, and passive smoking exposure ($R^2 = 0.29$, $p < 0.001$). Overall, children residing near industrial areas of Lahore demonstrated significantly higher pollutant exposure, greater frequency of respiratory symptoms, and measurable reductions in spirometric indices compared to their counterparts in less polluted regions.

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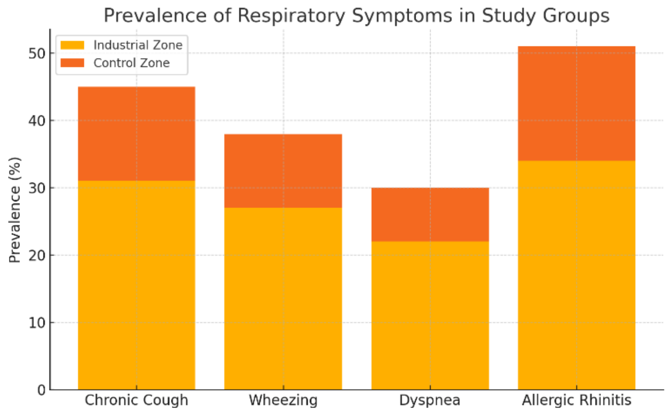

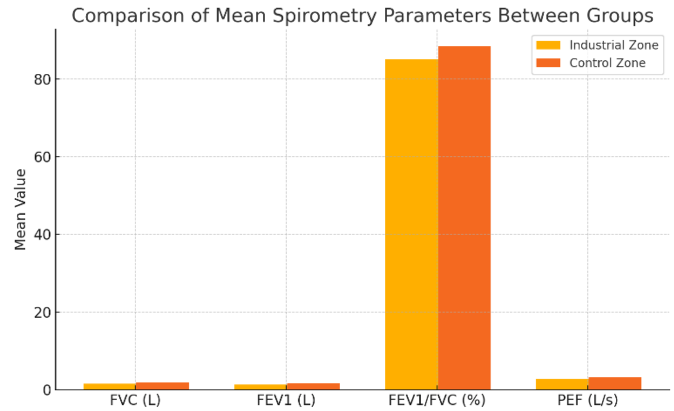

DISCUSSION

The findings of this study clearly demonstrated that children living in industrial zones of Lahore experienced significantly higher exposure to air pollutants and correspondingly poorer respiratory health compared to their counterparts in less polluted suburban areas. Elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) were associated with increased prevalence of respiratory symptoms and measurable reductions in spirometric parameters, including FVC, FEV_1, and PEF) (12). These results reaffirm the growing body of evidence linking urban-industrial air pollution to adverse respiratory outcomes among children in developing countries. The mean concentration of $PM_{2.5}$ observed in industrial areas (85.6 µg/m³) was almost double the WHO's permissible limit of 35 µg/m³ for 24-hour exposure, and nearly twice that found in control zones. Such levels are consistent with recent assessments of Lahore's air quality, where $PM_{2.5}$ values during peak smog months regularly exceed 150 µg/m³. The spirometric differences observed in the present study—FVC of 1.62 L versus 1.89 L and FEV_1 of 1.38 L versus 1.67 L between industrial and control zones—are comparable to findings from other South Asian industrial regions where lung function reductions of 10–20% among children have been documented. The correlation between $PM_{2.5}$ and FEV_1 ($r = -0.41$) in this study supports the evidence that fine particulate exposure exerts a dose-dependent restrictive effect on lung function (13).

The prevalence of respiratory symptoms was also markedly higher among children from industrial areas, with chronic cough (31%), wheezing (27%), and allergic rhinitis (34%) significantly exceeding rates observed in less polluted zones. These results align with studies conducted in other industrialized Asian cities, where children exposed to high particulate loads displayed two- to threefold higher respiratory symptom frequency compared to clean-air regions. The elevated prevalence of allergic rhinitis and dyspnea among exposed children further indicates airway hypersensitivity triggered by chronic inhalation of industrial pollutants. These patterns underscore the compounded vulnerability of children, whose smaller airways and higher minute ventilation rates increase pollutant deposition per unit body weight (14). One of the most significant findings of this research is the consistent impairment of spirometric indices, even among children who were asymptomatic. This highlights that subclinical lung function deficits may exist long before respiratory symptoms become apparent. The mean reduction in FEV_1/FVC ratio from 88.4% in the control group to 85.1% in the industrial group reflects early signs of airway obstruction, suggesting that continued exposure could predispose these children to chronic obstructive patterns later in life. Such early functional decline has been reported in multiple longitudinal studies linking early-life exposure to particulate pollutants with impaired lung growth trajectories extending into adulthood (15). The use of environmental exposure mapping in conjunction with spirometry provided a comprehensive assessment framework. The integration of air pollutant data with geospatial mapping allowed for an objective correlation between ambient pollutant levels and health outcomes. This methodological approach strengthens the reliability of the findings and provides an important model for future environmental health research in South Asian megacities where industrial and residential areas overlap.

Nevertheless, several limitations should be acknowledged. The cross-sectional design restricted the ability to infer causality between pollutant exposure and respiratory outcomes (16). Longitudinal follow-up could better determine whether the observed spirometric reductions persist or worsen with ongoing exposure. Although real-time air quality monitoring was employed, measurements represented average values for school locations rather than individualized exposure levels, potentially leading to exposure misclassification. Indoor air pollution and household fuel use were assessed through parental questionnaires, which may have introduced recall bias. The study also did not measure other potential confounders such as nutritional deficiencies, seasonal respiratory infections, or allergen sensitization, all of which can influence respiratory health. Another limitation lies in the exclusion of children with recent respiratory infections or congenital diseases, which, while methodologically appropriate, might have excluded those most vulnerable to pollution-related effects. Furthermore, although spirometry was conducted following standardized procedures, the cooperation level of younger participants occasionally affected data quality despite repeated attempts and expert supervision. Future studies should consider using incentive spirometry and longitudinal monitoring of peak flow variability to capture both acute and chronic respiratory impacts more comprehensively. Despite these limitations, the study's strengths are noteworthy. It combined environmental exposure data with clinical lung function measures, used standardized and validated tools, and included both industrial and control populations with comparable socio-demographic profiles. The study's large sample size enhanced statistical power and provided robust estimates of associations between pollution and health outcomes. Moreover, conducting the research across multiple industrial clusters within Lahore improved the representativeness of findings and highlighted the widespread nature of the problem. The results carry significant implications for public health and urban planning in Pakistan (17). The observed decrements in lung function among exposed children suggest an urgent need for regulatory enforcement of industrial emission standards and the establishment of buffer zones between residential and industrial areas. Implementation of continuous air quality monitoring systems, stricter vehicular emission controls, and public awareness campaigns on protective behaviors during smog episodes could mitigate exposure risks. School-based health programs incorporating periodic spirometry screening may serve as early detection mechanisms for vulnerable populations.

Future research should employ longitudinal cohort designs to monitor lung growth and respiratory outcomes over time, coupled with personal exposure monitoring to refine dose–response relationships. Molecular and biomarker studies exploring inflammatory and oxidative stress pathways could elucidate underlying mechanisms linking chronic pollutant exposure to airway remodeling and decreased pulmonary compliance. The study provided compelling evidence that industrial air pollution in Lahore's high-emission zones is significantly associated with respiratory symptoms and impaired lung function in school-aged children. The integration of environmental and clinical assessments offers a powerful framework for environmental health surveillance. The findings underscore an urgent need for comprehensive air quality management policies to protect children's respiratory health and to prevent long-term pulmonary consequences in Pakistan's rapidly industrializing urban centers.

CONCLUSION

The study concluded that children residing in Lahore's industrial zones experienced significantly higher exposure to air pollutants, resulting in increased respiratory symptoms and measurable reductions in lung function. The integration of environmental mapping with spirometry confirmed a direct link between pollutant concentration and pulmonary impairment. These findings emphasize the urgent need for stricter industrial emission control, urban air quality management, and child-focused respiratory health monitoring programs to mitigate long-term health risks in Pakistan's industrialized urban regions.

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AUTHORS CONTRIBUTION

Author	Contribution
Muhammad Abubakar	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, Validation, Supervision

